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Thermal Analysis of Drum Type Radioactive Material (RAM) Packaging Arrays in Storage

Narendra K. Gupta
Savannah River National Laboratory, Aiken, SC 29808
nick.gupta@srnl.doe.gov

ABSTRACT

Drum type packages are routinely used to transport radioactive material (RAM) in the U.S. Department of Energy (DOE) complex. These packages are designed to meet the federal regulations described in 10 CFR 71.[1] In recent years, there has been a greater need to use these packagings to store the excess fissile material, especially plutonium for long term storage. While the design requirements for safe transportation of these packagings are well defined, the requirements for safe long term storage are not well established. Since the RAM contents in the packagings produce decay heat, it is important that they are stored carefully to prevent overheating of the containment vessel (CV) seals to prevent any leakage and the impact limiter to maintain the package structural integrity. This paper analyzes different storage arrays for a typical 9977 packaging for thermal considerations and makes recommendations for their safe storage under normal operating conditions.

INTRODUCTION

The 9977 package is designed to meet the requirements of 10 CFR 71 for transportation. The requirements for storage are established by the facility custodians. Therefore, the package must be evaluated for storage conditions to ensure the safety of the packaged material.

9977 Package

The Department of Transportation 6M package has been removed from service. As a result, several new packagings are being designed to fill the need to transport different types of RAM across the DOE complex. The 9977 is one of those packages. The 9977 is designed to ship Heat Source and RTG contents.[2] Figure 1 is a schematic of the 9977 package. The package is 914.4 mm high and 469.9 mm in diameter. Contents for the package will be placed within the CV, which is closed with a cone seal plug that has a set of double O-rings. The package has multiple insulating materials for thermal protection during a fire event.

An important design limitation on 9977 is the maximum temperature of the polyurethane foam that act as an impact absorbing and fire insulating medium. The maximum temperature limit is 121°C (250°F). The foam temperature mainly depends upon the content heat generation rate, insulation thickness, and the ambient conditions. The ambient conditions include the air temperature and the surrounding conditions that afffect convection and radiation heat transfer.

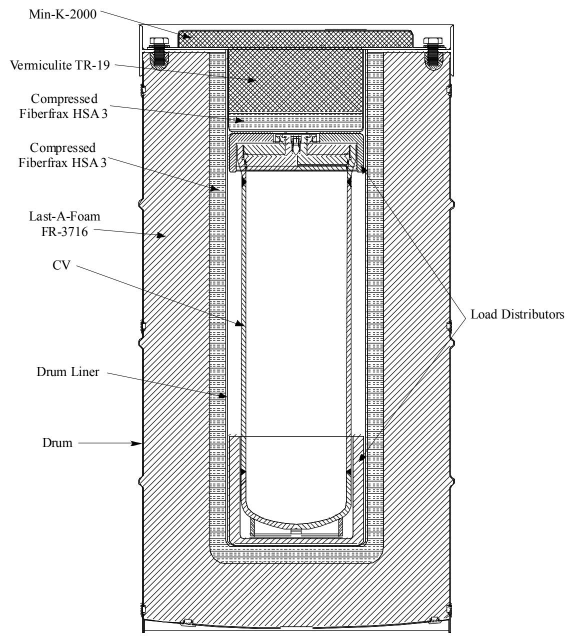

Figure 1 – 9977 Packaging

Packages in Storage

Figure 2 shows a typical storage configuration of RAM packages in a facility. The arrangement is a Stacked-3 configuration where 3 groups of 4 packages are stored on top of each other. Stacked-2 configuration will have only 2 groups of 4 packages stored on top of each other.

Figure 2 – Packages in Storage

Four Packages Storage Configuration

The pallet assumed in this analysis has the dimensions 1067 mm x 1067 mm x 133 mm used in the storage in Figure 2. Figure 3 depicts four packages stored on a carbon steel galvanized pallet where the packages are normally not touching each other. The packages are kept apart by a pipe spacer to promote convection cooling. The pallets can be Stacked-2 or Stacked-3 high. This storage configuration is then repeated by placing additional pallets 51 to 76 mm apart.

