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Radiation Heat Transfer Environment in Fire and Furnace Tests of Radioactive Materials Packages.

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ABSTRACT

The Hypothetical Accident Conditions (HAC) sequential test of radioactive materials packages includes a thermal test to confirm the ability of the package to withstand a transportation fire event. The test specified by the regulations (10 CFR 71) consists of a 30 minute, all engulfing, hydrocarbon fuel fire, with an average flame temperature of at least 800 C. The requirements specify an average emissivity for the fire of at least 0.9, which implies an essentially black radiation environment. Alternate test which provide equivalent total heat input at the 800 C time averaged environmental temperature may also be employed. When alternate tests methods are employed, such as furnace or gaseous fuel fires, the equivalence of the radiation environment may require justification. The effects of furnace and open confinement fire environments are compared with the regulatory fire environment, including the effects of gases resulting from decomposition of package overpack materials. The results indicate that furnace tests can produce the required radiation heat transfer environment, i.e., equivalent to the postulated pool fire. An open enclosure, with transparent (low emissivity) fire does not produce an equivalent radiation environment.

INTRODUCTION

Thermal tests of prototype packages at Savannah River, including the 5320 and the GPFP, have been performed in a heat treatment furnace in N-Area. Depending on package size, the N-Area furnace is marginal for regulatory tests, but adequate for prototype tests. All subsequent regulatory tests have been pool fires at the South Carolina Fire Academy or performed at Sandia.

The effect of gaseous decomposition products from overpack materials on the radiation heat transfer environment in the N-Area furnace has been questioned. Resolution of this question is needed to evaluate the suitability of furnace tests in this facility for future packages. The purpose of this investigation is to compare the effects of the presence of the gaseous decomposition products on the radiation heat transfer to the package in various test environments.

NOMENCLATURE

- A_1 Area of Surface 1 (The package is Surface 1 in this analyses.)
- E_b Black body emissive power
- F_{12} Geometric shape factor for radiation between surface 1 and surface 2.
- T Absolute Temperature of surface or gas
- T_R Test Regulatory reference temperature, 800ºC
- q_{12} rate of radiation heat transfer between surfaces 1 and 2
- α Absorptivity
- ε Emissivity
- σ Stefan-Boltzman Constant

REGULATORY REQUIREMENTS

The Hypothetical Accident Conditions (HAC) sequential test of radioactive materials packages includes a thermal test to confirm the ability of the package to withstand a transportation fire event. The test specified by the regulations (10 CFR 71.73) consists of a 30 minute, all engulfing, hydrocarbon fuel fire, with an average flame temperature of at least 800ºC [1]. The requirements specify an average emissivity for the fire of at least 0.9, which implies an essentially black radiation environment. Alternate tests which provide equivalent total heat input at the 800ºC time averaged environmental temperature may also be employed. The requirements of 10 CFR 71 are based on the IAEA Regulations for the Safe Transport of Radioactive Materials, TS-R-1 [2]. ASTM Thermal Testing Standard E 2230 provides guidance for pool fire tests and furnace tests to satisfy the regulatory requirements [3].

Pool Fire Test

The reference thermal test envisioned by the regulations is the 800ºC pool fire. The hydrocarbon fuel, as described in TS-R-1, should be a liquid similar to kerosene or JP-4 jet engine fuel. Under pool fire conditions, such fuels burn with a sooty, luminous flame with a high emissivity. Combined with the extent (thickness) of the fire the high emissivity flame is opaque and results in a near black body radiation heat transfer environment. The guidance documents allow for the use of furnaces or use of other fuels, provided that the temperature and radiation heat transfer conditions are achieved. Open air pool fires are subject to weather and cannot be conducted in windy or rainy conditions. The fire induces significant local wind, which exacerbates the effects of any breeze which may be present.

Figure 1. Pool fire test of 9977 package.

Furnace Tests

Furnace tests are the most common alternate to the pool fire tests specified by the regulations. Principal reasons for furnace tests are convenience and state environmental restrictions, furnaces are not affected by wind gusts and other weather conditions. Both gas fired and electrically heated furnaces have been successfully employed for testing various packages. ASTM provides guidance on size of furnace for performing tests. The furnace should be sufficiently large to allow convection around the package and to insure that the package does not significantly reduce the furnace temperature when it is inserted.

