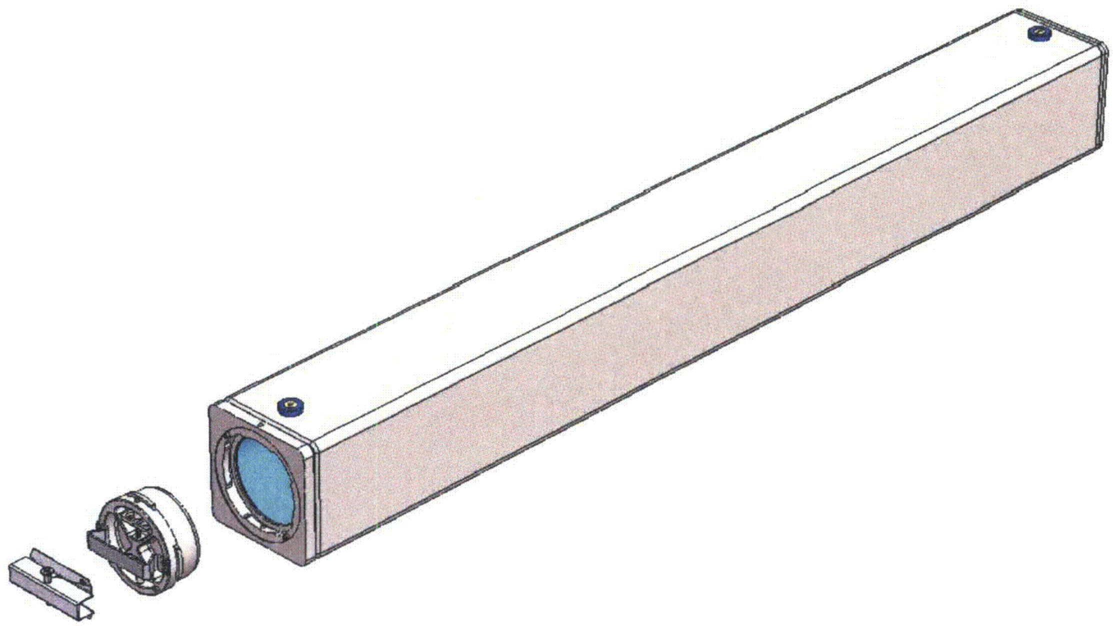
Safety Analysis Report



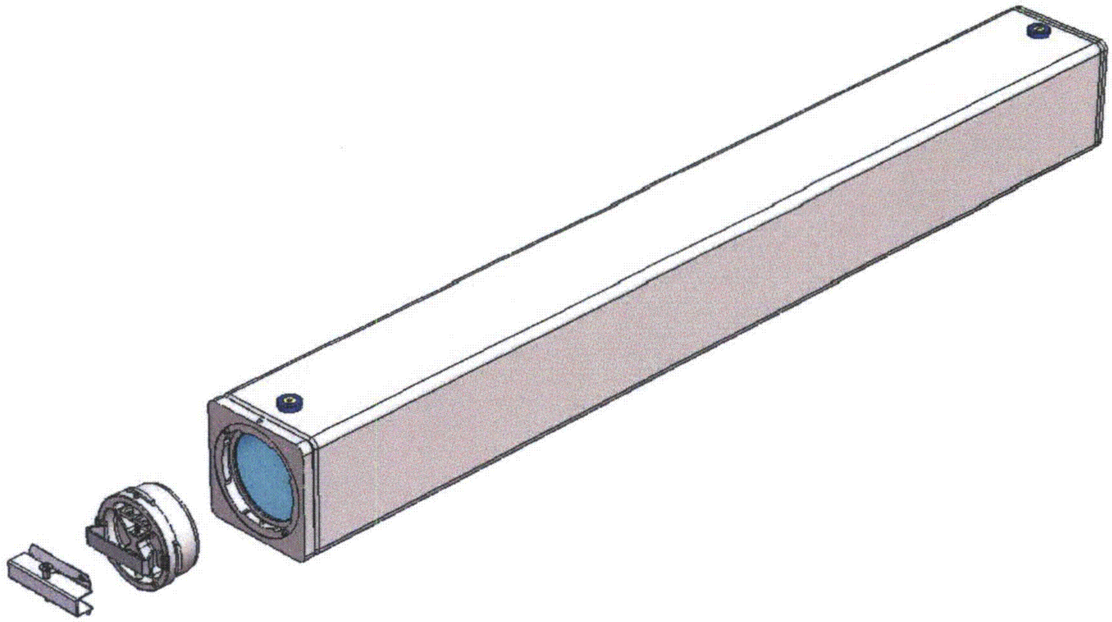
Advanced Test Reactor Fresh Fuel Shipping Container (ATR FFSC)