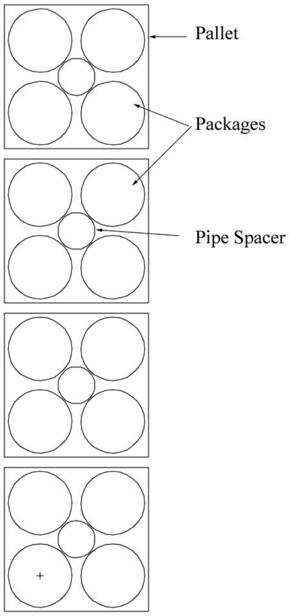

Figure 3 – Package Storage Configuration on Pallets

The above storage configuration alters the surroundings of the package by restricting the flow of cooling air around the packages. This paper analyzes the temperature distribution when the packages are stacked and placed in rows. The following configurations will be analyzed using detailed finite element thermal models to estimate the temperature of the critical components inside the package:

1. Four packages touching each other and stacked three high
2. Four packages with a spacer and stacked three high

Package Functional Requirements

As mentioned before, the two critical components of the 9977 package are its seals and its impact limiter. The containment vessel seals are O-rings that must be maintained below certain temperature for the seals to remain leaktight. Similarly the impact limiter thermal properties must not degrade due to high temperatures from internal heating. Table 1 gives the temperature limits for these two components for their structural and thermal integrity.

Table 1: Temperature Limits °C (ºF)

Component	Long Term
Impact Limiter	121 (250)
O-Rings	204 (400)

An important requirement for the O-ring functionality is the yearly inspection and testing for their leak-tight integrity.[3] This requirement is very challenging to meet in a storage where thousands of packages are stored and retrieval of each and individual package for O-ring inspection is expensive and time consuming. At SRS this requirement is being addressed by an extensive surveillance program of the stored packages and their O-rings. The program is basically attempting to justify an increase in the inspection period to 5 years by proving their leak-tight integrity through testing and analysis. Since the leak-tight integrity is tied with temperature exposure, this consideration is important in this study.

Scoping Analyses

The scoping analyses were performed to simplify the true 3D axisymmetric models to 2D models. The 9977 package is a rather complex mechanical device with multiple materials, metal surfaces, gaps, vessels, and boundary conditions. To analyze the various storage configuration using 3D models would be quite challenging and expensive. The scoping analyses help in identifying the upper bound internal heat generation per unit length of the package height for a simpler 2D model which is much easier to analyze for multiple packages in storage configuration.

Spacer

The drums are banded together on the pallet for stability during handling and storage. A spacer is normally used to keep the drums apart and to promote convection cooling. If the spacer diameter is large enough to provide a minimum spacing of twice the boundary layer (BL) thickness between the drums, natural convection cooling will still be effective. The BL thickness for natural convection for a vertical flat plate can be approximately calculated by using Equation 1.[4]

$$\frac{\delta}{y} = 3.93\,\mathrm{Pr}^{-1/2} \times (0.952 + \mathrm{Pr})^{1/4}\, Gr_y^{-1/4} \qquad (1)$$

where:

δ is the BL thickness
y is the distance from the leading edge
Pr is the Prandtl number
Gr_y is the Grashof number at location y

MATHEMATICAL MODEL

The computational thermal models solve the following steady state heat transfer equation in cylindrical coordinates.

$$k_1 \frac{\partial^2 T}{\partial r^2} + \frac{k_1}{r}\frac{\partial T}{\partial r} + k_2 \frac{\partial^2 T}{\partial z^2} + q''' = 0 \qquad (2)$$

Where q''' is the volumetric heat generation by the fissile material per unit time, k_1 and k_2 are the thermal conductivities of the materials in the r and z directions, and T is the temperature. k_1 and k_2 are the same since the materials are isotropic. However, for some materials, thermal conductivity is a function of temperature.

3D MODEL ANALYSES

3D analyses are for the ideal conditions where a package does not interact with other packages in the surroundings. The package geometry is cylindrical and can be accurately modeled using an axisymmetric model. Two models are analyzed: (1) A single package stored on the floor; and (2) two packages in a stacked configuration. The main purpose for analyzing these configurations is to estimate the heat loss from the drum surfaces, estimate source power per unit length for the 2D models, and to estimate the convection BL thickness. These analyses will help in building 2D models for the storage configurations with multiple drums on a pallet. Figure 4 shows an axisymmetric finite element model of the single package configuration. Only half of the model is shown and the edge on the left hand side is the center line of the model.