Figure 2. Typical 9977 package following fire test.

The furnace employed by SRS for GPFP prototype tests was electrically heated (Figure 3) [4, 5]. Gas fired furnaces have been used for thermal test of other packages, such as the ES-3100.

During testing of packages with energy absorbing overpacks made of organic materials, heating of the overpack material typically results in discharge of gaseous decomposition products into the furnace environment. The effect of the presence of these gases on the radiation environment has not been addressed in the literature, in articles reporting furnace tests of RAM packagings.

Figure 3. Furnace test of GPFP prototype.

ANALYSIS OF THERMAL TEST RADIATION ENVIRONMENT

Reference Case, Pool Fire

The thermal test requirements are satisfied by the pool fire described in the regulations. As noted above, any other alternative thermal test must be able to produce heat transfer conditions equal to the pool fire environment. Accordingly, the pool fire environment is the reference condition against which other thermal test methods must be evaluated, Figure 1 [6, 7, and 8].

The pool fire conditions specified in the regulations address the characteristics of the flame and the dimensions of the fire, relative to the package. The minimum thickness of the flame is established by requiring the pool dimensions to exceed the package dimensions by at least one meter (but no more than three meters), and the package to be supported one meter above the pool surface. This results in a fire which is thick enough to meet the radiation heat transfer requirement, but not so thick that its interior is oxygen starved. The fuel specified and conditions of the fire result in a sooty, luminous, opaque flame, in which the soot particles are thermal radiation sources. The results is a fire in which conditions are essentially those of a black body radiation source, which completely surrounds the package. The regulations require that the package surface be assumed to have an emissivity of “that value which the package may be expected to possess if exposed to the fire specified or 0.8, whichever is greater. In practice, the surface of a package typically quickly tarnishes and becomes soot covered, so that the package emissivity is high, Figure 2.

For purposes of analysis, the flame is assumed to act as a black body at the specified flame temperature. For this analysis, the package is assumed to be a convex body, so that the radiation shape factor from the package to the surrounding enclosure or gas is one.

For a luminous flame which is sufficiently thick and sooty that it acts as an opaque black body, the expression for radiation heat transfer between the flame and the package is [9, 10, and 11]:

$$q_{f\text{-}1} = \varepsilon_1 \varepsilon_f A_1 F_{1f} [E_{bf} - E_{b1}] = \sigma \varepsilon_1 \varepsilon_f A_1 F_{1f} [T_f^4 - T_1^4]$$

where the package is denoted by subscript 1 and the flame denoted by subscript f.

The package is assumed to act as a black body (emissivity of 1.0). This is justified since, in fire tests, the surface of test packages typically become oxidized and covered with soot, Figure 2.

For the fully engulfing black fire and a black package surface, the expression above becomes:

$$q_{f\text{-}1} = A_1[E_{bf} - E_{b1}] = \sigma A_1 [T_f^4 - T_1^4] = \sigma A_1 [T_R^4 - T_1^4] \quad [1]$$

Where T_R is the flame temperature specified by the regulations, 800 ºC.

Reference Furnace

The ideal furnace completely encloses the package, is large enough that the presence of the package does not significantly reduce the radiation heat flux field present within it, and has uniform wall temperature, Figure 3.

Refractory surfaces, such as those in furnaces, have high values of emissivity (i.e., $\geq$ 0.9) and the furnace approaches an isothermal enclosure. Under these conditions, the furnace is a very good approximation to a black radiation enclosure.

At the test temperature and in the fire or furnace test environments, the emissivity of the stainless steel shell of typical RAM packages typically will exceed the regulatory minimum of $\varepsilon = 0.8$. In addition, experience has shown that soot deposits typically form on packages if the decomposition products include organic gases, Figure 4. For the purpose of comparison of test environments, this analysis assumes the package to be black ($\varepsilon = 1$).

Figure 4. Package removed from furnace at end of thermal test. Flames are burning gaseous decomposition products.

