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ANALYSIS OF THE PRESSURE TRANSIENT AND BURST PRESSURE FOR EXPOSURE OF THE 9975 PRIMARY CONTAINMENT VESSEL TO FIRE

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ABSTRACT

Bare shipping package containment vessels can be utilized to stage plutonium oxide at the Savannah River Site. Pressurization and subsequent release could occur due to a hypothetical facility fire. Pressurization due to adsorbed moisture on the plutonium oxide and plastic packaging materials could result in rupture of the containment vessel. The containment vessel was evaluated to determine rupture pressure when subjected to the fire conditions. The rupture pressure is compared with pressures developed due to radiolytic gas generation.

INTRODUCTION

To support the calculation of potential dose consequences, an analysis of the pressure transient inside a 9975 primary containment vessel (PCV) exposed to a postulated 800 °C fire was conducted to determine if the internal vessel pressure will exceed the burst pressure at the elevated container temperature. A schematic of the PCV is shown in Figure 1.

Within the PCV, plutonium oxide is packaged inside a slip lid can (SLC) within an inner can (IC). Plastic bags (usually polyethylene) are used with these cans for contamination control. The lid of the SLC is attached with tape. The PCV may also contain a hydrogen getter assembly consisting of a mixture of polyphenyl ether ($C_{30}H_{22}O_4$), and/or a Type 3A zeolite molecular sieve and a honeycombed aluminum spacer. The getter material, plastic bags, and tape will decompose when heated by the fire.

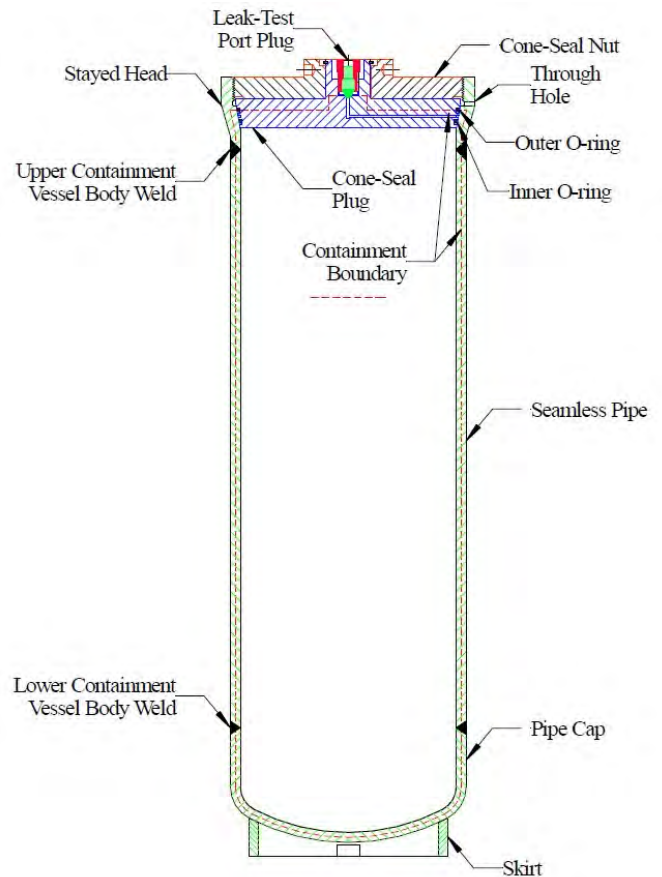


FIG 1. 9975 PRIMARY CONTAINMENT VESSEL (PCV)

NOMENCLATURE

B_1	factor for calculation of burst pressure from yield strength
d_t	PCV lid thread root diameter
F_l	force acting on threads of PCV lid
m	radius to wall thickness ratio
n_g	number of monolayers of adsorbed moisture
P	pressure inside PCV
P_b	PCV burst pressure
R	gas law constant
S_u	ultimate strength
S_y	yield strength
T	temperature, K
V_{PCV}	gas space volume inside PCV
β	ratio of yield strength to ultimate strength
ψ	factor for calculation of burst pressure from yield strength

PRESSURIZATION CALCULATION

The hypothetical fire is assumed to heat the PCV and its contents to 800 °C. During exposure to the fire, the pressure inside the PCV will increase due to volumetric expansion of the gas initially present inside the PCV, evaporation of moisture adsorbed onto the plutonium oxide and/or the zeolite inside the PCV, and gas generation from pyrolysis of the hydrogen getter material, plastic bagging material, other organic material inside the PCV, and the o-rings that seal the PCV. All organic materials except the getter material are treated conservatively as polyethylene in the pressure calculations. All gas pressures are calculated using the ideal gas law.