Revision 7, August 2011

Docket 71-9330

Prepared by:	*Prepared for:*
AREVA **AREVA Federal Services LLC**	INL Idaho National Laboratory **Battelle Energy Alliance, LLC (BEA)**

Safety Analysis Report



Advanced Test Reactor Fresh Fuel Shipping Container (ATR FFSC)

Revision 7, August 2011

Docket 71-9330

Prepared by:	*Prepared for:*
AREVA AREVA Federal Services LLC	INL Idaho National Laboratory Battelle Energy Alliance, LLC (BEA)

TABLE OF CONTENTS

1.2.2.4 Small Quantity Payload

The small quantity payload consists of a class of research and development plate-type fuels with U-235 as the fissile isotope (i.e., no U-233 or plutonium), with a bounding U-235 loading ≤ 400 g, and U-235 enrichment ≤ 94%. Fuel types that fall into the small quantity payload category include RINSC fuel elements, AFIP elements, U-Mo foils, DDEs, MIT loose fuel element plates, and MURR loose fuel element plates.

Individual small quantity payloads are discussed below. Although the fissile mass and enrichment is stated for each payload type, the acceptable limits for any small quantity payload are the bounding quantity of 400 g fissile mass and 94% enrichment. The maximum weight of any small quantity payload, including the SQFHE, is 50 lbs. As stated above, the RINSC fuel element is shipped in the dedicated RINSC FHE.

With the exception of RINSC fuel, which utilizes the RINSC FHE, all small quantity payload items fall within the maximum dimensional bounds of the SQFHE, or approximately 55-in x 3.4-in x 3.4-in. The minimum dimensions for a small quantity payload item are approximately 10-in x 1.5-in x 0.008-in.

1.2.2.4.1 RINSC Fuel Element

Each RINSC element contains up to 283 g U-235, enriched up to 20 wt.%. The weight percents of the remaining uranium isotopes are 0.5 wt.% U-234 (max), 1.0 wt.% U-236 (max), with the balance U-238. The RINSC fuel element fissile material is uranium silicide (U_3Si_2) dispersed in aluminum powder. The fuel element weighs not more than 17 lbs, and is enclosed in the RINSC FHE weighing 28 lbs.

Each RINSC fuel element contains 22 flat fuel plates, as shown in Figure 1.2-14. The fuel plates are fabricated and swaged into the two fuel element side plates. The fuel "meat" is a mixture of uranium silicide and aluminum powder, while the cladding and structural materials are an aluminum alloy. The fissile material (uranium silicide) is nominally 0.02-in thick and the cladding is nominally 0.015-in thick. Fuel element side plates are fabricated of ASTM B 209, aluminum alloy 6061-T6 and 6061-T651 and are approximately 0.050-in thick. The maximum channel thickness between fuel plates is 0.096 inches.

1.2.2.4.2 AFIP Fuel Element

Each AFIP element contains up to 365 g U-235, enriched up to approximately 20 wt.%. Each AFIP element typically contains 4 curved fuel plates, as shown in Figure 1.2-16. The fuel plates are fabricated and swaged into the two fuel element side plates. The fuel "meat" may be either dispersion or monolithic. Dispersion fuel meat consists of uranium 7 wt.% molybdenum alloy (U-7Mo) particles dispersed in an aluminum-silicon matrix. Monolithic fuel meat consists of uranium 10 wt.% molybdenum alloy (U-10Mo) coated with a thin zirconium interlayer. Both fuel types are clad in 6061 aluminum. Fuel side plates are fabricated from 6061 aluminum. Loose plates from an AFIP fuel element are also an allowed content.