For an electrically heated furnace, without significant package outgassing, the atmosphere within the furnace can be considered transparent to radiation and non-emitting. The radiation heat transfer takes place between the two surfaces, the furnace wall and the package. The network representing this case is shown in Fig 5.

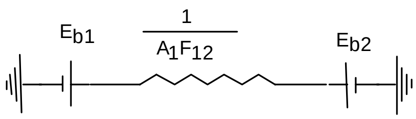

Figure 5. Equivalent radiation network for the reference furnace case.

The shape factor relationship for the rectangular furnace enclosure and convex package body is:

$$A_1F_{12} = A_2F_{21}$$

With $F_{12} = 1.0$

Where A_1 is the package area and A_2 the area of the furnace wall.

For this case

$$q_{2\text{-}1} = A_1F_{12}\,[E_{b2} - E_{b1}] = \sigma\, A_1F_{12}\,[T_2^4 - T_1^4]$$

Which reduces to

$$q_{2\text{-}1} = A_1\,[E_{b2} - E_{b1}] = \sigma\, A_1[T_2^4 - T_1^4] = \sigma A_1\,[T_R^4 - T_1^4] \quad [2]$$

Where T_R is the flame temperature specified by the regulations, 800 ºC.

It will be noted that this is the same as Equation [1], above.

Furnace with radiating gas environment

A common way of heating furnaces is by natural gas or liquefied petroleum gas burners [12]. For such furnaces, the furnace environment would consist of combustion products from the burners (in the absence of significant package outgassing). The products of combustion for these gases are carbon dioxide and water vapor, both of which are have significant absorptivity and emissivity. For this case, the radiation heat transfer analysis must consider absorption of radiant energy by the combustion products and emission of radiant energy by the combustion products. The radiation heat transfer exchange is represented by the network in Figure 6.

In Figure 6, surface 1 is the package and surface 2 the furnace wall. The gas conditions are denoted by subscript g. Since the furnace is gas fired, and the furnace preheated to the required temperature before the package is inserted, the furnace wall temperature will be close to the temperature of the gas flame.

$$T_g = T_2$$

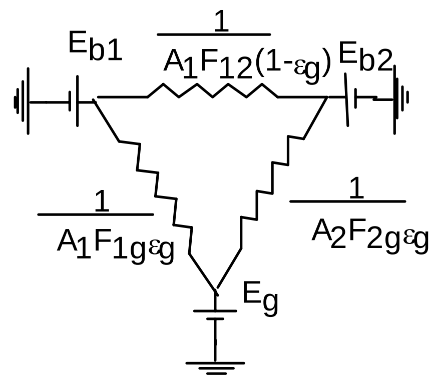

Figure 6. Equivalent radiation network for the radiating gas environment furnace case.

As a result, once the furnace is preheated to operating temperature (i.e., test temperature), the heat transfer between the flame and wall is only that required to maintain the wall temperature against loses due to conduction and colder items placed in the furnace.

The geometric shape factor between the package and the furnace is the same as for the previous, electrically heated furnace case, that is $F_{12} = 1$

The gas fully engulfs the package, so that the shape factor between the package and the gas, $F_{1g} = 1$.

From Kirchhoffs Law for Current, the radiant heat transfer to the package is the sum of the heat transfer from the enclosure and the gas.

$$q_{1total} = q_1 = q_{21} + q_{g1}$$

Where

$$q_{21} = \frac{(E_{b2} - E_{b1})}{\dfrac{1}{A_1F_{12}\,(1 - \varepsilon_g)}}$$

and

$$q_{g1} = \frac{(E_{bg} - E_{b1})}{\dfrac{1}{A_1F_{1g}\,\varepsilon_g}}$$

Substituting,

$$q_1 = A_1F_{12}(1 - \varepsilon_g)(E_{b2} - E_{b1}) + A_1F_{1g}\,\varepsilon_g\,(E_{bg} - E_{b1})$$

$$= \sigma A_1F_{12}(1 - \varepsilon_g)(T^4{}_2 - T^4{}_1) + \sigma A_1F_{1g}\,\varepsilon_g\,(T^4{}_g - T^4{}_1)$$

Recall the gas temperature is close to the furnace wall temperature for the gas fired furnace, so we assume ($T_g = T_2$).