All water adsorbed on the plutonium dioxide or zeolite is assumed to evaporate into the vapor space during the postulated fire, adding to the moles of gas in the vapor space.

The amount of gas generated by pyrolysis is estimated from the mass of the getter material, the plastic bagging material, and the o-rings and knowledge of the getter material, bagging material, and o-ring chemistry. The PCV is sealed by inner and outer o-rings inserted between the cap and the base. It is assumed that the gases from the decomposition of the inner o-ring enter the PCV gas space and therefore pressurize the PCV, while gases from the outer o-ring are vented to the secondary containment vessel (SCV); this arrangement is consistent with the assumption of no venting of the PCV. The specified o-ring material is either Viton® GLT or GLS. Viton® GLT is a polymer with the monomeric chemical formula $-\text{CH}_2-\text{CF}_2-\text{CF}_2-\text{CF}(\text{OCF}_3)-\text{CF}_2-\text{CF}_2-$ and an approximate monomeric molecular mass of 330 g/mol.¹ Thermogravimetric analyses (TGA) of Viton® materials indicate that the thermal decomposition of Viton® generates nearly all gaseous products and leaves little solid residue.¹ Accordingly, the analysis

assumes that complete decomposition of the o-ring occurs at 800 °C. The number of moles of gas is estimated by assuming that the pyrolysis takes place in a reducing (oxygen-limited) atmosphere due to the presence of the plutonium oxide and that, consequently, the primary pyrolysis product gases per mole of monomer are one mole each of $\text{C}_2\text{H}_2\text{F}_2$, CO, and F_2 and two moles of C_2F_4 . Under this assumption, the pyrolysis of Viton® GLT would generate five moles of gas per mole of monomer.

The bagging material is polyethylene, which is a polymer with the monomeric formula $-\text{C}_2\text{H}_4-$ and an approximate molecular mass of 28 g/mol.² The decomposition kinetics for polyethylene are nearly identical to those for Viton®, i.e., polyethylene decomposes nearly completely between 475 °C and 525 °C when heated at 40 °C/min.³ It is assumed that the pyrolysis of polyethylene under the reducing atmosphere present in the PCV generates C_2H_4 gas at a rate of one mole per mole of monomer. Measured gas compositions for the pyrolysis of polyethylene confirm that C_2H_4 (ethylene) is one of the principal gas species generated by thermal decomposition in the absence of oxidizing gases.⁴ Moreover, an assumption that the pyrolysis gas is comprised of C_2H_4 provides a close bound to the number of moles of gas generated per unit mass of polyethylene. The PCV gas space is calculated using the ideal gas law:

$$P = \frac{n_{\text{gas}}RT}{V_{\text{PCV}}} \quad (1)$$

The total moles of gas, n_{gas} , is the sum of the moles of gas initially present, the moles of adsorbed water and the moles of degradation products from the thermally decomposed polymers.

The ideal gas law does not include the compressibility correction, which, at high temperatures and pressures, slightly reduces the volume a gas occupies at a given pressure. The compressibility factor also decreases the pressure for a given temperature and a fixed volume, so its omission in this analysis is conservative.

The pressurization due to moisture evaporation and material decomposition is inversely proportional to the volume of the gas space inside the PCV. The gas space is computed by subtracting the volumes of the Hanford Can and SLC walls, the plastic, the plutonium oxide, and the adsorbed moisture from the interior volume of the PCV. For packaging of product material from HB-Line, the plutonium oxide volume is based on a pycnometric density of 9.5 g/cm³, measured for pure PuO_2 calcined at 600 °C.⁵ This density represents a limiting density for low temperature calcination of plutonium oxalate and conservatively bounds the value recommended by the DOE Standard 3013, which is 90% of the crystalline density of PuO_2 .⁶ The crystalline density of PuO_2 is 11.46 g/cm³.⁷ No specific allowance is made for any volume occupied by salts or other impurities contained in HB-Line oxide. The total available gas space in the PCV for HB-Line oxide, subtracting all components including the hydrogen getter, is 4191 cm³. For

[®] Viton is a registered trademark of DuPont Performance Elastomers LLC of Wilmington, Delaware.

packaging of material from K-Area or other sources, the oxide volume is based on an assumed limiting pycnometric density of 4.8 g/cm³. This density accounts for the presence of salts and other impurities. The available gas space for material from K-Area or other sources is 4005 cm³. Table 1 summarizes the calculation of the available gas space inside the PCV containers.