The finite element analyses are performed using Patran/Thermal software.[5]

Boundary Conditions and Model Parameters:

1. The bottom of the package is adiabatic.
2. The heat generation is 19 watts.
3. Storage surroundings are large enough that all thermal radiation from the package is absorbed.
4. Storage room temperatures are 38°C (100ºF) and 66°C (150ºF). 38°C represents normal maximum and 66°C represents off-normal maximum conditions[1].
5. Heat is lost through natural convection and radiation.
6. There is no interaction with other packages in the storage.

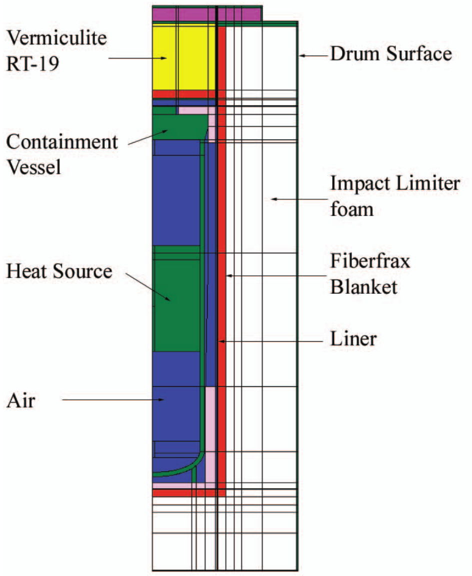

Figure 4 – Basic Single Package on the Floor

The results of the single and two stacked drum configurations are summarized in Table 2:

Table 2 – Heat Loss Distribution, Watts (Btu/hr)[2]

Configuration	Top	Side	Total
Single Drum (Stacked-1 High)	4.07 (13.87)	14.94 (50.96)	19.00 (64.83)
Two Drums (Stacked-2 High)	3.83 (13.08)	34.17 (116.58)	38.00 (129.66)

If three drums are stacked, it is safe to assume that the losses from the top will be about 3.81 watts (13 Btu/hr). These losses include both convective and radiation losses. The heat loss from the side of a Stacked-3 configuration (3 packages) will be:

19 watts/Package x 3 Packages x 3.412 Btu/hr/watt
- 13 Btu/hr = 181.484 Btu/hr

Since each package is 914 mm (3 feet) high, the equivalent heat loss rate for a <u>2D model</u> will be 181.484/9 = 20.165 Btu/hr-ft = 5.896 watts/ft.

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[1] A temperature of 58°C (137˚F) was calculated at a SRS storage facility for small fire scenario.

[2] All computations were performed in Btu-Hr-Ft-F units.

The boundary layer (BL) thickness is calculated for a Stacked-1 configuration. The pallet supporting the packages has openings through which air can pass and keep the pallet cooler than the package surfaces. In addition, the pallet edges extend beyond the package surfaces and disrupt the continuity of the boundary layer from the lower packages to the upper packages. The BL thickness is maximum at the top of the drum. It is calculated using Eq. 1 and is found to be 30.73 mm (1.21"). Therefore, if the separation between the drums is more than 2 x 30.73 = 61.47 mm (2.42"), convection cooling is still affective. The following parameters are used in calculating the BL thickness:

$y = 914.4$ mm (36"); $Pr = 0.74$
$Gr = 5.82 \times 10^8$; $Ra = Pr\ Gr = 4.31 \times 10^8 < 10^9$

Since the Rayleigh No., Ra, is less than 10^9, the flow is laminar. Other significant results are given in Table 3.

Table 3 – Impact Limiter and O-ring Temperatures °C (ºF)

Configuration	Ambient Temp.	Impact Limiter	O-ring Seals
Single Drum (Stacked-1 High)	38 (100) 66 (150)	53 (182) 67 (228)	52 (176) 65 (221)
Two Drums (Stacked-2 High)	38 (100) 66 (150)	54 (185) 67 (229)	52 (179) 66 (224)

It is worth noting that the increase in temperature of the components is only about 1°C (3°F) from Stacked-1 high configuration to Stacked-2 high configuration.