Collecting terms:

$$q_1 = \sigma A_1 \left[F_{12}(1 - \varepsilon_g) + F_{1g}\, \varepsilon_g \right] (T^4_2 - T^4_1)$$

For $F_{12} = F_{1g} = 1$, this becomes

$$q_1 = \sigma A_1 \left[(1 - \varepsilon_g) + \varepsilon_g \right] (T^4_2 - T^4_1) = \sigma A_1 (T^4_2 - T^4_1)$$

or, if the furnace wall is at the test temperature T_R,

$$q_1 = \sigma A_1 (T^4_2 - T^4_1) = \sigma A_1 (T^4_R - T^4_1) \qquad [3]$$

This is the same as Equations 1 & 2.

Furnace with radiating gas environment where the gas is at radiation equilibrium within enclosure

If the furnace gas environment is not the result of combustion of the fuel used as the heat source for the furnace, the gases will be at in intermediate temperature at which the gases emit as much heat as they absorb. This will be the case if the furnace environment contains significant amounts of gaseous decomposition products from the package. The radiation heat transfer exchange is represented by the network in Figure 7.

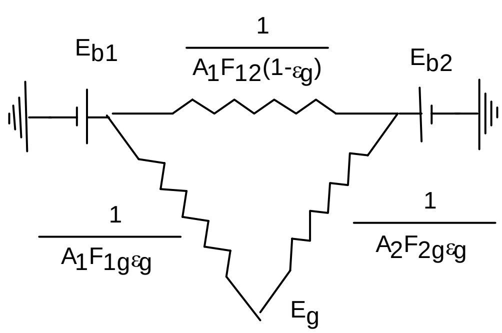

Figure 7. Equivalent radiation network for the gas at radiation equilibrium within the furnace.

In Figure 7, surface 1 is the package and surface 2 the furnace wall. The gas conditions are denoted by subscript g.

The geometric shape factor between the package and the furnace is the same as for the previous, electrically heated furnace case, that is $F_{12} = 1$. The gas fully engulfs the package, so that the shape factor between the package and the gas, $F_{1g} = 1$.

For the network shown, the equivalent overall resistance $(1/R_5)$ is

$$R_{12} = \frac{1}{A_1 F_{12}\,(1 - e_g)}$$

$$R_{1g2} = \frac{1}{A_1 F_{1g}\, e_g} + \frac{1}{A_2 F_{2g}\, e_g}$$

For resistances in parallel:

$$\frac{1}{R_5} = \frac{1}{R_{12}} + \frac{1}{R_{1g2}}$$

Substituting

$$\frac{1}{R_5} = \frac{1}{\dfrac{1}{A_1 F_{12}\,(1 - e_g)}} + \frac{1}{\dfrac{1}{A_1 F_{1g}\, e_g} + \dfrac{1}{A_2 F_{2g}\, e_g}}$$

$$= A_1 F_{12}\,(1 - e_g) + \frac{1}{\dfrac{1}{A_1 F_{1g}\, e_g} + \dfrac{1}{A_2 F_{2g}\, e_g}}$$

The radiation heat transfer between the enclosure and gases and the package is:

$$q_{21} = (1/R_5)\,(E_{b2} - E_{b1})$$

Compare to ideal black case

q_{21}absorbing gas / q enclosure black = Fraction of Black Body Rad HT $=1/A_1R_5$

For the GPFP test case, furnace is essentially cubical with edge length of 5 ft and the package a cylinder 18.25 in. in diameter and 34.75 in. long. For these dimension, the areas of the package and furnace are:

$A_{package} = A_1 = 17.5\ ft^2$
$A_{furnace} = A_2 = 150\ ft^2$

For this case, the Fraction of Black Body HT as function of ε, for the SRNL test case is shown in Figure 8.

So

$$q_{21} = \sigma A_1(\text{Fraction})(T^4_2 - T^4_1) = \sigma A_1(\text{Fraction})(T^4_R - T^4_1) \quad [4]$$

For the case represented by Figure 8, where the Fraction of black body radiant heat transfer is very nearly 1.0, Equation 4 is virtually the same as Eq 1, above. This result confirms the acceptability of the radiation environment in GPFP tests.