1.2.2.4.3 U-Mo Foils

Uranium-Molybdenum (U-Mo) foils are used in the fabrication of test fuels, such as AFIPs and DDEs. A U-Mo foil contains up to 160 g U-235, enriched up to 94%. The foils are thin and may contain a zirconium coating, although cladding would not typically be present. The fuel meat description provided for the AFIP elements also applies to U-Mo foils. More than one U-Mo foil type may be transported per ATR FFSC.

1.2.2.4.4 Design Demonstration Elements (DDEs)

Each DDE contains up to 365 g U-235, enriched up to 94 wt.%. DDEs are available for the National Bureau of Standard Reactor (NBSR), the Massachusetts Institute of Technology Reactor (MITR), and the University of Missouri Reactor (MURR), and are abbreviated as DDE-NBSR, DDE-MITR, and DDE-MURR. Sketches of the three DDEs are provided in Figures 1.2-17, -18, and -19. Loose plates from a DDE are also an allowed content.

DDEs may contain either flat or curved fuel plates. Fuel meat consists of U-Mo, so the fuel meat description provided for the AFIP elements also applies to DDEs.

1.2.2.4.5 MIT and MURR Loose Fuel Element Plates

MIT and MURR loose plates transported as a small quantity payload are limited to 400 grams U-235. MIT fuel plates have approximately 34.3 g U-235 per plate, and MURR fuel plates have approximately 19 to 46 g U-235 per fuel plate. The plates may either be flat or rolled to the geometry required for assembly into the fuel element. Additionally, the plates may be banded or wire tied in a bundle. A mixture of MIT and MURR fuel plates may be shipped together.

1.2.2.5 ATR Loose Fuel Plates

The maximum weight of the ATR loose plate payload (Figure 1.2-15) is 50 lbs. This weight is made up of the maximum basket contents weight of 20 lbs and the loose fuel plate basket weight of 30 lbs.

The loose plate payload is limited to 600 grams U-235. The plates are limited to those used in ATR fuel elements. The plates may either be flat or rolled to the geometry required for assembly into the fuel element. For handling convenience, the loose plate basket will be loaded with either flat or rolled plates. Additionally, the plates may be banded or wire tied in a bundle.

7.1.2 Loading of Contents - ATR Fuel Assembly

1. Remove the closure by depressing the spring-loaded pins and rotating the closure 45° to align the closure locking tabs with the mating cut-outs in the body. Remove the closure from the body.
2. Remove the fuel handling enclosure if present in the payload cavity.
3. Prior to loading, visually inspect the ATR fuel handling enclosure for damage, corrosion, and missing hardware to ensure compliance with Appendix 1.3.2, *Packaging General Arrangement Drawings.*
4. Open the ATR fuel handling enclosure lid and place a fuel element into the holder with the narrow end of the fuel element facing the bottom side of the fuel handling enclosure. As a property protection precaution, the fuel element may optionally be inserted into a polyethylene bag prior to placement in the fuel handling enclosure. Verify the total mass of polyethylene per ATR FFSC is ≤ 100 g.
    a. To open the fuel handling enclosure, release the lid by pulling on the spring plunger located at each end and rotate the lid about the hinged side.
    b. To close the fuel handling enclosure, rotate the lid to the closed position, pull the spring plunger located at each end to allow the lid to fully close, align then release the spring plungers with the receiving holes, gently lift the lid to confirm no movement and that the spring plungers are in the locked position.
5. Insert the fuel handling enclosure into the package.
6. Depress the package closure spring-loaded pins, insert closure onto package body by aligning the closure locking tabs with the mating cut-outs in the body, and rotate the closure to the locked position. Release the spring-loaded pins so that they engage with the mating holes in the package body. Observe the pins to ensure they are in the locked position as illustrated in Figure 7.1-1. The closure is fully locked when both locking pins are compressing the sleeve between the locking pin handle and the closure body.

