# TRUPACT-III

# PREx

Revision 0
June 2007

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# 1.0 INTRODUCTION

The TRUPACT-III Payload Requirements under 10 CFR §71.43(d) Exemption (TRUPACT-III PREx) describes the methodology for TRUPACT-III shipments of payloads potentially exceeding the flammable gas limits specified in the TRUPACT-III Authorized Methods for Payload Control (TRUPACT-III TRAMPAC).[1] The TRUPACT-III TRAMPAC flammable gas limits are based on ensuring ≤5% hydrogen concentration in the innermost confinement layer of the payload during the applicable shipping period. The potential to exceed these flammable gas limits may be due to the presence of sealed containers, aerosol cans, and/or high-wattage waste in the TRUPACT-III package.[2] The TRUPACT-III shipment of such a payload requires an exemption from the requirements of 10 CFR §71.43(d).[3] Section 1.4, *Methodology Overview*, provides the technical basis and justification for an exemption from the requirements of 10 CFR §71.43(d) for the use of the TRUPACT-III for this purpose.

## 1.1 Background

The TRUPACT-III packaging is considered a cost-effective and safe alternative to designing, building, and operating repackaging and size-reduction facilities at each of the sites to repackage the oversized waste inventory into smaller containers for transportation in the TRUPACT-II packaging. A percentage of the existing oversized waste inventory may contain sealed containers and/or partially filled aerosol cans. The flammable gas compliance methodology of the TRUPACT-III TRAMPAC prohibits the presence of sealed containers >4 liters in size and aerosol cans, thus requiring repackaging to remove or mitigate these waste components. The TRUPACT-III PREx accounts for the presence of sealed containers and aerosol cans in the oversized waste inventory. As such, the methodology outlined herein enables the use of the TRUPACT-III for the safe shipment of oversized boxes consistent with as-low-as-reasonably-achievable (ALARA) considerations by reducing the amount of waste that must be repackaged or opened for mitigation activities. In addition, the implementation of the methodology outlined herein allows the shipment of any wastes that exceed the TRUPACT-III TRAMPAC flammable gas limits due to high wattage values.

[1] U.S. Department of Energy (DOE), *TRUPACT-III Authorized Methods for Payload Control (TRUPACT-III TRAMPAC)*, current revision, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

[2] Packaging Technology, Inc., *Safety Analysis Report for the TRUPACT-III Shipping Package*, current revision, USNRC Docket No. 71-9305, Packaging Technology, Inc., Tacoma, Washington.

[3] Title 10, Code of Federal Regulations, Part 71 (10 CFR 71), *Packaging and Transportation of Radioactive Material*, 01-01-07 Edition.

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# 1.2 Purpose

This document defines the technical safety basis for and conditions and controls under which payloads potentially exceeding TRUPACT-III TRAMPAC flammable gas limits and/or related restrictions on sealed containers or aerosol cans can be safely shipped in the TRUPACT-III.

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# 1.3 Scope

The methodology outlined in this document applies to Standard Large Box 2 (SLB2) payload containers of Contact-Handled Transuranic (CH-TRU) waste that may have the potential for exceeding TRUPACT-III TRAMPAC flammable gas limits (based on ensuring ≤5% hydrogen concentration in the innermost confinement layer during the applicable shipping period). This potential may result from one or a combination of the following:

- Presence of sealed containers greater than 4 liters in size in the SLB2
- Presence of aerosol cans that are either unpunctured or not empty in the SLB2
- High wattage values resulting in non-compliance with flammable gas limits specified in the TRUPACT-III TRAMPAC.

The methodology implements an evacuation and backfill with inert gas process for the loaded TRUPACT-III package that renders all unsealed layers of confinement and void space of the TRUPACT-III and SLB2 non-flammable and accounts for all sources of pressure inside of the TRUPACT-III to ensure that the maximum normal operating pressure (MNOP) of the package is not exceeded during transport. The methodology accounts for the occurrence of a significant chemical reaction (e.g., deflagration of a flammable mixture of gases inside a sealed container with the sealed container assumed to rupture). As outlined in Section 1.4, *Methodology Overview*, the shipment of CH-TRU waste under the payload requirements outlined in this document requires an exemption from the requirements of 10 CFR §71.43(d).[1]

Specific analyses and requirements of the TRUPACT-III Safety Analysis Report (SAR)[2] and the TRUPACT-III TRAMPAC[3] document are applicable to the TRUPACT-III payloads qualified for shipment using the methodology described in this document as follows:

- Applicability of TRUPACT-III SAR

  The analyses presented in the TRUPACT-III SAR remain valid.

- Applicability of TRUPACT-III TRAMPAC

  The TRUPACT-III TRAMPAC requirements and compliance methodologies are applicable except for the following (revised requirements and compliance methodologies for each of the following are included in this document):

  - Prohibition on sealed containers >4 liters in size
  - Prohibition on aerosol cans
  - Gas generation properties requirements

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[1] Title 10, Code of Federal Regulations, Part 71 (10 CFR 71), *Packaging and Transportation of Radioactive Material*, 01-01-07 Edition.

[2] Packaging Technology, Inc., *Safety Analysis Report for the TRUPACT-III Shipping Package*, current revision, USNRC Docket No. 71-9305, Packaging Technology, Inc., Tacoma, Washington.

[3] U.S. Department of Energy (DOE), *TRUPACT-III Authorized Methods for Payload Control (TRUPACT-III TRAMPAC)*, current revision, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

- Payload assembly requirements, including the requirement to assign a TRUPACT-III Content Code
- Compliance methodologies associated with gas generation and payload assembly requirements.

Requirements and compliance methodologies defined in the following sections of the TRUPACT-III TRAMPAC apply to payloads qualified for TRUPACT-III shipment in accordance with this document:

- Chapter 1.0, *Introduction* (except Section 1.6, *TRUPACT-III Content Codes Document*)
- Chapter 2.0, *Container and Physical Properties* (except Section 2.7, *Sealed Containers*)
- Chapter 3.0, *Nuclear Properties Requirements*
- Chapter 4.0, *Chemical Properties Requirements* (except for the prohibition on aerosol cans specified in Section 4.2, *Explosives, Corrosives, and Compressed Gases*).

In addition to the payload container specification of Section 2.8.1, *Specification for Authorized Payload Container*, of the TRUPACT-III TRAMPAC[1], SLB2s qualified for TRUPACT-III shipment in accordance with this document must comply with the design drawings presented in Appendix 1.5.1, *Payload Container General Arrangement Drawings.*

# 1.4 Methodology Overview

The methodology outlined in this document for TRUPACT-III shipment of sealed containers >4 liters in size, aerosol cans that are either unpunctured or not empty, and/or high-wattage payloads in the TRUPACT-III is founded on three governing principles.

The first principle is that all flammable gas within the TRUPACT-III void space, SLB2 void space, and unsealed layers of confinement are rendered non-flammable through the controlled removal of oxygen by an evacuation and backfill with inert gas process of the loaded package. The evacuation model that analytically demonstrates the time and vacuum pressure required to remove oxygen to below flammable limits in the payload is provided in Appendix 2.4.1, *Model for Evacuation of the TRUPACT-III*. Additionally, as documented in Appendix 2.4.2, *Oxygen Generation During Transportation of TRUPACT-III Payloads*, any potential oxygen generation during the shipping duration is insignificant and will have no impact on the evacuation/backfill methodology for reducing oxygen concentration in unsealed layers of confinement.

The second principle is that sealed containers that potentially contain a flammable gas mixture are limited and controlled from both a size and pressure capacity perspective to ensure that any potential deflagration inside the sealed container does not impair the ability of the package to maintain containment. Any sealed containers are accounted for in the MNOP determination by assuming that they undergo a stoichiometric hydrogen and air deflagration with an initial pressure equal to the burst/leakage pressure of the sealed container. The model described in Section 2.1.1, *Adiabatic Constant Volume Deflagration Pressure Model*, provides a conservative estimate of the percent contribution to MNOP resulting from a sealed container deflagration as a function of the size and burst/leakage pressure of the sealed container. It models the deflagration as an adiabatic constant volume stoichiometric process, which is then adjusted to account for the void volume outside of the sealed container available within the SLB2 and TRUPACT-III using Boyle's Law. Stoichiometric deflagration testing presented in Section 2.1.2, *Deflagration Pressure Testing and Pressure Model Validation*, was performed on a large sealed container within the SLB2 and a mock-up of the TRUPACT-III containment vessel to validate and demonstrate the analytical deflagration model as conservative. An initial inventory of sealed containers potentially present in TRUPACT-III payloads was tested to establish the burst/leakage pressure capacities as presented in Section 2.1.3, *Sealed Container Burst Pressure Testing*. Section 2.1.3 also enumerates the requirements to expand the inventory through additional testing. The burst/leakage pressure defines the maximum pressure inside the sealed container that could be present prior to initiation of a deflagration.

The third principle is that limits on the decay heat per SLB2, determined by accounting for all potential sources of pressure including the size and pressure capacity of sealed containers and the number of aerosol cans, ensure that the MNOP of the package is not exceeded over the shipping duration. Potential gas release from aerosol cans is evaluated in Section 2.2, *Pressure due to Aerosol Can Contents Release*, to establish the percent contribution to MNOP resulting from a potential release into the inerted void space of the SLB2 and/or TRUPACT-III. The deflagration model presented in Section 2.1, *Pressure due to Sealed Container Deflagration*, conservatively accounts for the potential release of flammable aerosol can contents and potential subsequent deflagration inside a sealed container. The MNOP compliance methodology, which accounts for total gas generation due to radiolysis, any pressure increase due to potential sealed container

deflagration, and potential aerosol can contents release, is presented in Section 2.3, *MNOP Compliance Methodology*.

# 1.5 Appendix

## 1.5.1 Payload Container General Arrangement Drawings

This section presents the SLB2 (top and bottom loading) general arrangement drawings.[1] The top-loading version consists of two sheets and is entitled, *SLB2 (Top-Loading) SAR Drawing, Drawing Number 51199-701*. The bottom-loading version consists of two sheets and is entitled, *SLB2 (Bottom-Loading) SAR Drawing, Drawing Number 51199-702*.

[1] The general arrangement drawings utilize the uniform standard practices of ASME Y14.5M, *Dimensioning and Tolerancing*, American National Standards Institute, Inc. (ANSI).

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# FIGURE WITHHELD UNDER 10 CFR 2.390

| ITEM | QTY | NEXT ASSY | | |
|---|---|---|---|---|
| - | - | B. HARGO | REL [signature] | 6/13/07 |
| - | - | - | APPD | |
| - | - | - | APPD | |
| - | - | D. Hillstrom | APPD [signature] | 6/12/07 |
| - | - | G. Clark | PM [signature] | 6/13/07 |
| - | - | B. Gauterway | QA [signature] | 6/12/07 |
| - | - | D. Stevenson | CHECK [signature] | 6-12-07 |
| | | | DRAWN J.M.NEVAREZ | 11/28/06 |

Prepared for
U.S. Department of Energy
by PACKAGING TECHNOLOGY, INC.

SLB2 (TOP–LOADING)
SAR DRAWING

WASTE ISOLATION PILOT PLANT
WIPP

| | |
|---|---|
| SCALE: 1/16 | WT. N/A |
| REV: 0 | SHEET 1 OF 2 |
| DWG SIZE D | DWG NO. 51199–701 |
| | CADFILE: 5119970110.DWG |

# FIGURE WITHHELD UNDER 10 CFR 2.390

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| – | – | – | REL | |
| – | – | – | APPD | |
| – | – | – | APPD | |
| – | – | – | APPD | 6/12/07 |
| – | – | – | PM | 6/13/07 |
| – | – | – | QA | 6/12/07 |
| – | – | – | CHECK | 6/12/07 |
| ITEM | QTY | NEXT ASSY | DRAWN J.M.NEVAREZ | 11/28/06 |

Prepared for
U.S. Department of Energy
by PACKAGING TECHNOLOGY, INC.

SLB2 (TOP-LOADING)
SAR DRAWING

WASTE ISOLATION PILOT PLANT WIPP

| | |
|---|---|
| SCALE: 1/16 | WT. N/A |
| REV: 0 | SHEET 2 OF 2 |
| DWG SIZE D | DWG NO. 51199-701 |
| | CADFILE: 5119970120.DWG |

# FIGURE WITHHELD UNDER 10 CFR 2.390

| ITEM | QTY | NEXT ASSY | | |
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| – | – | – | REL | 6/13/07 |
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| – | – | – | APPD | |
| – | – | – | APPD | 6/12/07 |
| – | – | – | PM | 6/13/07 |
| – | – | – | QA | 6/12/07 |
| – | – | – | CHECK | 6-12-07 |
| ITEM | QTY | NEXT ASSY | DRAWN J.M.NEVAREZ | 11/28/06 |

Prepared for
U.S. Department of Energy
by PACKAGING TECHNOLOGY, INC.

SLB2 (BOTTOM-LOADING)
SAR DRAWING

WASTE ISOLATION PILOT PLANT (WIPP)

| | |
|---|---|
| SCALE: 1/16 | WT. N/A |
| REV: 0 | SHEET 1 OF 2 |
| DWG SIZE D | DWG NO. 51199-702 |
| | CADFILE: 5119970210.DWG |

# FIGURE WITHHELD UNDER 10 CFR 2.390

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|---|---|---|---|---|
| – | – | – | REL | |
| – | – | – | APPD | |
| – | – | – | APPD | |
| – | – | – | APPD | 6/12/07 |
| – | – | – | PM | 6/13/07 |
| – | – | – | QA | 6/12/07 |
| – | – | – | CHECK | 6/12/07 |
| ITEM | QTY | NEXT ASSY | DRAWN J.M.NEVAREZ | 11/28/06 |

Prepared for
U.S. Department of Energy
by PACKAGING TECHNOLOGY, INC.

SLB2 (BOTTOM–LOADING)
SAR DRAWING

WASTE ISOLATION PILOT PLANT
WIPP

| | |
|---|---|
| SCALE: 1/16 | WT. N/A |
| REV: 0 | SHEET 2 OF 2 |
| DWG SIZE D | DWG NO. 51199–702 |
| | CADFILE: 5119970220.DWG |

## 1.5.2 Glossary of Terms and Acronyms

**ALARA** – as-low-as-reasonably-achievable.

**ASME** – American Society of Mechanical Engineers.

**ATGGR** – allowable total gas generation rate.

**CH-TRU** – contact-handled transuranic.

**DOE-CBFO** – Department of Energy, Carlsbad Field Office.

**DOT** – U.S. Department of Transportation.

**EMRTC** – Energetic Materials Research and Testing Center.

**HAC** – Hypothetical Accident Conditions.

**LOC** – limiting oxidant concentration.

**MNOP** – maximum normal operating pressure.

**MOC** – maximum oxygen concentration.

**Mock CV** – Mock TRUPACT-III containment vessel. A test article used to simulate the TRUPACT-III containment vessel.

**NCT** – Normal Conditions of Transport.

**NFPA** – National Fire Protection Association.

**Packaging** – The assembly of components necessary to ensure compliance with packaging requirements as defined in 10 CFR §71.4. Within this document, the packaging is denoted as the TRUPACT-III packaging.

**Package** – The packaging with its radioactive contents, or payload, as presented for transportation as defined in 10 CFR §71.4. Within this document, the package is denoted as the TRUPACT-III package.

**Payload** – Contact-handled transuranic waste or other authorized contents contained within the approved payload container.

**Payload Container** – Payload container is an SLB2.

**PPTCD** – PREx Payload Transportation Certification Document.

**PREx** – Payload Requirements under 10 CFR §71.43(d) Exemption (this document).

**SAR** – Safety Analysis Report.

**Sealed Container** – Any waste packaging boundary greater than 4 liters in size that is assumed to prohibit the release of gas across the boundary. A waste packaging component meeting this definition does not have a known release rate of hydrogen gas out of its confined space. Examples of sealed containers are rigid unfiltered containers with fully-welded or gasketed lid closures.

**SLB2** – Standard Large Box 2. A specialized payload container with a top-loading and a bottom-loading option for use within the TRUPACT-III packaging.

**SLB2 Dunnage** – An L-shaped structure used as a test article to consume void space within the SLB2.

**SSC** – Surrogate Sealed Container. A test article used to simulate a large sealed container.

**STP** – Standard temperature and pressure (1 atm and 273 K).

**TCO** – Transportation Certification Official.

**TRU** – transuranic.

**TRUPACT-III CV** – TRUPACT-III containment vessel.

**TRUPACT-III Package** – The package consisting of a TRUPACT-III packaging and the payload.

**TRUPACT-III Packaging** – The packaging consisting of a body, closure lid, and an overpack cover.

**TRUPACT-III TRAMPAC** – TRUPACT-III Authorized Methods for Payload Control.

**Unsealed Layer of Confinement** – Any waste packaging boundary that restricts, but does not prohibit, the release of gas across the boundary. A waste packaging component meeting this definition has a known release rate of hydrogen gas out of its confined space. Examples of unsealed layers of confinement are twist-and-tape plastic bags, heat-sealed plastic bags, filtered plastic bags, and metal containers or drums fitted with filters. Waste packaging materials that allow for the free release of gas (e.g., punctured plastic bags, bags open at the end, pieces of plastic sheeting wrapped around the waste for handling, and metal containers with lid closures that allow free gas release) do not meet this definition and are simply considered to be part of the waste.

# 2.0 PRESSURE EVALUATION

## 2.1 Pressure due to Sealed Container Deflagration

### 2.1.1 Adiabatic Constant Volume Deflagration Pressure Model

Sealed containers in the TRUPACT-III payload can potentially contain flammable concentrations of fuel and oxidizer. The fuel is hydrogen generated due to radiolysis in the payload, the content and propellant in aerosol cans, and/or volatile organic compounds released from the waste matrix. The oxidizer is the oxygen present in atmospheric air inside the sealed container prior to closure. In the presence of an ignition source, a flammable gas mixture can potentially deflagrate within the sealed container causing pressure build-up due to flame propagation and burning in the confined volume.

This section presents a model that conservatively estimates the pressure build-up in the TRUPACT-III containment vessel (CV) resulting from a stoichiometric constant volume deflagration inside of a sealed container as a function of the initial size and pressure of the sealed container. The model was validated by testing as described in Section 2.1.2, *Deflagration Pressure Testing and Pressure Model Validation.*

#### 2.1.1.1 Fuel and Fuel/Oxidizer Ratio

The adiabatic constant volume deflagration pressure model utilizes hydrogen as the fuel at a stoichiometric fuel/oxidizer ratio. Hydrogen is chosen as the fuel for the model due to its predominance as a flammable gas in CH-TRU waste and its high heat of combustion in comparison with other flammable gases such as ethane, propane, and ethylene. Additionally, hydrogen represents the most energetic flammable gas for a deflagration in a TRUPACT-III sealed container due to its very high laminar burn velocity in comparison with other flammable gases such as ethane, propane, ethylene, and acetylene.[1]

A stoichiometric mixture of fuel (hydrogen) and oxidizer (oxygen in air) is chosen as the mixture that produces the highest adiabatic constant volume combustion pressure and temperature attributed to complete combustion of the reactants. The stoichiometric combustion reaction of hydrogen with air is presented by the following chemical equation:

$$2H_2 + O_2 + 3.76N_2 \rightarrow 2H_2O + 3.76N_2$$

Therefore, the volume percent of hydrogen in air (21% $O_2$, 79% $N_2$) required to produce a stoichiometric hydrogen-and-air mixture is as follows:

$$\%H_2 = \frac{\text{mol}(H_2)}{\text{mol}(\text{Air}) + \text{mol}(H_2)} \times 100 = \frac{2}{(1 + 3.76) + 2} \times 100 = 29.58\%$$

[1] Shaw Environmental & Infrastructure, Inc., June 2006, *Confined Deflagration Pressures Generated by Hydrogen*, Rev. 0, Shaw Environmental & Infrastructure, Inc., Albuquerque, New Mexico.

The volumetric air-to-hydrogen ratio for a stoichiometric mixture is similarly calculated as follows:

$$\frac{V_{Air}}{V_{H_2}} = \frac{mol(Air)}{mol(H_2)} = \frac{(1+3.76)}{2} = 2.38$$

#### 2.1.1.2 Cheetah Adiabatic Constant Volume Deflagration

Figure 2.1-1 (from Shaw[1]) gives the adiabatic constant volume hydrogen deflagration (combustion) pressures and temperatures as a function of equivalence ratio (fuel concentration / stoichiometric fuel concentration). The combustion temperatures and pressures were calculated by Cheetah 4.0, a thermochemical-kinetics code developed by Lawrence Livermore National Laboratory.[2] The results are presented for initial conditions at 1 atm and 293 K. The ordinate of the figure for pressure can alternatively be interpreted as a pressure factor and multiplied by any initial absolute pressure to determine the resulting deflagration absolute pressure.

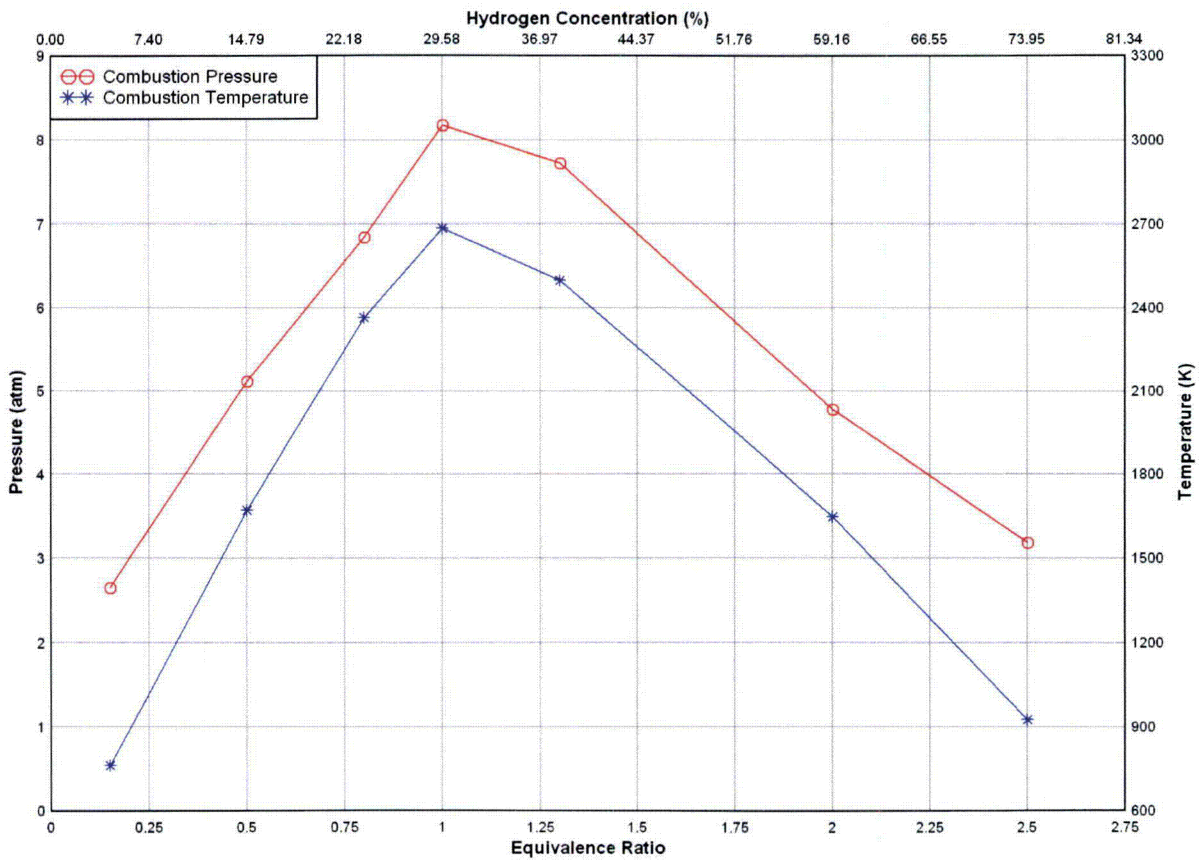


**Figure 2.1-1** – Cheetah-Computed Deflagration Pressure and Temperature

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[2] Lawrence Livermore National Laboratory, 2004, *Cheetah, Version 4.0*, Energetic Materials Center, Lawrence Livermore National Laboratory, Livermore, California.

As seen in Figure 2.1-1, the adiabatic constant volume deflagration pressure and temperature is maximized when the equivalence ratio is unity such that the hydrogen concentration in air is 29.58%. Correspondingly, the pressure increase factor, $P_{factor}$, for an adiabatic constant volume hydrogen deflagration at stoichiometric conditions is 8.18. The Cheetah results are valid for and can be applied to any fixed volume since the calculations are based on a given fuel mixture density.

### 2.1.1.3 Void Volume Scaling

Under the assumption that a sealed container undergoes a stoichiometric deflagration and releases the combustion gases into the void space in the SLB2, which in turn releases the combustion gases into the void space in the TRUPACT-III CV, Boyle's Law can be used to conservatively calculate the resulting pressure increase experienced by the TRUPACT-III as a result of the deflagration. This approach attributes the pressure to heat-up and expansion of combustion gases as predicted by the thermochemical-kinetics code with pressure reductions due to a progressively increasing void space (i.e., sealed container to SLB2 to TRUPACT-III) and neglects any overpressure due to the propagating flame front. Due to the length scales, modest ignition energy potential in the payload, and geometric aspect ratio of the sealed container(s), SLB2, and TRUPACT-III CV, the deflagration assumption is valid. Neglecting the flame front overpressure is appropriate when combined with other model conservatisms since a spherical flame front must travel at exceedingly high effective burning velocities (over 20 meters per second or about 50 times the normal burning velocity of most hydrocarbons) before damaging blast waves (overpressures >0.3 atm) can be generated by a deflagration.[3]

The gauge pressure generated inside a sealed container, $P_{sc\_defl}$, from an adiabatic constant volume deflagration under stoichiometric conditions is given as a function of the initial gauge pressure inside the sealed container, $P_{sc\_init}$, and atmospheric pressure, $P_{atm}$, as follows:

## Equation 1

$$P_{sc\_defl} = [P_{factor} \times (P_{atm} + P_{sc\_init})] - P_{atm}$$

If the sealed container were to breach during the deflagration and release gases into the SLB2, the gauge pressure generated inside the SLB2, $P_{slb2\_defl}$, is proportional to the increase in volume available for gas expansion per Boyle's Law (i.e., $P_1V_1 = P_2V_2$). For a given void volume in the sealed container, $V_{sc\_void}$, and void volume in the SLB2, $V_{slb2\_void}$, the final gauge pressure in the SLB2 is given as follows:

## Equation 2

$$\begin{aligned} P_{slb2\_defl} &= \frac{([P_{atm} + P_{sc\_defl}] \times V_{sc\_void}) + (P_{atm} \times V_{slb2\_void})}{(V_{sc\_void} + V_{slb2\_void})} - P_{atm} \\ &= P_{sc\_defl} \times \frac{V_{sc\_void}}{(V_{sc\_void} + V_{slb2\_void})} \end{aligned}$$

[3] Strehlow, R.A., Luckritz, R.T., Adamczyk, A.A. and Shimpi, S.A., 1979, *The Blast Wave Generated by Spherical Flames*, Combustion and Flame 35, pp. 297-310, Combustion Institute, Pittsburgh, Pennsylvania.

Correspondingly, if the SLB2 were to breach and release gases into the TRUPACT-III CV, the gauge pressure generated inside the CV, $P_{cv\_defl}$, is additionally given as a function of the void volume in the CV, $V_{cv\_void}$, as follows:

## Equation 3

$$P_{cv\_defl} = \frac{([P_{atm} + P_{slb2\_defl}] \times [V_{sc\_void} + V_{slb2\_void}]) + (P_{atm} \times V_{cv\_void})}{(V_{sc\_void} + V_{slb2\_void} + V_{cv\_void})} - P_{atm}$$

$$= P_{sc\_defl} \times \frac{V_{sc\_void}}{(V_{sc\_void} + V_{slb2\_void} + V_{cv\_void})}$$

The above approach conservatively over-predicts the maximum pressure due to heat-up and expansion of combustion gases from a sealed container deflagration within the TRUPACT-III. The constant volume pressure factor is based on an adiabatic assumption that neglects the energy absorbed in breaching the sealed container and SLB2 and any heat losses into the payload, payload container, or packaging. As shown in Section 2.1.1.4, *Percent Contribution to MNOP*, additional conservatism is built into the model through the assumptions regarding the void volumes available for gas expansion.

### 2.1.1.4 Percent Contribution to MNOP

For a given internal volume of sealed container, $V_{sc\_int}$, the initial sealed container gauge pressure required to produce a defined percentage contribution to MNOP, $\%_{mnop}$, in the TRUPACT-III CV resulting from a stoichiometric deflagration inside the sealed container can be determined by the solution of Equation 1, Equation 2, and Equation 3. From Section 3.3.2, *Maximum Normal Operating Pressure*, of the TRUPACT-III SAR, the MNOP of the TRUPACT-III CV is defined as 172 kPa (25 psig).[4] Therefore, Equation 3 can be rewritten as follows:

$$\frac{\%_{mnop} \times 25\text{ psig}}{100} = \frac{([P_{atm} + P_{slb2\_defl}] \times [V_{sc\_void} + V_{slb2\_void}]) + (P_{atm} \times V_{cv\_void})}{(V_{sc\_void} + V_{slb2\_void} + V_{cv\_void})} - P_{atm}$$

or

$$\%_{mnop} = \left( \left[ \frac{P_{sc\_defl}}{25\text{ psig}} \right] \times \left[ \frac{V_{sc\_void}}{(V_{sc\_void} + V_{slb2\_void} + V_{cv\_void})} \right] \right) \times 100$$

Appendix 7.1.5, *Determination of Void Volumes for TRUPACT-III Payload*, of the TRUPACT-III TRAMPAC provides the internal volume, $V_{slb2\_int}$ = 7,394 liters, and external volume, $V_{slb2\_ext}$ = 7,665 liters, of the SLB2 and internal volume, $V_{cv\_int}$ = 10,019 liters, of the TRUPACT-III CV, which accounts for the presence of ancillary handling equipment.[5]

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[4] Packaging Technology, Inc., *Safety Analysis Report for the TRUPACT-III Shipping Package*, current revision, USNRC Docket No. 71-9305, Packaging Technology, Inc., Tacoma, Washington.

[5] U.S. Department of Energy (DOE), *TRUPACT-III Authorized Methods for Payload Control (TRUPACT-III TRAMPAC)*, current revision, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

To account for the void space taken up by the materials of construction of the sealed container, the external volume, $V_{sc\_ext}$, is conservatively assumed to be 10% greater than the internal volume of the sealed container, or

$$V_{sc\_ext} = 1.10 \times V_{sc\_int}.$$

By comparison, the external volume of the SLB2 is only approximately 3.5% greater than the internal volume.

To account for the void space taken up by the gas generating contents of the sealed container, the sealed container is assumed to have 25% of its internal volume occupied by waste such that the void space available in the sealed container is

$$V_{sc\_void} = (1 - 0.25) \times V_{sc\_int}.$$

Credit is taken for the volume occupied by the gas generating contents of the sealed container to reasonably account for the fact that gas generation would not occur in the absence of hydrogenous contents being subject to radiolysis. The contents are assumed to minimally occupy 25% of the sealed container void space, consistent with a low packing fraction for TRU waste that is predominantly debris.

Additionally, the space taken up by other contents of the SLB2 is conservatively assumed to be 75% of the void space available outside of the sealed container and inside the SLB2 such that the void space available in the SLB2 is

$$V_{slb2\_void} = (1 - 0.75) \times (V_{slb2\_int} - V_{sc\_ext}).$$

The void volume in the TRUPACT-III CV is given as the difference between the internal volume of the CV and the external volume of the SLB2 (where ancillary handling equipment is already accounted for in the CV internal volume calculation), or

$$V_{cv\_void} = V_{cv\_int} - V_{slb2\_ext}.$$

The void volumes described above are schematically depicted in Figure 2.1-2.

#### 2.1.1.4.1 Example Calculation

Consider the determination of the initial pressure of a 4-liter sealed container required to produce a 1% contribution to MNOP in the TRUPACT-III CV resulting from a stoichiometric deflagration inside the sealed container at ambient conditions. The internal, external, and void volumes of the system are calculated as follows:

$$V_{sc\_int} = 4 \text{ liters}, \ \%_{mnop'} = 1\%,$$

$$V_{sc\_ext} = 1.10 \times 4 = 4.40 \text{ liters}, \ V_{sc\_void} = 0.75 \times 4 = 3.00 \text{ liters},$$

$$V_{slb2\_void} = 0.25 \times (7{,}394 - 4.40) = 1{,}847.40 \text{ liters},$$

$$V_{cv\_void} = 10{,}019 - 7{,}665 = 2{,}354 \text{ liters}$$

As an initial estimate to start an iterative solution, the initial pressure for the 4-liter sealed container is assumed at $P_{sc\_init}$ = 20 psig, such that

$$P_{sc\_defl} = [8.18 \times (14.7 + 20)] - 14.7 = 269.15 \text{ psig}$$

and

$$\%_{mnop} = \left( \left[ \frac{269.15}{25} \right] \times \left[ \frac{3.00}{(3.00 + 1,847.40 + 2,354)} \right] \right) \times 100 = 0.77\%.$$

The solution process continues iteratively until $\%_{mnop'}$ equals $\%_{mnop}$ such that $P_{sc\_init}$ = 29.93 psig. In summary, if a 4-liter sealed container is initially at 29.93 psig and undergoes a stoichiometric deflagration inside an SLB2 that is 75% full of waste, the resulting maximum predicted pressure inside the TRUPACT-III CV is 1% of MNOP or 0.25 psig. For comparison purposes, the 4-liter sealed container initial pressure required to generate a pressure in the TRUPACT-III CV equal to MNOP (25 psig) is ~4,270 psig.

#### 2.1.1.4.2 Application to Sealed Container Inventory

Due to the fact that the initial pressure required to have an appreciable contribution to MNOP for any sealed container ≤4 liters (1.057 gallons) in size is very high, sealed containers ≤4 liters in size are considered inconsequential and are not restricted in the payload. Solution of the above equations was obtained and is presented in Table 2.1-1 to establish a relationship between the initial pressure of a sealed container and the percent contribution to MNOP in the TRUPACT-III CV resulting from a stoichiometric hydrogen/air deflagration inside the sealed container. For a sealed container with a known size and burst/leakage pressure, its percent contribution to MNOP can be conservatively determined from Table 2.1-1 by finding the $\%_{mnop}$ value associated with the size and pressure value in the table that is greater than or equal to the known size and burst/leakage pressure of the sealed container. The maximum initial pressure, conservatively defined as the pressure associated with hydrostatic burst or the pressure that fails to increase because of leakage when the sealed container is subject to an input flow rate that is greater than or equal to 0.25% of the sealed container volume per minute, for an inventory of sealed containers is established by test in Section 2.1.3, *Sealed Container Burst Pressure Testing*.