TABLE 1. VOLUMES AND GAS SPACES INSIDE PRIMARY CONTAINMENT VESSEL (PCV)

Description	Volume (cm ³)
PCV Interior	5129
Hanford Can Exterior	1751
Hanford Can Interior	1548
Hanford Can Wall	203
Slip Lid Can Exterior	949
Slip Lid Can Interior	873
Slip Lid Can Wall	76
Slip Lid Filter	23
Getter Can Wall	60
Steel	400
Zeolite recombiner	69
Polyphenyl ether	158
Viton o-ring	4
Polyethylene bags, HB-Line	110
Polyethylene bags, K-Area	121
Plastic, HB-Line	272
Plastic, K-Area	283
Plutonium oxide, HB-Line = $\frac{1700}{9.5}$	= 179
Plutonium oxide, K-Area = $\frac{1700}{4.8}$	= 354
Aluminum honeycomb	18
Net Volume for HB-Line oxide = 5129 – 400 – 69 – 272 – 179 – 18	= 4191
Net Volume for K-Area material = 5129 – 400 – 69 – 283 – 354 – 18	= 4005

Note 1: Moisture is subtracted from the Net Volume as mass of adsorbed water divided by density at 1.0 g/cm³.

Note 2: The bag mass for the HB-Line packaging is conservatively set at 100 g to calculate the displacement volume. A mass of 65 g is used in the calculation of the pyrolytic gas generation.

Note 3: The steel volume in the Slip Lid Can, Hanford Can, and Getter Can is rounded up approximately 10% to account for deviations from nominal specified dimensions and approximations made in the calculation of the wall volumes

Note 4: The volume of the Hanford can bounds the volume of the FB-Line can.

STRUCTURAL ANALYSIS

The analysis calculates the failure pressure for the primary containment vessel (PCV) used in the nuclear material package 9975. The PCV is fabricated to ASME Section III, Subsection NB code.⁸ The PCV base is a 5-inch Sch. 40 seamless pipe fabricated from stainless steel Type 304L. ASME code does not permit Type 304L for pressure components beyond 1000 °F. ASME code permits Type 304 for high temperature application

and its material strength properties, yield stress (S_y) and ultimate stress (S_u), are given in the ASME code, Subsection NH up to 1500 °F.⁸ Some code guidance is used from the SS304 properties to derive SS304L properties beyond 1000 °F.

High temperature exposure of the PCV is limited to one hour. For this short time, thermal creep is not important. In addition, the fire loading is a one-time event and, therefore, no thermal fatigue consideration is given in the evaluation. The burst pressure evaluation is based on simplified formulation, PCV burst pressure data, and guidance from the ASME Code. No attempt is made to meet all the Code requirements.

Type 304L strength properties are taken from the ASME code.⁸ The code gives minimum strength values for Type 304L up to 1000 °F only. A comparison of SS304 and SS304L minimum yield strengths up to 1000°F shows that the reduction is 48.3% and 46.8%, respectively. Therefore, the reduction in strength values for 304L at 1500 °F is assumed to be same as Type 304. In addition, the reduction in yield strength for the SS304 between 1000 °F and the 1500 °F is fairly linear. The minimum properties of SS304L are given in Table 3 and are presented here for comparison only with the average or typical properties.

TABLE 3. MINIMUM STRENGTH PROPERTIES

Temp (°F)	S_u (ksi)	S_y (ksi)	Temp (°F)	S_u (ksi)	S_y (ksi)
100	70.0	25.0	700	56.4	15.0
200	66.1	21.4	800	55.4	14.5
300	61.2	19.2	900	54.6	14.0
400	58.4	17.5	1000	52.3	13.3
500	57.5	16.4	1472	21.08	8.06
600	56.9	15.5	1500	19.23	7.75

As pointed out before, code does not permit the use of Type 304L for code certified vessels operating at temperatures above 1000 °F. The material does retain considerable strength and the industry does permit Type 304L for continuous usage up to 1600 °F.⁹ Average or typical strength properties are obtained from the industry literature.¹⁰ Average properties are given in Table 4. The numbers in red are interpolated for the ultimate strength while the value for yield strength is linearly extrapolated from 1200 °F and 1400 °F values. Since the material SS304L retains considerable strength up to 1600 °F, a small extrapolation to 1472 °F is acceptable.