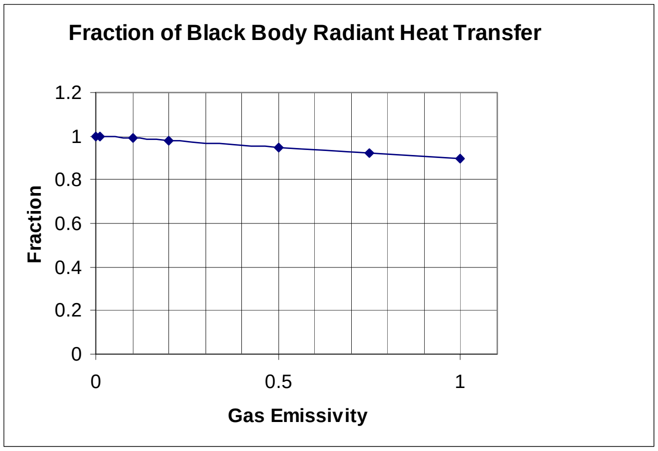

Figure 8. Fraction of black body heat transfer as function of gas emissivity for gas at radiation equilibrium in the furnace.

Resulting gas temperature for GPFP test case can be determined from the network.

$$T_g = (0.82(T_2^4 - T_1^4) + T_1^4)^{1/4}$$

For the typical GPFP test temperatures for furnace and package of 850 and 780ºC, respectively, this gives a gas temperature of 794ºC.

Open top radiation enclosure without radiating gas

A radiation enclosure in which the package is completely enclosed by radiating surfaces is the same as a furnace with respect to its radiation environment. However, if an enclosure has an open side or top this is not the case. If all surfaces of the enclosure are at the same temperature, the enclosure can be considered a single radiating surface. Assuming that the radiating surfaces are black the radiation network for the package and enclosure is:

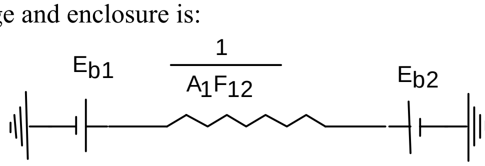

Figure 9. Equivalent radiation network for an open enclosure with no radiation exchange through the open side.

Neglecting solar input, the radiation heat transfer from the enclosure to the package is:

$$q_{21} = A_1F_{12}\,(E_{b1} - E_{b2})$$

It is assumed that all radiant energy passing out the open side is lost. For cubical enclosure with top removed, but walls uniformly black at T_R, F12 = 5/6.

$$q_{21} = 5/6\, A_1(E_{b1} - E_{b2}) = (5/6)\sigma A_1\,(T^4_2 - T^4_1) = (5/6)\sigma A_1\,(T^4_R - T^4_1) \qquad [5]$$

Open top enclosure with engulfing Propane flame

Thermal testing employing a natural gas or liquefied petroleum gas flame in an open enclosure has been proposed for some large packages. Evaluation of this approach requires determination of the radiation heat transfer from the combustion products of the gaseous fuel. Hottel and Ebgert's method of evaluating radiation heat transfer for gases enable us to evaluate the radiation heat transfer for this case [10]. It is assumed that the flame fills the open top cubical enclosure and extends in a hemispherical zone above the enclosure. As in the case of the gas fired furnace, it is assumed that the enclosure walls are heated by the combustion of the gas and are at the same temperature as the gas. That is, the enclosure walls are at T_R. The network representing this case is show in Figure 10.

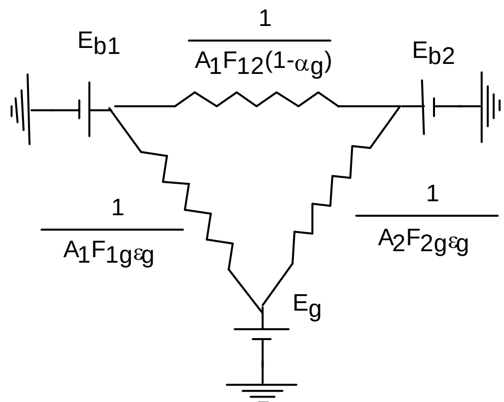

Figure 10. Equivalent radiation network for an enclosure filled with radiating gas.