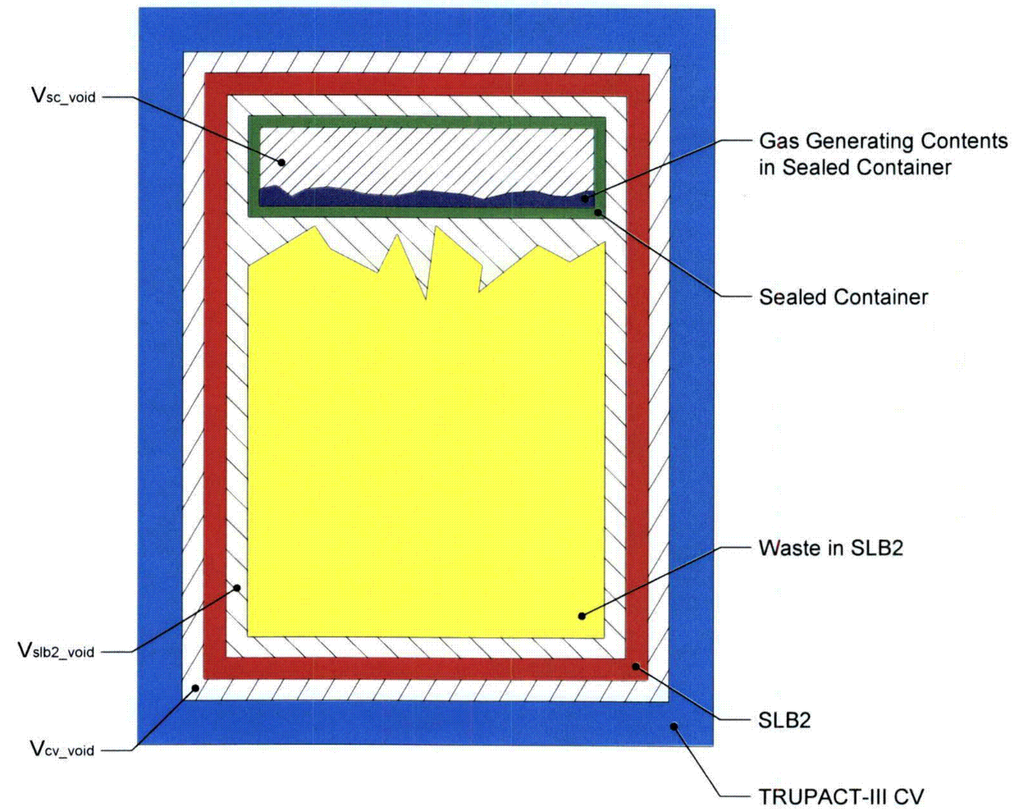


**Figure 2.1-2** – Void Volumes within TRUPACT-III

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**Table 2.1-1** – Percent Contribution to MNOP from a Sealed Container Deflagration

| Sealed Container Burst/Leakage Pressure (psig) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Sealed Container Size (1 thru 10 gal) | | | | | | | | | |
| $\%_{mnop}$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 32.36 | 9.74 | 2.20 | | | | | | | |
| 2 | 77.62 | 32.38 | 17.30 | 9.76 | 5.23 | 2.22 | 0.06 | | | |
| 3 | 122.90 | 55.01 | 32.39 | 21.08 | 14.30 | 9.78 | 6.54 | 4.12 | 2.24 | 0.73 |
| 4 | 168.10 | 77.65 | 47.49 | 32.41 | 23.37 | 17.33 | 13.03 | 9.79 | 7.28 | 5.27 |
| 5 | 213.40 | 100.30 | 62.59 | 43.74 | 32.43 | 24.89 | 19.51 | 15.47 | 12.33 | 9.81 |
| 6 | 258.70 | 122.90 | 77.69 | 55.07 | 41.50 | 32.45 | 25.99 | 21.14 | 17.37 | 14.36 |
| 7 | 303.90 | 145.60 | 92.79 | 66.40 | 50.57 | 40.01 | 32.47 | 26.82 | 22.42 | 18.90 |
| 8 | 349.20 | 168.20 | 107.90 | 77.73 | 59.64 | 47.57 | 38.95 | 32.49 | 27.47 | 23.44 |
| 9 | 394.40 | 190.90 | 123.00 | 89.06 | 68.70 | 55.13 | 45.44 | 38.17 | 32.51 | 27.99 |
| 10 | 439.70 | 213.50 | 138.10 | 100.40 | 77.77 | 62.69 | 51.92 | 43.84 | 37.56 | 32.53 |
| 12 | 530.20 | 258.80 | 168.30 | 123.00 | 95.90 | 77.81 | 64.88 | 55.19 | 47.65 | 41.62 |
| 14 | 620.70 | 304.00 | 198.50 | 145.70 | 114.00 | 92.93 | 77.85 | 66.54 | 57.74 | 50.70 |
| 16 | 711.20 | 349.30 | 228.70 | 168.40 | 132.20 | 108.00 | 90.81 | 77.89 | 67.83 | 59.79 |
| 18 | 801.80 | 394.60 | 258.90 | 191.00 | 150.30 | 123.20 | 103.80 | 89.23 | 77.92 | 68.88 |
| 20 | 892.30 | 439.90 | 289.10 | 213.70 | 168.40 | 138.30 | 116.70 | 100.60 | 88.02 | 77.96 |
| 25 | 1119.00 | 553.10 | 364.60 | 270.30 | 213.80 | 176.10 | 149.20 | 129.00 | 113.20 | 100.70 |
| 30 | 1345.00 | 666.30 | 440.10 | 327.00 | 259.10 | 213.90 | 181.60 | 157.30 | 138.50 | 123.40 |
| 35 | 1571.00 | 779.50 | 515.60 | 383.60 | 304.50 | 251.70 | 214.00 | 185.70 | 163.70 | 146.10 |
| 40 | 1797.00 | 892.70 | 591.10 | 440.30 | 349.80 | 289.50 | 246.40 | 214.10 | 188.90 | 168.80 |
| 45 | 2024.00 | 1006.00 | 666.60 | 496.90 | 395.10 | 327.30 | 278.80 | 242.40 | 214.20 | 191.50 |
| 50 | 2250.00 | 1119.00 | 742.10 | 553.60 | 440.50 | 365.10 | 311.20 | 270.80 | 239.40 | 214.30 |
| 55 | 2476.00 | 1232.00 | 817.60 | 610.20 | 485.80 | 402.90 | 343.60 | 299.20 | 264.60 | 237.00 |
| 60 | 2703.00 | 1345.00 | 893.10 | 666.90 | 531.10 | 440.70 | 376.00 | 327.60 | 289.90 | 259.70 |
| 65 | 2929.00 | 1459.00 | 968.50 | 723.50 | 576.50 | 478.50 | 408.40 | 355.90 | 315.10 | 282.40 |
| 70 | 3155.00 | 1572.00 | 1044.00 | 780.10 | 621.80 | 516.20 | 440.80 | 384.30 | 340.30 | 305.10 |
| 75 | 3382.00 | 1685.00 | 1120.00 | 836.80 | 667.10 | 554.00 | 473.30 | 412.70 | 365.50 | 327.80 |
| 80 | 3608.00 | 1798.00 | 1195.00 | 893.40 | 712.50 | 591.80 | 505.70 | 441.00 | 390.80 | 350.60 |
| 85 | 3834.00 | 1911.00 | 1271.00 | 950.10 | 757.80 | 629.60 | 538.10 | 469.40 | 416.00 | 373.30 |
| 90 | 4060.00 | 2025.00 | 1346.00 | 1007.00 | 803.20 | 667.40 | 570.50 | 497.80 | 441.20 | 396.00 |
| 95 | 4287.00 | 2138.00 | 1422.00 | 1063.00 | 848.50 | 705.20 | 602.90 | 526.20 | 466.50 | 418.70 |
| 100 | 4513.00 | 2251.00 | 1497.00 | 1120.00 | 893.80 | 743.00 | 635.30 | 554.50 | 491.70 | 441.40 |

| Sealed Container Burst/Leakage Pressure (psig) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Sealed Container Size (12 thru 45 gal) | | | | | | | | | |
| $\%_{mnop}$ | 12 | 14 | 16 | 18 | 20 | 25 | 30 | 35 | 40 | 45 |
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| 4 | 2.25 | 0.10 | | | | | | | | |
| 5 | 6.04 | 3.35 | 1.33 | | | | | | | |
| 6 | 9.83 | 6.60 | 4.18 | 2.29 | 0.79 | | | | | |
| 7 | 13.62 | 9.85 | 7.03 | 4.83 | 3.07 | | | | | |
| 8 | 17.41 | 13.10 | 9.87 | 7.36 | 5.35 | 1.73 | | | | |
| 9 | 21.20 | 16.35 | 12.72 | 9.89 | 7.63 | 3.56 | 0.84 | | | |
| 10 | 24.99 | 19.60 | 15.57 | 12.42 | 9.91 | 5.39 | 2.37 | 0.22 | | |
| 12 | 32.57 | 26.11 | 21.26 | 17.49 | 14.47 | 9.04 | 5.43 | 2.84 | 0.90 | |
| 14 | 40.15 | 32.61 | 26.95 | 22.55 | 19.04 | 12.70 | 8.48 | 5.46 | 3.20 | 1.44 |
| 16 | 47.73 | 39.11 | 32.65 | 27.62 | 23.60 | 16.36 | 11.53 | 8.09 | 5.50 | 3.49 |
| 18 | 55.31 | 45.61 | 38.34 | 32.69 | 28.16 | 20.02 | 14.59 | 10.71 | 7.80 | 5.54 |
| 20 | 62.88 | 52.11 | 44.03 | 37.75 | 32.72 | 23.68 | 17.64 | 13.34 | 10.10 | 7.59 |
| 25 | 81.83 | 68.37 | 58.27 | 50.41 | 44.13 | 32.82 | 25.28 | 19.90 | 15.86 | 12.71 |
| 30 | 100.80 | 84.62 | 72.50 | 63.08 | 55.54 | 41.97 | 32.92 | 26.45 | 21.61 | 17.84 |
| 35 | 119.70 | 100.90 | 86.74 | 75.74 | 66.94 | 51.11 | 40.55 | 33.01 | 27.36 | 22.96 |
| 40 | 138.70 | 117.10 | 101.00 | 88.40 | 78.35 | 60.25 | 48.19 | 39.57 | 33.11 | 28.08 |
| 45 | 157.60 | 133.40 | 115.20 | 101.10 | 89.76 | 69.40 | 55.83 | 46.13 | 38.86 | 33.21 |
| 50 | 176.60 | 149.60 | 129.40 | 113.70 | 101.20 | 78.54 | 63.46 | 52.69 | 44.61 | 38.33 |
| 55 | 195.50 | 165.90 | 143.70 | 126.40 | 112.60 | 87.69 | 71.10 | 59.25 | 50.37 | 43.45 |
| 60 | 214.50 | 182.10 | 157.90 | 139.10 | 124.00 | 96.83 | 78.74 | 65.81 | 56.12 | 48.58 |
| 65 | 233.40 | 198.40 | 172.10 | 151.70 | 135.40 | 106.00 | 86.37 | 72.37 | 61.87 | 53.70 |
| 70 | 252.40 | 214.70 | 186.40 | 164.40 | 146.80 | 115.10 | 94.01 | 78.93 | 67.62 | 58.82 |
| 75 | 271.30 | 230.90 | 200.60 | 177.00 | 158.20 | 124.30 | 101.60 | 85.49 | 73.37 | 63.95 |
| 80 | 290.20 | 247.20 | 214.80 | 189.70 | 169.60 | 133.40 | 109.30 | 92.05 | 79.13 | 69.07 |
| 85 | 309.20 | 263.40 | 229.10 | 202.40 | 181.00 | 142.60 | 116.90 | 98.61 | 84.88 | 74.20 |
| 90 | 328.10 | 279.70 | 243.30 | 215.00 | 192.40 | 151.70 | 124.60 | 105.20 | 90.63 | 79.32 |
| 95 | 347.10 | 295.90 | 257.50 | 227.70 | 203.80 | 160.80 | 132.20 | 111.70 | 96.38 | 84.44 |
| 100 | 366.00 | 312.20 | 271.80 | 240.40 | 215.20 | 170.00 | 139.80 | 118.30 | 102.10 | 89.57 |

| Sealed Container Burst/Leakage Pressure (psig) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Sealed Container Size (50 thru 95 gal) | | | | | | | | | |
| $\%_{mnop}$ | **50** | **55** | **60** | **65** | **70** | **75** | **80** | **85** | **90** | **95** |
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| 4 | | | | | | | | | | |
| 5 | | | | | | | | | | |
| 6 | | | | | | | | | | |
| 7 | | | | | | | | | | |
| 8 | | | | | | | | | | |
| 9 | | | | | | | | | | |
| 10 | | | | | | | | | | |
| 12 | | | | | | | | | | |
| 14 | 0.04 | | | | | | | | | |
| 16 | 1.88 | 0.57 | | | | | | | | |
| 18 | 3.73 | 2.25 | 1.02 | | | | | | | |
| 20 | 5.58 | 3.94 | 2.56 | 1.40 | 0.41 | | | | | |
| 25 | 10.20 | 8.14 | 6.43 | 4.98 | 3.74 | 2.66 | 1.72 | 0.89 | 0.15 | |
| 30 | 14.82 | 12.35 | 10.30 | 8.56 | 7.07 | 5.77 | 4.64 | 3.65 | 2.76 | 1.96 |
| 35 | 19.44 | 16.56 | 14.16 | 12.13 | 10.39 | 8.89 | 7.57 | 6.40 | 5.37 | 4.44 |
| 40 | 24.06 | 20.77 | 18.03 | 15.71 | 13.72 | 12.00 | 10.49 | 9.16 | 7.98 | 6.92 |
| 45 | 28.68 | 24.98 | 21.90 | 19.29 | 17.05 | 15.11 | 13.42 | 11.92 | 10.59 | 9.40 |
| 50 | 33.30 | 29.19 | 25.76 | 22.86 | 20.38 | 18.22 | 16.34 | 14.68 | 13.20 | 11.88 |
| 55 | 37.93 | 33.40 | 29.63 | 26.44 | 23.71 | 21.34 | 19.26 | 17.43 | 15.81 | 14.35 |
| 60 | 42.55 | 37.61 | 33.50 | 30.02 | 27.04 | 24.45 | 22.19 | 20.19 | 18.42 | 16.83 |
| 65 | 47.17 | 41.82 | 37.36 | 33.59 | 30.36 | 27.56 | 25.11 | 22.95 | 21.03 | 19.31 |
| 70 | 51.79 | 46.03 | 41.23 | 37.17 | 33.69 | 30.68 | 28.04 | 25.71 | 23.64 | 21.79 |
| 75 | 56.41 | 50.24 | 45.10 | 40.75 | 37.02 | 33.79 | 30.96 | 28.47 | 26.25 | 24.26 |
| 80 | 61.03 | 54.45 | 48.97 | 44.33 | 40.35 | 36.90 | 33.89 | 31.22 | 28.86 | 26.74 |
| 85 | 65.65 | 58.66 | 52.83 | 47.90 | 43.68 | 40.01 | 36.81 | 33.98 | 31.47 | 29.22 |
| 90 | 70.27 | 62.87 | 56.70 | 51.48 | 47.00 | 43.13 | 39.73 | 36.74 | 34.08 | 31.70 |
| 95 | 74.89 | 67.08 | 60.57 | 55.06 | 50.33 | 46.24 | 42.66 | 39.50 | 36.69 | 34.18 |
| 100 | 79.51 | 71.29 | 64.43 | 58.63 | 53.66 | 49.35 | 45.58 | 42.26 | 39.30 | 36.65 |

| Sealed Container Burst/Leakage Pressure (psig) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Sealed Container Size (100 thru 190 gal) | | | | | | | | | |
| $\%_{mnop}$ | **100** | **110** | **120** | **130** | **140** | **150** | **160** | **170** | **180** | **190** |
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| 4 | | | | | | | | | | |
| 5 | | | | | | | | | | |
| 6 | | | | | | | | | | |
| 7 | | | | | | | | | | |
| 8 | | | | | | | | | | |
| 9 | | | | | | | | | | |
| 10 | | | | | | | | | | |
| 12 | | | | | | | | | | |
| 14 | | | | | | | | | | |
| 16 | | | | | | | | | | |
| 18 | | | | | | | | | | |
| 20 | | | | | | | | | | |
| 25 | | | | | | | | | | |
| 30 | 1.25 | 0.02 | | | | | | | | |
| 35 | 3.61 | 2.17 | 0.97 | | | | | | | |
| 40 | 5.97 | 4.32 | 2.95 | 1.79 | 0.80 | | | | | |
| 45 | 8.33 | 6.48 | 4.93 | 3.63 | 2.51 | 1.54 | 0.69 | | | |
| 50 | 10.68 | 8.63 | 6.92 | 5.47 | 4.22 | 3.15 | 2.20 | 1.37 | 0.63 | |
| 55 | 13.04 | 10.78 | 8.90 | 7.30 | 5.93 | 4.75 | 3.71 | 2.80 | 1.99 | 1.26 |
| 60 | 15.40 | 12.93 | 10.88 | 9.14 | 7.65 | 6.35 | 5.22 | 4.23 | 3.34 | 2.55 |
| 65 | 17.76 | 15.09 | 12.86 | 10.98 | 9.36 | 7.96 | 6.73 | 5.65 | 4.69 | 3.83 |
| 70 | 20.12 | 17.24 | 14.84 | 12.81 | 11.07 | 9.56 | 8.24 | 7.08 | 6.05 | 5.12 |
| 75 | 22.48 | 19.39 | 16.82 | 14.65 | 12.78 | 11.17 | 9.76 | 8.51 | 7.40 | 6.41 |
| 80 | 24.84 | 21.55 | 18.81 | 16.49 | 14.50 | 12.77 | 11.27 | 9.94 | 8.75 | 7.69 |
| 85 | 27.20 | 23.70 | 20.79 | 18.32 | 16.21 | 14.38 | 12.78 | 11.36 | 10.11 | 8.98 |
| 90 | 29.55 | 25.85 | 22.77 | 20.16 | 17.92 | 15.98 | 14.29 | 12.79 | 11.46 | 10.27 |
| 95 | 31.91 | 28.01 | 24.75 | 22.00 | 19.63 | 17.59 | 15.80 | 14.22 | 12.81 | 11.56 |
| 100 | 34.27 | 30.16 | 26.73 | 23.83 | 21.35 | 19.19 | 17.31 | 15.64 | 14.17 | 12.84 |

| Sealed Container Burst/Leakage Pressure (psig) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Sealed Container Size (200 thru 380 gal) | | | | | | | | | |
| $\%_{mnop}$ | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 |
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| 4 | | | | | | | | | | |
| 5 | | | | | | | | | | |
| 6 | | | | | | | | | | |
| 7 | | | | | | | | | | |
| 8 | | | | | | | | | | |
| 9 | | | | | | | | | | |
| 10 | | | | | | | | | | |
| 12 | | | | | | | | | | |
| 14 | | | | | | | | | | |
| 16 | | | | | | | | | | |
| 18 | | | | | | | | | | |
| 20 | | | | | | | | | | |
| 25 | | | | | | | | | | |
| 30 | | | | | | | | | | |
| 35 | | | | | | | | | | |
| 40 | | | | | | | | | | |
| 45 | | | | | | | | | | |
| 50 | | | | | | | | | | |
| 55 | 0.60 | | | | | | | | | |
| 60 | 1.83 | 0.60 | | | | | | | | |
| 65 | 3.06 | 1.72 | 0.61 | | | | | | | |
| 70 | 4.29 | 2.85 | 1.65 | 0.63 | | | | | | |
| 75 | 5.51 | 3.97 | 2.69 | 1.60 | 0.67 | | | | | |
| 80 | 6.74 | 5.10 | 3.73 | 2.57 | 1.57 | 0.71 | | | | |
| 85 | 7.97 | 6.22 | 4.77 | 3.53 | 2.48 | 1.56 | 0.76 | 0.05 | | |
| 90 | 9.20 | 7.35 | 5.80 | 4.50 | 3.38 | 2.41 | 1.56 | 0.81 | 0.15 | |
| 95 | 10.42 | 8.47 | 6.84 | 5.47 | 4.29 | 3.26 | 2.37 | 1.58 | 0.87 | 0.25 |
| 100 | 11.65 | 9.60 | 7.88 | 6.43 | 5.19 | 4.11 | 3.17 | 2.34 | 1.60 | 0.94 |

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## 2.1.2 Deflagration Pressure Testing and Pressure Model Validation

### 2.1.2.1 Introduction

Stoichiometric hydrogen deflagration tests were performed utilizing a large surrogate sealed container (SSC) designed to initially contain the pressurized hydrogen/air mixture, a prototypic payload container (SLB2), a rigid dunnage assembly (SLB2 dunnage) designed for testing to consume void space inside the SLB2, and a mock-up of the TRUPACT-III containment vessel (Mock CV) designed as a vessel to contain and facilitate measurement of the deflagration pressure. The testing was performed at the Energetic Materials Research and Testing Center (EMRTC) at New Mexico Tech University in Socorro, New Mexico.[1,2] The test articles were sized utilizing the model developed in Section 2.1.1, *Adiabatic Constant Volume Deflagration Pressure Model*, to theoretically produce a pressure in the Mock CV equal to the MNOP of the TRUPACT-III CV. Two variations on the test configuration were implemented, one with filter vents installed and one with the filter ports open in the SLB2 to determine whether the measured Mock CV pressures were affected by the rate of combustion gas throttling through the vent port/filter openings. The objectives of the testing were to 1) compare the pressure measured in the Mock CV void space to validate the pressure predicted by the adiabatic constant volume deflagration model and 2) observe the structural response of the SLB2 and Mock CV to a deflagration test environment that was more severe than what would potentially exist in the actual TRUPACT-III payload.

### 2.1.2.2 Test Article Design

#### 2.1.2.2.1 Surrogate Sealed Container

The SSC was developed as a low-carbon steel right-circular cylindrical vessel (∅33.5 in. inside diameter, 53 in. inside height, 10-ga. wall thickness) with a ⅜ in. thick welded bottom and bolted and gasketed lid. The weight of the SSC assembly was approximately 500 lb. To retain the pressurized stoichiometric hydrogen/air mixture prior to ignition and subsequently absorb minimal energy in releasing the SSC lid during the deflagration event, the SSC lid was secured to the body with six (6) ½-13UNC closure bolts (SAE Grade 5) with an ∅⅛ in. necked-down shank torqued to 40 lb*in.

The internal volume, $V_{ssc\_int}$, and external volume, $V_{ssc\_ext}$, of the SSC can be calculated from the above dimensions, weight, and the density of steel (0.284 lb/in$^3$) as follows:

$$V_{ssc\_int} = \left(\frac{\pi}{4}\right) \times (33.5)^2 \times (53) \times \left(\frac{1}{61.02}\frac{\text{liter}}{\text{in}^3}\right) = 766 \text{ liters}$$

$$V_{ssc\_ext} = 766 + \left(\frac{500}{0.284}\right) \times \left(\frac{1}{61.02}\frac{\text{liter}}{\text{in}^3}\right) = 794 \text{ liters}$$

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[1] Packaging Technology, Inc., August 2006, *Deflagration Test Procedure – TRUPACT-III Payload Test Assembly*, TP-048, Revision 0, Packaging Technology, Inc., Tacoma, Washington.

[2] Packaging Technology, Inc., December 2006, *Deflagration Test Report – TRUPACT-III Payload Test Assembly*, TR-022, Revision 0, Packaging Technology, Inc., Tacoma, Washington.

The SSC body was fitted with an instrumentation flange containing four (4) ½-14NPT threaded ports to accommodate a dynamic pressure transducer, static pressure transducer, hydrogen fill hose, and electric match. The SSC is shown schematically in Figure 2.1-3.

#### 2.1.2.2.2 Standard Large Box 2

The SLB2 design utilized in the deflagration testing was modified from the top-loading design given in Appendix 1.5.1, *Payload Container General Arrangement Drawings*, by the addition of an instrumentation flange that provided a pass-thru for the SSC ports and a dynamic pressure transducer port for measuring pressure in the SLB2 void volume. The SLB2 has internal nominal dimensions of 65-¼ in. wide by 104-¼ in. long by 66-½ in. tall, which, accounting for internal stiffeners and a labyrinth gasket region, results in an internal volume of $V_{slb2\_int}$ = 7,394 liters as given in Appendix 7.1.5, *Determination of Void Volumes for TRUPACT-III Payload*, of the TRUPACT-III TRAMPAC.[3] The SLB2 body panels and lid (top-loading) are constructed from low-carbon steel with a wall thickness of 3⁄16 in. and the lid and body are assembled utilizing fifty-six (56) ½-13UNC closure bolts (SAE Grade 5) torqued to 55 lb*ft. The body and lid panels are supported on the exterior by low-carbon steel square tubing bumpers, 1-½ in. by 1-½ in. by 1⁄16 in. wall, and the body end and side panels are supported on the interior by 1-⅛ in. by ⅜ in. thick flat bar. Fork lift skids constructed of low-carbon steel tubing, 4 in. by 4 in. by ⅛ in. wall, are located along the bottom body panel. A face gasket and a labyrinth gasket (elastomeric) are utilized to seal the bolted lid and body assemblies. Per Appendix 7.1.5, *Determination of Void Volumes for TRUPACT-III Payload*, of the TRUPACT-III TRAMPAC, the external volume of the assembly is $V_{slb2\_ext}$ = 7,665 liters.[3]

Two configurations of the SLB2 were tested, one with a NUCFIL 016SS H nuclear filter installed in each of the six (6) SLB2 filter ports (2-11.5NPSM half coupling) and one with the six (6) filter ports open (i.e., neither filtered nor plugged). The SLB2 design utilized in the deflagration testing is shown schematically in Figure 2.1-4.

The bottom-loading SLB2 version has the location of the lid and body flange interface at the bottom rather than the top of the container, but structurally the designs are considered equivalent.

#### 2.1.2.2.3 SLB2 Dunnage

The SLB2 dunnage was developed as an L-shaped structure of low-carbon steel filled with nominally 3 lb/ft$^3$ closed-cell rigid urethane foam. Sized to consume 75% of the void space inside of the SLB2 surrounding the SSC, the SLB2 dunnage had external dimensions of 100-¾ in. overall length, 61-¾ in. overall width, and 64-13⁄16 in. overall height with a 39-½ in. square cut-out section to accommodate the SSC. The ¼ in. wall thickness and approximately 25 psi compressive strength at 10% strain rigid foam, poured-in-place through a top center fill port, was designed to resist significant deformation due to the deflagration pressures and to be a bounding representation of void volume consuming payload materials.

[3] U.S. Department of Energy (DOE), *TRUPACT-III Authorized Methods for Payload Control (TRUPACT-III TRAMPAC)*, current revision, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

The external volume of the SLB2 dunnage can be calculated from the above dimensions as follows:

$$V_{dunnage\_ext} = [(100.75 \times 61.75 \times 64.81) - (39.50 \times 39.50 \times 64.81)] \times \left( \frac{1}{61.02} \frac{\text{liter}}{\text{in}^3} \right) = 4{,}950 \text{ liters}$$

The SLB2 dunnage is shown schematically in Figure 2.1-5.

#### 2.1.2.2.4 Mock TRUPACT-III Containment Vessel

The Mock CV was developed to simulate a TRUPACT-III CV in the tests by providing an equivalent void space for measurement of the deflagration pressures. Although not as structurally robust as the TRUPACT-III CV, the Mock CV was constructed from ½ in. thick low-carbon plate reinforced on all sides with 6 in. by 4 in. by ⅜ in. wall thickness structural tubing having sufficient overall stiffness to ensure minimal deflection and associated minimal change in void space when subject to the deflagration pressures. The Mock CV had internal nominal dimensions of 73 in. wide by 112 in. long by 74 ⅞ in. tall, resulting in an internal volume equal to the void volume of the TRUPACT-III CV, $V_{cv\_int}$ = 10,019 liters as given in Appendix 7.1.5, *Determination of Void Volumes for TRUPACT-III Payload*, of the TRUPACT-III TRAMPAC.[3] The Mock CV lid and body were sealed with an EPDM gasket and assembled utilizing fifty-eight (58) ½-13UNC closure bolts (SAE Grade 5) torqued to 55 lb*ft. Five (5) ½-14NPT pipe couplings were welded to the approximate center of unsupported sections of the Mock CV walls to provide dynamic pressure transducer ports with the sixth dynamic pressure transducer port located in a pass-thru instrumentation flange. The Mock CV is shown schematically in Figure 2.1-6.

#### 2.1.2.2.5 Deflagration Test Assembly

As illustrated in Figure 2.1-7, the deflagration test assembly consisted of an SSC placed inside and bolted to the SLB2 via a gasketed instrumentation flange, SLB2 dunnage placed inside of the SLB2, and the SLB2 placed inside and bolted to the Mock CV via a gasketed instrumentation flange. The SSC and SLB2 instrumentation flanges were connected with six (6) ½-13UNC by 3-¾ in. long cap screws (Grade 8) and the SLB2 and Mock CV instrumentation flanges were connected with six (6) ½-13UNC by 2-½ in. long cap screws (Grade 8). Both instrumentation flanges were sealed with ½ in. thick silicone rubber or neoprene (60 Shore A) gaskets.

Eight (8) piezoelectric dynamic pressure transducers were installed in the test assembly; five located in the Mock CV coupling ports (labeled P1 thru P5) with three located in the Mock CV, SLB2, and SSC instrumentation flanges (labeled P6 thru P8, respectively) as shown in Figure 2.1-8. The piezoelectric dynamic pressure transducers (PCB Piezotronics Model No. 102A05) are ICP® (Integrated Circuit Piezoelectric) quartz crystal voltage-mode type sensors with built-in microelectronic amplifiers that convert high-impedance charge into a low-impedance voltage output (Figure 2.1-9). The outputs of all dynamic pressure transducers were attached via coaxial cable to a digital data acquisition system (PCB Piezotronics Model No. 481A) capable of capturing data at a rate of 125,000 samples per second.

Also located in the SSC instrumentation flange was a ½-14NPT threaded brass plug with an approximately ∅⅛ in. through-hole to serve as the electric match port. The electric match leads were passed through the plug and sealed with a quick-set epoxy compound, leaving the head of the match extending into the SSC by approximately 13 in. (Figure 2.1-10). One of the ports in

the SSC instrumentation flange was utilized to connect a static pressure transducer that incorporated tubing and valving to isolate the pressure transducer to measure the pressure inside the SSC and open the system to atmosphere to allow ambient pressure measurements. The last port in the SSC instrumentation flange was utilized to accommodate the hydrogen/air fill hose, which was valved and connected to dry air and hydrogen gas sources. The assembled instrumentation flange is shown in Figure 2.1-11, and the overall plumbing arrangement is shown in Figure 2.1-12. Additionally, a thermocouple was utilized both in free air and attached to the flange end sidewall of the Mock CV for measuring ambient and Mock CV wall temperatures.