TABLE 4. AVERAGE/TYPICAL STRENGTH PROPERTIES

Temp (°F)	S_u (ksi)	S_y (ksi)
Room	85.00	35.00
400	72.00	23.00
600	68.00	19.50
800	64.00	16.50
1000	56.00	14.00
1200	44.00	12.50
1400	29.00	11.00
1472	24.32	10.46
1600	16.00	Not Available

The intent of this evaluation is to calculate the allowable pressure for the PCV during fire. The method relies on the use of PCV test data to verify the accuracy of the methodology. Since the accuracy test uses the typical strength properties rather than minimum properties, the results are typical collapse pressures. A safety margin is applied using the code guidance to arrive at the final result. A schematic of the PCV with its components is shown in Fig. 1. The PCV failure scenarios are:

- Vessel shell bursting
- Cone seal nut failure
- Cone seal nut thread failure

The PCV was tested at room temperature to assess its burst pressure in the design and certification of the package 9975. The burst pressure was 7560 psig at room temperature. During testing the failure occurred on its shell longitudinally. The seal nut and the threads did not fail. It is assumed that even at high temperatures, the failure mode will be the same since it is a one-time thermal loading. The evaluation presented here is based on text book formulas that are regarded good for preliminary design. The formula is tested for accuracy for the PCV burst pressure observed at room temperature and is then used to calculate the burst pressure at 1472 °F (800 °C). The cone seal nut did not fail in any tests due to its large thickness. The pressure load is transmitted to the seal nut via cone seal plug and does not result in any bending loads on the cone seal nut. Therefore, the pressure load is essentially transmitted as a shear load to the seal nut threads. Consequently, only threads are analyzed for shear failure.

The evaluation for shell bursting relies on the burst pressure (collapse load) of the PCV; no detailed plastic analysis is performed to meet the ASME Code requirements. Non-mandatory Appendix F (Section F-1331.1(c)(2)) of the Code⁸ gives guidance when using the collapse load for evaluation. Appendix F requires that the calculated collapse load shall be multiplied by a factor 0.90 to calculate the allowable load. The calculation steps are:

1. Calculate the collapse load at 1472°F,
2. Calculate the allowable load by multiplying results from Step 1 by 0.9.

The PCV was hydro tested until failure occurred. Figure 1 shows a failed specimen and an intact sample. The failure is longitudinal and is caused by higher hoop stresses.



FIG 3. PCV (INVERTED) AFTER AND BEFORE THE BURST TEST

The burst pressure is calculated using the thick shell assumption:¹¹

$$P_b = S_y \psi B_1 \quad (2)$$

The factors ψ and B_1 are given in Figures 35.9 and 35.10 of Reference 11. The factor B_1 depends upon the strength ratio

β , where $\beta = \frac{S_y}{S_u}$ is the ultimate strength. The material

properties are calculated at the operating temperature. The formula for the burst pressure is tested for the observed failure pressure of the PCV at room temperature. At the room temperature, the average strength properties for 304L are taken from the AK Steel catalog:¹⁰ $S_y = 35000$ psi, $S_u = 85000$ psi.

This gives $\beta = 0.412$. Using linear extrapolation from Figure 35.10 of Reference 10, B_1 is found to be 2.214. Figure 35.9 of Reference 11 gives the geometry factor $\psi = 0.1$ for $m = 10.28$, where m is the radius to thickness ratio. Equation 1 then gives the burst pressure P_b . The mean radius-to-thickness (R/T) ratio of 10.28 of the PCV shell is at the upper end ($R/T = 10$) of the thick shell formula, so the application of equation 2 is assumed to be acceptable. At room temperature $P_b = 35000 \times 0.1 \times 2.214 = 7749$ psig.

If a factor of 0.9, as stated in the beginning of this section, is used to the above calculated burst pressure, we get a value of 6974 psig. This estimate is less than the burst pressure of 7560 psig found in the PCV test. This accuracy test gives confidence that the simple formula can be used to calculate the burst pressure at higher temperatures.

At a PCV temperature of 1472 °F (800 °C), Table 4 gives $S_y = 10460$ psi and $S_u = 24320$ psi. This gives $\beta = 0.430$.