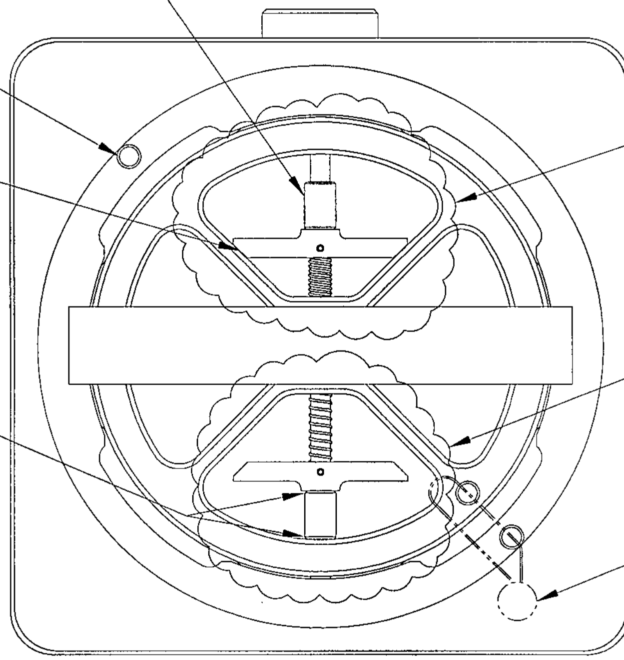


Figure 7.1-1 - Closure Locking Positions

7.1.3 Loading of Contents - Loose ATR Fuel Plates

1. Remove the closure by depressing the spring-loaded pins and rotating the closure 45° to align the closure locking tabs with the mating cut-outs in the body. Remove the closure from the body.
2. Remove the fuel plate basket if present in the payload cavity.
3. Prior to loading, visually inspect the loose fuel plate basket for damage, corrosion, and missing hardware/fastening devices to ensure compliance with Appendix 1.3.2, *Packaging General Arrangement Drawings*.
4. Open the loose fuel plate basket by removing the 8 wing nut fasteners securing each half of the basket.
5. Place the fuel plates into one half of the loose fuel plate basket
    a. Ensure the combined weight of the loose fuel plates and optional dunnage is 20 lbs or less. The loose fuel plates may only be ATR fuel plates.
    b. Ensure the combined fissile mass of the loose fuel plates does not exceed 600 g uranium-235.
    c. Flat and curved fuel plates may not be mixed in the same basket.

   d. As a property protection precaution, the fuel plates may optionally be inserted into polyethylene bag(s) prior to placement in the fuel plate basket. Verify the total mass of polyethylene per ATR FFSC is ≤ 100 g.
   e. Dunnage plates may also be included with the loose fuel plates to reduce any gaps with the basket cavity as a property protection precaution. The dunnage plates may be any aluminum alloy and any size deemed appropriate.
6. Close the fuel plate basket and verify the basket fasteners are installed and finger tight.
   a. With one half of the basket loaded, carefully place the second half over the fuel plates and match the fastener holes.
   b. Insert the 8 spade head screws through the holes and secure with corresponding wing nut (washer optional).
   c. Tighten the 8 wing nut fasteners finger tight.
   d. Visually check the 4 hex head screws located in the center of the basket to verify that they have not loosened. In the event the screws appear to be loose, tighten the fasteners to drawing requirements.
7. Insert the loose fuel plate basket into the package.
8. Depress the package closure spring-loaded pins, insert closure onto package body by aligning the closure locking tabs with the mating cut-outs in the body, and rotate the closure to the locked position. Release the spring-loaded pins so that they engage with the mating holes in the package body. Observe the pins to ensure they are in the locked position as illustrated in Figure 7.1-1. The closure is fully locked when both locking pins are compressing the sleeve between the locking pin handle and the closure body.

7.1.4 Loading of Contents – MIT, MURR, or RINSC Fuel Assembly

The loading of MIT, MURR, and RINSC fuel elements is procedurally identical.

1. Remove the closure by depressing the spring-loaded pins and rotating the closure 45° to align the closure locking tabs with the mating cut-outs in the body. Remove the closure from the body.
2. Remove the fuel handling enclosure if present in the payload cavity.
3. Prior to loading, visually inspect the fuel handling enclosure for damage, corrosion, and missing hardware to ensure compliance with Appendix 1.3.2, *Packaging General Arrangement Drawings*.
4. Open (disassemble) the fuel handling enclosure and place a fuel element into one enclosure half. Ensure that the MIT, MURR, or RINSC fuel element is only used with the corresponding MIT, MURR, or RINSC fuel handling enclosure. As a property protection precaution, the fuel element may optionally be inserted into a polyethylene bag prior to placement in the fuel handling enclosure. Verify the total mass of polyethylene per ATR FFSC is ≤ 100 g.