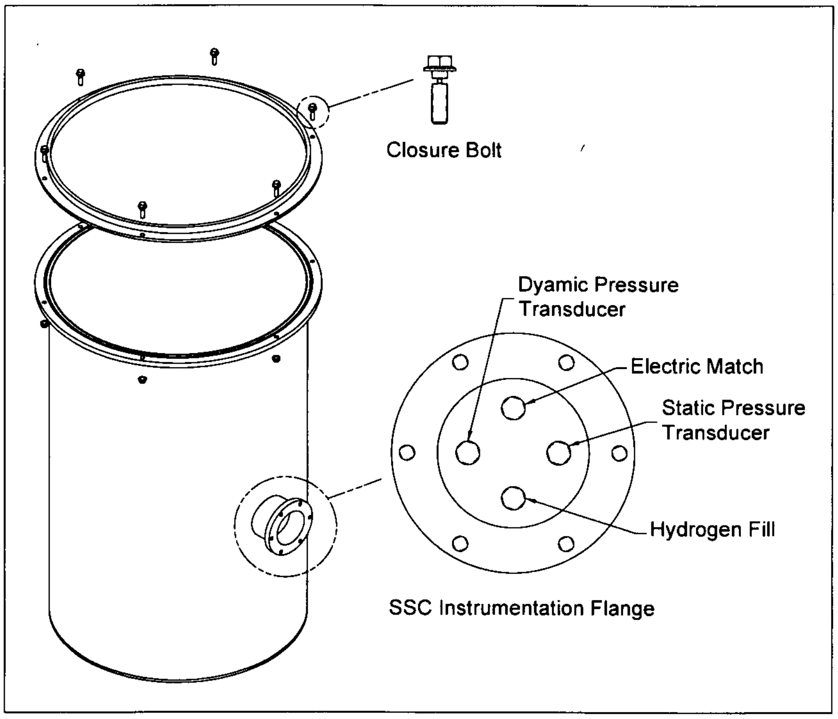


**Figure 2.1-3** – Surrogate Sealed Container

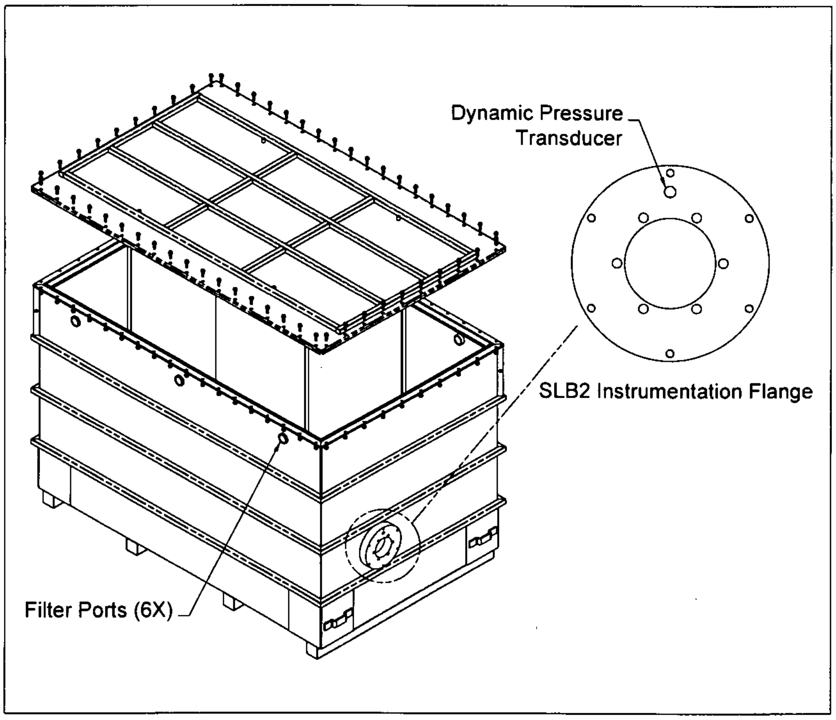


**Figure 2.1-4** – Standard Large Box 2

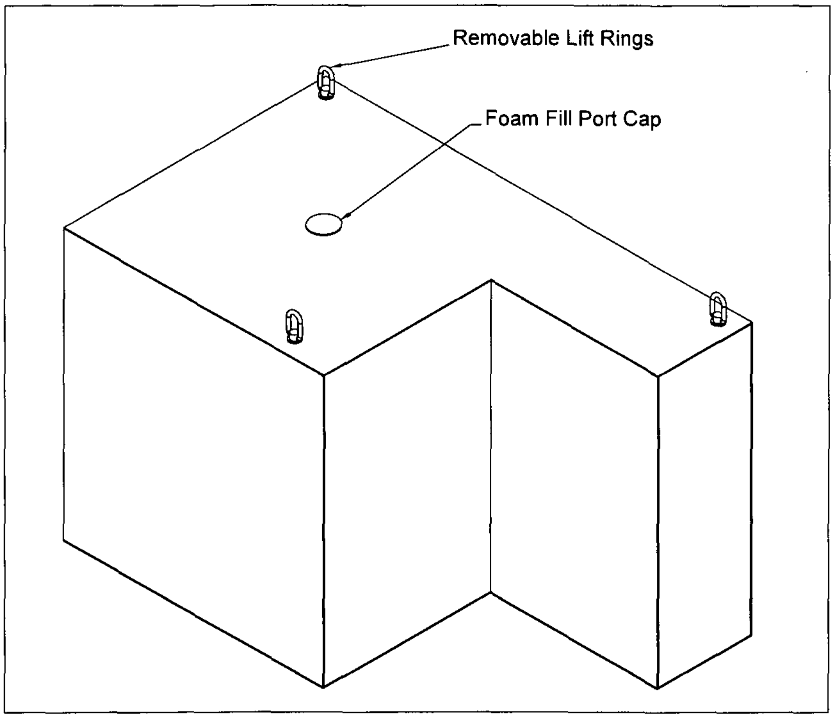


**Figure 2.1-5** – SLB2 Dunnage

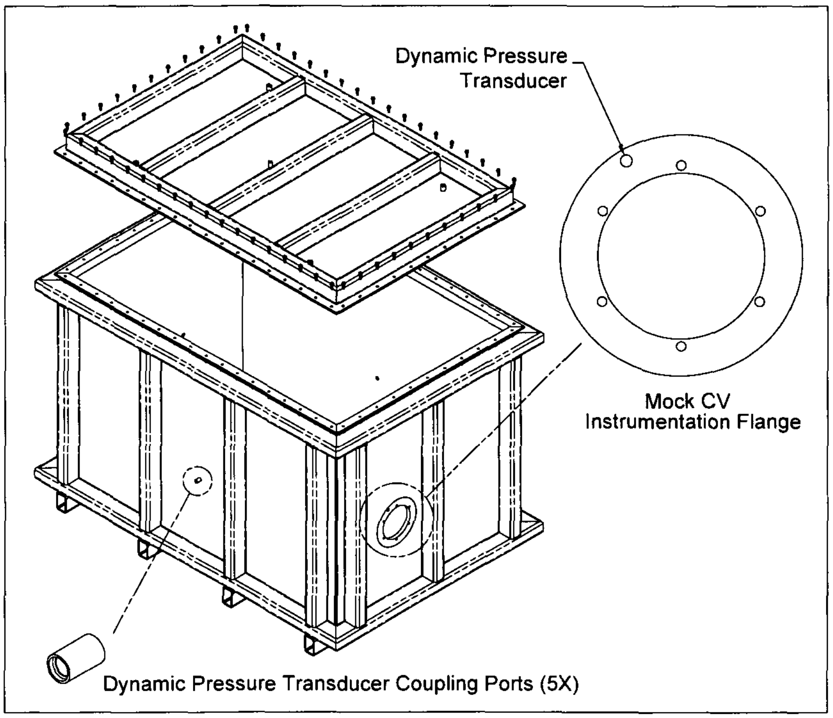


**Figure 2.1-6** – Mock Containment Vessel

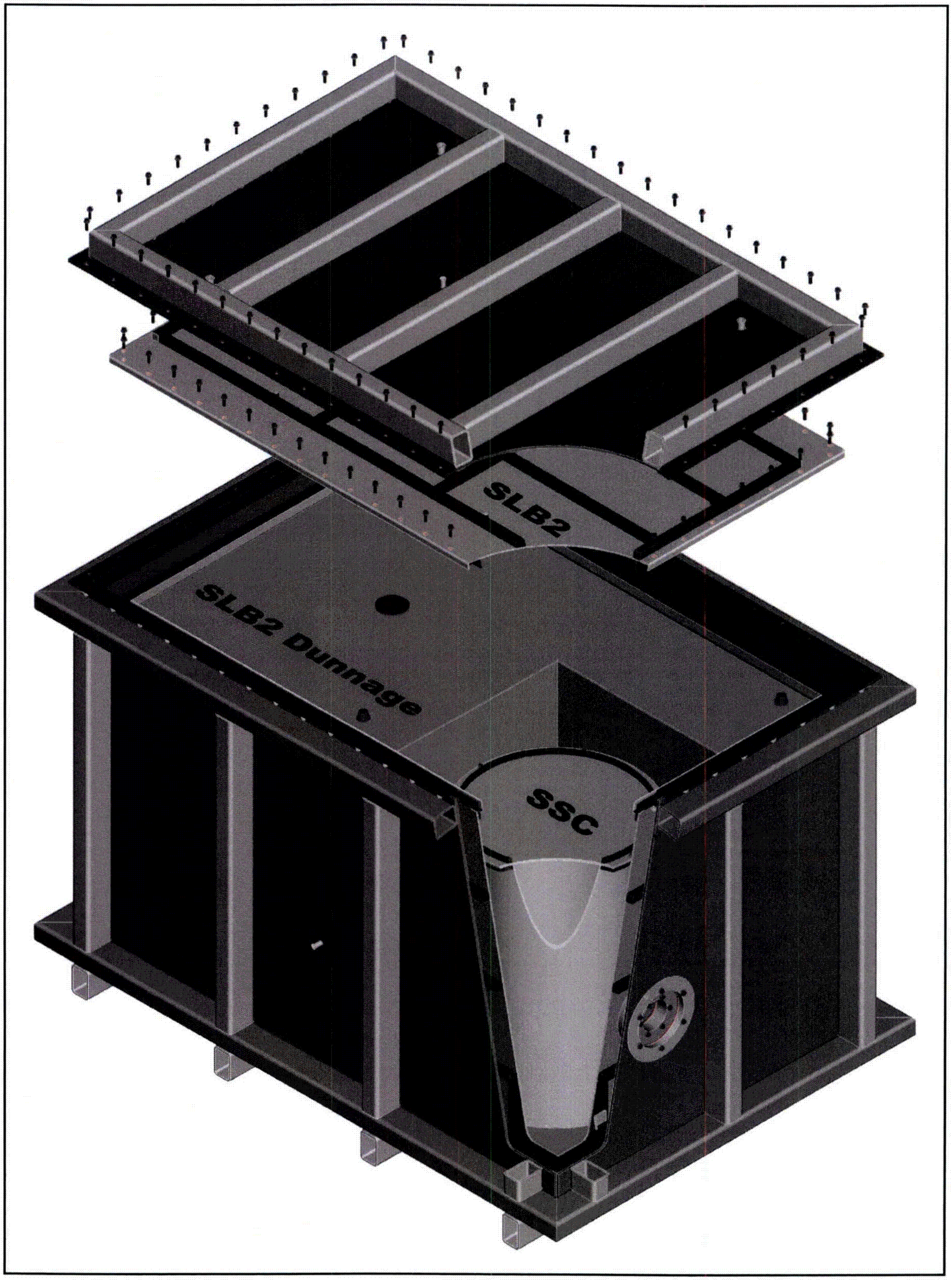


**Figure 2.1-7** – Deflagration Test Assembly

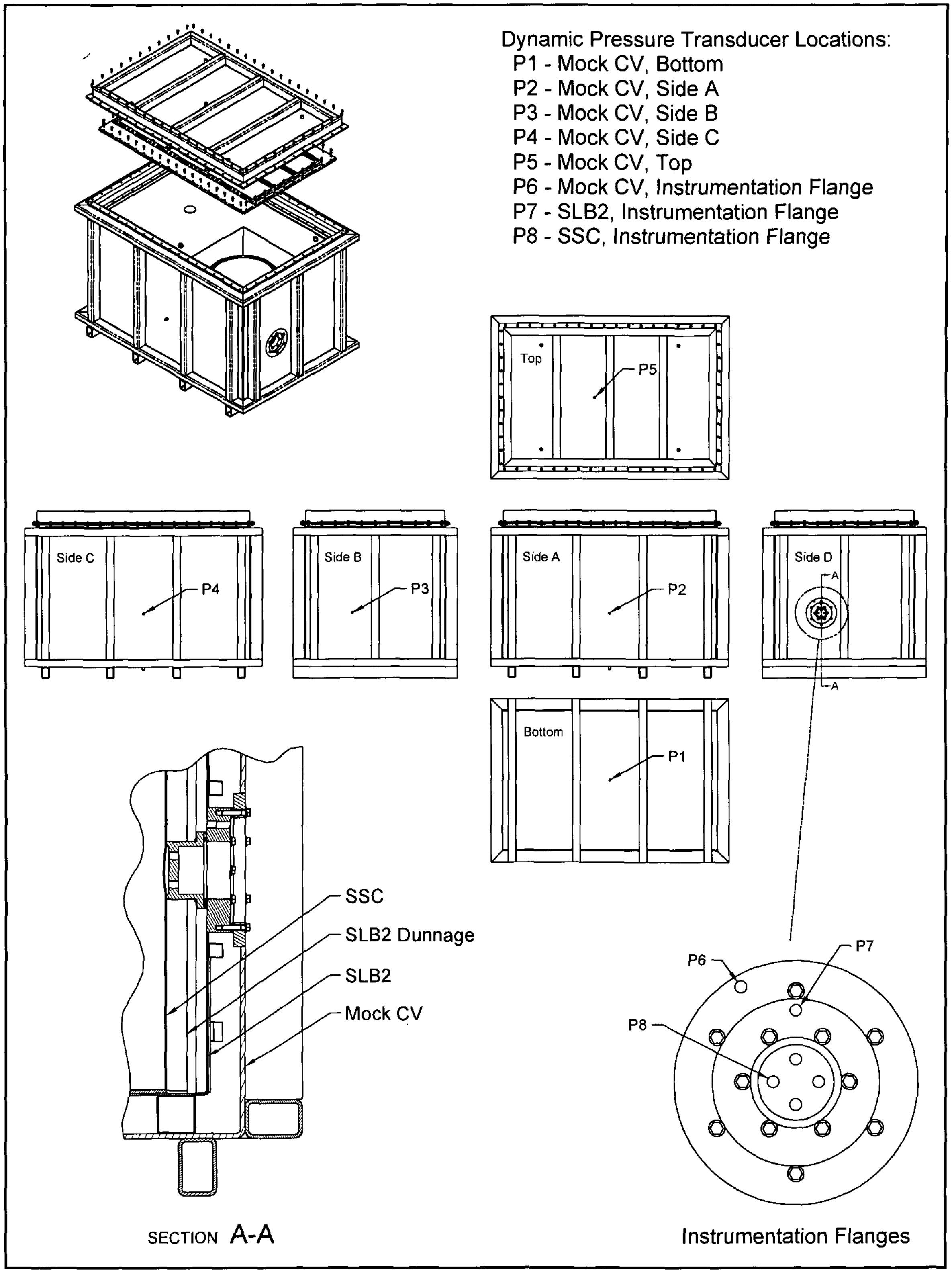


**Figure 2.1-8** – Deflagration Test Assembly Transducer Map

**Figure 2.1-9** – ICP® Dynamic Pressure Transducer

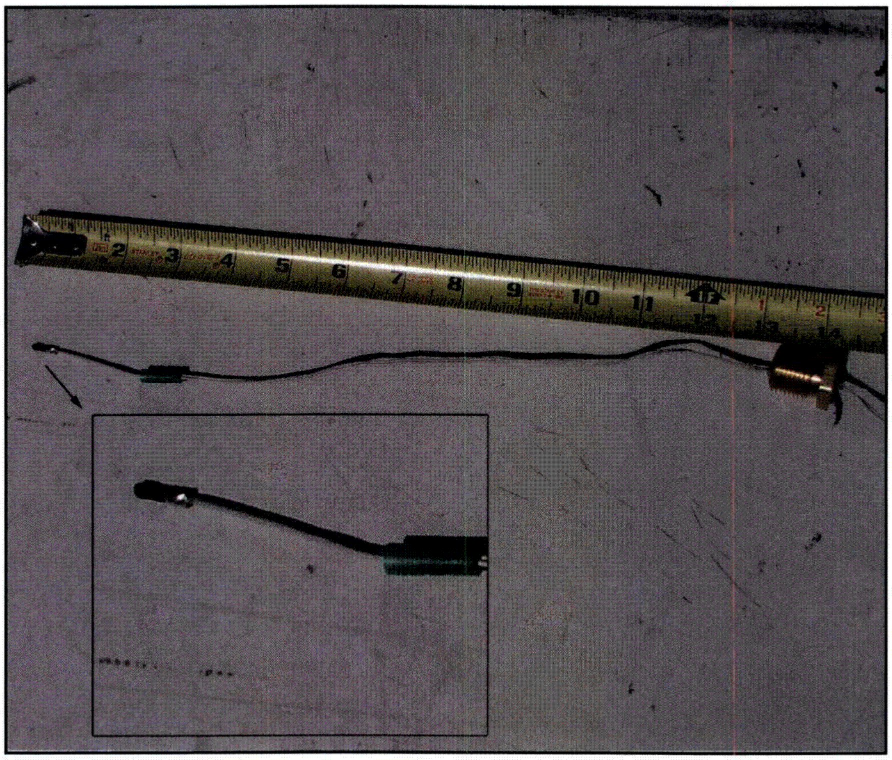

**Figure 2.1-10** – Electric Match

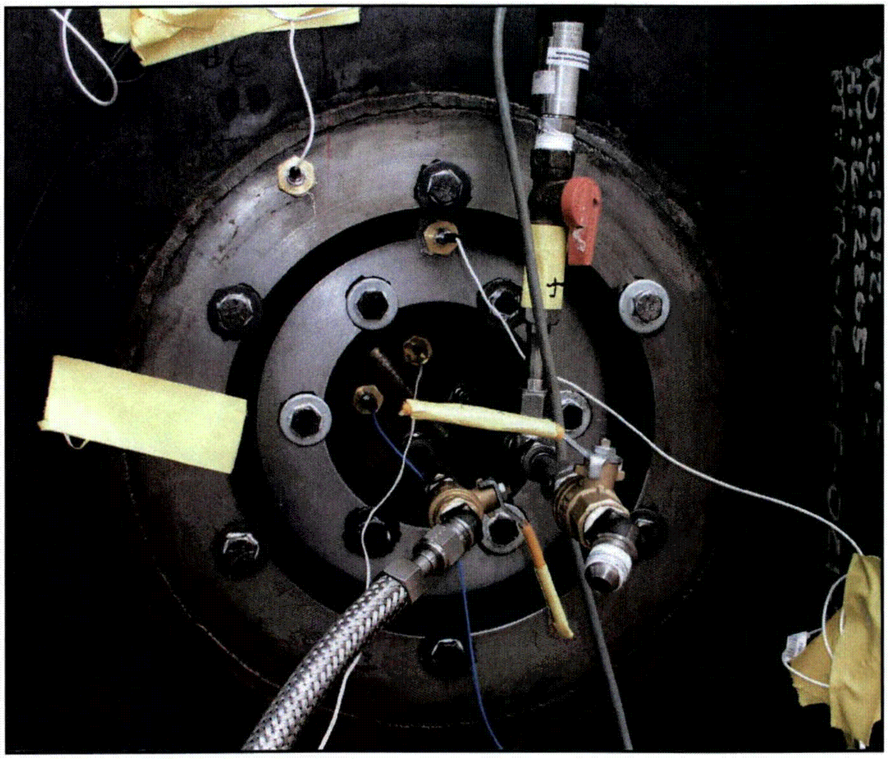

**Figure 2.1-11** – Instrumentation Flange Assembly

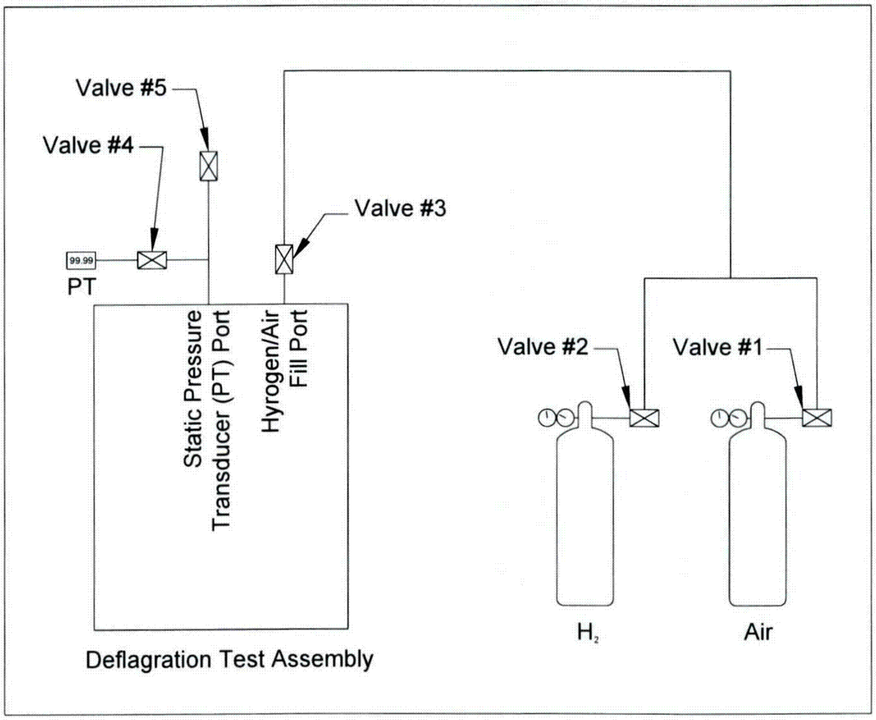


**Figure 2.1-12** – Deflagration Test Assembly Plumbing

### 2.1.2.3 Technical Basis for Tests

The test articles described in Section 2.1.2.2, *Test Article Design*, were sized (with appropriate exceptions outlined below) utilizing the deflagration pressure model presented in Section 2.1.1, *Adiabatic Constant Volume Deflagration Pressure Model*, to theoretically produce a pressure inside the Mock CV of 25 psig. Since the flammable gas mixture was injected into the SSC rather than being produced by volume consuming waste contents, the void volume inside the SSC was set equal to the internal volume of the SSC. Additionally, the external volume of the SSC was calculated as shown in Section 2.1.2.2.1, *Surrogate Sealed Container*, rather than being conservatively assumed as 10% greater than the internal volume.

As the primary objective of the deflagration tests was to validate the analytical deflagration pressure model, which correlates the size and initial pressure of a sealed container undergoing a stoichiometric hydrogen/air deflagration to a pressure in the TRUPACT-III CV, an appropriate selection of the SSC size and initial pressure was required. To minimize potential test difficulties associated with achieving a stoichiometric hydrogen/air mixture, the SSC was sized based on a decision that hydrogen would be added to the atmospheric air initially present inside the SSC to a pressure that would produce a stoichiometric mixture. This process was considered more reliable than adding both pressurized air and hydrogen into the sealed container to achieve a stoichiometric mixture at higher pressures. The gauge pressure of the SSC required to achieve a stoichiometric mixture, by adding hydrogen to the air initially present in the SSC at ambient conditions, is given as follows:

$$P_{ssc\_init} = P_{atm} \times \left(1 + \frac{1}{V_{Air} / V_{H_2}}\right) - P_{atm} = 14.7 \times \left(1 + \frac{1}{2.38}\right) - 14.7 = 6.17 \text{ psig}$$

The SSC size was determined by satisfying Equation 1, Equation 2, and Equation 3, given in Section 2.1.1.3, *Void Volume Scaling*, using the stoichiometric pressure increase factor of 8.18 to theoretically produce a Mock CV pressure equal to 25 psig. The SSC and SLB2 dunnage sizing and Mock CV pressure calculations are provided below.

$$V_{ssc\_int} = 766 \text{ liters}, \quad V_{ssc\_ext} = 794 \text{ liters}, \quad V_{ssc\_void} = V_{ssc\_int} = 766 \text{ liters},$$

$$V_{slb2\_void} = 0.25 \times (7{,}394 - 794) = 1{,}650 \text{ liters},$$

$$V_{dunnage\_ext} = V_{slb2\_int} - V_{slb2\_void} - V_{ssc\_ext} = 7{,}394 - 1{,}650 - 794 = 4{,}950 \text{ liters},$$

$$V_{mockcv\_void} = 10{,}019 - 7{,}665 = 2{,}354 \text{ liters},$$

$$P_{ssc\_defl} = [8.18 \times (14.7 + 6.17)] - 14.7 = 156 \text{ psig},$$

$$P_{slb2\_defl} = \frac{([14.7 + 156] \times 766) + (14.7 \times 1{,}650)}{(766 + 1{,}650)} - 14.7 = 49 \text{ psig, and}$$

$$P_{mockcv\_defl} = \frac{([14.7 + 49] \times [766 + 1{,}650]) + (14.7 \times 2{,}354)}{(766 + 1{,}650 + 2{,}354)} - 14.7 = 25 \text{ psig.}$$

The size and initial pressurization of the SSC is considered an appropriate test case for validation of the analytical pressure model due to the following:

- The initial pressure is based on the only credible condition causing a pressurized stoichiometric hydrogen and air mixture to form (i.e., hydrogen build-up from radiolysis mixing with the ambient air initially in the void space of the sealed container prior to being sealed). Sealed containers with higher pressure would contain a non-stoichiometric fuel-rich mixture since oxidizer production in the waste is not capable of significantly contributing to the sealed container pressurization and thus of maintaining a 2:1 hydrogen-to-oxygen molar ratio (see Appendix 2.4.2, *Oxygen Generation During Transportation of TRUPACT-III Payloads*).
- The use of a single large sealed container, with an initial pressure and size to theoretically produce 25 psig in the TRUPACT-III CV, is considered appropriate since multiple smaller sealed containers at the same initial pressure would be required to theoretically achieve an equivalent deflagration pressure. The initiation of a deflagration event is such that multiple smaller containers deflagrating simultaneously is extremely unlikely. The more likely condition of progressive deflagration of smaller containers would produce a lower pressure spike when compared to a single larger container due to the inherent staggering of the small time duration pressure pulses.

Overall, the technical basis for the confirmatory deflagration testing is consistent with the bounding conservatism in the adiabatic constant volume deflagration pressure model. The test was designed to maximize the deflagration pressure increase factor by igniting a stoichiometric hydrogen/air mixture. Hydrogen was chosen as the test flammable gas because of its high heat of combustion and its high laminar burn velocity. The test was designed to absorb minimal energy in releasing the combustion gases from the sealed container through the utilization of an engineered lid release mechanism. It utilized rigid dunnage to consume 75% of the void space in the SLB2 surrounding the SSC and, by avoiding significant contents crushing, minimized the void space and maximized the pressures seen by the SLB2 and Mock CV. Also, the Mock CV was utilized to replicate the TRUPACT-III CV void volume and resist significant deformation to provide an equivalent void space for measuring the deflagration pressures. Finally, the prototypic SLB2 was evaluated utilizing two configurations of the filter ports (filter vents installed, filter ports open) to evaluate the effects of combustion gas throttling through the most likely paths of leakage from the SLB2 into the Mock CV.

### 2.1.2.4 Test Procedure

Prior to the deflagration test and during the test article assembly process, the SSC, SLB2, Mock CV, and deflagration test assembly were bubble leak tested to verify the leak-tightness of the test articles (including the instrumentation flange connections) to a sensitivity of $1 \times 10^{-3}$ std. cc/sec air. Additionally, the test articles were individually dimensionally inspected to establish the pre-test dimensional configuration.

When the deflagration test assembly was ready for testing, the initial condition for valves in the system were as follows: a) dry air valve #1 – closed, b) hydrogen valve #2 – closed, c) hydrogen/air fill port valve #3 – closed, d) pressure transducer isolation valve #4 – open, and e) atmospheric vent valve #5 – open (Figure 2.1-12). The hydrogen/air fill hose (including valve #3) was disconnected from the SSC fill port, and valves #2 and #3 were opened for

approximately 30 seconds to allow hydrogen to flow freely through the length of the hose, purging air from and filling the hose with hydrogen. Once the hose was filled with hydrogen, valves #2 and #3 were again closed, and the hose/valve #3 assembly was reattached to the SSC fill port. The pressure transducer P7 was removed and reattached to vent the SLB2 to atmosphere, and the process was repeated for P6 to vent the Mock CV to atmosphere.

With valves #4 and #5 remaining in the open position and the SSC vented to atmosphere, the ambient pressure and temperature were recorded utilizing the static pressure transducer attached to valve #4 and the thermocouple attached to the wall of the Mock CV, respectively. The static pressure transducer was subsequently tared (set to read gauge pressure) and valve #5 was closed to seal the SSC. A calculation, based on the measured atmospheric pressure, was performed to determine the set-point to achieve the stoichiometric hydrogen/air mixture and valves #2 and #3 were opened to allow hydrogen to begin filling the SSC to the desired set-point. Valve #2 was actuated repeatedly over an approximately 15-30 minute time frame to allow additional hydrogen to flow into the SSC and the system to thermally stabilize to the pressure set-point. Once the system had thermally stabilized with valve #2 in the closed position, valve #3 was also closed and a 30-minute dwell time was initiated to allow the hydrogen and air to mix in the SSC.

For safety purposes, during the dwell time, the hydrogen/air fill hose was disconnected from valve #3 and valve #1 was opened to allow dry air to purge any hydrogen from the hose. Upon completion of the hose purging process, valve #1 was closed and the supply hose reconnected to valve #3 (closed). After the 30-minute dwell time had been achieved, the static gauge pressure inside the SSC was verified as remaining within a ±2% of the calculated set-point, and valve #4 was closed to isolate and protect the static pressure gauge from the deflagration pressures.

The electric match leads were subsequently attached to the trigger source with both high-speed camera and digital data acquisition systems (for the dynamic pressure transducers) armed. The ordinance countdown resulted in initiation of the deflagration and subsequent data acquisition. When ordinance safety procedures were satisfied, valve #4 was opened to allow measurement of the static gauge pressure inside the deflagration test assembly and, for the second test, monitoring of the internal pressure and external surface temperature of the assembly for 10 minutes.

Following the deflagration test, the deflagration test assembly was subjected to a 4 psig (+1 -0 psig) pressure decrement test to verify the overall structural integrity of the pressure boundary (Mock CV and the SLB2/SSC instrumentation flange connections). The units were subsequently disassembled, and dimensional inspections were performed along with photographic documentation of the post-deflagration state of the test articles.

#### 2.1.2.5 Test Results

Two deflagration tests were performed, one with the SLB2 filter ports "filtered" and one with the SLB2 filter ports "open". A third test that had the SLB2 ports "plugged" was scheduled but not performed due to an evaluation of the first two tests that concluded the third test was not a bounding configuration and was, therefore, unnecessary. The "filtered" and "open" tests each utilized a new SLB2 and SSC test article, but the same Mock CV and SLB2 dunnage assembly was utilized for both deflagration tests. Both the "filtered" and "open" tests demonstrated that the analytical model defined in Section 2.1.1, *Adiabatic Constant Volume Deflagration Pressure*

*Model*, can be utilized to conservatively bound the pressure exerted on the TRUPACT-III CV resulting from a stoichiometric hydrogen/air deflagration inside a pressurized sealed container.

Dynamic pressure transducers and an associated digital data acquisition system were employed to measure the dynamic pressure at six locations in the Mock CV, one location in the SLB2, and one location in the SSC. The dynamic pressure data was sampled for all transducer locations from time zero (defined by triggering of the electric match) to one second at a sampling rate of 125,000 readings per second. The dynamic pressure results for the configuration that incorporated filters in the six SLB2 filter ports are provided in Figure 2.1-13 through Figure 2.1-20 over the range of interest from zero to 200 msec. The dynamic pressure results for the configuration that utilized an SLB2 with filter ports open to communicate with the Mock CV void space are provided in Figure 2.1-21 through Figure 2.1-28 over the range of interest from zero to 200 msec. Each plot contains the raw pressure data (converted via the transducer calibration sheets from voltage to gauge pressure) and the raw data averaged over a 1-msec time duration to filter excessive oscillations of the piezoelectric dynamic pressure transducer data. A discussion of the results of the dynamic pressure measurements and post-deflagration damage assessment of the test articles is provided in Section 2.1.2.5.1, *Deflagration Test #1 Results – SLB2 Ports "Filtered"* and Section 2.1.2.5.2, *Deflagration Test #2 Results – SLB2 Ports "Open"*.

#### 2.1.2.5.1 Deflagration Test #1 Results – SLB2 Ports "Filtered"

As seen in Figure 2.1-20, upon initiation of the electric match at time zero the pressure in the SSC (P8) increased from a steady-state initial condition to a 1-msec avg peak of 41.8 psig (21.3 msec). Due to the approximately 1-sec discharge time constant for the transducer, the 5.52 psig initial static pressure of the hydrogen/air mixture is not reflected in the recorded data since the signal had decayed to zero during the mixing dwell time. However, the initial static pressure decay issue does not lead to an under-prediction of the peak reported P8 pressure because the SSC lid ejects and opens the P8 transducer to the initially ambient pressure in the SLB2 at approximately 18 msec. The rapid reduction in the recorded P8 pressure at time greater than 60 msec is attributed to the effects of radiant heat input and associated expansion of the piezoelectric pressure transducer housing located within the combustion zone, which leads to an expansion of the housing and relief of preload on the piezoelectric crystals.[4] However, this effect occurs significantly after the time frame of interest (i.e., the time of peak pressure measurement).

Also shown in Figure 2.1-19, the SLB2 pressure (P7) reached a 1-msec avg peak of 50.0 psig (21.4 msec). A significant amount of pressure oscillation is reported by the P7 transducer from 18 to 55 msec and attributed to the effects of dynamic impact during the SSC lid release and subsequent excitation of the SSC/SLB2 flange interface.

The Mock CV pressure transducer (P6), located near P7 and P8 in the instrumentation flange, reached a 1-msec avg peak of 18.8 psig (42.4 msec). Due to the fact that the peak pressure occurs after the initial peak of approximately 11 psig at 26 msec followed by a dip and subsequent rise (Figure 2.1-18), it is likely that the 18.8 psig pressure is partially over predicted due to dynamic excitation from the bolted SLB2 flange connection interacting with the Mock CV

[4] Walter, Patrick L., *Introduction to Air Blast Measurements ~ Part V: Alternate Technologies?*, Technical Note TN-22, PCB Piezotronics, Inc., Depew, New York.

flange and associated P6 transducer. From a comparison with Figure 2.1-19, it can be seen that the SLB2 and Mock CV are equalized in pressure and are acting as a common void space at time greater than 160 msec.

Due to a considerable amount of dynamic impact between the long sidewall bumpers and lid bumpers of the SLB2 with the associated Mock CV internal surfaces, the pressure transducer readings for P5, P4, and P2, shown respectively in Figure 2.1-17, Figure 2.1-16, and Figure 2.1-14, are considered erroneous. As shown in Figure 2.1-35, the extent of structural damage imparted on the SLB2 bumpers correlates with these transducer locations and provides structural evidence of the significant dynamic impact and excitation that caused the erroneous response of the transducers. Although the pressure traces from all other transducers are relatively quiet for time greater than 50 msec, the P5, P4, and P2 transducers are all clipping beyond scale, while the other transducers provide evidence that the structure was not still being significantly excited. A correlation between the magnitude of the erroneous pressure readings and the amount of structural crushing of the associated SLB2 bumpers is presented in Table 2.1-2, further supporting that the dynamic impact was erroneously affecting the combustion gas pressure readings of the pressure transducers located near the impact points. The additional clearance gap between the short ends of the SLB2 and the Mock CV when compared to the long sides, the bolted instrumentation flange connection at the short end, and the initial contact between the SLB2 and Mock CV bottom minimized the dynamic impact and associated excitation of the P1, P3, and P6 Mock CV pressure transducers and facilitated more accurate pressure readings at these locations.

The Mock CV pressure transducer (P3), located in the short end opposite the P6, P7 and P8 transducers, reached a 1-msec avg peak of 22.3 psig (30.5 msec) (Figure 2.1-15). Again, although less pronounced than for the P5, P4, and P2 transducers, the peak pressure is considered over predicted due to structural impact between the SLB2 short end bumpers and the Mock CV.

The Mock CV pressure transducer (P1), located in the bottom of the Mock CV, reached a peak 1-msec avg pressure of 15.4 psig (22.1 msec). Further discussion is provided in Section 2.1.2.6.1, *Deflagration Test #1 Validation – SLB2 Ports "Filtered"*.

In addition to the measurement and recording of the deflagration pressures, each test article comprising the deflagration test assembly was visually inspected to determine the response of each to the deflagration event. The following is a summary of the structural investigation:

- A visual inspection of the Mock CV exterior found no obvious structural damage (Figure 2.1-32). Each of the Mock CV closure bolts was inspected with 12 of the closure bolts, located near the mid-plane of the long sides, having a reduced torque. The preload reduction is attributed to a slight flattening of the serrations on the underneath side of the hex flange bolt heads at these locations.
- A post-deflagration pressure degradation test was successfully performed to verify that the gross structural integrity of the Mock CV was not compromised by the deflagration event. Immediately following the deflagration test, the Mock CV assembly was subjected to a 4.45 psig internal pressure and the pressure was monitored over a 10-minute duration with the final pressure recorded as 4.27 psig. Slight movement of the SSC and reduction in gasket preload at the SSC/SLB2 instrumentation flange interface caused a radially-inward slippage and minor leakage of the SSC/SLB2 flange gasket.

Based on the pressure degradation test results, the leakage was not of a magnitude that could have adversely affected the deflagration pressure readings.

- Upon removal and inspection of the Mock CV lid, slight abrasion marks (primarily associated with rust transfer) were witnessed on the underneath side of the lid that corresponded to the location of impact from the SLB2 lid bumpers.
- Removal and inspection of the SLB2 revealed no gross structural failure of the assembly although each of the six sides of the container were permanently plastically deformed outward (Figure 2.1-33). The largest outward deformation was associated with the lid and long sides, with the center of each protruding approximately 2-½ in. beyond the pre-test condition. Due to the lid deformation, some of the SLB2 closure bolts were significantly bent, but all bolt heads/nuts were intact with a high bolt preload. All six of the filters remained housed within the SLB2 filter ports, but all filter screens and membranes were dislodged from their original location in the filter housing, with some being blown into the SLB2 cavity (Figure 2.1-34).
- As previously discussed, the SLB2 external bumpers experienced compressive deformation resulting from impact with the Mock CV walls as the SLB2 expanded outward due to the deflagration pressures. The largest crushing was associated with the middle bumpers along the long sidewalls and on the lid (Figure 2.1-35, Table 2.1-2).
- Upon removal and inspection of the SLB2 lid, a slight crescent-shaped indentation could be observed on the underneath side of the lid that corresponded to the location of impact from the SSC lid. All six of the SSC closure bolts failed in the necked-down region and facilitated the SSC lid ejection.
- The top surface of the SLB2 dunnage was modestly deformed inward/downward due to the deflagration pressures. The top location of the foam fill port and the observation that no other sides of the dunnage were deformed inward leads to a conclusion that the poured-in-place rigid urethane foam did not completely fill to the inside top surface, which left areas of the dunnage unsupported (Figure 2.1-36). Additionally, movement of the dunnage and impact with one of the SLB2 internal vertical stiffeners caused a ½-inch wide localized shear failure of the dunnage side-to-bottom panel weld. Inspection of the damage concluded that the closed-cell foam fully filled this location, and there was no affect on the void volume due to the localized tear.
- Beyond the designed failure of the SSC closure bolts, no significant structural damage was observed on the SSC. The SSC lid gasket/O-ring was torn in multiple pieces, but the body, lid, bottom, and instrumentation flange were all intact (Figure 2.1-37). There was no evidence of burning/scorching beyond the insulation of the electric match and discoloration of the filter screens (Figure 2.1-38).

#### 2.1.2.5.2 Deflagration Test #2 Results – SLB2 Ports "Open"

As seen in Figure 2.1-28, upon initiation of the electric match at time zero the pressure in the SSC (P8) increased from a steady-state initial condition to a 1-msec avg peak of 29.1 psig (25.2 msec). Due to the approximately 1-sec discharge time constant for the transducer, the 5.08 psig initial static pressure of the hydrogen/air mixture is not reflected in the recorded data since the signal had decayed to zero during the mixing dwell time. However, the initial static

pressure decay issue does not lead to an under-prediction of the peak reported P8 pressure because the SSC lid ejects and opens the P8 transducer to the initially ambient pressure in the SLB2 at approximately 22 msec. The rapid reduction in the recorded P8 pressure at time greater than 60 msec is again attributed to the effects of radiant heat input.

Also shown in Figure 2.1-27, the SLB2 pressure (P7) reached a 1-msec avg peak of 32.0 psig (26.4 msec). A significant amount of pressure oscillation is reported by the P7 transducer from 22 to 75 msec and attributed to the effects of dynamic impact during the SSC lid release and subsequent excitation of the SSC/SLB2 flange interface.

The Mock CV pressure transducer (P6), located near P7 and P8 in the instrumentation flange, reached a 1-msec avg peak of 15.8 psig (44.3 msec). Due to the fact that the peak pressure occurs after the initial peak of approximately 9 psig at 32 msec followed by a dip and subsequent rise (Figure 2.1-26), it is likely that the 15.8 psig pressure is partially over predicted due to dynamic excitation from the bolted SLB2 flange connection interacting with the Mock CV flange and associated P6 transducer. From a comparison with Figure 2.1-27, it can be seen that the SLB2 and Mock CV are equalized in pressure and are acting as a common void space at time greater than 130 msec.

Due to a considerable amount of dynamic impact between the long sidewall bumpers and lid bumpers of the SLB2 with the associated Mock CV internal surfaces, the pressure transducer readings for P5, P4, and P2, shown respectively in Figure 2.1-25, Figure 2.1-24, and Figure 2.1-22, are again considered erroneous. As shown in Figure 2.1-42, the extent of structural damage imparted on the SLB2 bumpers correlates with these transducer locations and provides structural evidence of the significant dynamic impact and excitation that caused the erroneous response of the transducers. Although the pressure traces from all other transducers are relatively quiet for time greater than 55 msec, the P5, P4, and P2 transducers are all clipping beyond scale, while the other transducers provide evidence that the structure was not still being significantly excited. A correlation between the magnitude of the erroneous pressure readings and the amount of structural crushing of the associated SLB2 bumpers is presented in Table 2.1-3, further supporting that the dynamic impact was erroneously affecting the combustion gas pressure readings of the pressure transducers located near the impact points. Again, the additional clearance gap between the short ends of the SLB2 and the Mock CV when compared to the long sides, the bolted instrumentation flange connection at the short end, and the initial contact between the SLB2 and Mock CV bottom minimized the dynamic impact and associated excitation of the P1, P3, and P6 Mock CV pressure transducers and facilitated more accurate pressure readings at these locations.

The Mock CV pressure transducer (P3), located in the short end opposite the P6, P7 and P8 transducers, reached a 1-msec avg peak of 18.7 psig (35.2 msec) (Figure 2.1-23). Again, although less pronounced than for the P5, P4, and P2 transducers, the peak pressure is considered over predicted due to structural impact between the SLB2 short end bumpers and the Mock CV.

The Mock CV pressure transducer (P1), located in the bottom of the Mock CV, reached a peak 1-msec avg pressure of 11.9 psig (25.2 msec). Further discussion is provided in Section 2.1.2.6.2, *Deflagration Test #2 Validation – SLB2 Ports "Open"*.

In addition to the measurement and recording of the deflagration pressures, each test article comprising the deflagration test assembly was visually inspected to determine the response of each to the deflagration event. The following is a summary of the structural investigation:

- A visual inspection of the Mock CV exterior found no obvious structural damage (Figure 2.1-39). Each of the Mock CV closure bolts was inspected with 2 of the closure bolts, located near the mid-plane of the long sides, having a reduced torque. The preload reduction is attributed to a slight flattening of the serrations on the underneath side of the hex flange bolt heads at these locations. The preload reduction was less in this test sequence due to implementing an added torque verification sequence prior to the test to eliminate preload reduction caused by gasket compression-set and temperature reduction from sitting overnight.
- A post-deflagration pressure degradation test was successfully performed to verify that the gross structural integrity of the Mock CV was not compromised by the deflagration event. Immediately following the deflagration test, the Mock CV assembly was subjected to a 4.50 psig internal pressure and the pressure was monitored over a 10-minute duration with the final pressure recorded as 4.40 psig. A higher bolt preload and associated compression of the flange gaskets during assembly eliminated any slip and/or minor leakage at the SSC/SLB2 instrumentation flange interface as seen in the prior test. Based on the pressure degradation test results, any leakage was very small and did not adversely affect the deflagration pressure readings.
- Upon removal and inspection of the Mock CV lid, slight abrasion marks (primarily associated with rust transfer) were witnessed on the underneath side of the lid, which corresponded to the location of impact from the SLB2 lid bumpers.
- Removal and inspection of the SLB2 revealed no gross structural failure of the assembly, although each of the six sides of the container was permanently plastically deformed outward (Figure 2.1-40). The largest outward deformation was associated with the lid and long sides, with the center of each protruding approximately 2 in. beyond the pre-test condition. Due to the lid deformation, some of the SLB2 closure bolts were significantly bent, but all bolt heads/nuts were intact with a high bolt preload. The four vertical SLB2 body seam welds had areas of separation from the base material on the inside, but the overall integrity of the body was intact and all external vertical body seam welds were not cracked or separated (Figure 2.1-41).
- As previously discussed, the SLB2 external bumpers experienced compressive deformation resulting from impact with the Mock CV walls as the SLB2 expanded outward due to the deflagration pressures. The largest crushing was associated with the middle bumpers along the long sidewalls and on the lid (Figure 2.1-42, Table 2.1-3).
- Upon removal and inspection of the SLB2 lid, a slight crescent-shaped indentation could be observed on the underneath side of the lid that corresponded to the location of impact from the SSC lid. All six of the SSC closure bolts failed in the necked-down region and facilitated the SSC lid ejection.
- The SLB2 dunnage top surface was deformed inward/downward from the first test and experienced additional deformation during the second test. Again, the top location of the foam fill port and the observation that no other sides of the dunnage were deformed inward leads to a conclusion that the poured-in-place rigid urethane foam did not completely fill to the inside top surface, which left areas of the dunnage unsupported (Figure 2.1-43).

- Beyond the designed failure of the SSC closure bolts, no significant structural damage was observed on the SSC. The SSC lid gasket/O-ring was found undamaged resting around the circumference of the body, and the body, lid, bottom, and instrumentation flange were all intact (Figure 2.1-44). Again, there was no evidence of burning/scorching beyond the insulation of the electric match.

### 2.1.2.6 Pressure Model Validation

The actual deflagration test conditions for ambient pressure, SSC initial pressure, hydrogen/air mixture, and SLB2 void volume (affected by the SLB2 dunnage deformation) are all input variables that need to be taken into consideration when comparing the adiabatic constant volume deflagration pressure model to the measured deflagration test pressures. Due to the actual test conditions, the adiabatic constant volume deflagration pressure model predicts a Mock CV deflagration pressure slightly less than the 25 psig prediction for the as-designed test article as given in Section 2.1.2.3, *Technical Basis for Tests.*

#### 2.1.2.6.1 Deflagration Test #1 Validation – SLB2 Ports "Filtered"

Adjusting for the actual SLB2 dunnage external volume resulting from the dunnage top panel deformation, $V_{dunnage\_ext'}$ = 4,950 – 54 (deformation) = 4,896 liters, the SLB2 void volume is calculated as follows:

$$V_{slb2\_void} = V_{slb2\_int} - V_{dunnage\_ext'} - V_{ssc\_ext} = 7{,}394 - 4{,}896 - 794 = 1{,}704 \text{ liters}$$

This volume is utilized in an intermediate calculational step and is not representative of the actual SLB2 void volume since SLB2 side walls expand significantly during the deflagration event, but is relevant to the calculation of the Mock CV pressure. The ambient pressure at the time of hydrogen fill was recorded as $P_{atm}$ = 13.10 psia and resulted in a SSC hydrogen fill pressure set-point of

$$P_{ssc\_init} = 13.10 \times \left(1 + \frac{1}{2.38}\right) - 13.10 = 5.50 \text{ psig.}$$

The actual pressure measured prior to the deflagration initiation inside the SSC was 5.52 psig resulting in a 29.65% by volume hydrogen concentration. Linearly interpolating the constant volume deflagration pressure data in Figure 2.1-1 for the computed hydrogen concentration results in a pressure increase factor of 8.18. Therefore, the deflagration pressures predicted for the actual test conditions are calculated as follows:

$$P_{ssc\_defl} = [8.18 \times (13.10 + 5.52)] - 13.10 = 139 \text{ psig,}$$

$$P_{slb2\_defl} = \frac{([13.10 + 139] \times 766) + (13.10 \times 1{,}704)}{(766 + 1{,}704)} - 13.10 = 43 \text{ psig, and}$$

$$P_{mockcv\_defl} = \frac{([13.10 + 43] \times [766 + 1{,}704]) + (13.10 \times 2{,}354)}{(766 + 1{,}704 + 2{,}354)} - 13.10 = 22 \text{ psig.}$$

As presented in Section 2.1.2.5.1, *Deflagration Test #1 Results – SLB2 Ports "Filtered"*, the pressure traces for Mock CV transducer ports P2, P4, and P5 are not reliable and are removed for comparison due to the excessive data noise attributed to structural impact of the SLB2 long sides

and top with the Mock CV. As such, the 1-msec averaged or smoothed pressure transducer data is presented in Figure 2.1-29 for the remaining transducer locations. As shown in Figure 2.1-29, the largest 1-msec averaged pressure experienced by the Mock CV was 15.4 psig (22.1 msec), 22.3 psig (30.5 msec), and 18.8 psig (42.4 msec) at the P1, P3, and P6 transducer locations, respectively.

Due to the physical impossibility of the P1 transducer experiencing pressure build-up from the initiation of the deflagration event until the SSC opens and begins to release the combustion gases into the SLB2 at approximately 18 msec, the P1 transducer reading is regarded as reporting a phantom pressure in this time range due to the structural interaction between the bottom of the SSC bearing on the floor of the SLB2 and corresponding excitation of the Mock CV bottom panel and transducer port. The build-up of pressure in the SSC is logically communicating structural excitation to the P1 Mock CV port, since deflection of the SSC bottom is being restricted by the flanged instrumentation connection to the SLB2 and this load is being transferred through the floor of the SLB2 to the Mock CV. Additionally, the magnitude of the largest 1-msec averaged pressure reported by the P3 transducer is correspondingly considered due in part to excitation from structural impact of the SLB2 short side bumpers into the Mock CV. This interaction is less pronounced at the P6 transducer location as the instrumentation flange limits the amount of physical impact between the SLB2 and Mock CV at the flanged short end of the test assembly.

The SSC analytical pressure calculation cannot be directly compared to the P8 transducer measurement since the intermediate pressure calculation is based on the assumption that the SSC void volume remains constant and the void volume in reality expands significantly once the lid releases from the SSC. However, once the SSC lid releases, the P7 and P8 transducers are measuring pressure in the same void space (i.e., SLB2) and the maximum P8 1-msec averaged pressure reading of 41.8 psig (21.3 msec) compares well with the SLB2 predicted pressure of 43 psig. The maximum P7 1-msec pressure reading of 50.0 psig (21.4 msec) is higher than the predicted pressure but has a duration of <1 msec and appears to be attributed to a dynamic overshoot response of the transducer.

It is considered appropriate to compare the average pressure exerted on the Mock CV with the analytically predicted deflagration pressure since the design basis for MNOP in the TRUPACT-III CV is a static normal condition pressure and the package has a high capacity for withstanding short-duration dynamic impact loads as demonstrated in full-scale drop tests. From inspection of Figure 2.1-29, the average pressure exerted on the Mock CV (reported by transducers P1, P3, and P6) from 25 to 100 msec ranges from 6.6 psig to 12.7 psig with a sustained average over the 75 msec time duration of 10.4 psig. Due to the adiabatic assumption in the analytical model, the analytical predicted deflagration pressure (22 psig) is conservatively overestimating the average pressures experienced by the Mock CV during the deflagration event. Therefore, the test data demonstrates that the analytical model is appropriately conservative.

### 2.1.2.6.2 Deflagration Test #2 Validation – SLB2 Ports "Open"

Adjusting for the actual SLB2 dunnage external volume resulting from the top panel deformation, $V_{dunnage\_ext'} = 4{,}950 - 97$ (deformation) = 4,853 liters, the SLB2 void volume is calculated as follows:

$$V_{slb2\_void} = V_{slb2\_int} - V_{dunnage\_ext'} - V_{ssc\_ext} = 7{,}394 - 4{,}853 - 794 = 1{,}747 \text{ liters}$$

Again, this volume is utilized in an intermediate calculational step and is not representative of the actual SLB2 void volume since SLB2 side walls expand significantly during the deflagration event, but is relevant to the calculation of the Mock CV pressure. The ambient pressure at the time of hydrogen fill was recorded as $P_{atm}$ = 11.89 psia and resulted in a SSC hydrogen fill pressure set-point of

$$P_{ssc\_init} = 11.89 \times \left(1 + \frac{1}{2.38}\right) - 11.89 = 5.00 \text{ psig.}$$

The actual pressure measured prior to the deflagration initiation inside the SSC was 5.08 psig resulting in a 29.94% by volume hydrogen concentration. Linearly interpolating the constant volume deflagration pressure data in Figure 2.1-1 for the computed hydrogen concentration results in a pressure increase factor of 8.16. Therefore, the deflagration pressures predicted for the actual test conditions are calculated as follows:

$$P_{ssc\_defl} = [8.16 \times (11.89 + 5.08)] - 11.89 = 127 \text{ psig,}$$

$$P_{slb2\_defl} = \frac{([11.89 + 127] \times 766) + (11.89 \times 1{,}747)}{(766 + 1{,}747)} - 11.89 = 39 \text{ psig, and}$$

$$P_{mockcv\_defl} = \frac{([11.89 + 39] \times [766 + 1{,}747]) + (11.89 \times 2{,}354)}{(766 + 1{,}747 + 2{,}354)} - 11.89 = 20 \text{ psig.}$$

As presented in Section 2.1.2.5.2, *Deflagration Test #2 Results – SLB2 Ports "Open"*, the pressure traces for Mock CV transducer ports P2, P4, and P5 are not reliable and are removed for comparison due to the excessive data noise attributed to structural impact of the SLB2 long sides and top with the Mock CV. As such, the 1-msec averaged or smoothed pressure transducer data is presented in Figure 2.1-30 for the remaining transducer locations. As shown in Figure 2.1-30, the largest 1-msec averaged pressure experienced by the Mock CV was 11.9 psig (25.2 msec), 18.7 psig (35.2 msec), and 15.8 psig (44.3 msec) at the P1, P3, and P6 transducer locations, respectively.