2D MODEL ANALYSES

Model Validation

The data developed in 3D axisymmetric models can be used to create 2D models. The 2D models help in estimating the impact of interaction between drums when placed touching each other in storage. However, validation of the 2D model is necessary because it represents a significant simplification of the axisymmetric model. The 2D model assumes that the heat source is uniformly distributed along the entire length of the model while the axisymmetric model has heat source concentrated in a 6.35mm diameter and 25.4mm long cylinder in the central region of the package. The concentration of the heat source in the full model has increased thermal effect in the center of the package as compared to the 2D model. To validate the 2D model, the heat source strength is increased until the containment vessel (CV) temperature matches with the CV temperature in the full axisymmetric model. For validation, no consideration is given for the package interaction effect that is present in an actual storage. However, the boundary conditions are kept identical for the 2D and the axisymmetric models. For the axisymmetric model, the top and bottom of the model are kept adiabatic to match the 2D model. In addition, no radiation losses are considered to match the storage environment. The results of the validation with room temperature of 38°C (100°F) are shown in Table 4.

Table 4 – 2D Model Validation Results

Model	Heat Source (Watts)	Vessel °C (ºF)	Foam °C (ºF)
3D (Axisymmetric)	19.00	103 (218)	87 (188)
2D	20.08	103 (218)	88 (191)

The validation results are very good considering the model simplification from 3D to 2D geometry. The revised heat source of 20.08 watts will be used in the 2D models discussed below. For the 2D model, the heat source strength is per unit length of the package. This is equal to 6.694 watts/ft based on the 914.4 mm (36") height of the package.

Model Analyses

The 2D models have the following configurations.

1. Four packages touching each other and stacked three high
2. Four packages with a spacer and stacked three high

The first model is intended to evaluate the impact of trapped air if the packages are touching each other at the hoops. The second model will assess the benefit of the spacer that allows the flow of ambient air between the drum surfaces. If a 254 mm (10") pipe spacer is used, the minimum spacing between drums is found to be 68.07 mm (2.68") which is just greater than the 61.47 mm (2.42") needed for convection cooling. If a 304.8 mm (12") spacer pipe is used, the minimum spacing is found to be 104.14 mm (4.1"). Therefore, a 304.8 mm pipe spacer is recommended to get the between-drum spacing needed for effective convection cooling. Figure 5 shows the schematic of a drums/spacer configuration.

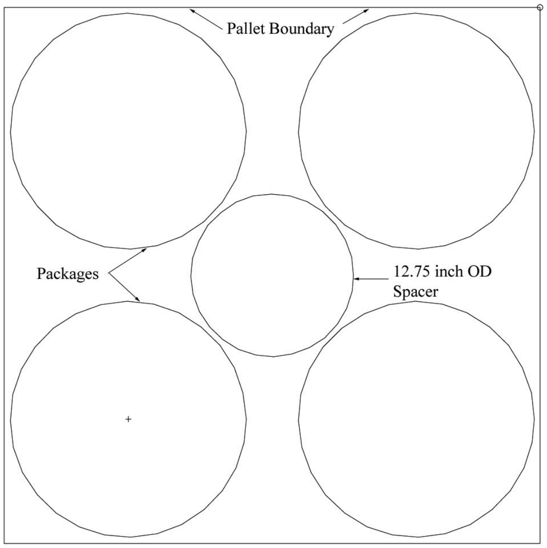

Figure 5 – Package Configuration on a Pallet

Boundary Conditions

For the 2D models, only the curved surface of the drums exchanges heat with the environment. For the packages stored as shown in Figure 2, it is apparent that the package surfaces see each other and exchange thermal radiations. It is therefore reasonable to assume that the temperatures of the drum surfaces are equal for all the drums. <u>The radiation cooling is therefore absent.</u> The convection cooling however depends upon the availability of the cooler air near the drum surface.

<u>Configuration 1</u>

Since the drums touch each other at the hoops, the spacing between the drum surfaces is well below the minimum spacing required for convection cooling. So for this case, fresh air supply is not available between the drum surfaces for cooling. For simplicity in modeling, it can be assumed that the air between the drums is trapped. (It should be noted that the pallets do have small spacing through which some warm air can flow upwards). So for Configuration 1, there is no convective cooling for quarter surface of each package. It should also be noticed that the spacing between the pallets is well above the minimum required for convection cooling. Therefore, only quarter surface of each package is impacted in this configuration.