   a. To open the fuel handling enclosure, remove the two ball lock pins securing each end spacer. Slide each end spacer from the center enclosure halves allowing the enclosure halves to freely come apart.
   b. To close the fuel handling enclosure, with one enclosure half loaded, carefully place the second enclosure half over the fuel element and align the circular ends. Slide one end spacer over the circular end and insert the ball lock pin through the end spacer and enclosure halve alignment holes. Ensure the ball lock pin is in the locked position by observing the pin and locking mechanism protruding from the back side. Repeat with the second end spacer and ensure it is locked in the same manner.
5. Insert the fuel handling enclosure into the package.
6. Depress the package closure spring-loaded pins, insert closure onto package body by aligning the closure locking tabs with the mating cut-outs in the body, and rotate the closure to the locked position. Release the spring-loaded pins so that they engage with the mating holes in the package body. Observe the pins to ensure they are in the locked position as illustrated in Figure 7.1-1. The closure is fully locked when both locking pins are compressing the sleeve between the locking pin handle and the closure body.

7.1.5 Loading of Contents – Small Quantity Payloads (except RINSC)

The loading of small quantity payloads is procedurally identical.

1. Remove the closure by depressing the spring-loaded pins and rotating the closure 45° to align the closure locking tabs with the mating cut-outs in the body. Remove the closure from the body.
2. Remove the fuel handling enclosure if present in the payload cavity.
3. Prior to loading, visually inspect the fuel handling enclosure for damage, corrosion, and missing hardware to ensure compliance with Appendix 1.3.2, *Packaging General Arrangement Drawings*.
4. Open (disassemble) the small quantity fuel handling enclosure and place the payload into one enclosure half. As a property protection precaution, the payload may optionally be inserted into polyethylene bag(s) prior to placement in the fuel handling enclosure. Verify the total mass of polyethylene per ATR FFSC is ≤ 100 g. Optionally add dunnage in the form of aluminum sheets, plates, or shapes if desired, up to a maximum weight of the loaded small quantity fuel handling enclosure of 50 lbs. Miscellaneous steel or aluminum fasteners may be used with the optional dunnage. Neoprene rub strips, 1/8 inch thick, may also be used as a property protection precaution. Neoprene rub strips may be used between the SQFHE and the small quantity payloads and/or between the optional aluminum dunnage and the small quantity payloads. The 1/8 inch neoprene rub strips shall not be stacked in more than two layers between the small quantity payload and any interior face of the SQFHE.
   a. To open the fuel handling enclosure, remove the two ball lock pins securing each end spacer. Slide each end spacer from the center enclosure halves allowing the enclosure halves to freely come apart.
   b. To close the fuel handling enclosure, with one enclosure half loaded, carefully place the second enclosure half over the fuel element, loose fuel plates, or foils and align

the circular ends. Slide one end spacer over the circular end and insert the ball lock pin through the end spacer and enclosure halve alignment holes. Ensure the ball lock pin is in the locked position by observing the pin and locking mechanism protruding from the back side. Repeat with the second end spacer and ensure it is locked in the same manner.

5. Insert the fuel handling enclosure into the package.
6. Depress the package closure spring-loaded pins, insert closure onto package body by aligning the closure locking tabs with the mating cut-outs in the body, and rotate the closure to the locked position. Release the spring-loaded pins so that they engage with the mating holes in the package body. Observe the pins to ensure they are in the locked position as illustrated in Figure 7.1-1. The closure is fully locked when both locking pins are compressing the sleeve between the locking pin handle and the closure body.

7.1.6 Preparation for Transport

1. Install the closure handle cover by aligning the cover against the handle and insert the fastener through the holes in the cover and behind the handle as illustrated in Figure 7.1-2. Once installed, the cover renders the handle inoperable for lifting or tiedown during transport. Option: In lieu of installing the cover, the closure handle may be removed as a method of rendering the handle inoperable for lifting or tiedown during transport.
2. Install the tamper indicating device between the posts on the package closure and body.
3. Perform a survey of the dose rates and levels of non-fixed (removable) radioactive contamination per 49CFR §173.441 and 49CFR §173.443, respectively. The contamination measurements shall be taken in the most appropriate locations to yield a representative assessment of the non-fixed contamination levels.
4. Complete the necessary shipping papers in accordance with Subpart C of 49 CFR §172.
5. Ensure that the package markings are in accordance with 10 CFR §71.85(c) and Subpart D of 49 CFR §172. Package labeling shall be in accordance with Subpart E of 49CFR §172. Package placarding, for either single package transport or the racked configuration, shall be in accordance with Subpart F of 49 CFR §172.
6. Transfer the package to the conveyance and secure the package(s).