Again, due to the physical impossibility of the P1 transducer experiencing pressure build-up from the initiation of the deflagration event until the SSC opens and begins to release the combustion gases into the SLB2 at approximately 22 msec, the P1 transducer reading is regarded as reporting a phantom pressure in this time range due to the structural interaction between the bottom of the SSC bearing on the floor of the SLB2 and corresponding excitation of the Mock CV bottom panel and transducer port. The build-up of pressure in the SSC is logically communicating structural excitation to the P1 Mock CV port, since deflection of the SSC bottom is being restricted by the flanged instrumentation connection to the SLB2 and this load is being transferred through the floor of the SLB2 to the Mock CV. Additionally, the magnitude of the largest 1-msec averaged pressure reported by the P3 transducer is correspondingly considered due in part to excitation from structural impact of the SLB2 short side bumpers into the Mock CV. This interaction is less pronounced at the P6 transducer location as the instrumentation flange limits the amount of physical impact between the SLB2 and Mock CV at the flanged short end of the test assembly.

The SSC analytical pressure calculation cannot be directly compared to the P8 transducer measurement since the intermediate pressure calculation is based on the assumption that the SSC

void volume remains constant and the void volume in reality expands significantly once the lid releases from the SSC. However, once the SSC lid releases, the P7 and P8 transducers are measuring pressure in the same void space (i.e., SLB2) and the maximum P8 1-msec averaged pressure reading of 29.1 psig (25.2 msec) is lower than the SLB2 predicted pressure of 39 psig. The maximum P7 1-msec pressure reading of 32.0 psig (26.4 msec) is also lower than the predicted pressure. Since the ports in the SLB2 were "open", the measured pressures are logically below the analytical prediction since the combustion gases are being throttled from the SLB2 into the void space of the Mock CV from the outset without the initial flow restriction evident in the "filtered" test measured versus predicted pressure comparison.

It is considered appropriate to compare the average pressure exerted on the Mock CV with the analytically predicted deflagration pressure since the design basis for MNOP in the TRUPACT-III CV is a static normal condition pressure and the package has a high capacity for withstanding short-duration dynamic impact loads as demonstrated in full-scale drop tests. From inspection of Figure 2.1-30, the average pressure exerted on the Mock CV (reported by transducers P1, P3, and P6) from 25 to 100 msec ranges from 4.8 psig to 11.7 psig with a sustained average over the 75 msec time duration of 10.0 psig. Due to the adiabatic assumption in the analytical model, the analytical predicted deflagration pressure (20 psig) is conservatively overestimating the average pressures experienced by the Mock CV during the deflagration event. Therefore, the test data demonstrates that the analytical model is appropriately conservative, even when compared to a test case where the combustion gases are allowed to flow freely through open SLB2 filter ports into the Mock CV.

### 2.1.2.6.3 Deflagration Tests #1 and #2 Comparison

As presented above, the initial conditions for each of the deflagration tests (i.e., ambient pressure, initial pressure and hydrogen concentration of SSC, and SLB2 dunnage deformation) are a source of variation between the measured pressures in each test. Additionally, the status of the filter ports in the SLB2 (filtered vs. open) generates test result variations that are more pronounced. However, these differences are primarily associated with the pressure readings in the SSC and SLB2 rather than the Mock CV. The pressure readings in the Mock CV are of primary interest and the relative comparison between the two tests can be seen in Figure 2.1-31 when comparing the P1, P3, and P6 pressure traces for both tests. The tracking of the pressure results between the two tests suggests that the primary factor affecting Mock CV pressure is the void volume that the combustion gases are available to expand into and not primarily the mechanism for release of those gases from the SLB2. Contrastingly, when comparing the pressure traces for both tests in the SSC (P8) and SLB2 (P7), it is clear that the pressures seen by the SLB2 are affected by the flow of combustion gases through the filter ports. The more restrictive flow out of the SLB2 in test #1 results in higher peak pressures in the SLB2 when compared to test #2. In both cases, the magnitude of pressures inside the SLB2 causes significant "ballooning" of the SLB2 and structural interaction between the SLB2 and the Mock CV, as ascertained from the damage assessment of the SLB2 bumpers. However, this interaction is well within the capabilities of the TRUPACT-III CV and is bounded by the Hypothetical Accident Condition (HAC) impact testing presented in the TRUPACT-III SAR.[5]

[5] Packaging Technology, Inc., *Safety Analysis Report for the TRUPACT-III Shipping Package*, current revision, USNRC Docket No. 71-9305, Packaging Technology, Inc., Tacoma, Washington..