From Figure 35.10 of Reference 11, $\beta = 0.430$ is slightly less than the limiting value of β (0.50), so extrapolation can be used to calculate B_1 . B_1 is found to be 2.16. For this value of B_1 , equation 1 is used to calculate the burst pressure at 1472 °F (800 °C). At 1472 °F (800 °C) $P_b = 10460 \times 0.1 \times 2.16 = 2259$ psig.

Using the guidance from Appendix F Section 1331.1(C)(2) the static load at 1472 °F is $2259 \times 0.90 = 2033$ psig.

The seal nut does not experience any bending loading and sees only compressive loading from the PCV cone seal plug and therefore will not fail. Therefore, no further evaluation is performed.

There are 12 threads per inch in the seal nut. The thread root diameter d_t is 5.063 in. The shear area of the threads at the roots is $= 3.14 \times 5.063 \times 0.625 = 9.9412 \text{ in.}^2$. The force acting on the threads, $F_1 = \text{Burst pressure} \times \text{Seal Plug Area} = 2033 \times \pi \times (5.27)^2/4 = 44300 \text{ lbf}$. The shear stress at the roots of the threads $= 44300/9.9412 = 4456 \text{ psi}$. The shear ultimate stress is approximately 42% of the ultimate tensile strength. Therefore, the shear strength $= 0.42 \times S_u = 10214 \text{ psi}$. Since the maximum shear stress at the root of the threads is only 4456 psi, the cone seal threads will not fail at the burst pressure.

DISCUSSION OF RESULTS

Separate parametric analyses were performed for material from K-Area and other sources (Case A) and for HB-Line plutonium oxide product (Case B). For K-Area material containing 1.5 kg of elemental plutonium (present as approximately 1.7 kg of oxide) and 110 g of polyethylene, Table 5 lists the calculated pressures at 800 °C. Pressures are tabulated as functions of the moisture content inside the PCV in g. For a tightly sealed PCV (i.e. without taking credit for venting) pressures for exposure to the 800 °C fire would range from 3329 psig for 75 g of moisture to 4200 psig for 120 g of moisture.

Table 6 lists pressures at 800 °C for HB-Line oxide containing 1.5 kg of elemental plutonium (1.7 kg of plutonium oxide) and 65 g of polyethylene bagging. The maximum pressures for the HB-line oxide range from 2650 psig for 75 g of moisture to 3466 psig for 120 g of moisture.

TABLE 5. EFFECT OF TOTAL MOISTURE LEVEL ON PCV PRESSURE FOR CASE A

Note: Case A is exposure of 1.7 kg of plutonium oxide with a pycnometric density of 4.8 g/cm³ to a 800 °C fire without venting and with a hydrogen getter and 110 g of packaging plastic.

Mass H ₂ O (g)	Pressure at 800 °C
75	3329
100	3810
120	4200

TABLE 6. EFFECT OF TOTAL MOISTURE LEVEL ON PCV PRESSURE FOR CASE B

Note: Case B is exposure of 1.7 kg of plutonium oxide with a pycnometric density of 9.5 g/cm³ to a 800 °C fire without venting and with a hydrogen getter and 65 g of packaging plastic.

Mass H ₂ O (g)	Pressure at 800 °C
75	2650
100	3101
120	3466

The contributions of evaporation of moisture, decomposition of the plastic bags and the o-ring, and volumetric expansion of gases present in the PCV prior to heating can be compared. For example, of the total pressure increase of 3101 psig for Case B with a total moisture content of 100 g, 1758 psig results from complete evaporation of the adsorbed moisture, 1560 psig is from the generation of gases from plastics decomposition, and 38 psig is due to volumetric expansion alone.

As the results in Tables 5 and 6 indicate, for a PCV containing 1.5 kg of elemental plutonium (1.7 kg of plutonium oxide) with at least 75 g of moisture and an appropriate amount of polyethylene bagging, the calculated pressures for fire exposure at 800 °C exceed the expected PCV burst pressure of 2033 psi at that temperature. Therefore, the PCV is expected to burst if exposed to an 800 °C fire.

Table 7 gives the calculated pressure at 800 °C without venting for a PCV charged with plutonium oxide, no more than 60 g, 90 g or 120 g of total plastic (the total plastic includes any Tyvek from the recombiner, tape, bag filters, o-ring or gasket on an inner can filter, etc.), and no hydrogen getter, but with a recombiner and fresh molecular sieve. The pressures in Table 7 are shown as a function of the oxide mass, plastic mass and percent adsorbed moisture. The pressure is a very nearly linear function of the oxide mass, plastic mass, or percent adsorbed moisture. A graph of the pressure versus any of these three independent variables will be very nearly linear and very slightly concave upwards. Therefore, a pressure calculated by linear interpolation between any two values in Table 6 will be accurate to within a few psig and slightly conservative.