The total radiation heat transfer to the package, Surface 1, is the sum of that by direct radiation from the enclosure and that from the hot gaseous combustion products.

In order to evaluate the radiation heat transfer environment for this case, an example enclosure and fuel must be employed. A typical fuel for such an application might be Propane.

For Propane burning at atmospheric pressure, the products of combustion are carbon dioxide and water vapor. To evaluate the radiation emitted by the products the average radiant beam length, L must first be determined. Using the expression for L from Reference 10:

$$L = 3.4\,\frac{\text{Volume of Enclosure}}{\text{Area of Enclosure}}$$

If the enclosure is a cube of side l, and the hemispherical gas envelop has diameter equal to the diagonal of the top opening, the volume and area of the enclosure are:

$$V = l^3 + (4/3)\pi r^3$$

$A = 5\, l^2 + 2\, \pi r^2$

Where $r = 0.707\, l$

For this case, $L = 1.02\, l$

The total heat input to the package is

$q_{1total} = q_1 = q_{21} + q_{g1}$

$q_{21} = (1 - \alpha_g)A_1F_{12}\,(E_{b2} - E_{b1})$

The radiation heat transfer from the gas is from both the carbon dioxide and water vapor. The emissive bands for these two gases overlap, so a corrected effective emissivity and absorptivity are determined.

$q_{g1\,CO2} = \sigma A_1(\varepsilon_{gCO2}T_g^4 - \alpha_{gbbCO2}T_1^4)$

and

$q_{g1\,H2O} = \sigma A_1(\varepsilon_{gH2O}T_g^4 - \alpha_{gbbH2O}T_1^4)$

The partial pressures of carbon dioxide and water vapor for combustion of propane at atmospheric pressure are determined, assuming that the fire uses stoichiometric air.

$C_3H_8 + 5O_2 + 18.9\, N_2 \rightarrow 3CO_2 + 4\, H_2O + 18.9N_2$

For this case, $P_{H2O} = 0.158$ atm, and $P_{CO2} = 0.116$ atm.

Employing the partial pressures and radiant beam length, L, and following the method or Hottel and Egbert the emissivity and absorptivity of the carbon dioxide and water vapor can be determined and corrected values for the mixture obtained. (Standard heat transfer texts provide the charts needed for this calculation, e.g., References 9, 10, and 11.) For a package having a maximum dimension of 1 m, and assuming a 1 m distance from the package to the enclosure wall, the dimensions of the enclosure must be approximately 3 m on a side. For purposes of this evaluation we will assume a cubical enclosure with edge length of 12 ft. The furnace temperature was assumed to be 800º

The results of these calculations are:

$\varepsilon_{mixture} = 0.4$

$\alpha_{mixture} = 0.35$

and $q_{g1} = \sigma A_1(\varepsilon_{mix}T_g^4 - \alpha_{mix}T_1^4)$

The total heat transfer to the package, Surface 1, is:

$q_{1total} = q_{21} + q_{g1} = (1 - \alpha_g)\sigma A_1F_{12}\,(T_2^4 - T_1^4) + \sigma A_1(\varepsilon_{mix}T_g^4 - \alpha_{mix}T_1^4)$

If the walls are heated by the flame and both wall and flame are at the same temperature, $T_g = T_2 = T_R$, this reduces to:

$$q_{1total} = (1 - \alpha_g)\sigma A_1F_{12}\,(T_R^4 - T_1^4) + \sigma A_1(\varepsilon_{mix}T_R^4 - \alpha_{mix}T_1^4) \quad [6]$$

For comparison with the previous expressions, it is instructive to recognize that $\varepsilon_{mixture}$ and $\alpha_{mixture}$ are approximately equal. For this case, the expression for q_{1total} becomes:

$$\begin{aligned} q_{1total} &= (1 - \alpha_g)\sigma A_1F_{12}\,(T_R^4 - T_1^4) + \varepsilon\sigma A_1(T_R^4 - T_1^4) \\ &= [(1 - \alpha_g)F_{12} + \varepsilon\,]\sigma A_1(T_R^4 - T_1^4) \end{aligned}$$

Recall for the open top cubical enclosure $F_{12} = 5/6$.