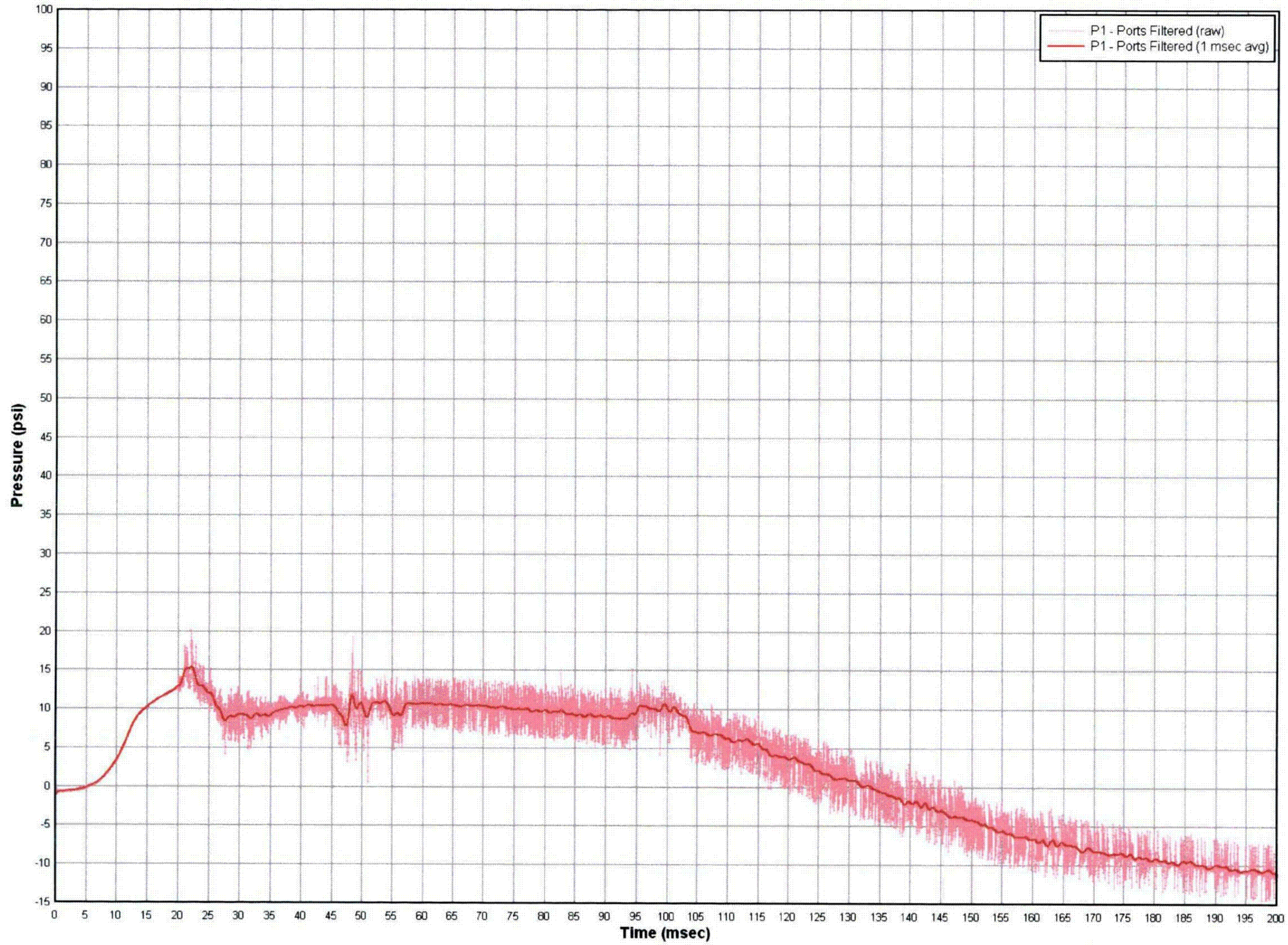


**Figure 2.1-13** – Deflagration Test #1, P1 (raw, 1-msec avg)

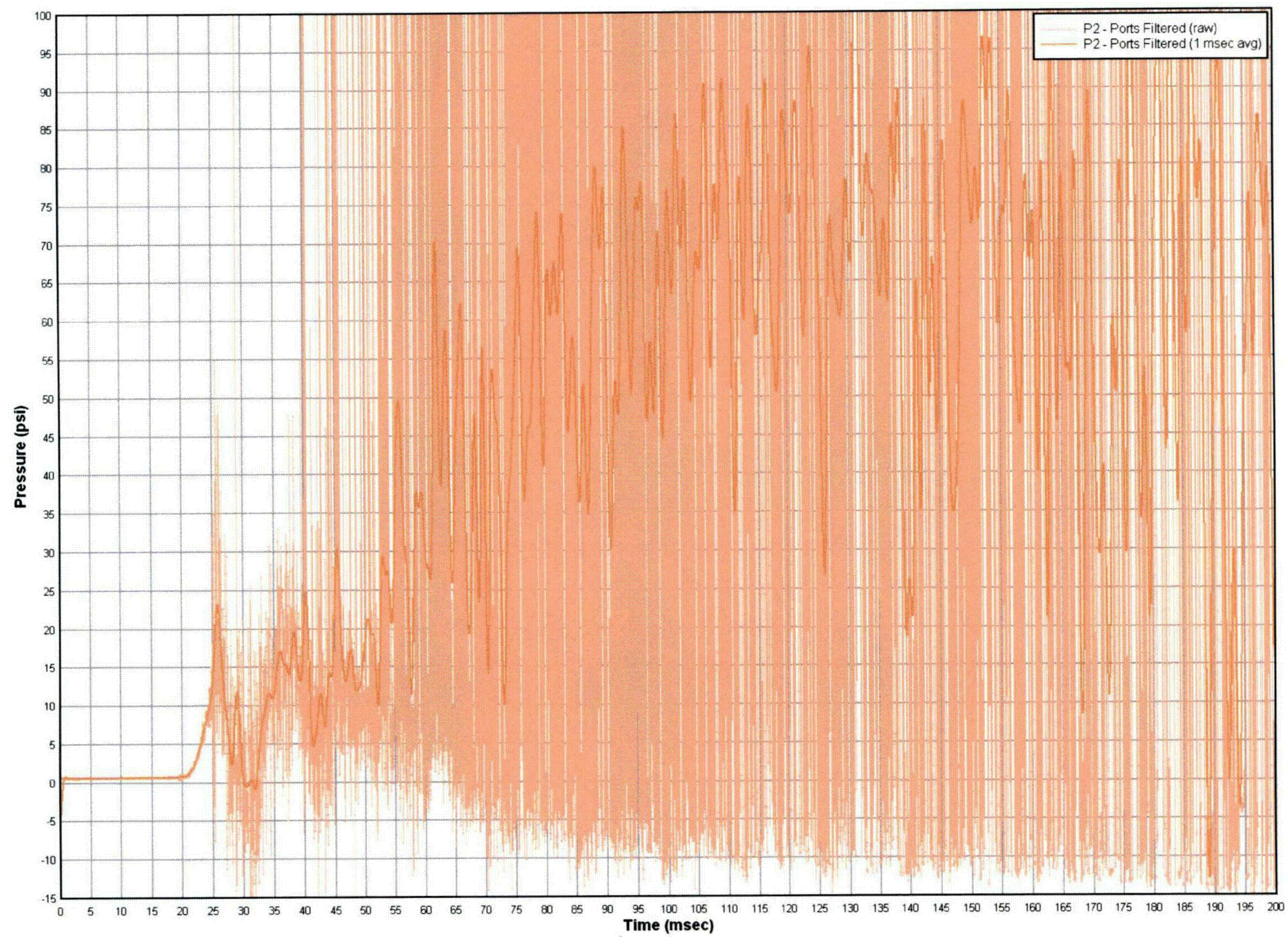


**Figure 2.1-14** – Deflagration Test #1, P2 (raw, 1-msec avg)

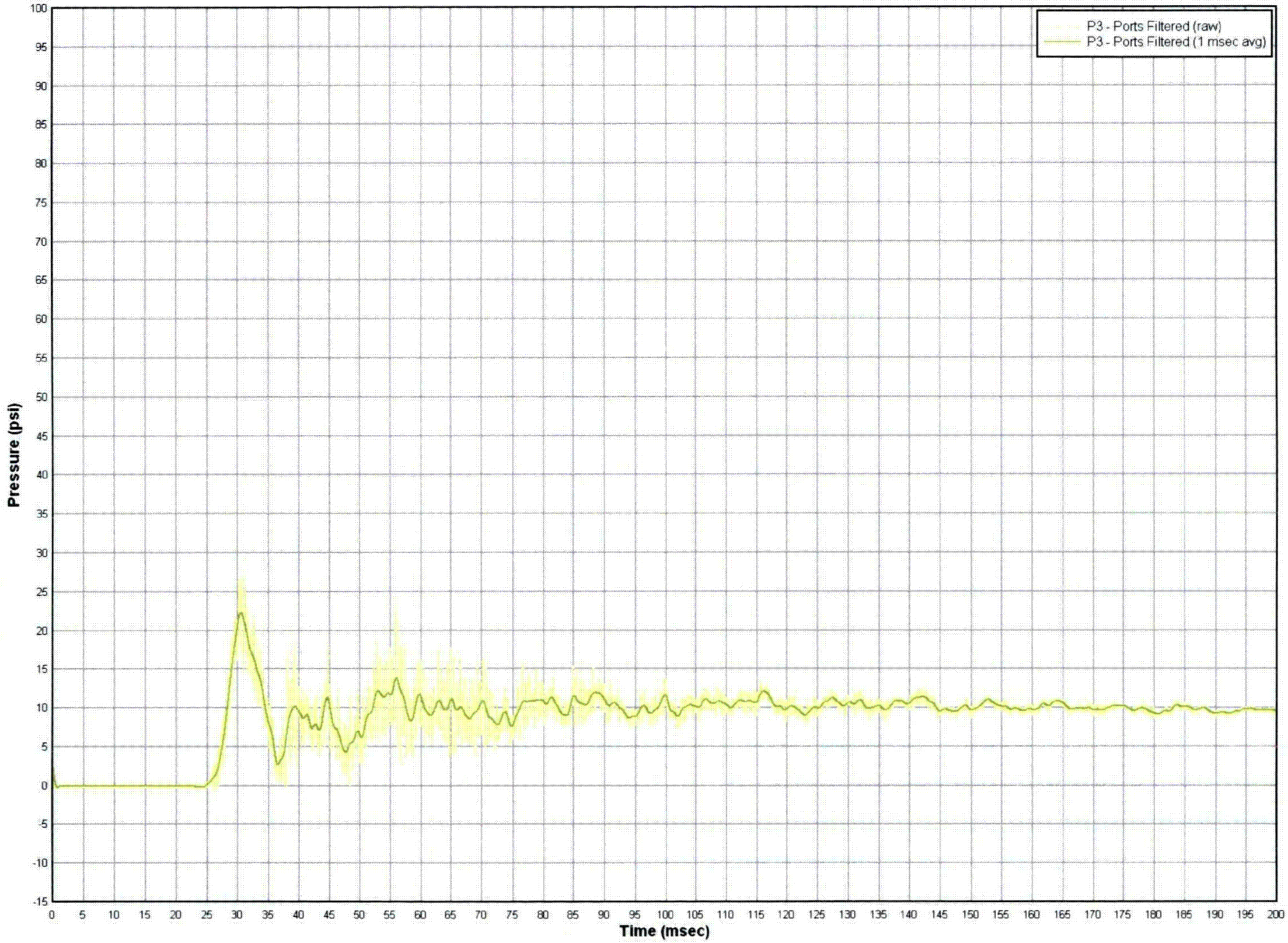


**Figure 2.1-15** – Deflagration Test #1, P3 (raw, 1-msec avg)

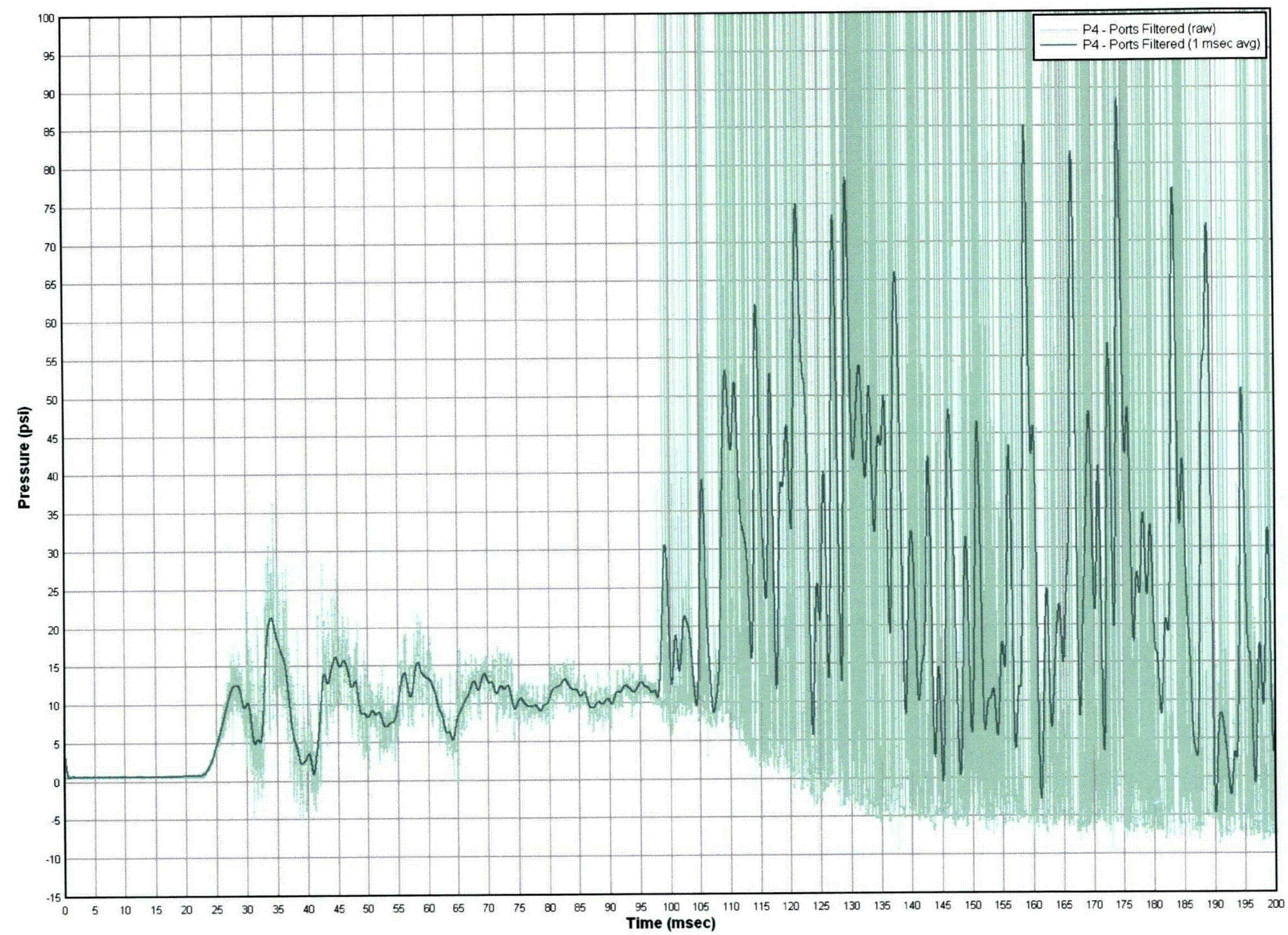


**Figure 2.1-16** – Deflagration Test #1, P4 (raw, 1-msec avg)

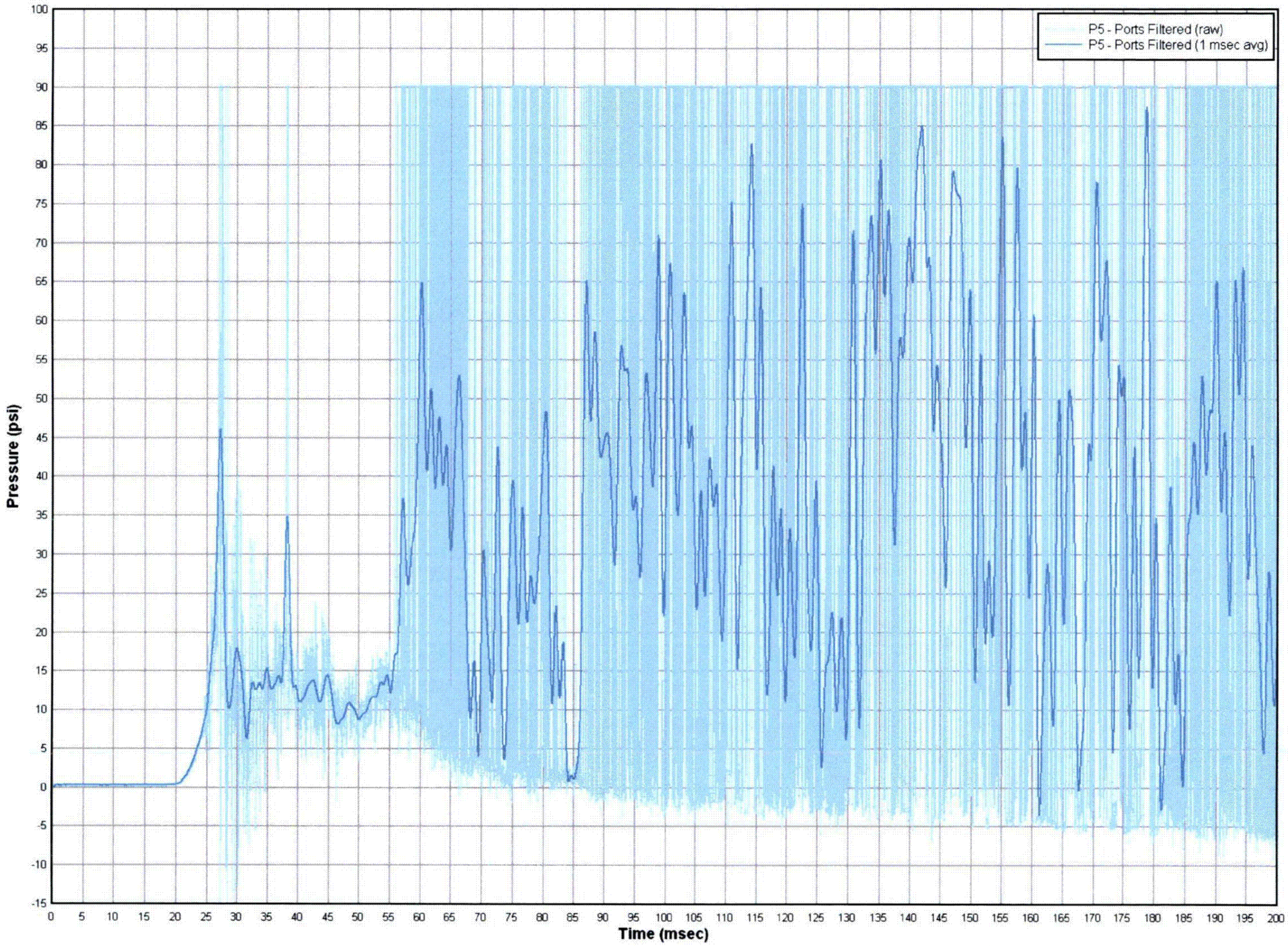


**Figure 2.1-17** – Deflagration Test #1, P5 (raw, 1-msec avg)

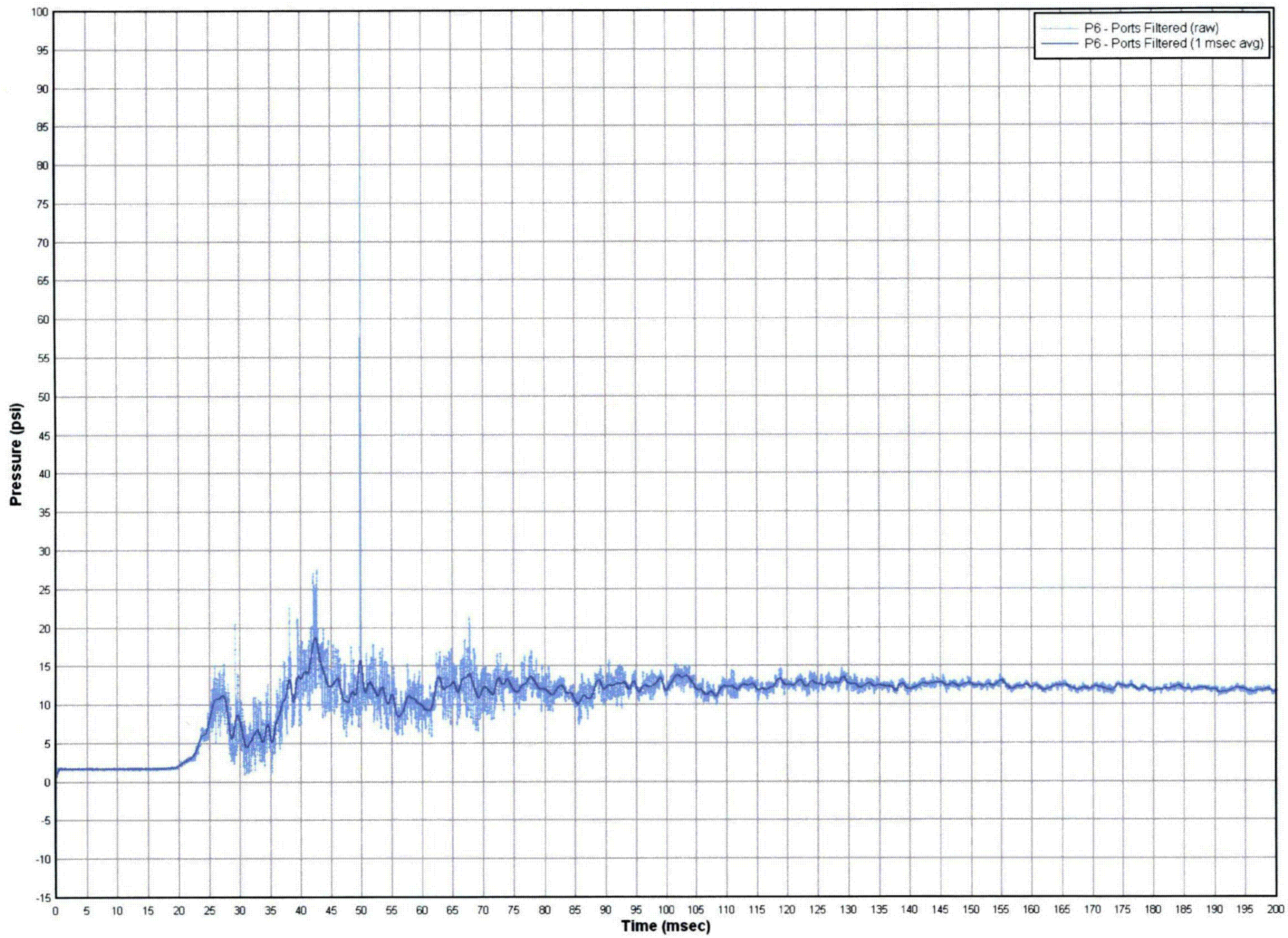


**Figure 2.1-18** – Deflagration Test #1, P6 (raw, 1-msec avg)

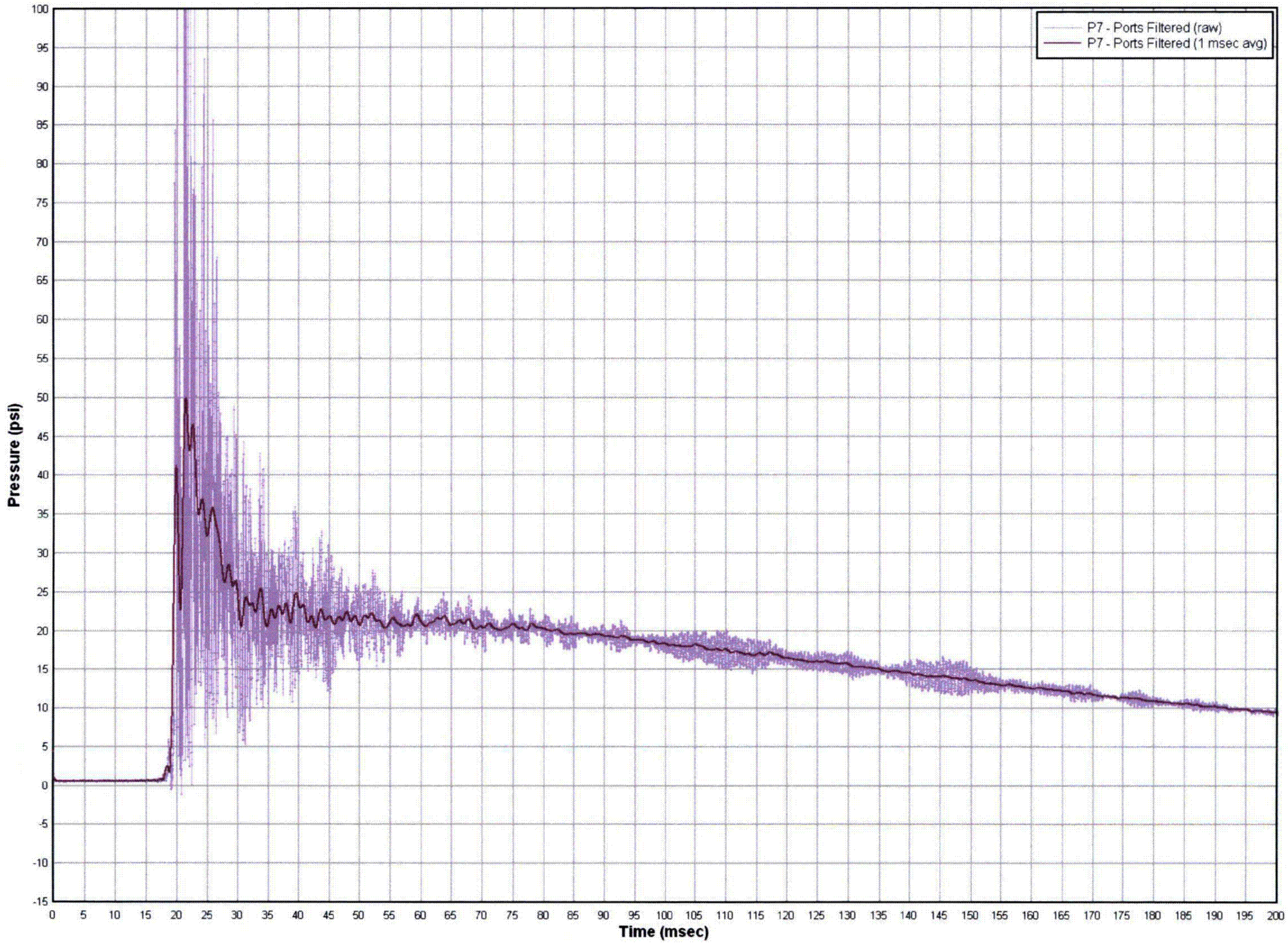


**Figure 2.1-19** – Deflagration Test #1, P7 (raw, 1-msec avg)

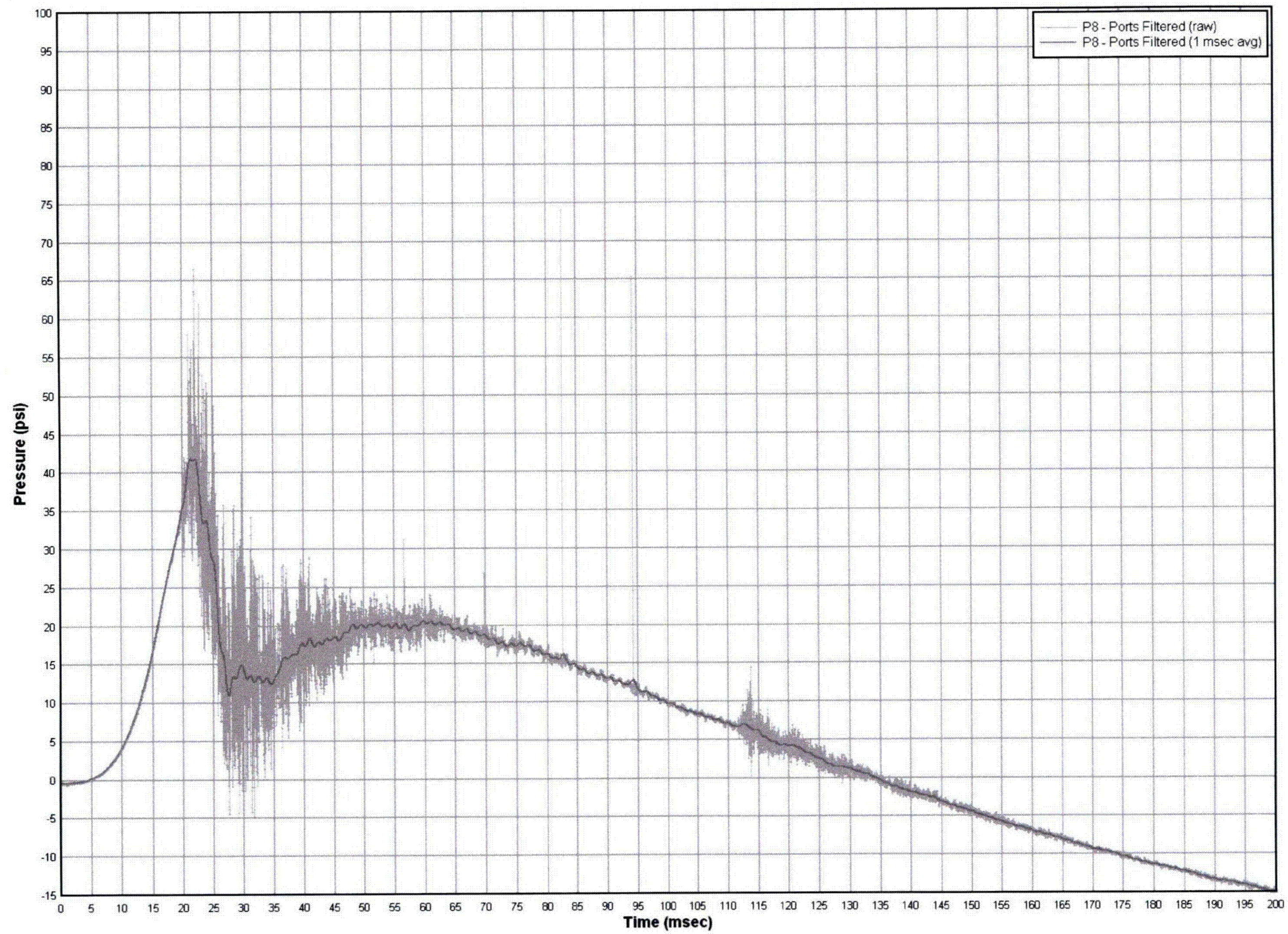


**Figure 2.1-20** – Deflagration Test #1, P8 (raw, 1-msec avg)

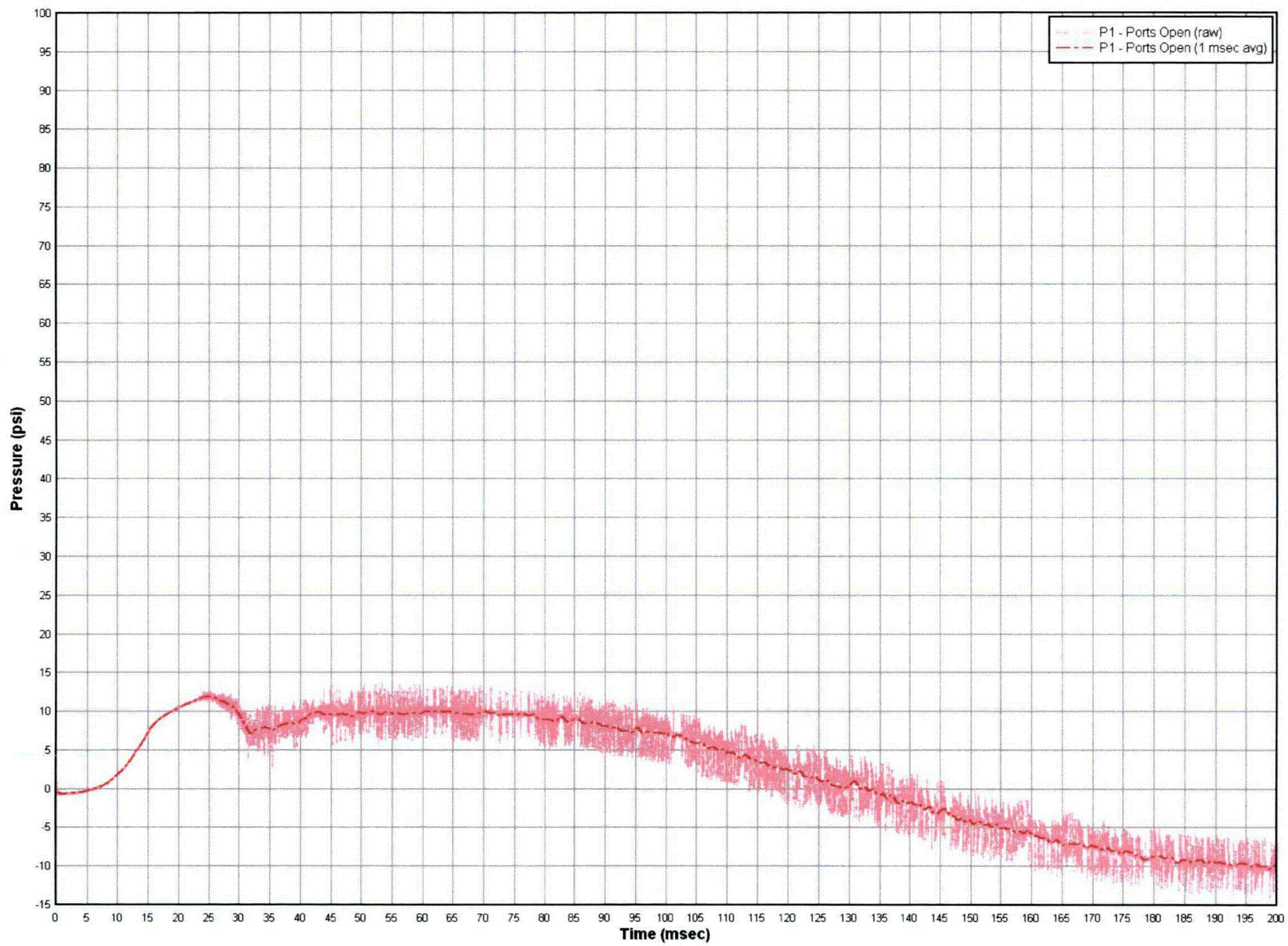


**Figure 2.1-21** – Deflagration Test #2, P1 (raw, 1-msec avg)

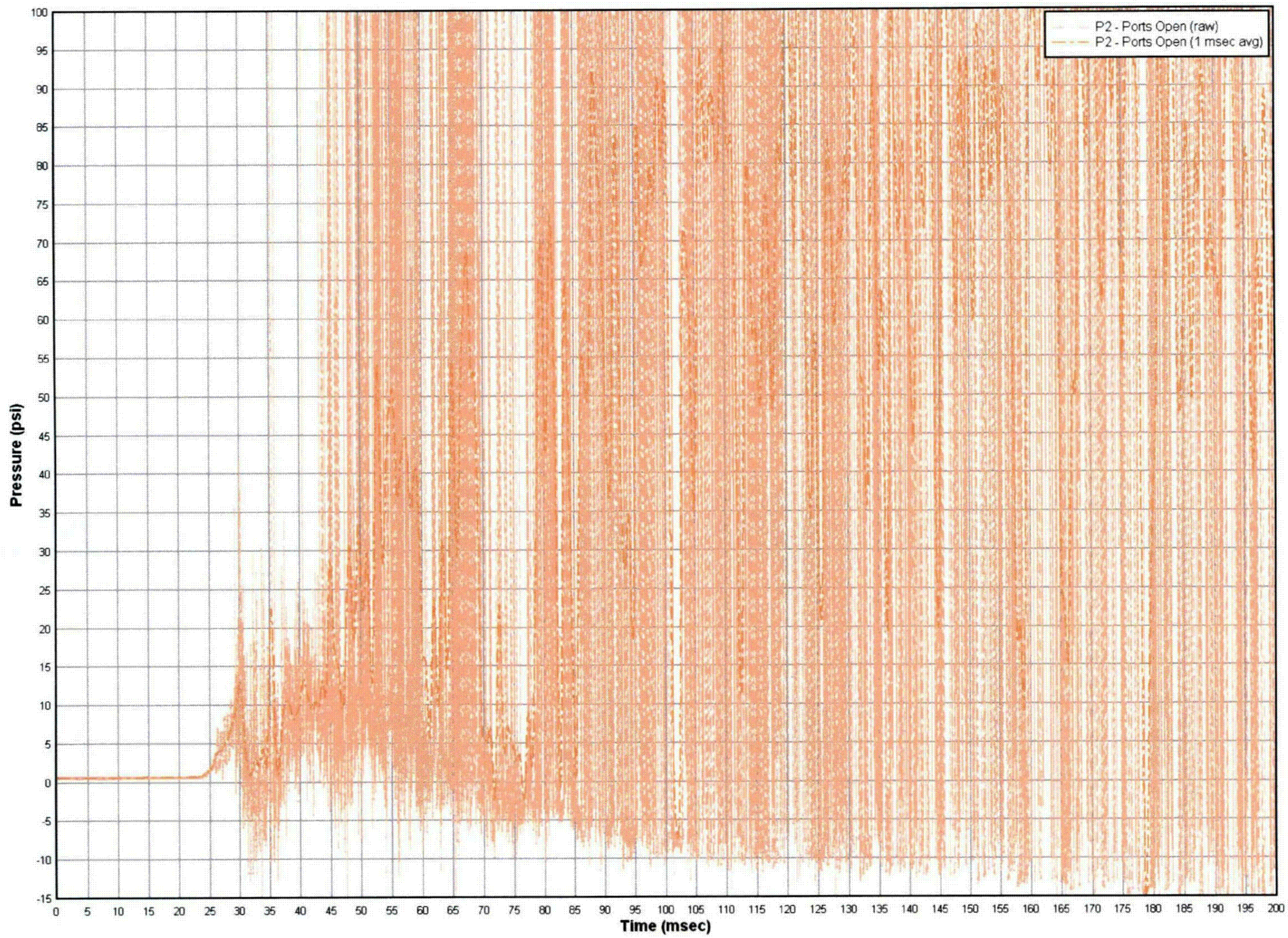


**Figure 2.1-22** – Deflagration Test #2, P2 (raw, 1-msec avg)

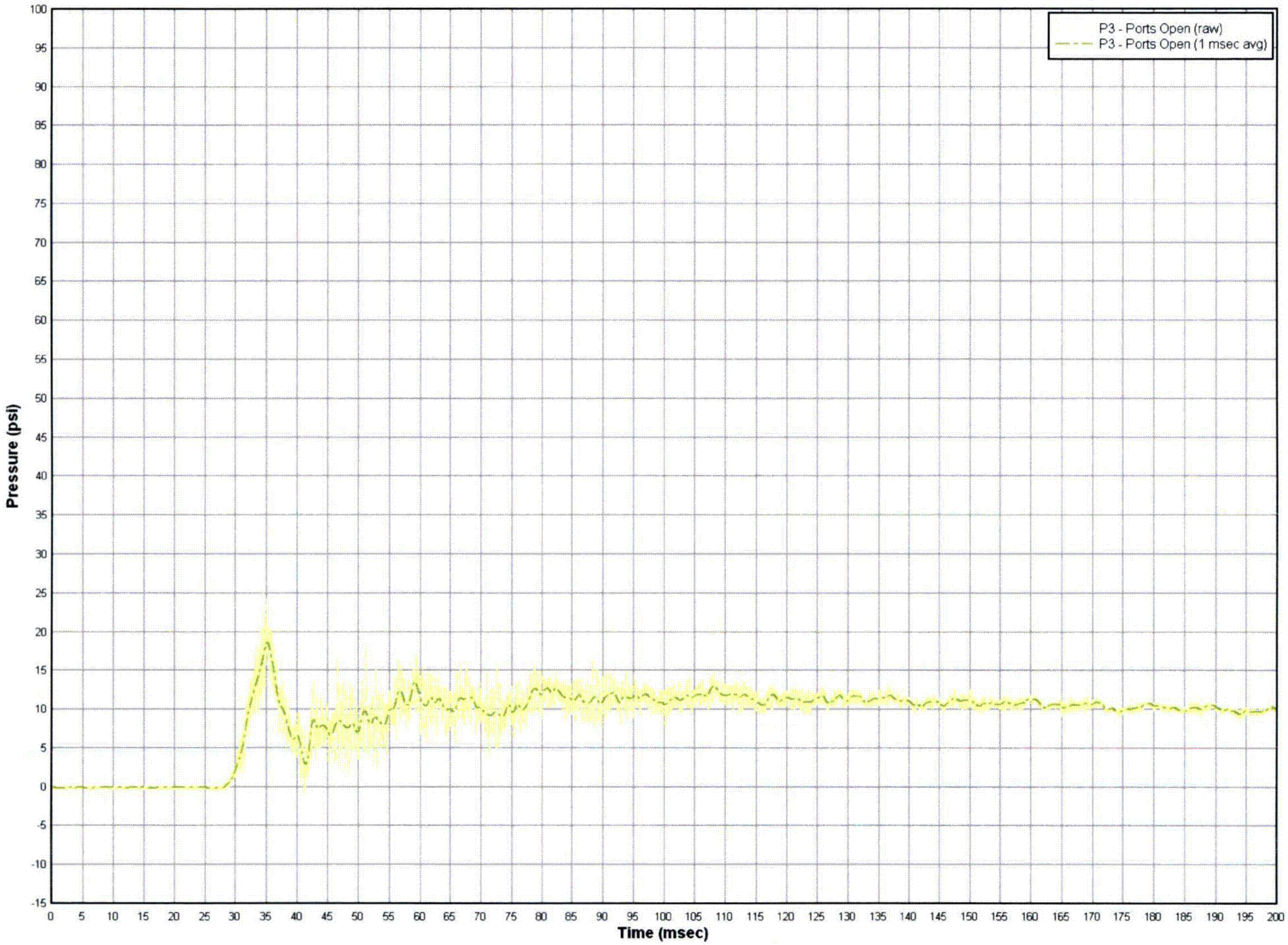


**Figure 2.1-23** – Deflagration Test #2, P3 (raw, 1-msec avg)

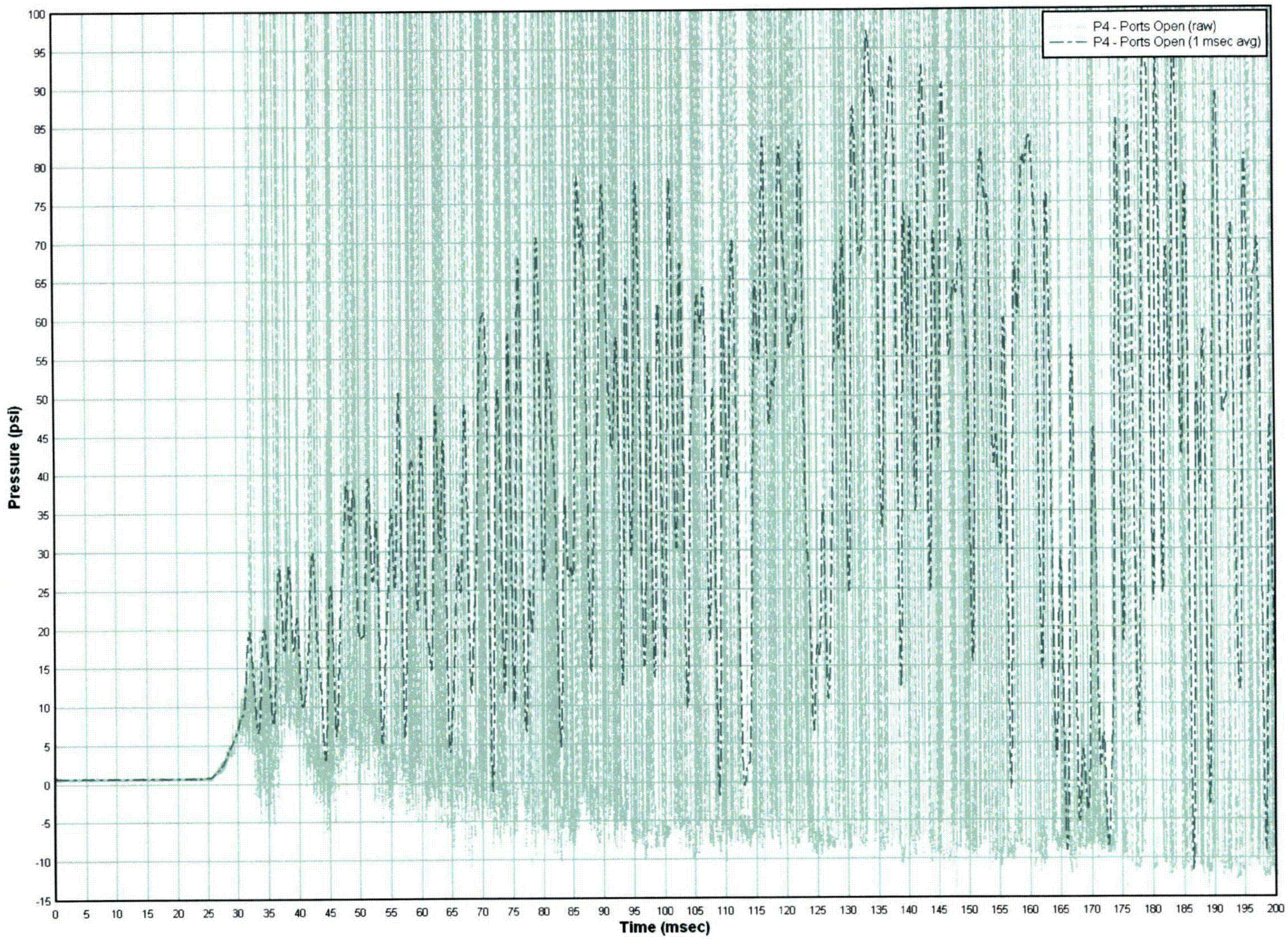


**Figure 2.1-24** – Deflagration Test #2, P4 (raw, 1-msec avg)

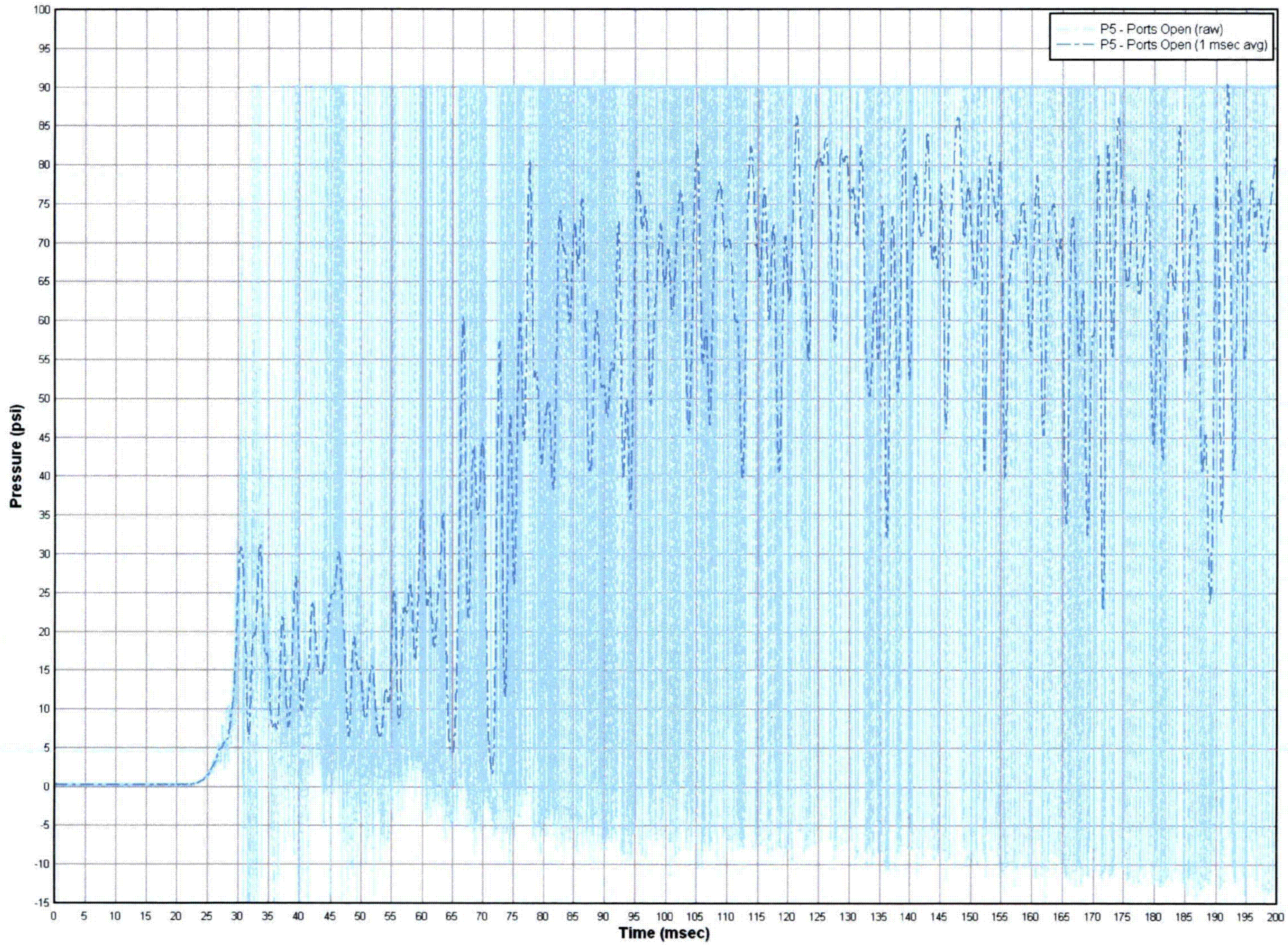


**Figure 2.1-25** – Deflagration Test #2, P5 (raw, 1-msec avg)

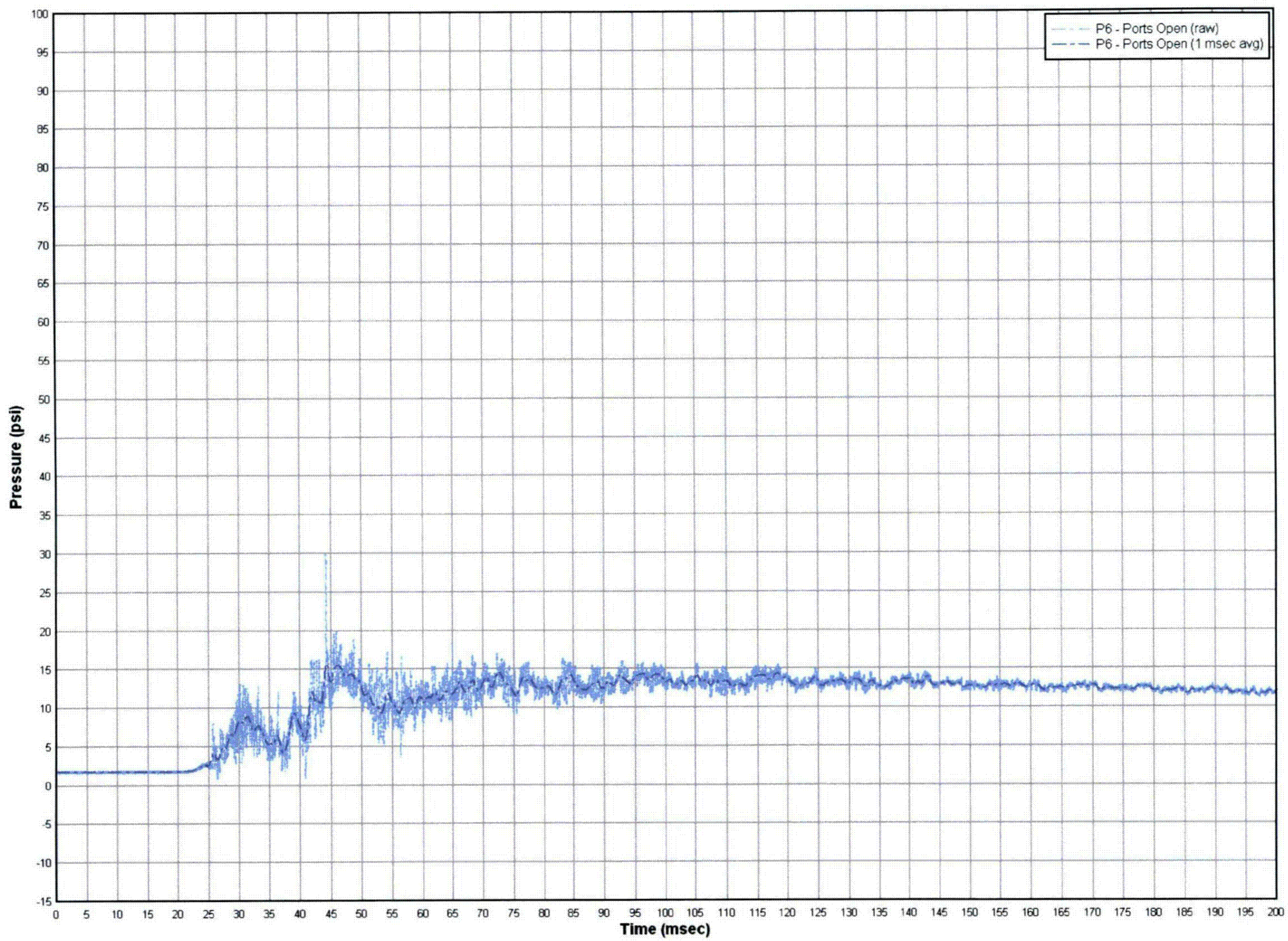


**Figure 2.1-26** – Deflagration Test #2, P6 (raw, 1-msec avg)

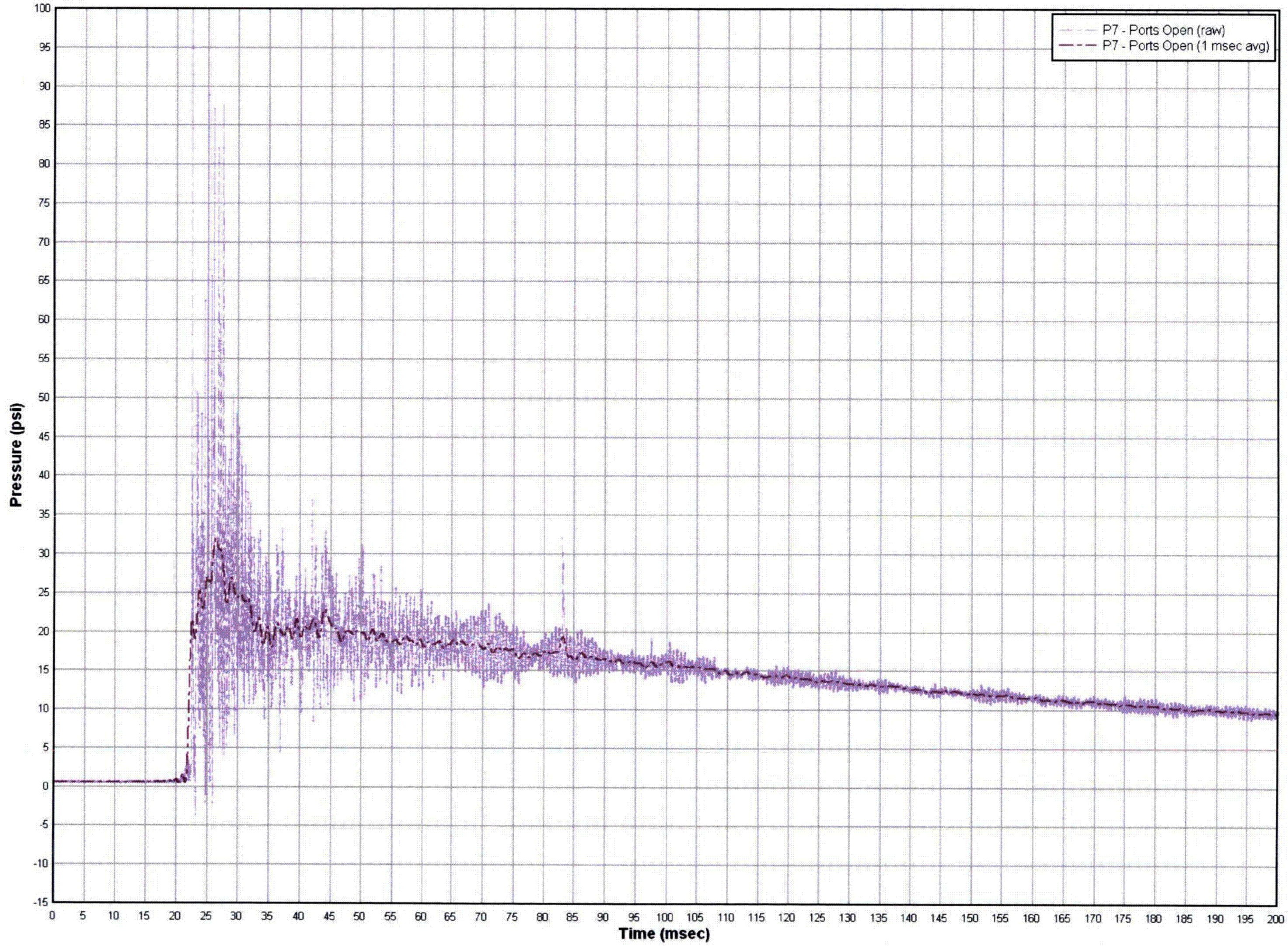


**Figure 2.1-27** – Deflagration Test #2, P7 (raw, 1-msec avg)

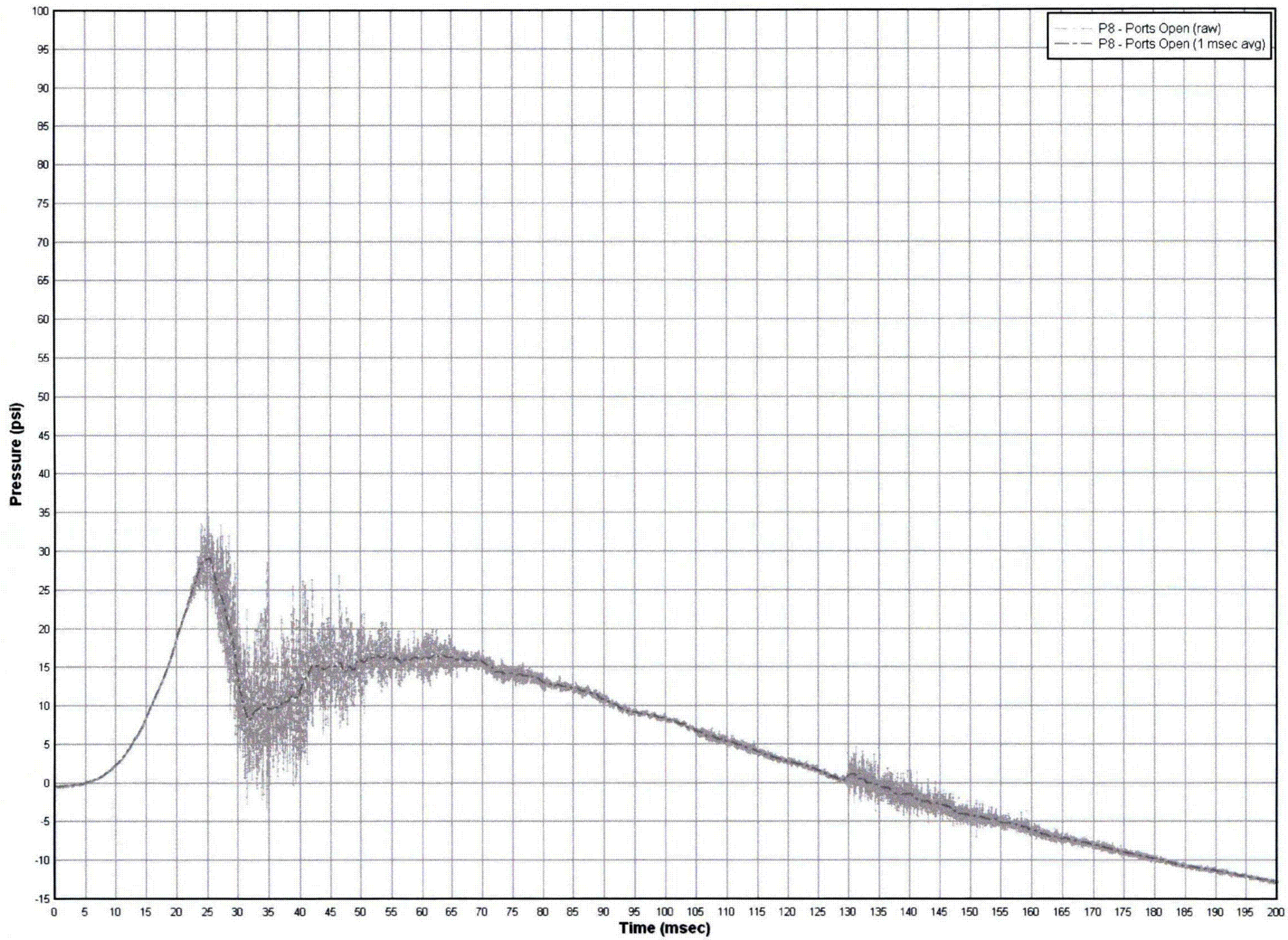


**Figure 2.1-28** – Deflagration Test #2, P8 (raw, 1-msec avg)

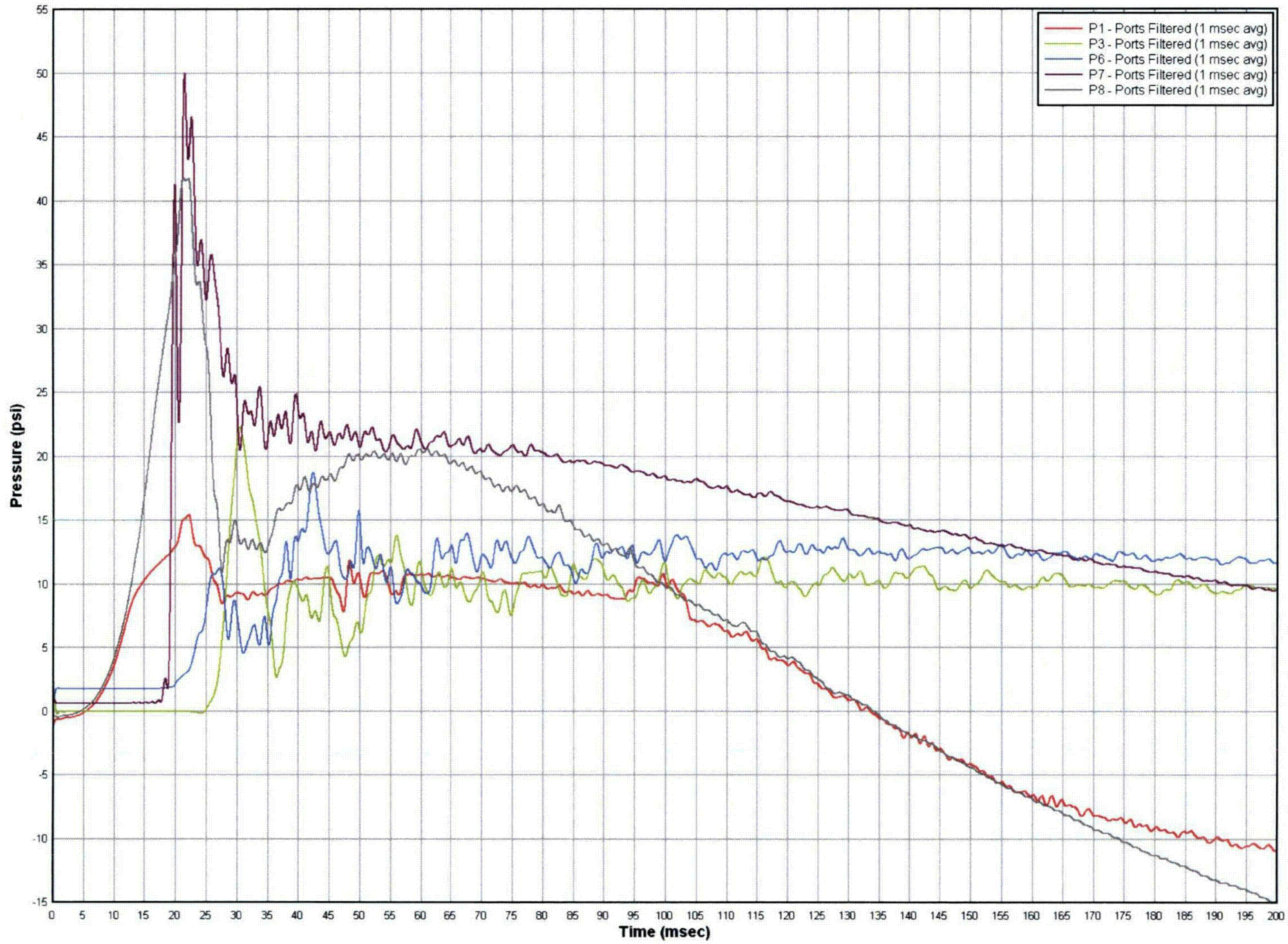


**Figure 2.1-29** – Deflagration Test #1: P1, P3, P6, P7, and P8 (1-msec avg)

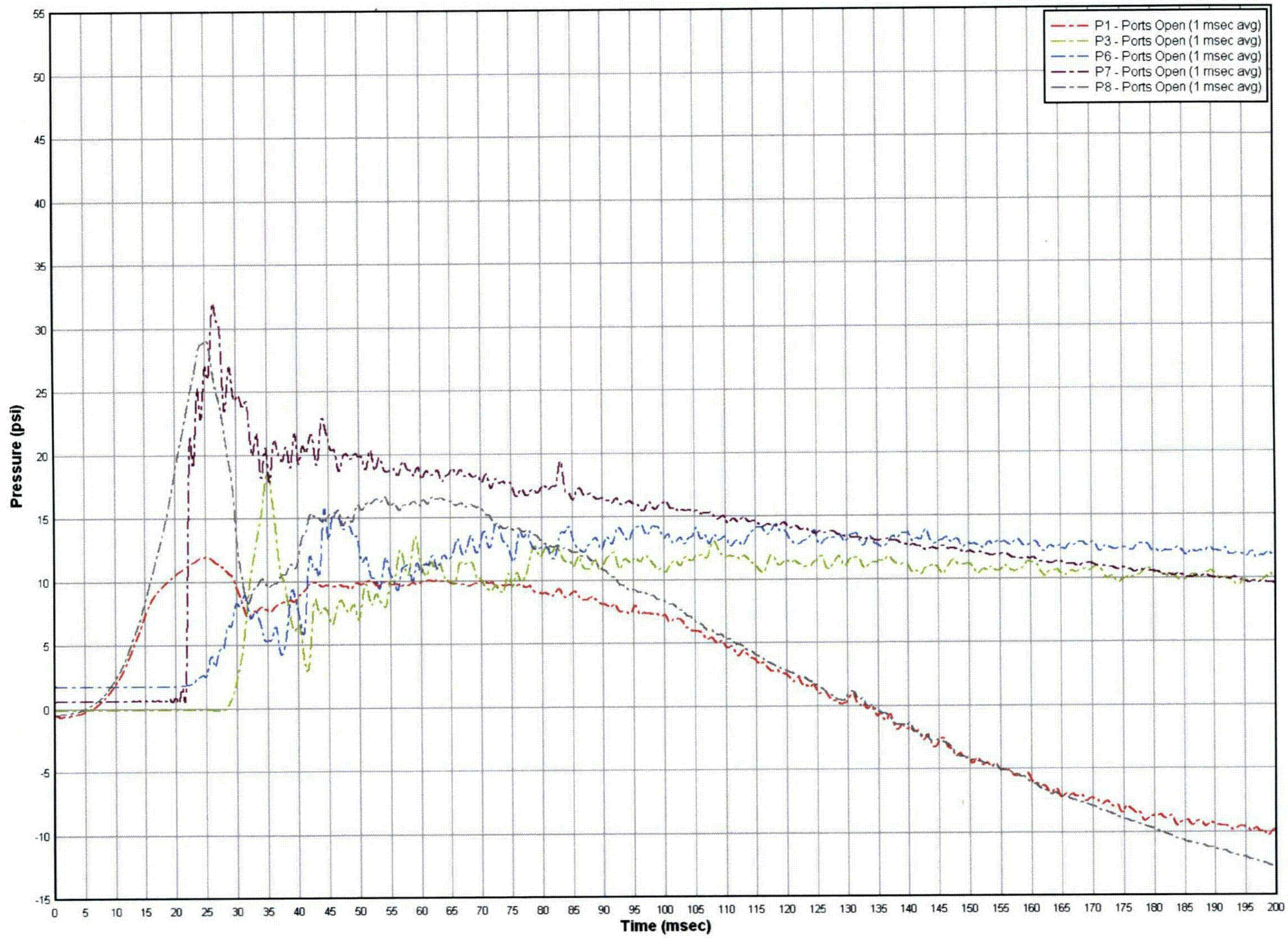


**Figure 2.1-30** – Deflagration Test #2: P1, P3, P6, P7, and P8 (1-msec avg)

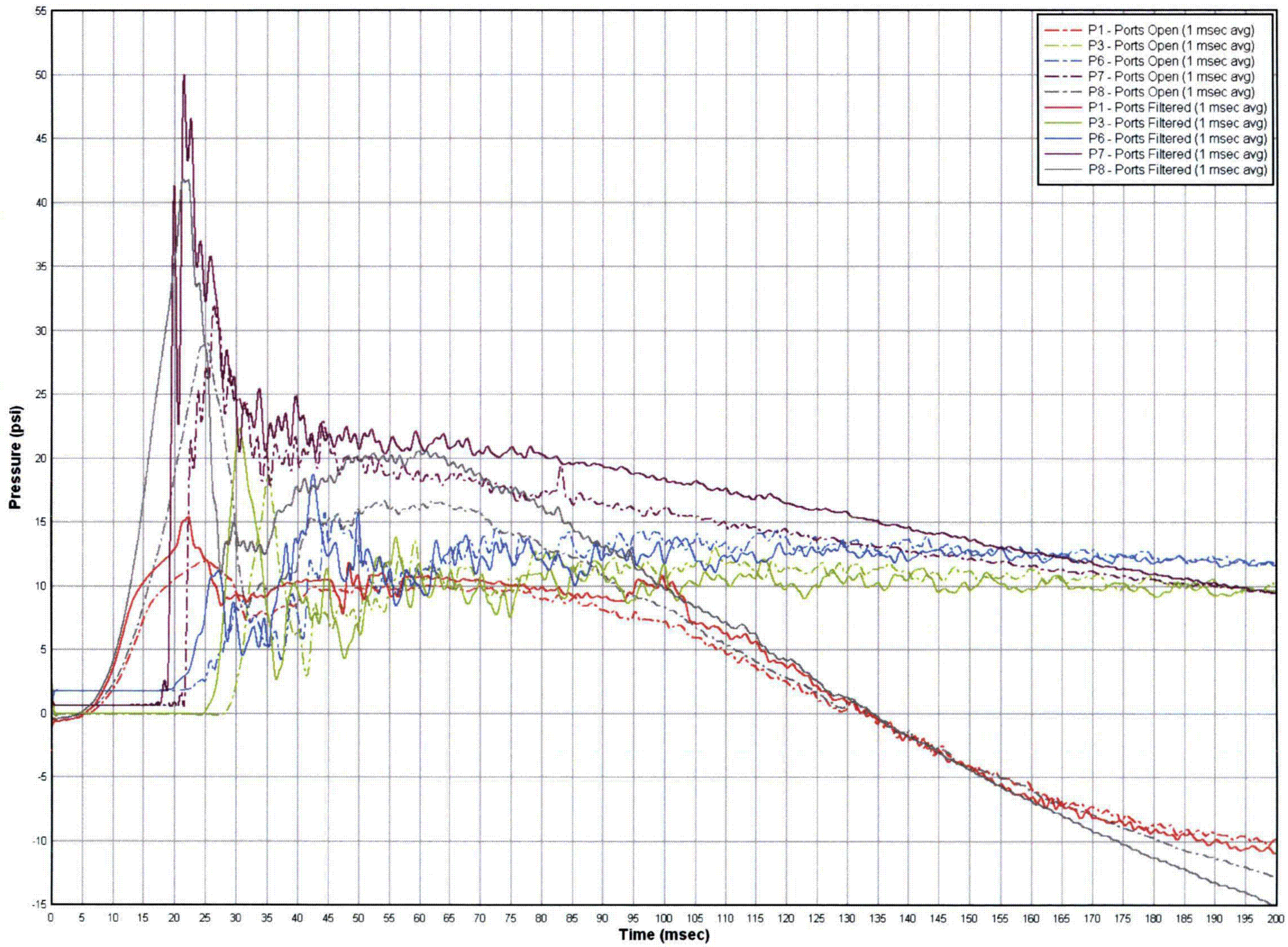


**Figure 2.1-31** – Deflagration Tests #1 and #2: P1, P3, P6, P7, and P8 (1-msec avg)

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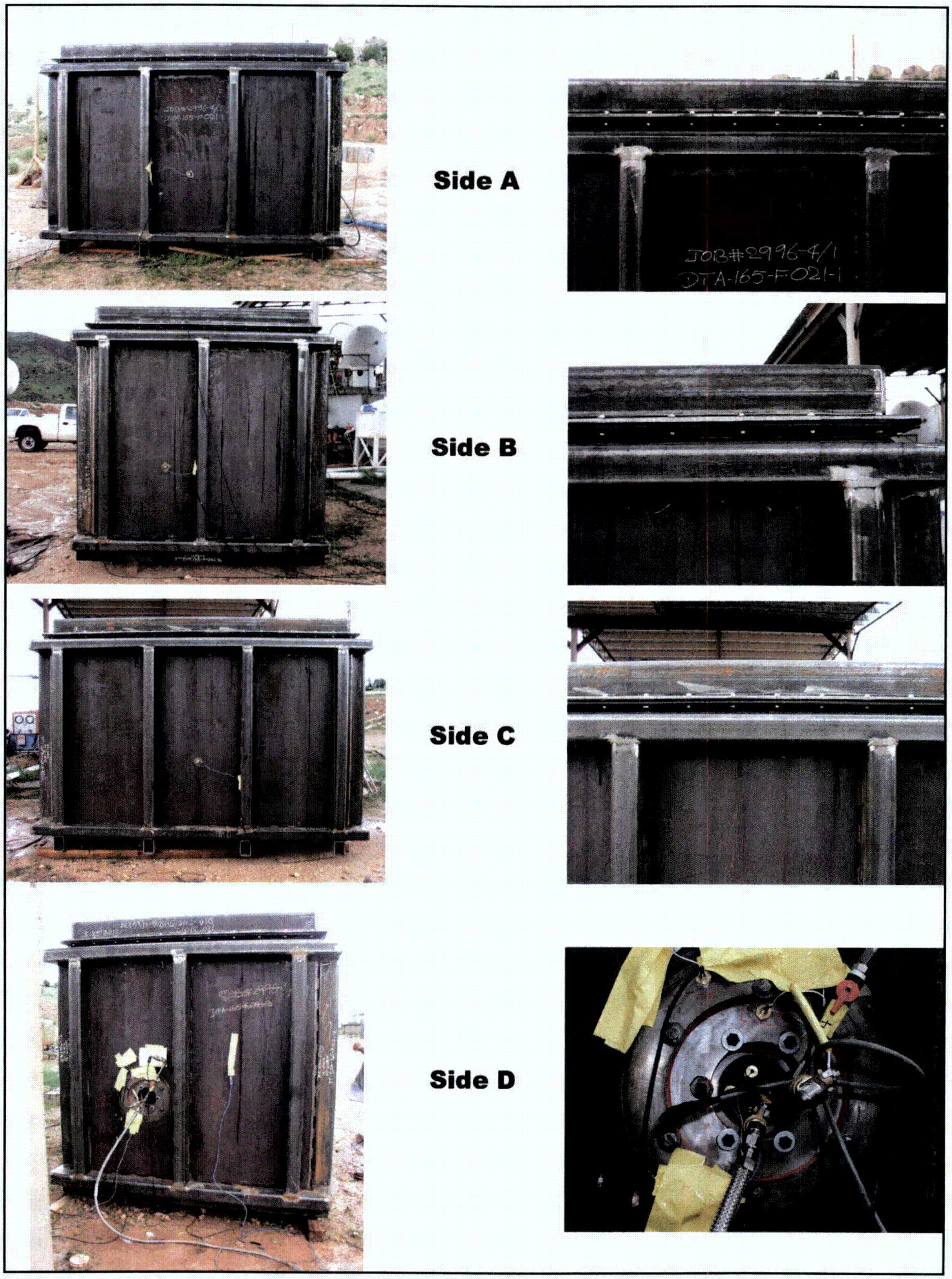