Combustion of Polyethylene Limiting in the ATR FFSC

The Request for Supplemental Information (RSI) submitted by the NRC for the ATR FFSC Safety Analysis Report[1] (SAR) includes the following observation on the thermal analysis:

> "Further clarification of the effect of burning polyethylene on the packaging and contents should be considered. Depending on the amount of available oxygen and polyethylene composition, polyethylene can have an auto-ignition temperature of approximately 320°C, which indicates it would sustain a flame and burn rather than decompose by pyrolysis. Considering polyethylene's high heat of combustion, the effect of the high, local temperatures on the package/contents should be analyzed/discussed further."

Although the SAR describes a full combustion duration of 4.5 seconds (SAR Section 3.4.3.1) for the polyethylene plastic wrap, a majority of the plastic will not burn. The polyethylene is within a confined space, with no path for air circulation, as discussed later. The quantity of polyethylene burned is limited by the amount of oxygen available, and only a small fraction of the 100 grams (SAR Section 1.2.2) of polyethylene will be consumed. This results in only a small increase in temperature over a limited time interval, which has only a minimal impact on the temperature of the packaging.

The thermal evaluation in Chapter 3 of the SAR includes analysis on both Normal Conditions of Transport (NCT) and Hypothetical Accident Condition (HAC) events. Since the 320°C (608°F) auto-ignition temperature of polyethylene quoted in the RSI Observation (the auto-ignition temperature of 320°C verified from one additional source[2]) is much higher than the highest predicted NCT temperature from Table 3.3-1 of the SAR of 85.6°C (186°F), it only reaches the auto ignition temperature during the HAC event. The temperature differential due to polyethylene combustion is limited since:

- Airflow into the package is restricted through a small cross-sectional area and to only one end of the package, limiting replacement of oxygen consumed.
- The elevated temperature of the air inside the package cavity assures us that the pressure within the package will not fall below the outside pressure during the fire, further limiting replacement of oxygen and preventing re-ignition of the polyethylene.
- Since the temperature of the gases within the center of the package payload cavity will never drop below that of the outside air, no negative pressure gradient will occur until after the package temperature drops below the outside air temperature.
- The air available for combustion at the auto ignition temperature of 320°C (608°F) is enough to burn less than one gram of polyethylene.
- Burning one gram of polyethylene releases less than 50 Btu of heat energy.

---

[1] Docket No. 71-9330, *Safety Analysis Report, Advanced Test Reactor Fresh Fuel Shipping Container (ATR FFSC)*, Rev 6, June 2011, Battelle Energy Alliance, LLC.

[2] *Polyethylene FA3220 Product Safety Information Sheet*, Borealis AG, Vienna Austria, Retrieved August 9th, 2011 from http://www.borealisgroup.com/datasheets/10020393.

- 50 Btu of heat will raise the average temperature of the fuel handling enclosure no more than 3.55°F (1.97°C), which is insignificant compared to:
  - The ATR fuel handling enclosure peak temperature of 812°F (433°C) (Figure 3.4-4 of the SAR) in the area of combustion (the enclosure as shown in Figure 1.2-9 of the SAR).
  - The FFSC-LFPB peak temperature of 735.3°F (390.7°C) (Figure 3.4-7 of the SAR) in the area of combustion (the volume surrounding the basket contents as shown in Figure 1.2-15).
  - The MIT fuel handling enclosure peak temperature of 662.5°F (350.3°C) (Figure 3.6-6 of the SAR) in the area of combustion (the enclosure as shown in Figure 1.2-6 of the SAR).
  - The MURR fuel handling enclosure peak temperature of 684.5°F (362.5°C) (Figure 3.6-7 of the SAR) in the area of combustion (the enclosure as shown in Figure 1.2-7 of the SAR).
  - The maximum allowable temperature of 1100°F (593.3°C) for the enclosures (Table 3.1-1 of the SAR).