Since the 4 packages will have identical temperature distribution, only ¼ model of the 4 package configuration is analyzed. The resulting model is a 2D model obtained by a cutting plane through the mid region of the drum. A top view of the package which gives a representation of the 2D model is shown in Figure 6. The z-axis represents the longitudinal direction of the package.

The above 2D model represents a package with a heat source in the middle region of the package stored in upright position. In this region of the package, radial heat transfer is dominant and, therefore, a 2D model should be a reasonably good approximation of the 3D model. In addition, CV and impact limiter temperatures are also close to the maximum values in a full model. The convection correlations used are the same as in the full 3D axisymmetric models.

<u>Configuration 2</u>

Configuration 2 of the 2D models represents the 4 packages on a pallet with a 12 inch spacer pipe spacer to promote natural convection cooling all around the package surface. In addition, as discussed in the boundary condition paragraph above, radiation cooling is also absent for this configuration since the drums are able to see each other in the storage configuration. Since the spacer permits convection cooling, this configuration becomes similar to the full axisymmetric Stacked-3 configuration. Therefore, Configuration 2 will be analyzed using the full axisymmetric model with the top and bottom surfaces assumed to be adiabatic. The simplification of top surface as adiabatic is reasonable considering the fact that the losses from the top are less than 7% of the total heat generated in the Stacked-3 configuration. Therefore, the error introduced will be small. In addition, we are interested in getting the maximum temperatures which are only slightly higher from a Stacked-1 configuration to Stacked-2 configuration, see Table 3.

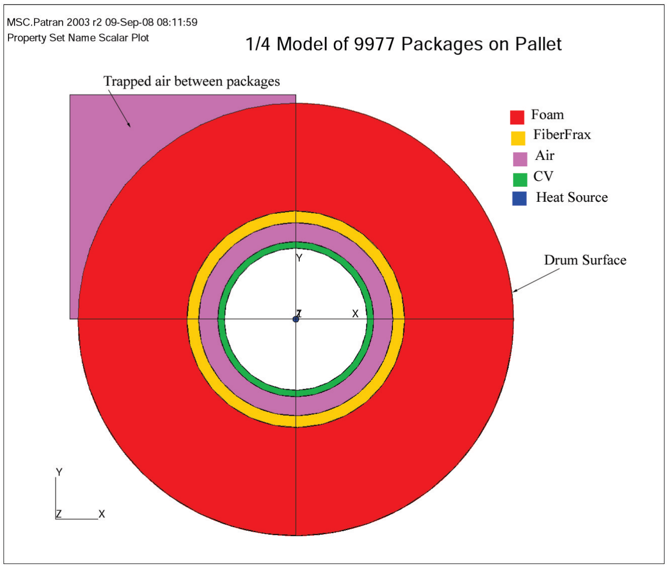

Figure 6 – ¼ Model for 4 Touching Packages on a Pallet

PALLET SPACING ANALYSIS

The BL thickness calculations show that the minimum spacing between the drums must be 61.47 mm (2.42") (page 4) to ensure convective cooling. The storage geometry in Figure 4 gives a clearance of 11.53 mm (0.454") between the pallet edge and the drum surface. Therefore, if the pallets are stored 51 mm apart, the minimum spacing between the package surfaces will be 74 mm (2.908"), just large enough to ensure convective cooling. However, the packages could be a little off-center on pallets and therefore a pallet spacing 51 to 75 mm should be maintained to ensure convective cooling.

RESULTS

Configuration 1 Results

The results of the analysis when the packages are touching each other are given in Table 5.

Table 5 – 2D Model Analysis Results

Storage Air Temperature °C (ºF)	Containment Vessel °C (ºF)	O-rings °C (ºF)	Foam °C (ºF)
38 (100)	113 (235)	113 (235)	104 (220)
66 (150)	136 (276)	136 (276)	128 (262)

O-ring temperatures are smaller than the maximum CV temperatures in full configuration. However, since the 2D model cannot model the O-rings region of the package separately, O-ring temperatures are conservatively assumed to be the same as the CV temperature. Foam temperatures are closer to the limiting value of 121°C (250˚F) and are shown in Figures 7 and 8. An azimuthal temperature increase of about 14°C (25˚F) can be attributed to the lack of a spacer that would allow more air for cooling the packages.