If $\varepsilon_{mixture}$ and $\alpha_{mixture}$ are approximately equal, this reduces to

$$\begin{aligned} q_{1total} &= [5/6 - (5/6)\varepsilon_g + \varepsilon\,]\sigma A_1(T_R^4 - T_1^4) \\ &= [5/6 + (1/6)\,\varepsilon_g]\,\sigma A_1(T_R^4 - T_1^4) \end{aligned}$$

So, the result is slightly greater radiant heat transfer than the case with no radiating gas in the open top enclosure.

To investigate the effect of changes in furnace conditions on $\varepsilon_{mixture}$ and $\alpha_{mixture}$ the evaluation was repeated for a furnace temperature of 900ºC. The results were $\varepsilon_{mixture} = 0.401$ and $\alpha_{mixture} = 0.347$. The differences in these value is too small to have a significant effect on the results.

Convection Effects

Estimates of the contribution of convection to the heat flux to a package during a pool fire are on the order of 10 to 20%. To compensate for reduced convection in a furnace, compared to a fire, the furnace temperature can be increased, so that the heat flux imposed on the package is the same. In thermal tests, the package surface temperature typically rises quickly to a temperature close to the fire or furnace temperature, then remains nearly constant for the duration of the test. For packages where there is a small gap between the overpack material and the outer shell of the package, such as packages with Celtoex overpack material, the shell temperature quickly approaches the test temperature. For Urethane foam packages where the plastic material is in contact with the drum shell and intumesces, so that the molten plastic material flows against the inside of the shell, the drum shell temperature is somewhat lower. Reference 4. For GPFP tests in the SRNL furnace, the furnace temperature and package temperatures were typically around 850 and 780ºC, respectively. To achieve a 20 % greater heat flux, the furnace temperature would need to be raised to 862ºC. It should be noted that the furnace conditions for the GPFP test were much more severe than the regulatory 800ºC test temperature.

DISCUSSION

The expressions for radiation heat transfer for the electrically heated and gas combustion heated furnace cases reduce to the same expression as that for the all engulfing pool fire case. The case of the furnace with a gas which is not burning, but is at radiation equilibrium in the furnace is very nearly equal to the other cases, since the Fraction of black body heat transfer is between 0.9 and 1.0. When the Fraction is 1.0, the equations are the same. For a case where the Fraction is less than 1.0, the test can compensate for the reduced heat transfer by increasing the furnace temperature by a few degrees.

Various studies have shown that the convection heat transfer in the fire test contributes between 10% and 20% additional heat flux. Testing in a furnace can also compensate for this effect by a small increase in furnace temperature.

It would be more difficult to achieve the required test conditions in an open top test enclosure. The principal heat transfer mechanism is radiation. In order to achieve the required thermal environment for a regulatory test, the walls of the enclosure must be maintained at the reference test temperature and must have high emissivity. The use of a gaseous heat source results in a transparent flame, and so without a full enclosure does not produce the environment required for regulatory testing.

CONCLUSIONS

Electrical furnaces and furnaces fired by combustion of gases, such as Propane, can produce a radiation environment fully equivalent with the regulatory pool fire. To achieve these conditions, the furnace must be large enough that the package does not seriously compromise the radiation environment. In addition, the furnace should be thoroughly preheated before package insertion, so that the effect of the cool package on the radiation environment is minimized.

Furnace tests of packages which emit decomposition products are very nearly the same as the reference fire test environment. The small reduction in radiation heat transfer resulting from the presence of the gaseous decomposition products can be compensated by a small increase in furnace temperature. The furnace environment for the GPFP, and similar tests, met the requirements of the pool fire radiation conditions.

It would be difficult to achieve the required radiation environment in an open top enclosure.

CONTRACT NUMBER

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DISCLAIMER

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