TABLE 7. PCV PRESSURE (PSIG) FOR EXPOSURE OF PLUTONIUM OXIDE WITH ADSORBED MOISTURE IN AN 800 °C FIRE WITHOUT VENTING

Grams Plastic	0.75% Moisture		1.0% Moisture		1.25% Moisture		1.5% Moisture		1.75% Moisture		2.0% Moisture	
	60	90	120	60	90	120	60	90	120	60	90	120
Grams Oxide												
2500	1178	1512	1850	1284	1619	1959	1391	1727	2068	2178	2504	2823
3000	1257	1595	1939	1386	1726	2072	1516	1858	2205	2338	2663	2998
3500	1337	1681	2030	1491	1836	2188	1644	1992	2345	2504	2823	3045
4000	1420	1770	2124	1598	1949	2307	1777	2130	2490	2674	2900	3274
4500	1506	1860	2221	1709	2066	2429	1913	2273	2639	2859	3129	3411
5000	1593	1954	2320	1822	2186	2555	2053	2419	2792	2953	3274	3511

At 1.0% moisture and 60 g of plastic, the pressure in a fire is less than the burst pressure of the PCV. This allows the amount of plastic to be increased and still remain below the burst pressure in a fire. For 5.0 kg of plutonium oxide with no more than 1.0% moisture, the allowable total plastic can be increased to 77 g with a resulting pressure of 2027 psig. At 1.5% moisture, the total plastic can be increased to 66 g for the case of 4.0 kg of plutonium oxide with a resulting pressure of 2027 psig. If the moisture can be shown to be at or below 0.5%, 5.0 kg of plutonium oxide and a total plastic mass of 115 g would result in a pressure of 2026 psig.

SUMMARY AND CONCLUSIONS

The minimum expected burst pressure of the primary containment vessel (PCV) at 1472 °F (800 °C) is 2033 psig. The seal cone nut or its threads will not fail at the PCV burst pressure.

The pressurization of the PCV during exposure to an 800 °C fire has been calculated without taking credit for venting, which is anticipated as the o-ring would fail at elevated temperatures. The primary contributors to the increase in pressure inside the PCV during heating are evaporation of moisture adsorbed on the plutonium oxide contents and the zeolite in the getter assembly and generation of gases from decomposition of plastic bagging material and hydrogen getter material. Pressure transients have been evaluated for a PCV with 1.5 kg elemental plutonium (present as approximately 1.7 kg plutonium oxide), from 75 to 120 g adsorbed moisture, and an appropriate amount of polyethylene bagging material. The calculated pressures at 800 °C range from 2650 psig for 75 g total moisture to 3466 psig for 120 g moisture. The corresponding pressures for material from K-Area or other sources are 3329 psig for 75 g moisture and 65 g of polyethylene bagging and 4200 psig for 120 g moisture and 110

g of polyethylene. These pressures exceed the expected burst pressure at this temperature, so the PCV is expected to burst if exposed to an 800 °C fire.

For the additional case, the calculated pressure at 800 °C is reduced by limiting the amount of water present. A PCV charged with 5.0 kg of plutonium oxide with no more than 1% moisture and no more than 77 grams of plastic present has a calculated pressure at 800 °C of 2027 psig, which is below the burst pressure. For this case, the PCV is expected to survive a 800 °C fire. At 1.5% moisture the total plastic can be increased to 66 g for the case of 4.0 kg of Pu oxide resulting in 2027 psig. Table 7 presents other combinations of plutonium oxide loading, % moisture, and grams of plastic that are also below the PCV burst pressure of 2033 psig.

It should be noted that the PCV o-ring is not rated for 800 °C, thus leakage through the PCV threaded closure cannot be precluded. Any leakage would reduce the PCV internal pressure.

The PCV pressurization analysis is conservative due to two simplifications:

1. The PCV is assumed rigid as internal volume expansion due to deformation of the vessel has been neglected.
2. The heating of the water vapor and gases inside the PCV is assumed to identically follow the transient fire temperature curve. In reality, the water vapor and gas temperature would be somewhat lower as the thermal inertia and thermal resistance of the system have been neglected for this limited duration fire.

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