**Figure 2.1-32** – Deflagration Test #1: Post-Test Mock CV

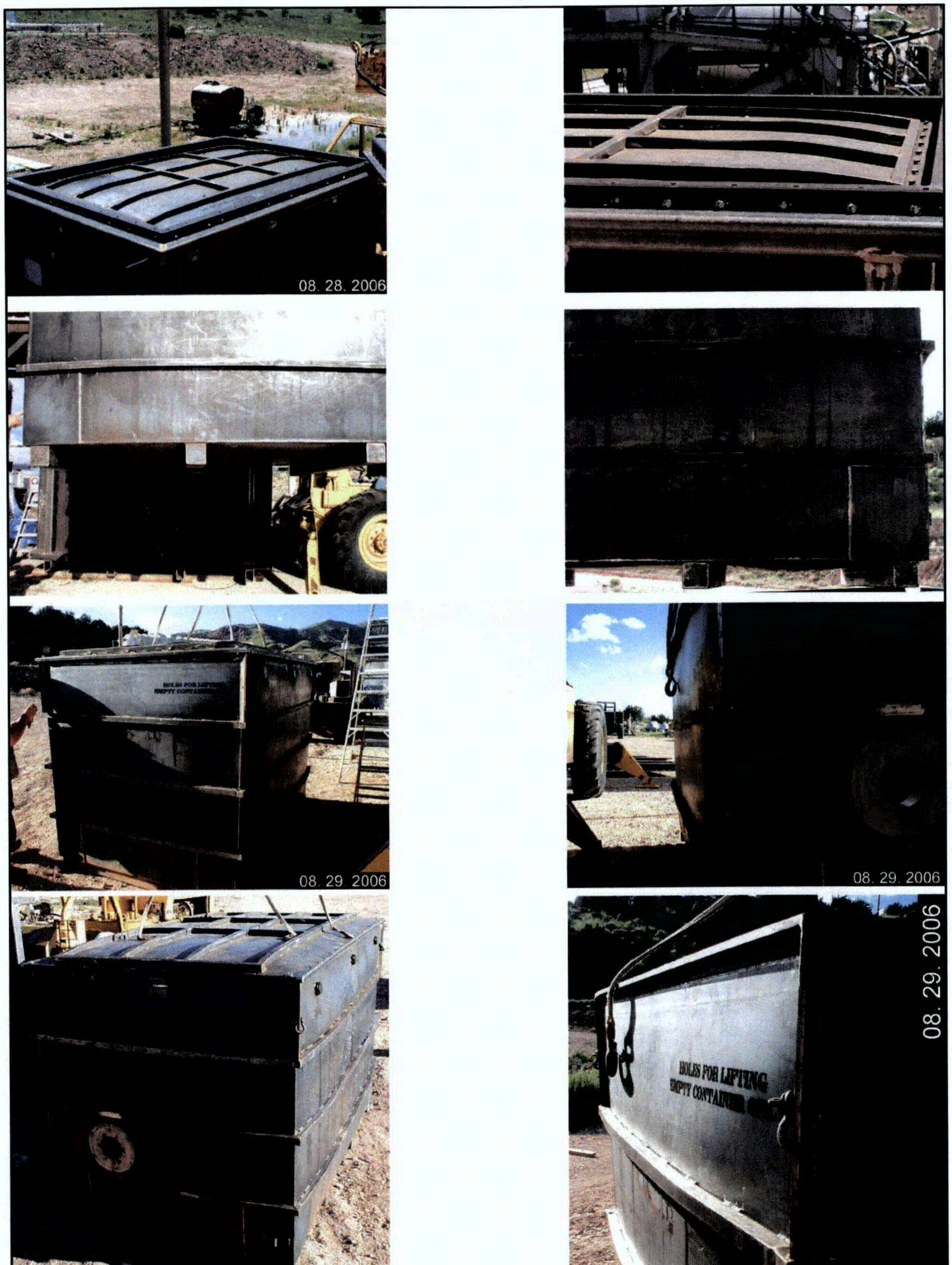



**Figure 2.1-33** – Deflagration Test #1: Post-Test SLB2

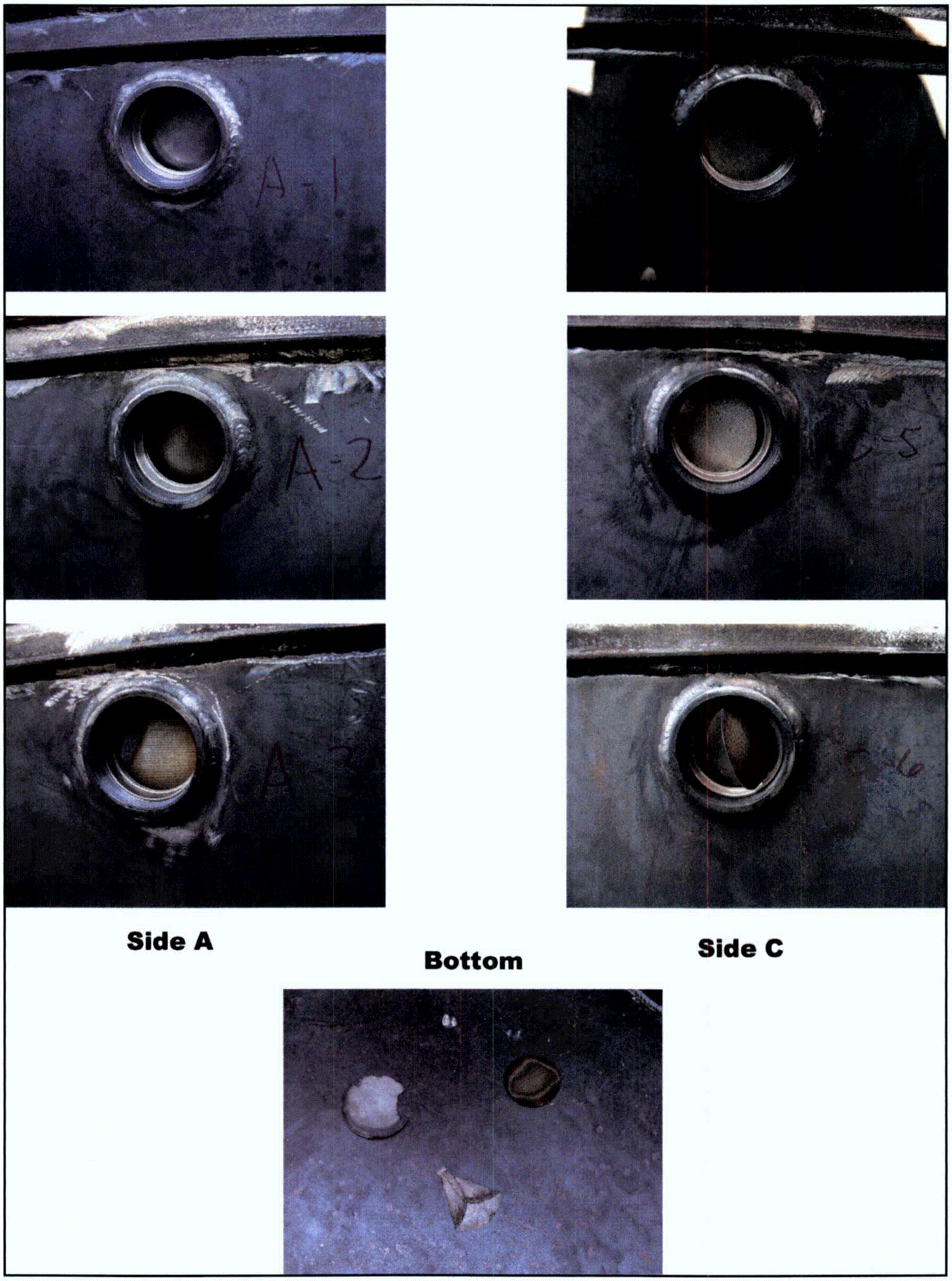



**Figure 2.1-34** – Deflagration Test #1: Post-Test SLB2 Filters

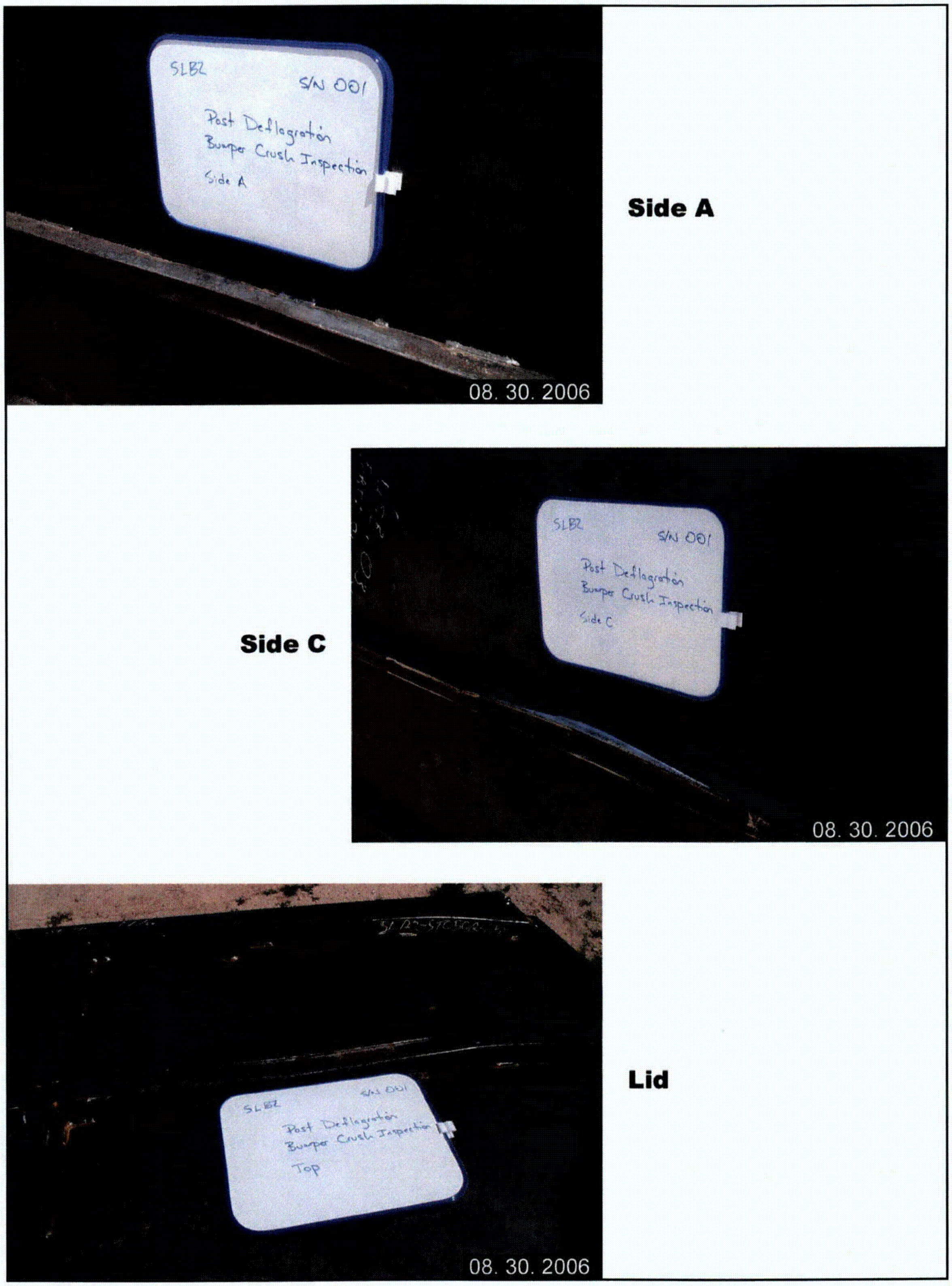



**Figure 2.1-35** – Deflagration Test #1: Post-Test SLB2 Bumpers

**Table 2.1-2** – Deflagration Test #1: SLB2 Bumper Crush Summary

| Location (distance from flange end, in.) | Crush Depth (in.) |
|---|---|
| Side A, Top Bumper, 34.5 | 0.04 |
| Side A, Top Bumper, 70.6 | 0.10 |
| Side A, Middle Bumper, 34.5 | 0.38 |
| Side A, Middle Bumper, 70.6 | 0.14 |
| Side A, Bottom Bumper, 34.5 | 0.18 |
| Side A, Bottom Bumper, 70.6 | 0.12 |
| Side C, Middle Bumper, 33.3 | 0.10 |
| Side C, Middle Bumper, 70.5 | 0.40 |
| Side C, Bottom Bumper, 70.3 | 0.15 |
| Lid, Middle A-side Bumper, 27.2 | 0.18 |
| Lid, Middle A-side Bumper, 55.5 | 0.08 |
| Lid, Middle A-side Bumper, 79.7 | 0.20 |
| Lid, Middle C-side Bumper, 27.1 | 0.18 |
| Lid, Middle C-side Bumper, 54.3 | 0.10 |
| Lid, Middle C-side Bumper, 80.5 | 0.30 |

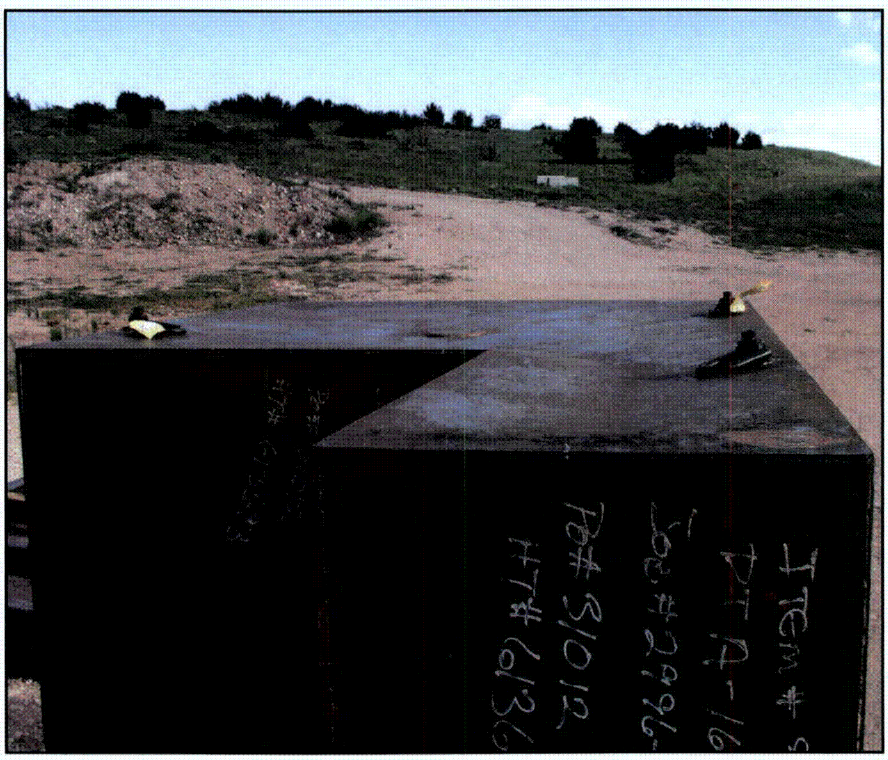



**Figure 2.1-36** – Deflagration Test #1: Post-Test SLB2 Dunnage


**Figure 2.1-37** – Deflagration Test #1: Post-Test SSC

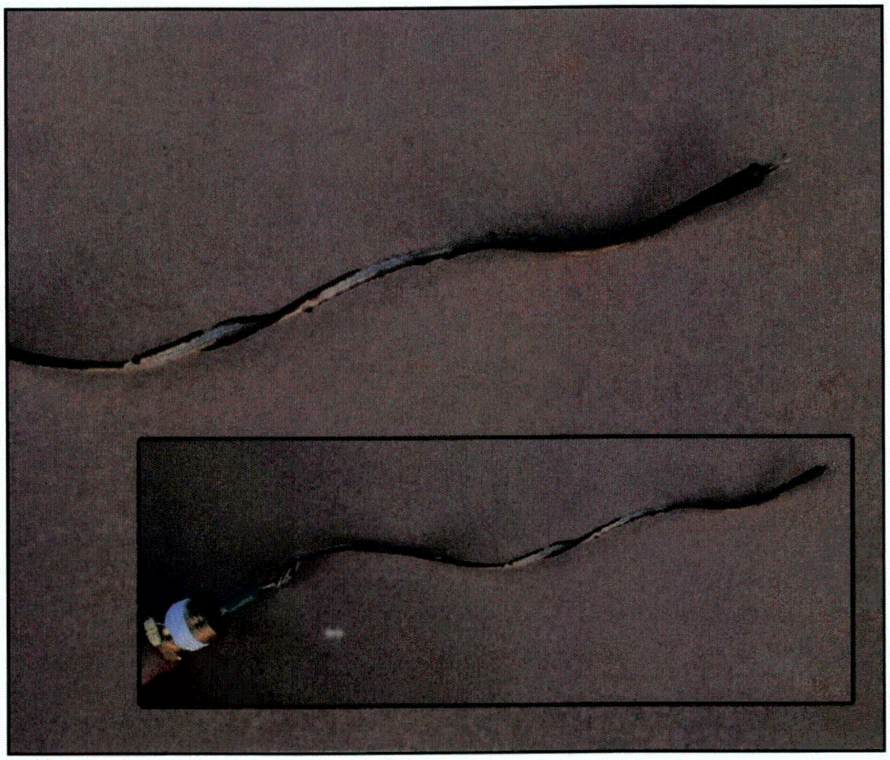


**Figure 2.1-38** – Deflagration Test #1: Post-Test Electric Match

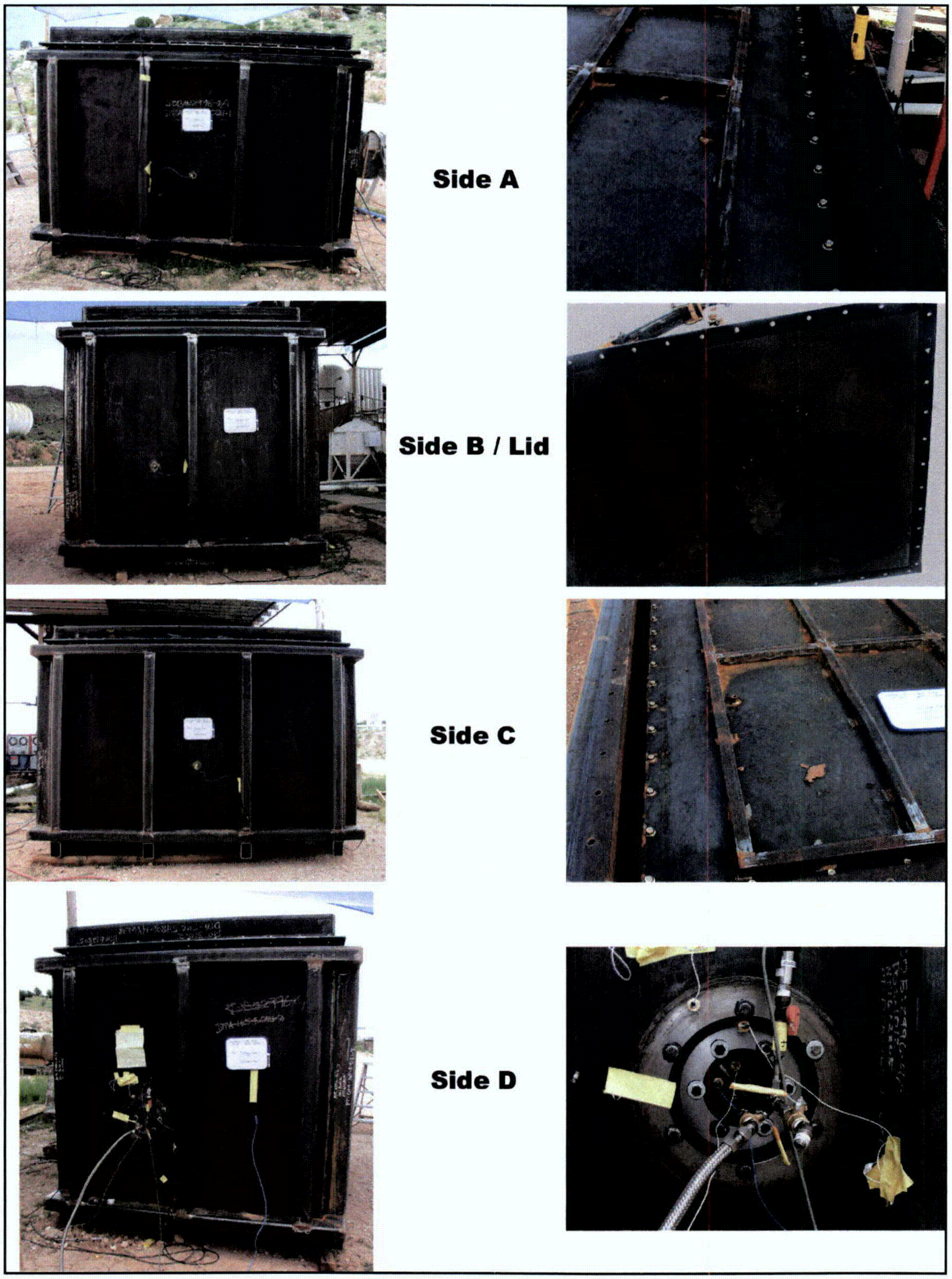



**Figure 2.1-39** – Deflagration Test #2: Post-Test Mock CV

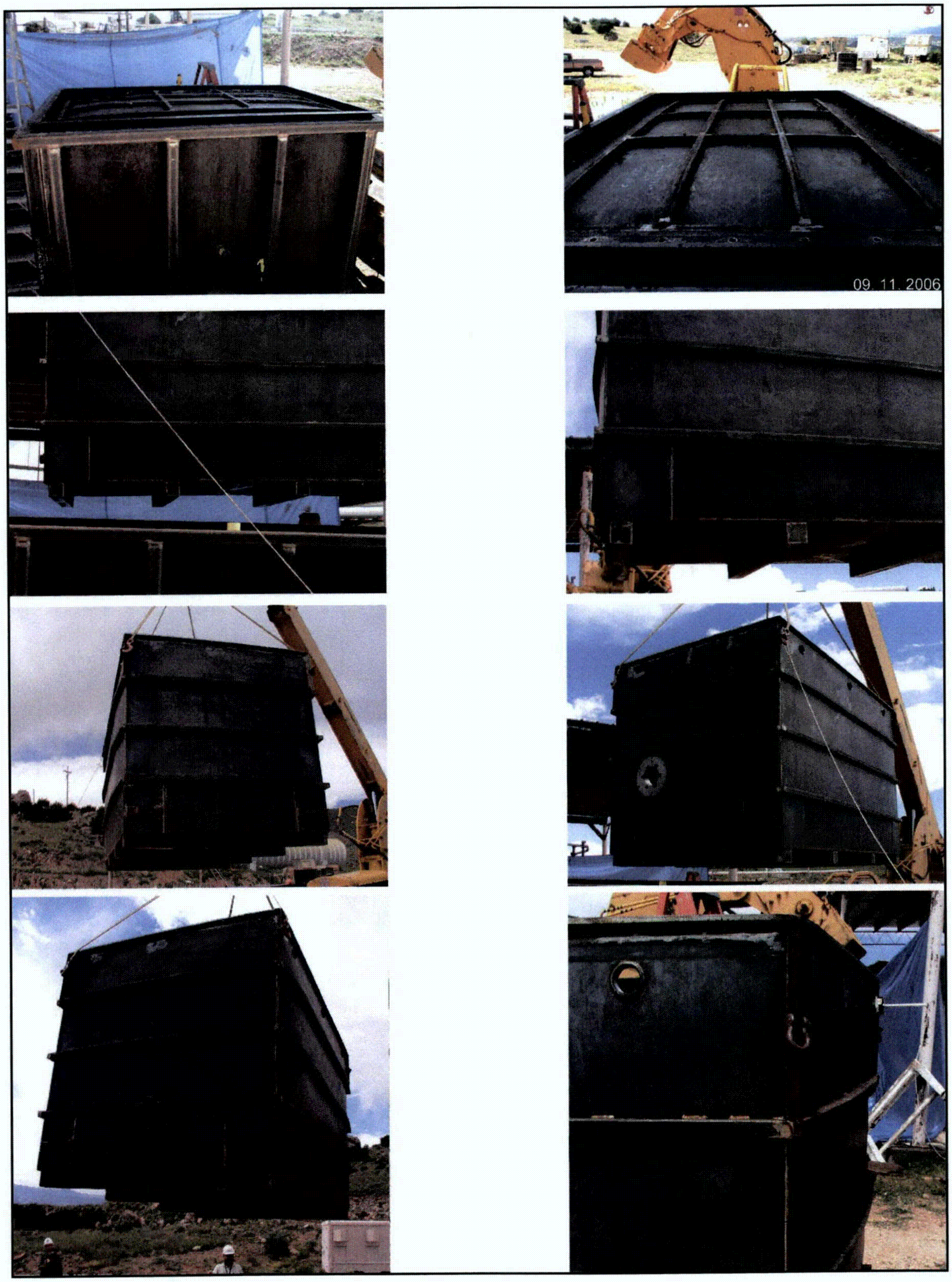



**Figure 2.1-40** – Deflagration Test #2: Post-Test SLB2

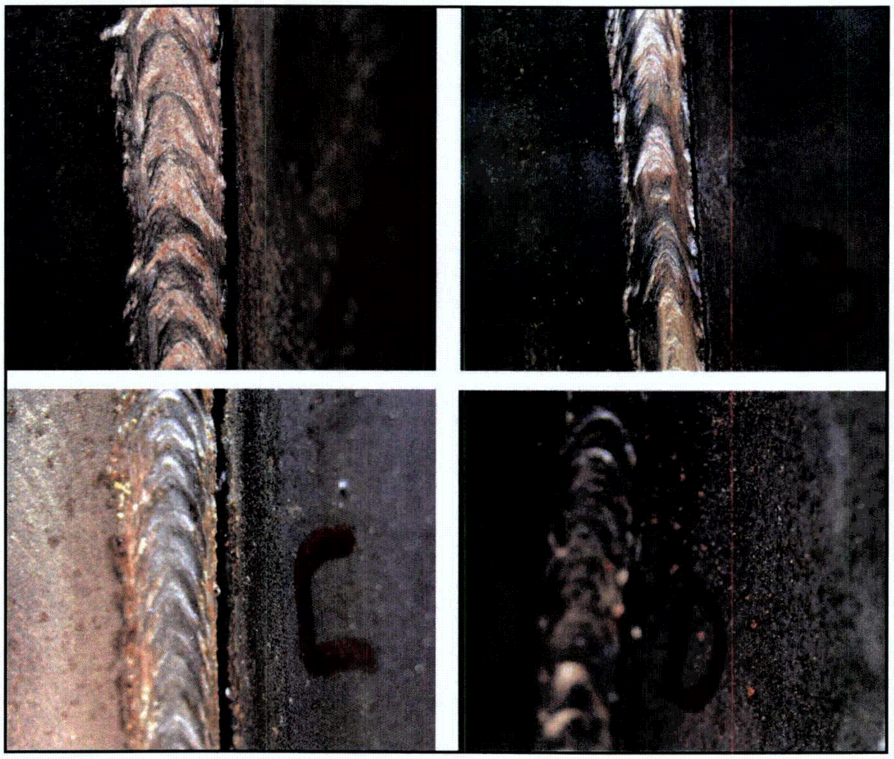
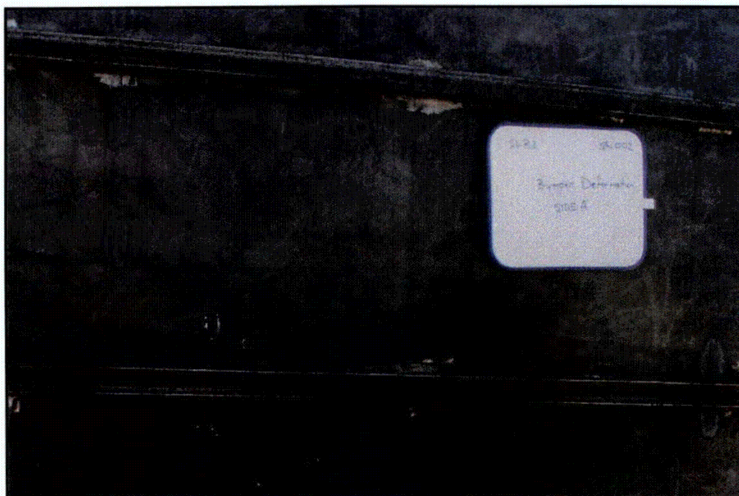


**Figure 2.1-41** – Deflagration Test #2: Post-Test SLB2 Welds

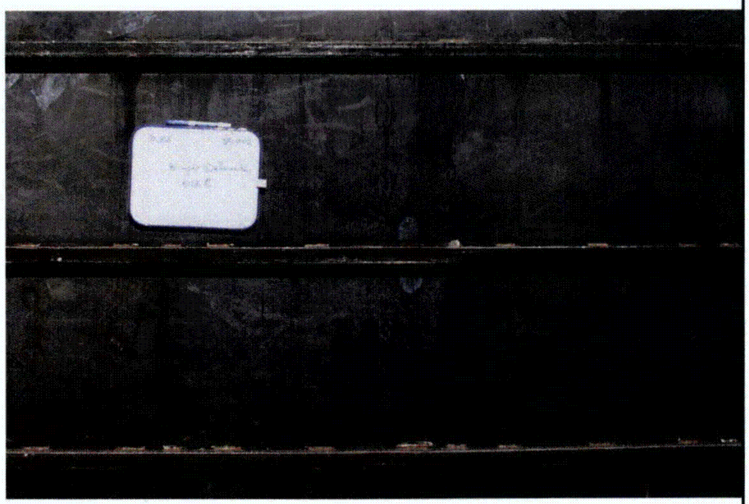
**Table 2.1-3** – Deflagration Test #2: SLB2 Bumper Crush Summary

| Location (distance from flange end, in.) | Crush Depth (in.) |
|---|---|
| Side A, Top Bumper, - | - |
| Side A, Top Bumper, 70.3 | 0.02 |
| Side A, Middle Bumper, 35.8 | 0.15 |
| Side A, Middle Bumper, 71.8 | 0.26 |
| Side A, Bottom Bumper, 36.3 | 0.10 |
| Side A, Bottom Bumper, 71.8 | 0.06 |
| Side C, Middle Bumper, 33.6 | 0.02 |
| Side C, Middle Bumper, 70.1 | 0.18 |
| Side C, Bottom Bumper, 70.1 | 0.08 |
| Lid, Middle A-side Bumper, 27.8 | 0.08 |
| Lid, Middle A-side Bumper, 53.5 | 0.04 |
| Lid, Middle A-side Bumper, 79.7 | 0.08 |
| Lid, Middle C-side Bumper, 27.8 | 0.04 |
| Lid, Middle C-side Bumper, 53.5 | 0.02 |
| Lid, Middle C-side Bumper, 80.5 | 0.12 |



**Side A**

**Side C**



**Lid**

**Figure 2.1-42** – Deflagration Test #2: Post-Test SLB2 Bumpers

**Figure 2.1-43** – Deflagration Test #2: Post-Test SLB2 Dunnage


**Figure 2.1-44** – Deflagration Test #2: Post-Test SSC

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## 2.1.3 Sealed Container Burst Pressure Testing

### 2.1.3.1 Introduction

Hydrostatic pressure tests were performed on an initial inventory of sealed containers to establish either the pressure at which the containers burst or the pressure that fails to increase further due to leakage from the container when subject to an input flow rate that is greater than or equal to 0.25% of the sealed container volume per minute. The testing was performed at the Washington Group International, Engineered Products Department in Carlsbad, New Mexico.[1,2] The test articles were selected from a sampling of common container types utilized in waste packaging/preparation activities. The list represents a subset of all types of potentially sealed containers. This section reviews the test procedure and results from testing of the initial inventory and further defines the application of the test methodology to evaluate and establish by test the burst/leakage pressure of other sealed containers that may be identified. As outlined in Section 2.1.1, *Adiabatic Constant Volume Deflagration Pressure Model*, the burst/leakage pressure of a sealed container is utilized as the bounding initial pressure that a sealed container could potentially achieve while containing a stoichiometric mixture of hydrogen and air.

### 2.1.3.2 Inventory of Sealed Containers

The initial tested inventory of sealed containers are common types of waste handling containers utilized by waste generating sites. They ranged in size from 1-gal to 85-gal, in construction material from plastic to steel, and in lid closure types from small diameter screw-top lids to full container diameter friction-fit lids and lids with bolted closure rings. The initial inventory of eight (8) sealed containers subjected to the hydrostatic burst testing are summarized in Table 2.1-4.

Additional sealed containers >4 liters can be inventoried and qualified by utilizing the test procedure outlined in Section 2.1.3.4, *Test Procedure*, to document the container type, volume capacity, materials of construction, and closure mechanism in addition to establishing its burst/leakage pressure.

### 2.1.3.3 Technical Basis for Tests

The primary objective of the sealed container burst pressure testing was to establish and associate each sealed container with a bounding pressure that could be achieved as an initial condition for a postulated stoichiometric hydrogen/air deflagration inside of the sealed container. Sealed containers in TRU waste typically exhibit a lack of ability to contain gas under pressure due to seal degradation from age, irradiation, and/or corrosion related leakage from the sealed container. However, the hydrostatic tests were designed to establish a bounding pressure capacity for each of the sealed containers in a new and pristine condition.

The bounding upper limit on the pressure at which a stoichiometric hydrogen/air deflagration could initiate is either the maximum pressure associated with burst (gross structural failure) of

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[1] Packaging Technology, Inc., August 2006, *Hydrostatic Test Procedure – Sealed Containers*, TP-047, Revision 0, Packaging Technology, Inc., Tacoma, Washington.

[2] Packaging Technology, Inc., November 2006, *Hydrostatic Test Report – Sealed Containers*, TR-021, Revision 0, Packaging Technology, Inc., Tacoma, Washington.

the container or a pressure that is limited by equilibrium between the internal gas generation rate and external leakage rate from the container. The minimum flow rate utilized in the hydrostatic testing was selected to ensure that the test conditions for input flow rate exceeded the potential gas generation rate in the sealed container.

Total radiolytic net gas generation is a function of the waste material type (G value) and decay heat. Summarizing from Section 5.3, *Compliance with Design Pressure and Total Gas Generation Limits*, of the TRUPACT-III TRAMPAC, the total radiolytic gas generation rate is given by the following equation: [3]

$$n_{gas\_total} = G \times W \times \left(1.04E{-}7 \frac{(g * mole)(100\,eV)}{(molecule)(watt * sec)}\right)$$

Using a bounding total net gas generation G value of 8.4 molecules/100 eV and a TRUPACT-III limit of 80 watts, the total net gas generation rate, $n_{gas\_total}$, in the payload is as follows:[4]

$$n_{gas\_total} = 8.4 \times 80 \times 1.04E{-}7 = 6.99E{-}5 \frac{moles}{sec}$$

This estimate conservatively neglects depletion of the G value to much lower values at high decay heat values (see Appendix 7.1.6, *Determination of Bounding Dose-Dependent Net Gas G Value for TRUPACT-III Payload*) of the TRUPACT-III TRAMPAC).[3]

Converting to standard conditions (using 22.4 liters/mole), the total net gas generation rate for the payload, $R_{gas\_total}$, is given as:

$$R_{gas\_total} = n_{gas\_total} \times \left(22.4 \frac{liters}{mole}\right)\left(\frac{1000\,ml}{liter}\right)\left(\frac{60\,sec}{min}\right) = 94 \frac{ml}{min}$$

In Section 3.1.1.2, *Payload Configuration*, of the TRUPACT-III SAR, it is assumed that all 80 watts could be consolidated into a volume of 425 gal (3'-2" x 3'-2" x 5'-8" box).[4] Utilizing that assumption, the wattage inside a sealed container less than 425 gal can proportionally be established as a function of its volume such that the bounding total net gas generation rate inside a sealed container, $R_{gas\_sc}$, is as follows:

$$R_{gas\_sc} = \left(\frac{V_{sc}\,(gal)}{425\,gal}\right) \times R_{gas\_total}$$

Table 2.1-5 establishes the minimum input flow rate (as a function of container size) for each hydrostatic test where the minimum input flow rate is set equal to the maximum gas generation rate potential for sealed containers calculated from the above equation. This minimum input flow rate ensures that leakage-based pressures are conservatively established in accordance with a bounding gas generation rate (i.e., the pressure fails to continue to increase due to a leakage that is consistent with the gas generation potential inside the sealed container). All sealed

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[3] U.S. Department of Energy (DOE), *TRUPACT-III Authorized Methods for Payload Control (TRUPACT-III TRAMPAC)*, current revision, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

[4] Packaging Technology, Inc., *Safety Analysis Report for the TRUPACT-III Shipping Package*, current revision, USNRC Docket No. 71-9305, Packaging Technology, Inc., Tacoma, Washington.

containers were tested at an input flow rate far exceeding the minimum input flow rate, which is conservative due to the following:

- Containers that are prone to fail due to viscoelastic creep (i.e., plastic) will do so at a higher pressure due to the test duration decreasing as the input flow rate increases.
- Containers that are prone to fail due to leakage (rather than burst) will do so at a proportionally higher pressure as the input flow rate increases.
- Containers that are prone to fail due to gross structural failure will do so at a higher pressures due to higher strain-rates and stress-stiffening as the flow rate increases.

### 2.1.3.4 Test Procedure

The test articles were received, inventoried, and pre-test dimensional measurements (body diameter, overall height, nominal wall thickness) for each of the eight (8) sealed container types were obtained. Each of the test articles was modified by the addition of a bulkhead fitting in either the body sidewall or the bottom of the container for use as a pressurization port.

Just prior to testing, each of the test articles was filled with potable water and a digital temperature indicating device was utilized to record the water temperature. The lid was secured per the manufacturer's instructions. The test articles were then moved to the test area, located in front of a ½-in. or 1-in. spaced grid, placed upon dunnage as a stand-off for clearance of the bulkhead fitting (where applicable), and connected via tubing to the test apparatus. For convenience with the smaller (≤5 gal) containers, the lids were installed in the test area after the connection to the test apparatus was made.