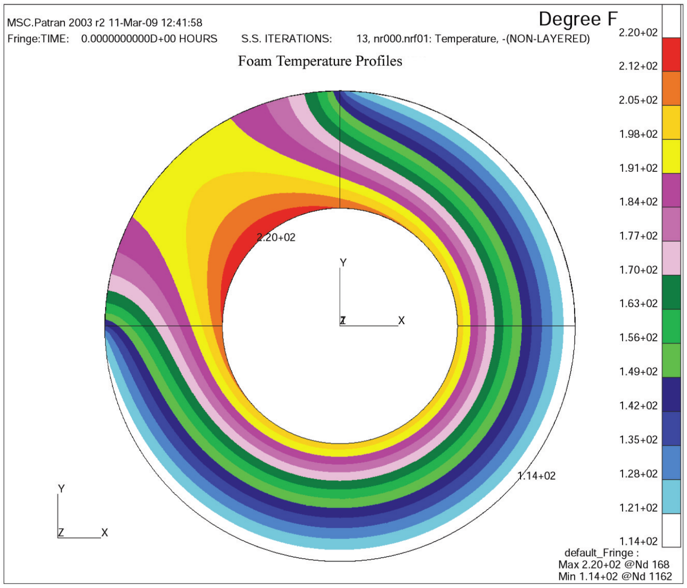

Figure 7 – Foam Temperatures with Air at 38°C (100°F)

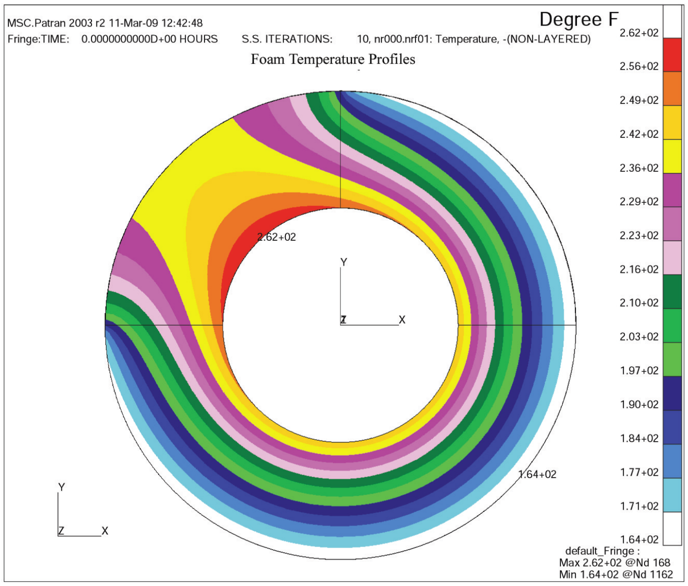

Figure 8 – Foam Temperatures with Air at 66°C (150°F)

Configuration 2 Results

The results for Configuration 2 are based on 3D axisymmetric model with the ends insulated. The 3D model with the ends insulated is very close to the Stacked-3 configuration where the top is open to the storage ambient conditions. In fact, the 3D model with the ends insulated should give conservative (higher) component temperatures. The component temperatures are given in Table 6.

Table 6 - 3D Model Analysis Results

Storage Air Temperature °C (ºF)	Containment Vessel °C (ºF)	O-rings °C (ºF)	Foam °C (ºF)
38 (100)	103 (218)	85 (185)	87 (188)
66 (150)	127 (261)	110 (230)	111 (232)

A comparison of the Configuration 1 and Configuration 2 results shows that there is substantial decrease in foam temperature when the 304.8 mm (12”) pipe spacer is inserted that helps in convection cooling. The O-ring temperatures in Table 6 are more accurate values obtained from the 3D axisymmetric model.

DISCUSSION

Radioactive material transportation packages are being considered for long term storage of the legacy material. The analyses in this paper show that such packages can be safely used in multi stacked configuration provided the packages are adequately separated to enable convection cooling. However, other considerations such as comprehensive surveillance and material testing programs must also be set up to ensure that materials do not degrade and maintain their structural and operational integrity over a long period of time.

CONCLUSIONS

1. The analyses show that radioactive material packages can be stored without any forced convection cooling.
2. The packages on pallets must be separated by placing spacers to promote convection cooling. It is recommended that a 308.8 mm (12”) pipe spacer be provided.
3. The pallets should be separated from each other by a gap of 51 to 76 mm.

DISCLAIMER

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