All available oxygen is consumed during the initial combustion. This results in an increase in temperature of the gases inside of the package which, in order to maintain a pressure equilibrium, forces venting of the combustion gases out of the package between the lid and the lid opening. Since the air is being forced out of the package, no fresh air can enter the package. This is due to the venting arrangement which restricts the flow of air, and exists on only one end of the package. In other words, Heat-driven circulation of air through the package is prevented .

The temperature inside the package remains high during the fire event ensuring that the pressure within the package will not drop below the external pressure. Any transient pressure events of any significance will remain above the outside air pressure, which remains low, since the air outside of the package is allowed to flow freely away from the package as it is heated. Since there is no pressure differential, airflow into the package will not occur during the remainder of the fire event, preventing re-ignition of the polyethylene.

After the fire event, the temperature inside the package initially remains higher than the outside air temperature, preventing immediate air flow into the package. As the gas inside the package cools, the pressure will decrease and air will flow into the package. Oxygen will slowly be reintroduced into the package due to the restricted opening. If at any time the polyethylene remains above its auto ignition temperature and it is exposed to fresh oxygen a small flare-up may occur. This will immediately consume the available oxygen (which will be less than allowed in the initial combustion due to the slow refresh rate), and exhaust itself as before. The package will continue to cool in spite of any possible polyethylene flare-ups.

Combustion Analysis:

Polyethylene has a chemical composition formula of C_2H_4 and a gross heat of combustion of 47.74 kJ/g[3]. The combustion of polyethylene with air is governed by the following equation:

$$C_2H_4 + 3(O_2 + 3.76N_2) \rightarrow 2CO_2 + 2H_2O + 11.28N_2$$

Based on this equation, the air to fuel ratio is:

[3] Walters, R.N., Hackett, S.M, Lyon, R.E., *Heats of Combustion of High Temperature Polymers*, Federal Aviation Administration, William J. Hughes Technical Center, Fire Safety Section AAR-422, Atlantic City International Airport, NJ.

$$AF = \frac{m_{air}}{m_{PE}} = \frac{3(1.00\ kmol + 3.76kmol)(28.97\ kg/kmol)}{(2kmol)(12\ kg/kmol) + (4kmol)1kg/kmol)} = 14.77$$

where the molar mass of air is 28.97 kg/kmol[4], and the molar mass of the polyethylene is calculated from the common values for the molar mass of carbon and hydrogen. The amount of air available for combustion is limited to the volume of the air in the payload cavity. The volume of air inside of the packaging cavity is the volume of the cavity minus the volume displaced by the small quantity fuel handling enclosure (basket) and the fuel. Conservatively, the volume displaced by the fuel will be neglected. The volume of air displaced by the basket is:

$$V_{basket} = \frac{m_{basket}}{\rho_{Al}} = \frac{30\ lb}{0.098\frac{lb}{in^3}} = 306\ in^3$$

where the mass of the basket is the mass of the small quantity fuel handling enclosure found in Table 2.1-1 of the SAR and the density of aluminum is taken from Section II, Part D, Table PRD of the ASME B&PV Code[5]. The volume of the package cavity is:

$$V_{cavity} = \left(\frac{\pi}{4}\right) d^2 l_{cavity} = \left(\frac{\pi}{4}\right)(5.76\ in)^2(67.88\ in) = 1{,}769\ in^3$$

where the mass of the basket and the dimensions of the package are the nominal values found in the SAR. The volume of air available for combustion is:

$$V_{air} = V_{cavity} - V_{basket} = 1{,}769\ in^3 - 306\ in^3 = 1{,}463\ in^3$$

Since the package is vented, for the purpose of determining the available mass of air, the average pressure inside the package may be conservatively assumed to remain at or about atmospheric pressure (101 kPa). For an ignition temperature of 320°C, and assuming ideal gas behavior, the density of air in the package is:

$$\rho_{air} = \frac{p}{RT} = \frac{101\ kPa}{\left(0.2870\frac{kJ}{kg \cdot K}\right)(320\ +\ 273.2)K} = 0.5933\frac{kg}{m^3}$$