The test apparatus consisted of a graduated cylinder (sight glass) with a total volume of 4,000 ml used as a reservoir for the supply water (refilled during the test as necessary), an air-operated diaphragm pump, a needle flow-control valve, a pressure transducer and digital readout, and tubing and fittings required to connect the components. For reference purposes, an electronic flow-meter was used to assist in setting the target flow rate of water into the test article, but the sight glass reservoir and elapsed time was the method utilized to measure the average input flow rate. Photographs of the test apparatus are provided in Figure 2.1-45.

Depending upon the point at which the lids were installed, the pressure transducer was set to zero psig gauge pressure (tared). For the smaller containers, the pressure transducer was tared after the connection of the bulkhead fitting to the test apparatus and just prior to lid installation. This was done so as to properly zero out any pressure head due to the location of the test article at an elevation above the pressure transducer and to properly capture pressure created inside the container as a result of the lid installation process. For larger containers, the pressure transducer was tared after lid installation and connection of the bulkhead fitting to the test apparatus and also after a relief valve was opened temporarily to relieve any internal pressurization due to lid installation.

Once each test article was connected to the test apparatus, video documentation of the procedure was initiated upon opening of the flow-control valve and fluid flow into the test article. The desired flow rate was achieved through control of the needle valve. The pressure readout was located in the video frame with the test article and was monitored over the duration of the test to observe distortion and leakage and to ultimately discern the point at which the container either burst or failed to continue to build pressure due to excessive leakage.

Upon completion of the test, each of the test articles was removed from the test apparatus, drained, photographed, and dimensionally inspected to determine the post-test deformation and confirm the mechanism of failure/leakage.

#### 2.1.3.5 Test Results

A total of five test articles for each sealed container type were subjected to the tests, with the maximum burst/leakage pressure measured for the five test articles used to establish the burst pressure for each sealed container type. The test articles reached their burst pressure limit due to the following mechanisms:

- Deformation with structural side-wall thinning and through-wall or body seam failure of plastic containers with screw-top lids/caps (TA-1 and TA-3 shown in Figure 2.1-46 and Figure 2.1-48)
- Ejection (i.e., pop-off) of the of the friction-fit lids on steel containers (TA-2 shown in Figure 2.1-47) and pop-off of the snap-fit lids on plastic containers (TA-5 shown in Figure 2.1-50)
- Deformation with lid distortion/distension and leakage at the lid to body gasket interface on steel buckets and drums (TA-4, TA-6, TA-7, and TA-8 shown in Figure 2.1-49, Figure 2.1-51, Figure 2.1-52, and Figure 2.1-53).

Table 2.1-6 summarizes the failure mode, flow rates, and burst pressure for each container type. The minimum tested flow rates were conservatively 50 times greater than that defined as a minimum requirement from Section 2.1.3.3, *Technical Basis for Tests.*

In summary, the hydrostatic burst tests establish a conservative maximum pressure that each sealed container could withstand due to internal gas generation. That pressure represents a bounding initial pressure that could be achieved prior to the initiation of a deflagration event inside of the sealed container. The maximum burst pressure for each of the sealed container types given in Table 2.1-6 is available for use in conjunction with Table 2.1-1 for determination of the percent contribution to MNOP resulting from a sealed container deflagration.

**Table 2.1-4** – Initial Inventory of Sealed Containers

| Test Article Number | Qty. Tested | Description | Construction Material | Approximate Size (in.) | Nominal Wall Thk. (in.) | Closure Mechanism |
|---|---|---|---|---|---|---|
| TA-1 | 5 | 1-gal Jug | Plastic | ∅6 x 12 H | 0.038 | Screw-top Lid |
| TA-2 | 5 | 1-gal Can (Paint) | Steel | ∅6-½ x 7 H | 0.016 | Friction-fit Lid |
| TA-3 | 5 | 5-gal Carboy | Plastic | ∅10-⅞ x 20-½ H | 0.112 | Screw-top Cap |
| TA-4 | 5 | 5-gal Bucket | Steel | ∅11-⅛ x 13 H | 0.018 | Crimped Lid |
| TA-5 | 5 | 5-gal Pail | Plastic | ∅11 x 14-¼ H | 0.097 | Snap-fit Lid |
| TA-6 | 5 | 30-gal Drum | Steel | ∅18-⅜ x 28-½ H | 0.047 | Bolted Closure Ring |
| TA-7 | 5 | 55-gal Drum | Steel | ∅22-½ x 33-⅝ H | 0.055 | Bolted Closure Ring |
| TA-8 | 5 | 85-gal Drum | Steel | ∅26-⅛ x 38-⅝ H | 0.055 | Bolted Closure Ring |

**Table 2.1-5** – Hydrostatic Burst Test Minimum Flow Rates

| Sealed Container Size (gal) | Sealed Container Size (ml) | Minimum Input Flow Rate (ml/min) |
|---|---|---|
| 1 | 3,785 | 0.22 |
| 5 | 18,927 | 1.11 |
| 30 | 113,562 | 6.64 |
| 55 | 208,198 | 12.2 |
| 85 | 321,760 | 18.8 |

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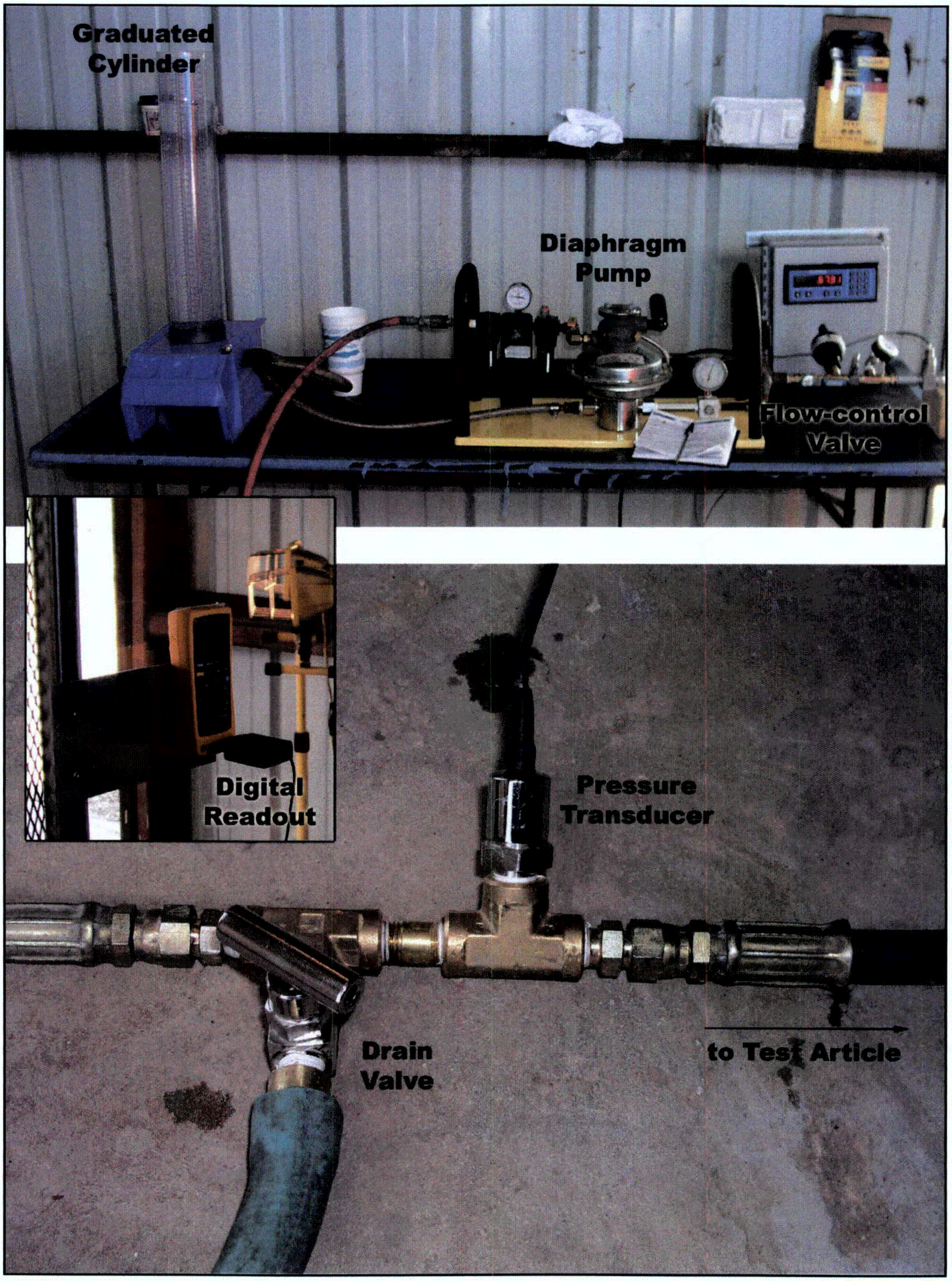


**Figure 2.1-45** – Hydrostatic Burst Test Apparatus

**Table 2.1-6** – Hydrostatic Burst Test Results

| Test Article Number | Failure Mode | Total Flow (ml) | Test Duration (dec min) | Flow Rate (ml/min) | Burst Pressure (psig) |
|---|---|---|---|---|---|
| TA-1-01 | Seam Burst | 550 | 8.48 | 65 | 22.1 |
| TA-1-02 | Side Burst | 1,450 | 21.25 | 68 | 22.8 |
| TA-1-03 | Seam Burst | 800 | 11.68 | 68 | 21.7 |
| TA-1-04 | Side Burst | 960 | 13.35 | 72 | 24.9 |
| TA-1-05 | Side Burst | 1,110 | 16.83 | 66 | 24.5 |
| **TA-1, 1-gal Jug, Plastic, Screw-top Lid** | | | | **65 minimum** | **24.9 maximum** |
| TA-2-01 | Lid Pop-off | 230 | 1.03 | 223 | 9.3 |
| TA-2-02 | Lid Pop-off | 100 | 1.10 | 91 | 4.5 |
| TA-2-03 | Lid Pop-off | 200 | 3.32 | 60 | 9.1 |
| TA-2-04 | Lid Pop-off | 175 | 2.25 | 78 | 8.3 |
| TA-2-05 | Lid Pop-off | 150 | 1.73 | 87 | 8.5 |
| **TA-2, 1-gal Can (Paint), Steel, Friction-fit Lid** | | | | **60 minimum** | **9.3 maximum** |
| TA-3-01 | Side Burst | 4,470 | 22.73 | 197 | 61.5 |
| TA-3-02 | Side Burst | 2,700 | 12.82 | 211 | 55.1 |
| TA-3-03 | Side Burst | 3,400 | 15.47 | 220 | 52.3 |
| TA-3-04 | Side Burst | 3,300 | 14.77 | 223 | 50.6 |
| TA-3-05 | Side Burst | 3,660 | 17.45 | 210 | 52.2 |
| **TA-3, 5-gal Carboy, Plastic, Screw-top Cap** | | | | **197 minimum** | **61.5 maximum** |
| TA-4-01 | Lid Leak | 1,400 | 9.98 | 140 | 16.0 |
| TA-4-02 | Lid Leak | 2,300 | 12.32 | 187 | 14.4 |
| TA-4-03 | Lid Leak | 2,675 | 11.63 | 230 | 15.1 |
| TA-4-04 | Lid Leak | 2,100 | 8.90 | 236 | 13.6 |
| TA-4-05 | Lid Leak | 1,575 | 7.28 | 216 | 13.3 |
| **TA-4, 5-gal Bucket, Steel, Crimped Lid** | | | | **140 minimum** | **16.0 maximum** |

| Test Article Number | Failure Mode | Total Flow (ml) | Test Duration (dec min) | Flow Rate (ml/min) | Burst Pressure (psig) |
|---|---|---|---|---|---|
| TA-5-01 | Lid Pop-off | 4,675 | 23.10 | 202 | 13.8 |
| TA-5-02 | Lid Pop-off | 3,850 | 15.30 | 252 | 15.8 |
| TA-5-03 | Lid Pop-off | 3,450 | 15.53 | 222 | 14.7 |
| TA-5-04 | Lid Pop-off | 2,600 | 11.05 | 235 | 12.5 |
| TA-5-05 | Lid Pop-off | 2,600 | 11.18 | 232 | 12.6 |
| **TA-5, 5-gal Pail, Plastic, Snap-fit Lid** | | | | **202 minimum** | **15.8 maximum** |
| TA-6-01 | Lid Leak | 13,500 | 18.87 | 716 | 21.9 |
| TA-6-02 | Lid Leak | 7,675 | 10.45 | 734 | 16.9 |
| TA-6-03 | Lid Leak | 6,290 | 9.48 | 663 | 17.0 |
| TA-6-04 | Lid Leak | 15,875 | 23.75 | 668 | 28.8 |
| TA-6-05 | Lid Leak | 16,575 | 24.98 | 663 | 28.3 |
| **TA-6, 30-gal Drum, Steel, Bolted Closure Ring** | | | | **663 minimum** | **28.8 maximum** |
| TA-7-01 | Lid Leak | 26,980 | 38.20 | 706 | 27.1 |
| TA-7-02 | Lid Leak | 25,640 | 30.47 | 842 | 25.2 |
| TA-7-03 | Lid Leak | 26,030 | 22.87 | 1,138 | 27.9 |
| TA-7-04 | Lid Leak | 25,625 | 23.88 | 1,073 | 26.5 |
| TA-7-05 | Lid Leak | 27,050 | 25.38 | 1,066 | 28.2 |
| **TA-7, 55-gal Drum, Steel, Bolted Closure Ring** | | | | **706 minimum** | **28.2 maximum** |
| TA-8-01 | Lid Leak | 33,650 | 25.75 | 1,307 | 18.2 |
| TA-8-02 | Lid Leak | 41,050 | 30.27 | 1,356 | 25.5 |
| TA-8-03 | Lid Leak | 41,275 | 27.52 | 1,500 | 29.5 |
| TA-8-04 | Lid Leak | 21,050 | 17.17 | 1,226 | 15.9 |
| TA-8-05 | Lid Leak | 36,550 | 28.17 | 1,298 | 24.1 |
| **TA-8, 85-gal Drum, Steel, Bolted Closure Ring** | | | | **1,226 minimum** | **29.5 maximum** |

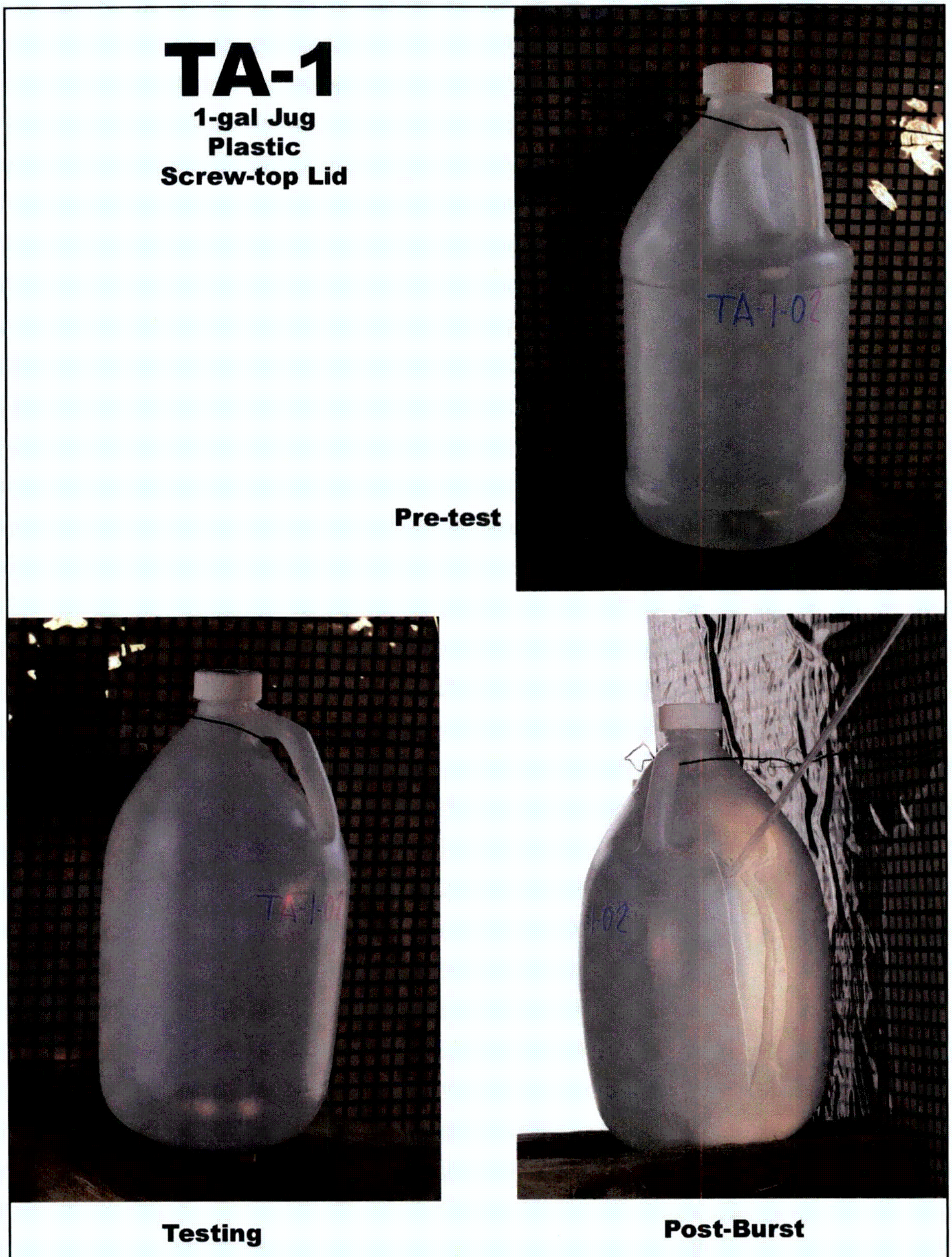


**Figure 2.1-46** – TA-1 Hydrostatic Burst Test

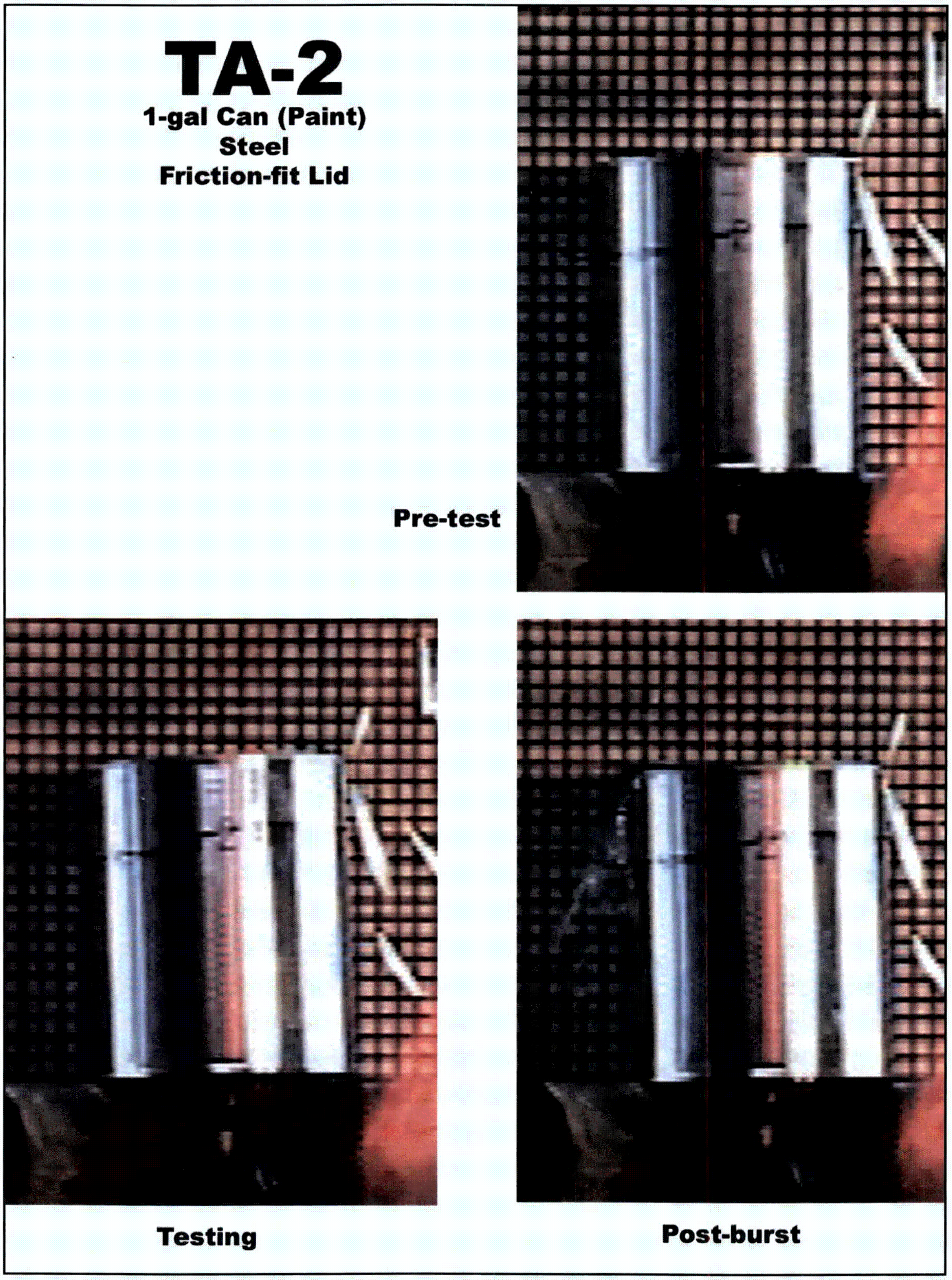


**Figure 2.1-47** – TA-2 Hydrostatic Burst Test

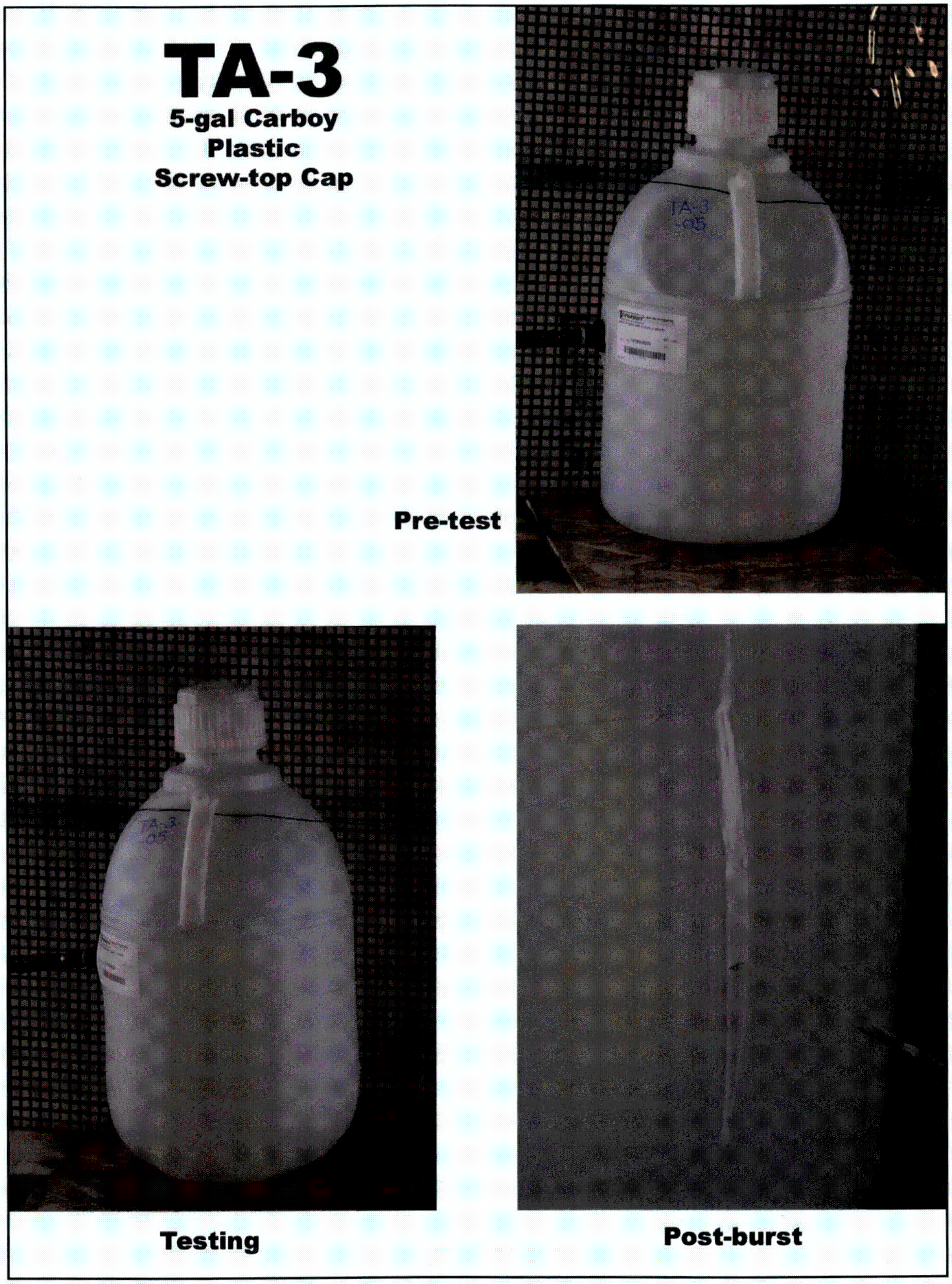


**Figure 2.1-48** – TA-3 Hydrostatic Burst Test

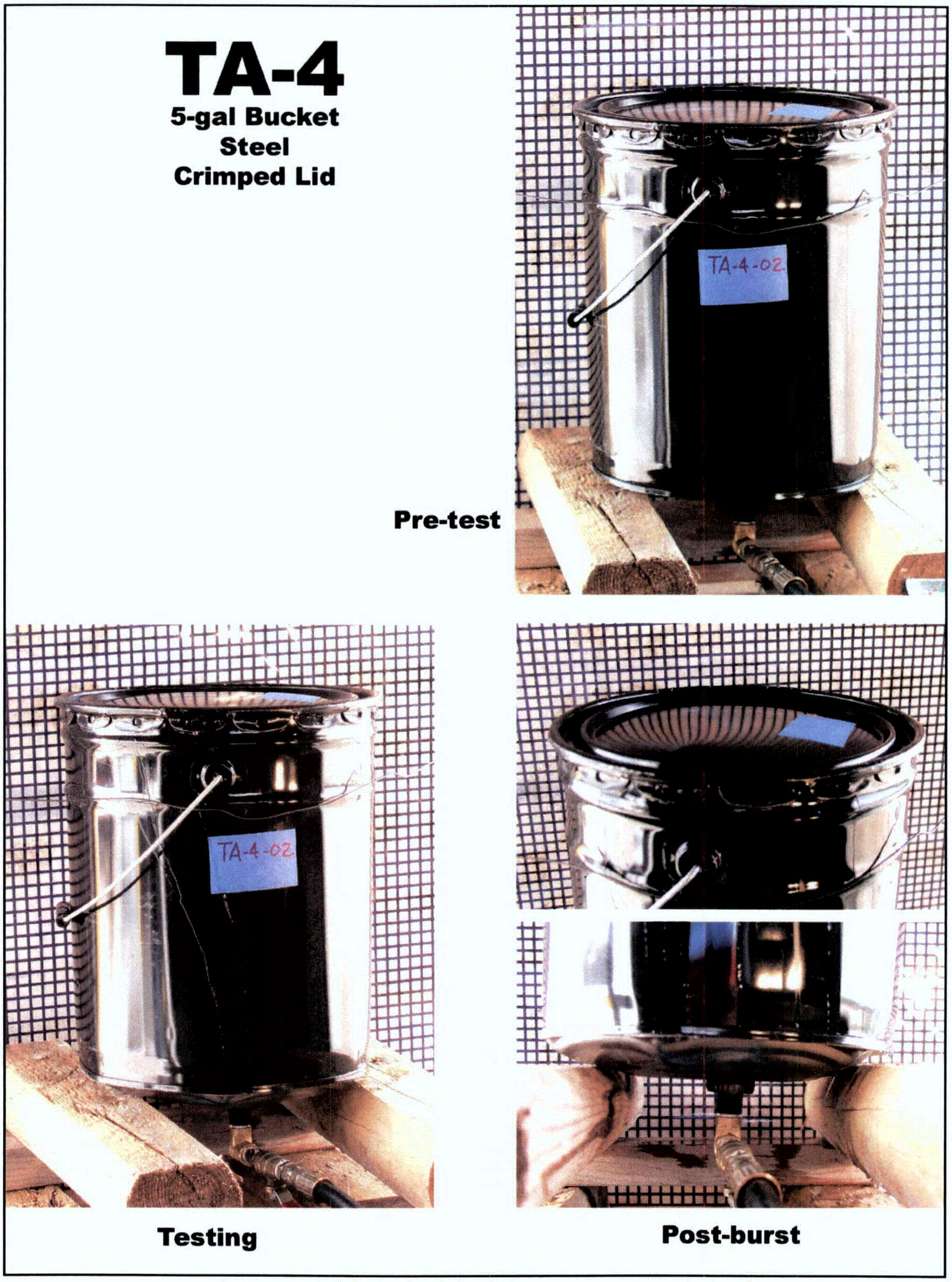


**Figure 2.1-49** – TA-4 Hydrostatic Burst Test

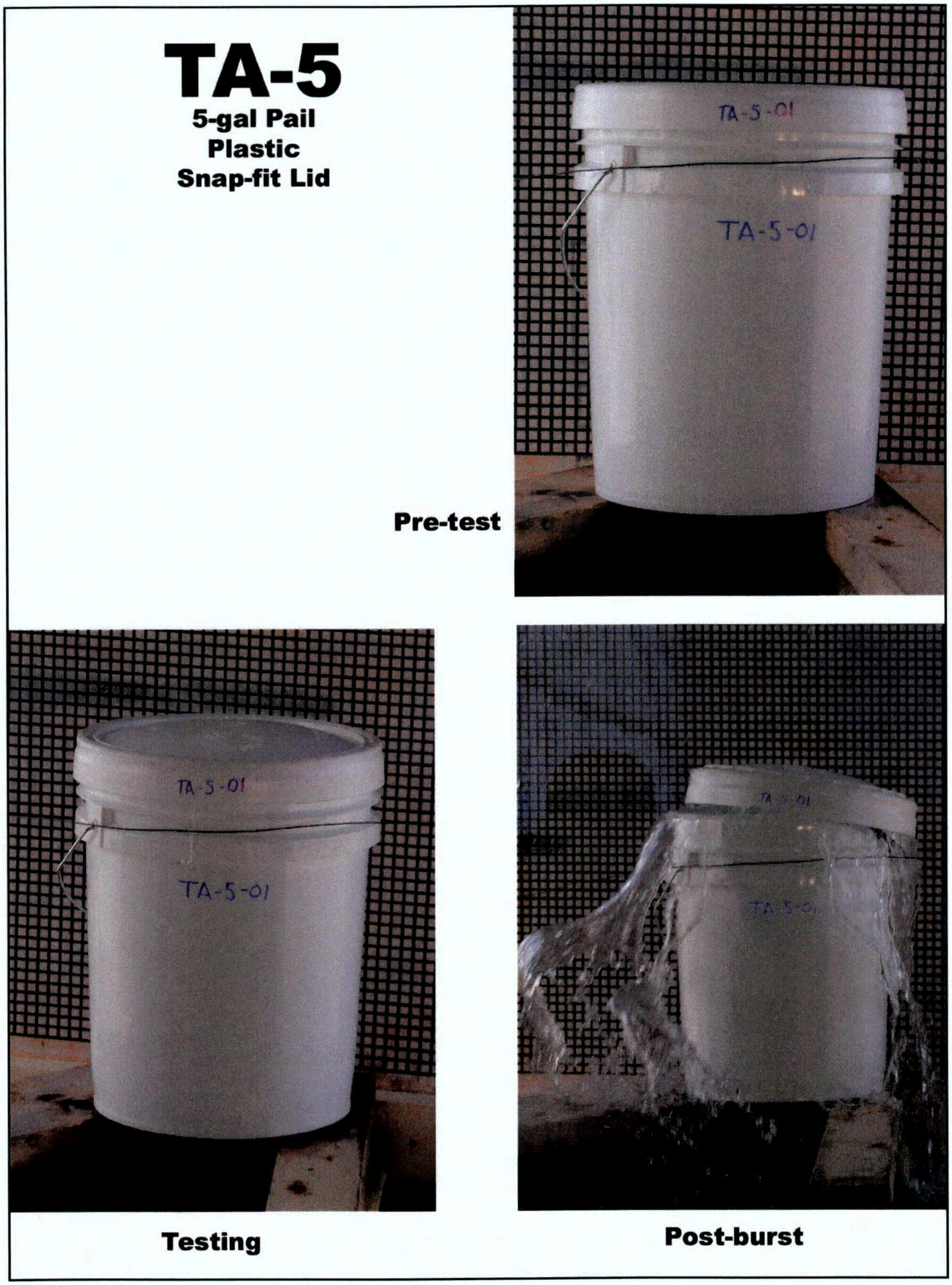


**Figure 2.1-50** – TA-5 Hydrostatic Burst Test


**Figure 2.1-51** – TA-6 Hydrostatic Burst Test

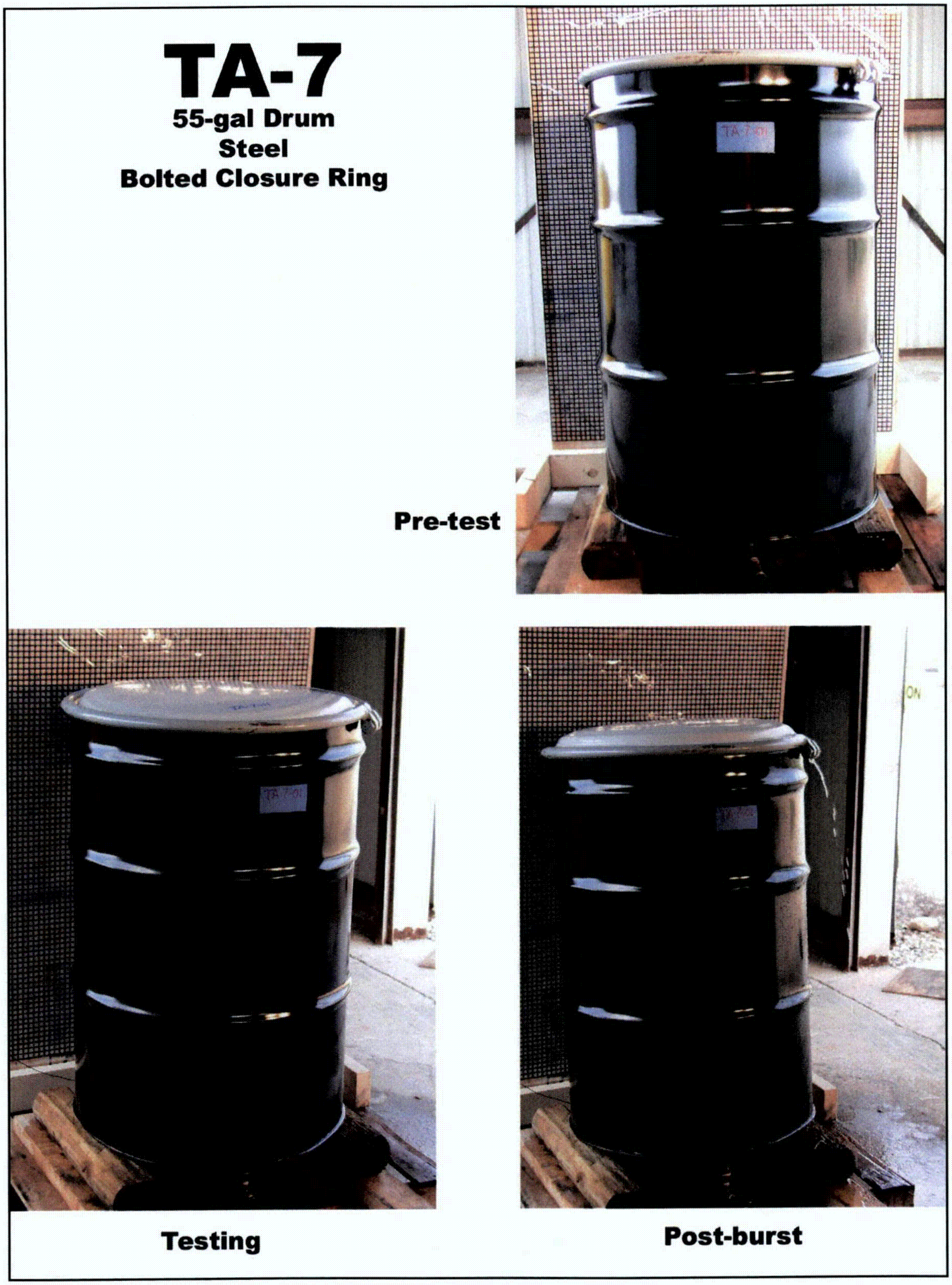


**Figure 2.1-52** – TA-7 Hydrostatic Burst Test

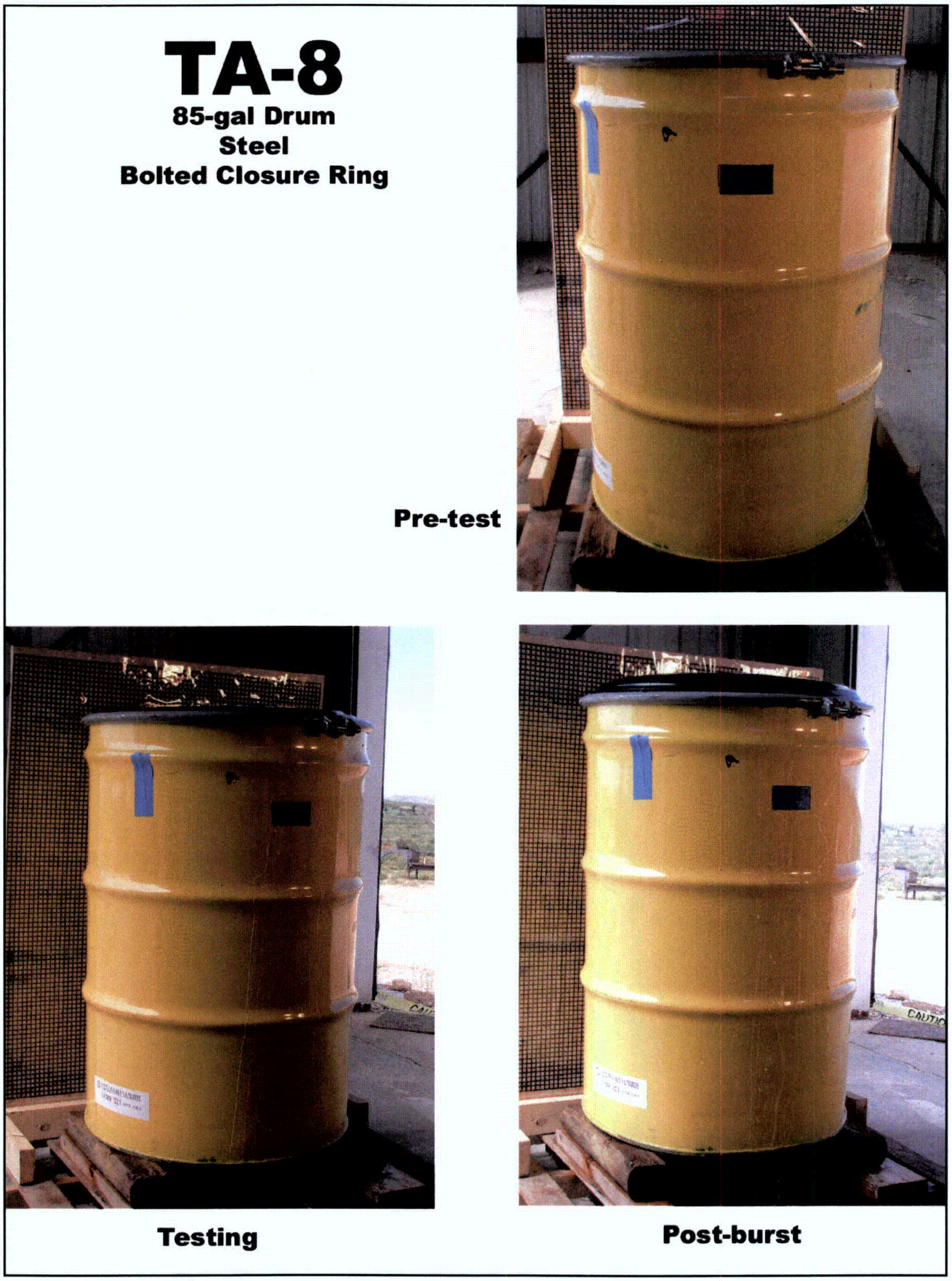


**Figure 2.1-53** – TA-8 Hydrostatic Burst Test

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# 2.2 Pressure due to Aerosol Can Contents Release

## 2.2.1 Introduction

In a TRUPACT-III payload of one loaded SLB2, the number of unpunctured aerosol cans must be known to ensure that a potential full release of the contents from the cans is accounted for in the MNOP determination for the package. Due to the evacuation and backfill process that renders all unsealed layers of confinement non-flammable (and, therefore, any aerosol can content release into the vented void space of the package non-flammable), the presence of aerosol cans is controlled to determine a contribution to MNOP in the package. The deflagration model presented in Section 2.1, *Pressure due to Sealed Container Deflagration*, conservatively accounts for the potential release of flammable aerosol can contents and potential subsequent deflagration inside a sealed container.