From the density and the volume of air, the initial mass of air available for combustion is:

$$m_{air} = V_{air}\rho_{air} = 1{,}463\ in^3\left(0.5933\frac{kg}{m^3}\right)\left(\frac{0.0254\ m}{1\ in}\right)^3\left(\frac{1000g}{1kg}\right) = 14.22\ g$$

From the air fuel ratio, the mass of fuel burned within the cavity is:

$$m_{burned} = \frac{m_{air}}{AF} = \frac{14.22\ g}{14.77} = 0.9628\ g$$

This shows that there is only enough air inside the cavity of the package to burn less than 1 g of polyethylene. The heat created by burning of the polyethylene is:

---

[4] Rohsenow, W.M., Hartnett, J.P., Cho, Y.I., *Handbook of Heat Transfer*, 3rd edition, McGraw-Hill, New York, NY, 1998.
[5] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (ASME B&PV) Code, Section II, Part D, 2010.

$$Q = Q_c\, m_{burned} = 47.74 \frac{kJ}{g}(0.9628g) = 45.96\, kJ = 43.56\, Btu$$

Temperature Change

Initially, the heat derived from combustion is distributed throughout the fuel, dunnage, and packaging. The initial thermal energy spike due to the combustion is rapidly dispersed over the mass of the package. Conservatively, the thermal energy added due to the polyethylene combustion is assumed to remain in the payload and the basket. The polyethylene bag is wrapped around the fuel and sandwiched between aluminum shoring within the aluminum basket.

The difference in the heat capacity of the fuel and the aluminum of the basket and dunnage is assumed to be negligible, therefore the total mass of aluminum and fuel in the small quantity fuel handling enclosure, as taken from Table 2.2-1 of the SAR, is 50 lb (22.68 kg). The specific heat of Alloy 6061 aluminum at 620°F, closest to the flash temperature of polyethylene at 320°C (608°F) from Table 3.2-2 of the SAR is $C_{Al} = 0.246 \frac{Btu}{lbm \cdot °F}$. The temperature rise in the aluminum due to the combustion of polyethylene is:

$$dT = \frac{Q}{m_{Al} C_{Al}} = \frac{45.96\, kJ}{22.68\, kg\left(0.246 \frac{Btu}{lb_m \cdot °F}\right)} \left(\frac{1 \frac{Btu}{lb_m \cdot °F}}{4.187 \frac{kJ}{kg \cdot K}}\right) = 1.97°C = 3.5°F$$

Amount of Refresh Air

The amount of air returning into the package after the fire event will be due to the package pressure equalization due to the pressure decrease as the package cools. Although the mass inflow is expected to occur over the period of time that the package will spend cooling down, it is the amount between the maximum and auto ignition temperatures that are of concern. Conservatively, the maximum average air temperature can be taken as the maximum peak fire temperature found within the package payload cavity. Also, for simplification of the model, the combustion can be taken all at once and not spread over the entire period of the cool-down interval. The density of hot air is:

$$\rho_{hot\ air} = \frac{p}{RT} = \frac{101\, kPa}{\left(0.2870 \frac{kJ}{kg \cdot K}\right)(547.2 + 273.2)K} = 0.4290 \frac{kg}{m^3}$$

where the gas constant for normal air mixture is assumed to be reasonable. From the density and the volume of air, the mass of air in the cavity is:

$$m_{hot\ air} = V_{air} \rho_{hot\ air} = 1{,}463\, in^3 \left(0.4290 \frac{kg}{m^3}\right)\left(\frac{0.0254\, m}{1\, in}\right)^3 = 10.28\, g$$

The replacement air mass is the difference between the mass of air at auto ignition temperature and the hot air temperature. The mass of replacement air is:

$$m_{air_2} = m_{air} - m_{hot\ air} = 14.22\, g - 10.28\, g = 3.94\, g$$

From the air to fuel ratio, the additional mass of burned polyethylene is:

$$m_{burned_2} = m_{burned}\frac{m_{air_2}}{m_{air}} = 0.9628g\frac{3.94g}{14.22g} = 0.267g$$

Which is much less than the original combustion amount and it will contribute approximately one-quarter of the original combustion's thermal energy. The actual combustion is expected to contribute less, since the oxygen is not expected to return all at once.