Typically, the generating and packaging procedures used at TRU waste sites do not allow unpunctured aerosol cans to be packaged with the waste. While these items have been used at the sites, their possible presence in the SLB2 would be incidental to the waste stream (i.e., not primary components of the waste stream). It is unlikely that a full aerosol can would be present in the waste. Aerosol cans that have been used for their intended purpose would likely be only partially full or empty if present in the waste. However, unpunctured aerosol cans are conservatively assumed full and accounted for in the MNOP determination as outlined below.

## 2.2.2 Aerosol Can Contents, Size, and Pressure

The contents of an aerosol can consist of a "product" and a "propellant". Propellants can be broadly classified as fluorocarbons ($C_wH_xF_y$, $C_wH_xCl_yF_z$, $C_wBR_xCl_yF_z$), hydrocarbons ($C_wH_x$), ethers ($C_wH_xO$, $C_wH_xF_yO$), compressed gases ($CO_2$, $N_2O$, $N_2$, A, etc.), and methylene chloride ($CH_2Cl_2$). Hydrocarbons have been the dominant propellant type used for aerosol cans since 1979.[1] Hydrocarbon propellants are typically comprised of a mixture of propane and isobutane to achieve the desired pressure of the propellant. As the product of the aerosol can is expelled, the remaining liquid propellant turns to vapor, maintaining a virtually constant interior pressure until all of the propellant gas is exhausted. The physical properties of purified hydrocarbon propellants are provided in Figure 2.2-1.[1]

Aerosol cans are produced in different sizes and with varying materials of construction. The U.S. Department of Transportation (DOT) specification for metal aerosol containers define, among other parameters, a maximum product and/or contents pressure at 130 °F of 140, 160, and 180 psig for the Specification 2N (standard), 2P, and 2Q containers, respectively.[1] Figure 2.2-2 summarizes the U.S. and European standard sizes for three-piece aerosol cans, where the U.S. standard sizes range from 1-13⁄16 to 3 inches in diameter and 2 to 10-½ inches tall with a full volume capacity ranging from 141 to 872 ml.[1]

[1] Johnsen, Montfort A., *Aerosol Handbook* (2nd Edition), Industry Publications, Inc. 1982.

### 2.2.3 Percent Contribution to MNOP

An aerosol can potentially contributes to pressure in the TRUPACT-III CV via the mechanism of liquid-to-gas volume expansion of the released propellant. The aerosol can product does not contribute significantly due to the fact that it typically remains a liquid at room temperature and/or due to limitations in the pressure capacity of aerosol cans containing compressed gas and no liquid propellants. Although ethane has the largest dispersion coefficient (i.e., liquid-to-gas volume expansion) of hydrocarbon propellants, it can be concluded from the vapor pressure data provided in Figure 2.2-1 that ethane can only be utilized as a co-propellant in small quantities since its room temperature vapor pressure is above the pressure capacity of DOT spec containers. The hydrocarbon propellants with the next highest dispersion coefficients are propane and isobutane. The mixture of propane and isobutane required to achieve a pressure of 180 psig at 130 °F (327.6 K), consistent with a DOT spec 2Q container, can be determined from the proportion of partial pressures of each liquefied gas as follows (Figure 2.2-3 and Figure 2.2-4):[2]

| | | | | | |
|---|---|---|---|---|---|
| Propane Partial Pressure | 305 psi | × | 29% | = | 88.4 psig @ 130 °F |
| Isobutane Partial Pressure | 129 psi | × | 71% | = | 91.6 psig @ 130 °F |
| Propellant Mixture Pressure | | | | | 180 psig @ 130 °F |

At room temperature (70 °F, 294.3 K) the pressure of the propane/isobutane propellant mixture is as follows:

| | | | | | |
|---|---|---|---|---|---|
| Propane Partial Pressure | 131 psi | × | 29% | = | 38.0 psig @ 70 °F |
| Isobutane Partial Pressure | 44 psi | × | 71% | = | 31.2 psig @ 70 °F |
| Propellant Mixture Pressure | | | | | 69.2 psig @ 70 °F |

Aerosol cans typically have a product-to-propellant volume ratio of 3:1 (i.e., 75% product and 25% propellant)[3] with a total volume limited by the full capacity of the standard size aerosol can. Due to the variable nature of the products marketed in aerosol cans, it is conservatively assumed that 50% by volume of the aerosol can is comprised of the propellant mixture. Additionally, the volume capacity of aerosol cans is assumed as the largest standard size of U.S. cans, 872 ml, given in Figure 2.2-2.

For a 211x1008 (i.e., ∅<u>2</u>-<u>11</u>/16 in. x <u>10</u>-<u>08</u>/16 or 10-1/2 in. tall) standard aerosol can, the liquid volume of propellant is equal to 50% of 872 ml, or 436 ml. Based on the 29% propane / 71% isobutane mixture and using the liquid-to-gas volumetric dispersion ratios for each, the total released gas volume at 1 atm and 70 °F is calculated as follows:

$$V_{ac\_70F} = (0.436 \text{ liters})[(0.29 \times 272.3) + (0.71 \times 229.3)] = 105.4 \text{ liters @ } 70\ ^\circ\text{F}$$

Conservatively excluding any void volume within the SLB2, the available void volume to accommodate the aerosol can release is assumed to be equal to the void volume outside of the SLB2 and inside the TRUPACT-III CV (Section 2.1.1.4, *Percent Contribution to MNOP*), $V_{cv\_void}$ = 2,354 liters.

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[2] Air Liquide, *Gas Encyclopaedia*, New York, Elsevier Science Publishing, 1976.

[3] National Institutes of Health, *Household Products Database*, http://householdproducts.nlm.nih.gov/ingredients.htm

The 105.4 liters of released aerosol gas is heated to the bulk average void volume (gas) temperature of 145.4 °F (63.0 °C, 336.2 K) based on 80 watts as summarized in Table 2.3-1. The released aerosol gas would occupy a volume, $V_{ac}$, of:

$$V_{ac} = (105.4\ \text{liters})\left(\frac{336.2\ \text{K}}{294.3\ \text{K}}\right) = 120.4\ \text{liters} @ 145.4\ ^{\circ}\text{F}$$

The release of aerosol gas (adjusted for heat-up to normal conditions) from one full aerosol can into the TRUPACT-III CV void space contributes a pressure, $P_{ac}$, of:

$$P_{ac} = \left(\frac{120.4\ \text{liters}}{2{,}354\ \text{liters}}\right) = 0.051\ \text{atm}\ (0.75\ \text{psia}) @ 145.4\ ^{\circ}\text{F}$$

Therefore, the percent contribution to MNOP from aerosol can contents release into the payload is given as a function of the number of aerosol cans, $N_{ac}$, as follows:

$$\%_{mnop} = \left(\frac{N_{ac} \times P_{ac}}{25\ \text{psig}}\right) \times 100 = 3.0 \times N_{ac}$$

The above equation conservatively accounts for aerosol can content release in the payload by assuming all aerosol cans are full, utilizing a propellant mixture consistent with the highest pressure capacity DOT spec container, assuming a 50% by volume propellant fill of the largest standard size aerosol can, and ignoring void space available for gas expansion inside the SLB2. Table 2.2-1 summarizes the percent contribution to MNOP as a function of the number of aerosol cans in the TRUPACT-III payload.

*Physical Properties of Purified Hydrocarbon Propellants*

| Property | Ethane* | Propane | Isobutane | N-butane | Isopentane* |
|---|---|---|---|---|---|
| Formula | $C_2H_6$ | $C_3H_8$ | $C_4H_{10}$ | $C_4H_{10}$ | $C_5H_{12}$ |
| Molecular Weight | 30.06 | 44.09 | 58.12 | 58.12 | 72.15 |
| Vapor Pressure (psig at 70°F) | 543 | 109.3 | 31.1 | 16.92 | -3.5 |
| Freezing Point (°F) (1 atm.) | -297.8 | -305.9 | -255.3 | -216.9 | -255.8 |
| Boiling Point (°F) (1 atm.) | -127.5 | -43.7 | 10.9 | 31.1 | 82,2 |
| Specific Gravity (liquid) (60°F) | 0.35 | 0.508 | 0.563 | 0.584 | 0.620 |
| Specific Gravity (gas) (60°F) (Air = 1) | 1.02 | 1.55 | 2.01 | 2.08 | 2.61 |
| Critical Temperature (°F) | 90.1 | 206.2 | 274.8 | 305.6 | 370.0 |
| Critical Pressure (psig) | 707.1 | 616.1 | 528.1 | 550.1 | 482.6 |
| Critical Density (g/ml) | 0.203 | 0.220 | 0.221 | 0.228 | 0.234 |
| Flash Point (°F) | < -200 | -156 | -117 | -101 | < -60 |
| Lower Explosive Limit (v% in air) | 3.12 | 2.20 | 1.78 | 1.84 | 1.39 |
| Upper Explosive Limit (v% in air) | 15.0 | 9.51 | 8.40 | 8.48 | 7.97 |
| Heat of Combustion (BTU/lb.) | 22,190 | 21,620 | 21,298 | 21,318 | 21,102 |
| Dispersion (Gas at 1 atm and 70°F) | | | | | |
| From 1 g (ml) | 793 | 540.2 | 414.0 | 400.6 | na |
| From 1 ml (ml) | 276 est. | 272.3 | 229.3 | 233.9 | na |
| Solubility of Water in Propellent (70°F) | 0.031 | 0.0168 | 0.0088 | 0.0075 | 0.0063 |
| Solubility of Propellent in Water (70°F) (w% at 1 atm) | 0.008 | 0.0079 | 0.0080 | 0.0080 | 0.0084 |

*Usually considered as co-propellents — present in commercial propellents.

**Figure 2.2-1** – Physical Properties of Purified Hydrocarbon Propellants

*Standard Sizes For Three-Piece Aerosols*

| U.S.A. Nominal Dimensions | European I.S.O.* Dimensions | European Commercial Description | Area Where Used | Brimful Capacity Fl. Oz. | ml |
|---|---|---|---|---|---|
| 113 × 313 | 45 × 97 | 140.045 | U.S.A. & Europe | 4.77 | 141 |
| 113 × 411 | 45 × 119 | 175.045 | U.S.A. & Europe | 5.95 | 176 |
| 113 × 509 | 45 × 140 | 210 | U.S.A. & Europe | 7.10 | 210 |
| 202 × 200 | 52 × 50 | 100.052 | U.S.A. | 3.5 | 102 |
| 202 × 213 | 52 × 72 | 140.052 | Europe** | 4.9 | 142 |
| 202 × 214 | 52 × 73 | 145.052 | U.S.A. | 5.0 | 147 |
| 202 × 307.5 | 52 × 88 | 175.052 | Europe** | 6.0 | 177 |
| 202 × 314 | 52 × 98 | 190.052 | U.S.A. | 6.8 | 192 |
| 202 × 402.5 | 52 × 105 | 210.052 | Europe | 7.2 | 212 |
| 202 × 405 ni | 52 × 109 ni | 210.052 ni | Europe | 7.2 | 212 |
| 202 × 406 | 52 × 111 | 225.052 | U.S.A. | 7.6 | 226 |
| 202 × 413 | 52 × 122 | 245.052 | U.S.A. | 8.3 | 246 |
| 202 × 503.5 | 52 × 132 | 270.052 | Europe | 9.2 | 272 |
| 202 × 506 ni | 52 × 136 ni | 270.052 ni | Europe | 9.2 | 272 |
| 202 × 509 | 52 × 141 | 290.052 | U.S.A. | 9.8 | 290 |
| 202 × 514 dni | 52 × 149 dni | 300.052 dni | U.S.A. | 10.2 | 301 |
| 202 × 605.5 | 52 × 161 | 335.052 | Europe | 11.4 | 337 |
| 337 × 608 ni | 52 × 165 ni | 335.052 ni | Europe | 11.4 | 337 |
| 202 × 700 | 52 × 177 | 365.052 | U.S.A. | 12.4 | 367 |
| 202 × 708 | 52 × 190 | 390.052 | U.S.A. | 13.4 | 391 |
| 202 × 711 | 52 × 195 | 405.052 | Europe | 13.8 | 407 |
| 202 × 804 | 52 × 209 | 450.052 | Europe | 15.2 | 450 |
| 205 × 409.5 ni | 57 × 117 ni | 270.057 ni | Europe | 9.2 | 272 |
| 205 × 508 ni | 57 × 140 ni | 335.057 ni | Europe | 11.4 | 337 |
| 205 × 607.5 ni | 57 × 164 ni | 405.057 ni | Europe | 13.8 | 407 |
| 205 × 802.5 ni | 57 × 207 ni | 520.057 ni | Europe | 17.7 | 522 |
| 205 × 1020 ni | 57 × 257 ni | 650.057 ni | Europe | 22.1 | 652 |
| 207.5 × 413 | 60 × 122 | 330.060 | U.S.A. | 11.3 | 332 |
| 207.5 × 509 | 60 × 141 | 390.060 | U.S.A. | 13.2 | 389 |
| 207.5 × 512 | 60 × 146 | 405.060 | Europe** | 13.7 | 407 |
| 207.5 × 605 | 60 × 160 | 450.060 | U.S.A. & Europe | 15.3 | 452 |
| 207.5 × 701 | 60 × 179 | 500.060 | U.S.A. & Europe | 16.8 | 498 |
| 207.5 × 705.5 | 60 × 186 | 520.060 | Europe | 17.7 | 522 |
| 207.5 × 708 | 60 × 190 | 525.060 | U.S.A. | 17.9 | 527 |
| 207.5 × 713 | 60 × 198 | 540.060 | U.S.A. | 18.4 | 541 |
| 207.5 × 903 | 60 × 232 | 650.060 | Europe | 22.1 | 652 |
| 211 × 407.5 | 65 × 113 | 375.065 | U.S.A. | 12.6 | 373 |
| 211 × 410.5 | 65 × 118 | 395.065 | Europe | 13.4 | 397 |
| 211 × 413 | 65 × 122 | 405.065 | U.S.A. & Europe | 13.7 | 404 |
| 211 × 510 | 65 × 142 | 470.065 | U.S.A. | 16.0 | 472 |
| 211 × 604 | 65 × 157 | 520.065 | U.S.A. & Europe | 17.8 | 522 |
| 211 × 612 | 65 × 171 | 565.065 | U.S.A. | 19.2 | 567 |
| 211 × 612 dni | 65 × 171 dni | 560.065 dni | U.S.A. - Exptl. | 18.9 | 559 |
| 211 × 702 | 65 × 181 | 600.065 | Europe | 20.4 | 602 |
| 211 × 711 | 65 × 195 | 650.065 | Europe | 22.1 | 652 |
| 211 × 713 | 65 × 198 | 655.065 | U.S.A. | 22.3 | 657 |
| 211 × 808 | 65 × 215 | 720.065 | U.S.A. | 24.3 | 720 |
| 211 × 908 | 65 × 238 | 795.065 | U.S.A. | 26.9 | 796 |
| 211 × 909 | 65 × 240 | 800.065 | Europe | 27.2 | 802 |
| 211 × 1008 | 65 × 266 | 870.065 | U.S.A. | 29.5 | 872 |
| 211 × 1114 | 65 × 300 | 1000.000 | Europe | 33.9 | 1002 |
| 300 × 709 | 76 × 192 | 795.076 | U.S.A. | 26.9 | 796 |
| 300 × 709 ni | 76 × 192 ni | 780.076 | U.S.A. - Exptl. | 26.4 | 781 |

**Figure 2.2-2** – Standard Sizes for Three-Piece Aerosols

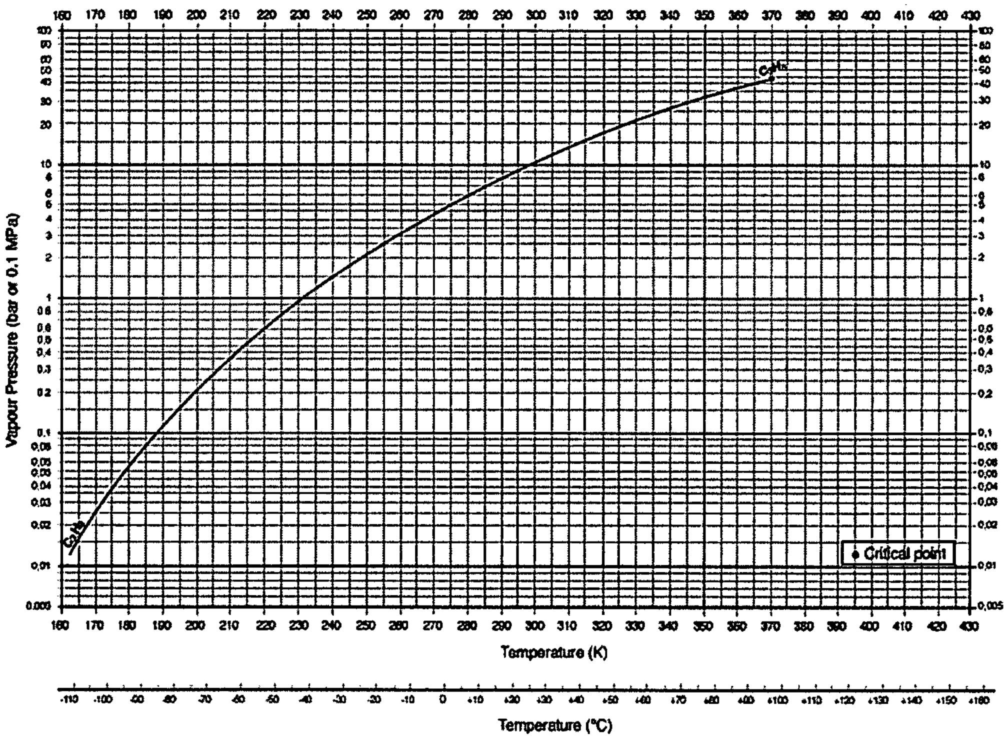


**Figure 2.2-3** – Propane Vapor Pressure as a Function of Temperature

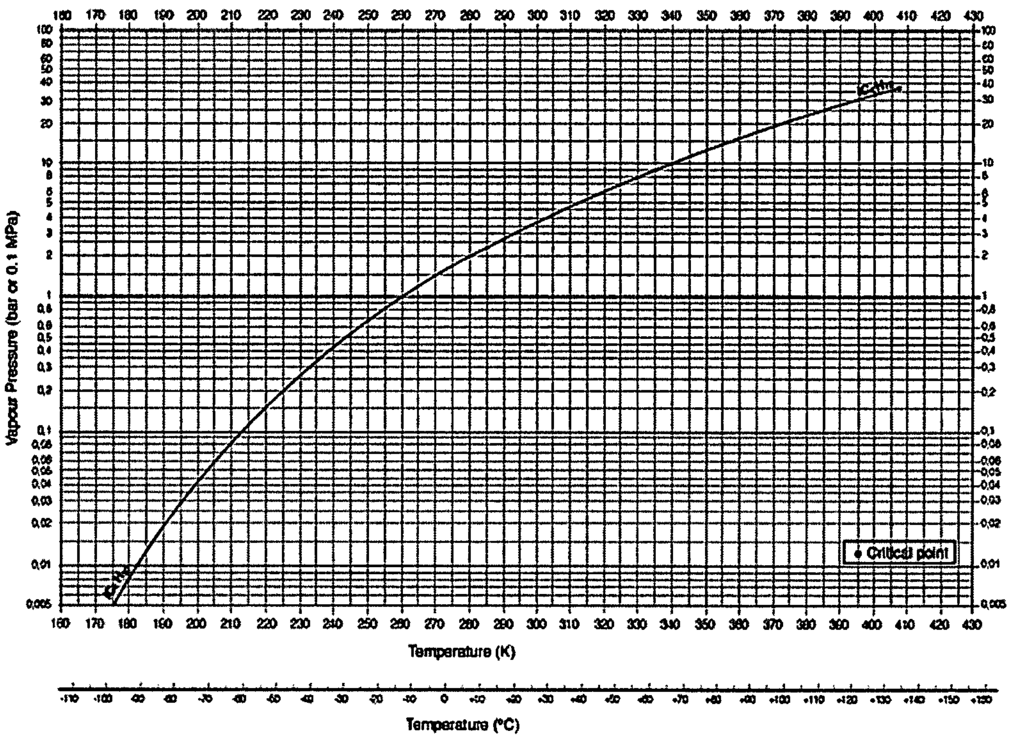


**Figure 2.2-4** – Isobutane Vapor Pressure as a Function of Temperature

**Table 2.2-1** – Percent Contribution to MNOP from Aerosol Can Release

| No. of Aerosol Cans | $\%_{mnop}$ |
|---|---|
| 1 | 3 |
| 2 | 6 |
| 3 | 9 |
| 4 | 12 |
| 5 | 15 |
| 6 | 18 |
| 7 | 21 |
| 8 | 24 |
| 9 | 27 |
| 10 | 30 |
| 11 | 33 |
| 12 | 36 |
| 13 | 39 |
| 14 | 42 |
| 15 | 45 |
| 16 | 48 |
| 17 | 51 |
| 18 | 54 |
| 19 | 57 |
| 20 | 60 |
| 21 | 63 |
| 22 | 66 |
| 23 | 69 |
| 24 | 72 |
| 25 | 75 |
| 26 | 78 |
| 27 | 81 |
| 28 | 84 |
| 29 | 87 |
| 30 | 90 |
| 33 | 99 |

# 2.3 MNOP Compliance Methodology

This section discusses the compliance methodology for meeting the MNOP in the TRUPACT-III CV. The MNOP may be converted into an allowable total gas generation rate (ATGGR) that is used to determine a limit on the decay heat per SLB2. The MNOP is reduced to account for the pressure contributions from any sealed containers and/or aerosol cans that are present in the SLB2. Bounding values for the pressure contributions associated with the number and size of sealed containers and with the number of aerosol cans have been established through testing and analysis as discussed in Section 2.1, *Pressure due to Sealed Container Deflagration*, and Section 2.2, *Pressure due to Aerosol Can Contents Release*. The sealed container pressure contribution is based on a stoichiometric deflagration at a bounding initial pressure limit (i.e., hydrostatic burst pressure). The aerosol can pressure contribution is based on the pressurized gas volume contained within an aerosol can of bounding size. The decay heat limit per SLB2 is calculated based on the remaining percentage of MNOP available over the shipping duration. The decay heat limit per SLB2 is determined on a case-by-case basis as it is dependent on the contents of the SLB2. If it can be shown for a given SLB2 that the applicable decay heat limit can be met, the MNOP will not be exceeded. The MNOP compliance methodology is detailed in Section 2.3.1, *Compliance with MNOP*. The derivation of decay heat limits based on MNOP is detailed in Section 2.3.2, *Derivation of Decay Heat Limit based on MNOP*.

## 2.3.1 Compliance with MNOP

The methodology described in this section shall be used by a site to determine the decay heat limit based on MNOP for each SLB2. The methodology detailed below is illustrated in Figure 2.3-1.

**Step 1, Payload-container-specific data** – The starting point for compliance evaluation is the payload container data package, which includes all data associated with the payload container. These data are gathered from one or more of the methods of payload compliance listed and defined in Section 1.5, *Methods of Compliance*, of the TRUPACT-III TRAMPAC (i.e., records and database information [knowledge of process], administrative and procurement controls, visual inspection, visual examination, nondestructive examination, measurement, and sampling program).[1]

**Step 2, Determine void volumes** – Estimates of the void volumes in each SLB2 and any unsealed layers of confinement are required to calculate the ATGGR as described in Section 2.3.2, *Derivation of Decay Heat Limit based on MNOP*. The determination of the available internal void volumes may be based on site records and database information (knowledge of process) or procedure documentation on percentage fill or radiography. If such information is not available, a conservative default value of 25 percent available internal void volume per SLB2 must be used for decay heat limit calculations. As described in Section 2.1.1.4, *Percent Contribution to MNOP*, based on the bulk densities of the loosely packed payload materials and fill factors in unsealed confinement layers, 25% is a conservative lower bound estimate of the void fraction in an SLB2. Following the determination of the void

[1] U.S. Department of Energy (DOE), *TRUPACT-III Authorized Methods for Payload Control (TRUPACT-III TRAMPAC)*, current revision, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

volumes of the SLB2 and any unsealed layers of confinement, proceed to **Step [3], Are sealed containers >4 liters and/or aerosol cans present?**.

**Step [3], Are sealed containers >4 liters and/or aerosol cans present?** – The presence or absence of sealed containers >4 liters and the presence or absence of aerosol cans (either unpunctured or not empty) are determined based on the information contained in the payload container data package. Data used to make this determination consist of process knowledge (e.g., knowledge of waste generation and packaging processes), records of visual examination, or nondestructive examination. If it can be determined based on available data that no sealed containers >4 liters or aerosol cans are present in the payload container, the compliance evaluation shall proceed to **Step [4], Calculate decay heat limit per SLB2**. If it is determined that sealed containers >4 liters and/or aerosol cans are present, the compliance evaluation shall proceed to **Step [9], Determine number and size of sealed container(s)**, and/or **Step [10], Determine number of aerosol can(s)**, as appropriate. If data are not available to make this determination, the payload container is not eligible for shipment and must be segregated for repackaging, treatment, or other mitigation measures. Following the completion of mitigation measures, the compliance evaluation shall proceed to **Step [1], Payload-container-specific data**.

**Step [4], Calculate decay heat limit per SLB2** – As described in Section 2.3.2, *Derivation of Decay Heat Limit based on MNOP*, calculate the decay heat limit for the SLB2 under evaluation. Following the calculation of the decay heat limit, proceed to **Step [5], Is decay heat plus error ≤decay heat limit per SLB2?**.

**Step [5], Is decay heat plus error ≤decay heat limit per SLB2?** – If the SLB2 exceeds the decay heat limit, the payload container cannot be approved for shipment in its current condition. Mitigation measures must be taken under **Step [6], Mitigate and update payload container data package**. If the SLB2 meets the decay heat limit, the MNOP limit is met and the compliance evaluation is complete (see **Step [7], Compliance with MNOP limit demonstrated for payload container**).

**Step [6], Mitigate and update payload container data package** – If the SLB2 exceeds the decay heat limit based on MNOP, the payload container is not eligible for shipment and must be segregated for repackaging, treatment, or other mitigation measures. Following the completion of mitigation measures, the compliance evaluation shall proceed to **Step [1], Payload-container-specific data**.

**Step [7], Compliance with MNOP limit demonstrated for payload container** – A payload container reaching this step meets the MNOP limit. The SLB2 is eligible for shipment only following its certification in accordance with Section 3.0, *Payload Assembly*, and the completion of **Step [8], Perform evacuation/backfill**, and if all other transportation requirements are satisfied.

**Step [8], Perform evacuation/backfill** – Following certification of the payload in accordance with Section 3.0, *Payload Assembly*, and the assembly of the SLB2 in the TRUPACT-III, the loaded TRUPACT-III is evacuated and backfilled at the site prior to transport as described in Section 3.2.3, *PREx Operating Controls and Conditions for Shipment*, and Section 3.2.4, *Controlled Shipments*. The site is required to use a 10-day shipping period (controlled shipment).

**Step [9], Determine number and size of sealed container(s)** – The determination of the number and size of sealed container(s) per SLB2 is required for the determination of their contribution to the MNOP. The number and size of sealed container(s) are determined based on the information contained in the payload container data package. Data used to make this determination consist of process knowledge or records of visual examination or nondestructive examination. Each of the sealed containers shall be classified by the parameters specified in Section 2.1.3, *Sealed Container Burst Pressure Testing*. If sealed containers >4 liters other than those included in Table 2.1-4 of Section 2.1.3 are present in the SLB2, burst test data for the additional sealed container types shall be collected in accordance with a test program equivalent to that described in Section 2.1.3 under a Department of Energy - Carlsbad Field Office (DOE-CBFO) approved quality assurance program. Following the determination of the number, size, and associated burst pressure (from Table 2.1-6 or a supplemental test program) of sealed container(s), proceed to **Step [11], Assign MNOP fractional contribution**. If data are not available to make this determination (number, size, and associated burst pressure of sealed containers(s)), the payload container is not eligible for shipment and must be segregated for repackaging, treatment, or other mitigation measures. Following the completion of mitigation measures, the compliance evaluation should proceed to **Step [1], Payload-container-specific data**.

**Step [10], Determine number of aerosol can(s)** – The determination of the number of unpunctured aerosol can(s) per SLB2 is required for the determination of their contribution to MNOP. The number of unpunctured aerosol can(s) is determined based on the information contained in the payload container data package. Data used to make this determination consist of process knowledge, records of visual examination, or nondestructive examination. Following the determination of the number of aerosol can(s), proceed to **Step [11], Assign MNOP fractional contribution**. If data are not available to make this determination (number of aerosol can(s)), the payload container is not eligible for shipment and must be segregated for repackaging, treatment, or other mitigation measures. Following the completion of mitigation measures, the compliance evaluation should proceed to **Step [1], Payload-container-specific data**.

**Step [11], Assign MNOP fractional contribution** – As applicable, using the sealed container classification(s) assigned in **Step [9], Determine number and size of sealed container(s)**, use Table 2.1-1 of Section 2.1, *Pressure due to Sealed Container Deflagration*, to determine the MNOP fractional contribution for each sealed container. As applicable, using the number of aerosol can(s) determined in **Step [10], Determine number of aerosol can(s),** use Table 2.2-1 of Section 2.2, *Pressure due to Aerosol Can Contents Release*, to determine the MNOP fractional contribution for aerosol cans. Following the assignment of the MNOP fractional contributions, the compliance evaluation shall proceed to **Step [12], Sum MNOP fractional contributions for all sealed container(s) and aerosol can(s).**

**Step [12], Sum MNOP fractional contributions for all sealed container(s) and aerosol can(s)** – The values determined in **Step [11], Assign MNOP fractional contribution**, are summed to determine the total MNOP fractional contribution from all sealed container(s) and aerosol can(s) present in the SLB2. Proceed to **Step [13], Is sum of MNOP fractional contributions <1?**.

**Step 13, Is sum of MNOP fractional contributions <1?** – If the sum of the MNOP fractional contributions for all sealed container(s) and aerosol can(s) is less than 1, proceed to **Step 14, Subtract from MNOP**. If the sum of the MNOP fractional contributions for all sealed container(s) and aerosol can(s) is greater than 1, the payload container is not eligible for shipment and must be segregated for repackaging, treatment, or other mitigation measures. Following the completion of mitigation measures, the compliance evaluation should proceed to **Step 1, Payload-container-specific data**.

**Step 14, Subtract from MNOP** – For SLB2s containing sealed container(s) and/or aerosol can(s), the MNOP must be adjusted (reduced from 25 psig) to account for the pressure contributions from the sealed container(s) and/or aerosol can(s). As described in Section 2.3.2, *Derivation of Decay Heat Limit based on MNOP*, a pressure-based ATGGR and the corresponding decay heat limit are calculated based on the allowable pressure remaining following the subtraction of the sum of the MNOP fractional contributions for all sealed container(s) and aerosol can(s). Proceed to **Step 4, Calculate decay heat limit per SLB2.**

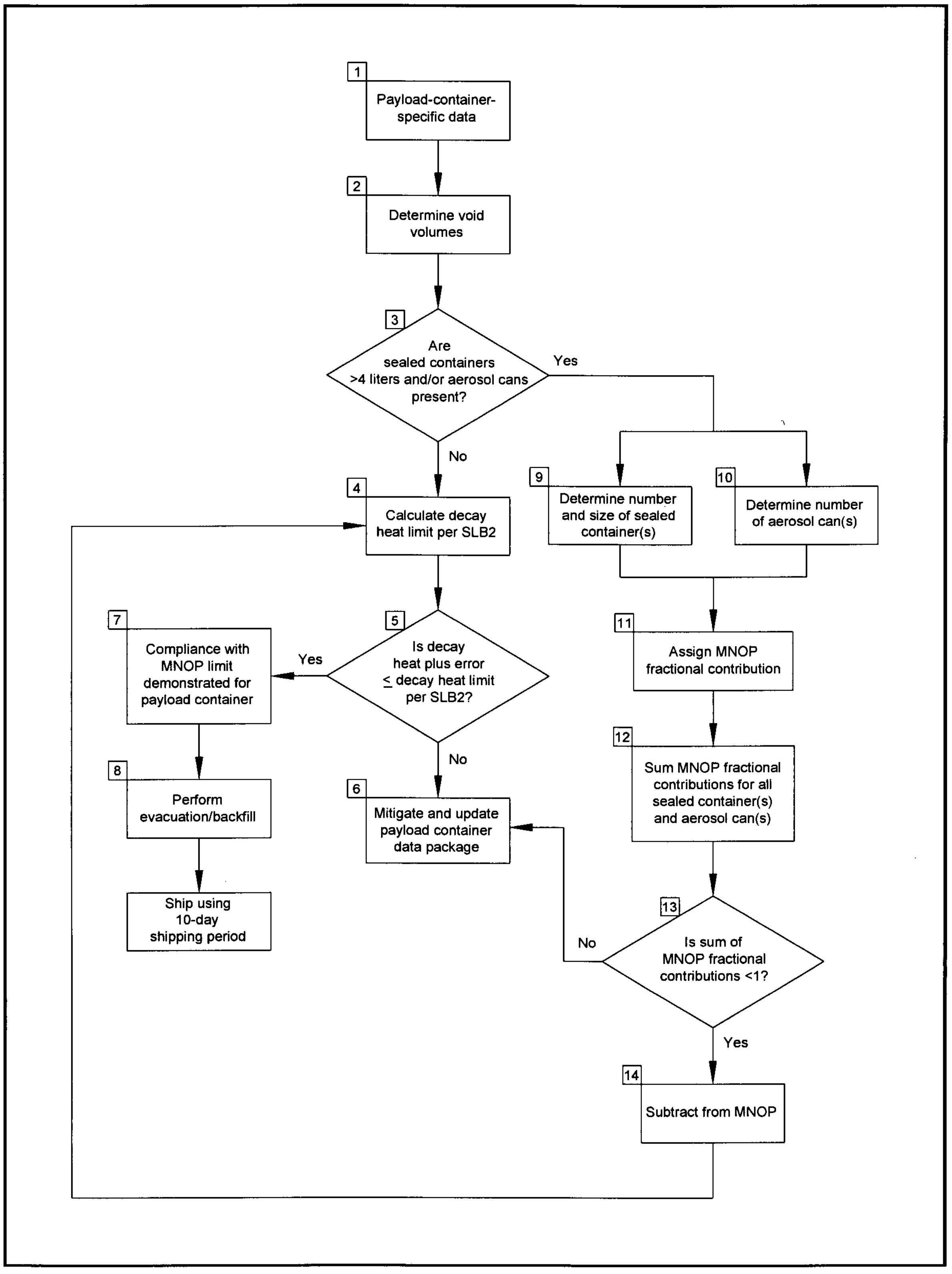


**Figure 2.3-1** – Compliance with MNOP Flow Chart

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## 2.3.2 Derivation of Decay Heat Limit based on MNOP

This section documents the methodology for calculating a pressure-based ATGGR and the corresponding decay heat limit to meet the 25 psig (172 kPa) MNOP restriction. As there is only a single SLB2 per TRUPACT-III payload, the limit per SLB2 is also the limit for the TRUPACT-III package. The ATGGR and decay heat limit are a function of the following:

- Shipping period
- Void volume within the SLB2
- Void volume within each unsealed layer of confinement within the SLB2
- Void volume within the TRUPACT-III with a single SLB2
- Pressure at the time the TRUPACT-III is closed for transport after the evacuation/backfill process
- Bulk average payload temperature ($T_{ap}$)
- Bulk average void volume temperature ($T_{avv}$)
- Water vapor pressure at the temperature of the coolest or condensing surface on the inner wall of the TRUPACT-III ($T_{minwall}$)
- Sum of the MNOP fractional contributions from any sealed containers and aerosol cans
- Effective, bounding net (total) gas generation potential (G value).

The 25 psig (172 kPa) MNOP is converted to an ATGGR for each SLB2. As discussed in Appendices 6.1, 6.5, and 6.6 of the CH-TRU Payload Appendices[1], gas generation due to chemical, biological, and thermal mechanisms is insignificant during transport, and radiolysis is the primary mechanism for net (total) gas generation in TRU wastes. Because radiolysis of the waste materials is the primary mechanism by which net (total) gas may be generated, the 25 psig (172 kPa) MNOP may be converted to a limit on the decay heat for each SLB2 based on the net (total) gas generation potential of the waste. The net (total) gas generation potential of waste materials is quantified by an effective, bounding G value. Using the bounding net (total) gas G value, the 25 psig (172 kPa) MNOP restriction can be converted to a decay heat limit as documented later in this section.

### Shipping Period

The maximum shipping period determines the maximum amount of time that any gases generated and released from the payload container can remain sealed in the TRUPACT-III package and impact the contribution to total pressure. TRUPACT-III payloads qualified for shipment under this document must be shipped as controlled shipments. For controlled shipments, the analysis presented in Appendix 7.1.3, *Shipping Period – Controlled Shipments*, of the TRUPACT-III TRAMPAC, justifies using a maximum shipping period of 10 days.[2] The

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[1] U.S. Department of Energy (DOE), *CH-TRU Payload Appendices*, current revision, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

[2] U.S. Department of Energy (DOE), *TRUPACT-III Authorized Methods for Payload Control (TRUPACT-III TRAMPAC)*, current revision, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

conditions specified in Section 3.2.4, *Controlled Shipments*, must be met for use of the controlled shipment shipping period.

## Void Volumes

Void volumes for net (total) gas accumulation within unsealed layers of confinement, within the SLB2, and within the TRUPACT-III CV are required to calculate decay heat limits. Because of the characteristics of the filters or other venting mechanism on any unsealed layer of confinement and on the SLB2, no pressure build-up can occur in any unsealed layer of confinement and, thus, the sum of all unsealed layers of confinement void volumes is available for net (total) gas accumulation. For a given SLB2, this summed (i.e., total) void volume will be used to calculate the decay heat limit. As determined in Appendix 7.1.5, *Determination of Void Volumes for TRUPACT-III Payload*, of the TRUPACT-III TRAMPAC, the TRUPACT-III CV void volume of 2,354 liters is calculated as the difference between an empty TRUPACT-III (10,019 liters, accounting for interior protruding features and ancillary handling equipment) and the external volume of the SLB2 (7,665 liters).[2] The void volumes within the SLB2 and within unsealed layers of confinement will be based on waste characterization data or a conservative estimate of the waste void fraction (25% per SLB2 per Section 2.1.1.4, *Percent Contribution to MNOP*).

## Pressure

The absolute gas pressure at the time the TRUPACT-III is closed for transport following the evacuation and backfill process is assumed to be equal to one atmosphere (101.325 kPa).

## Temperature

The major factors affecting the TRUPACT-III CV internal pressure are net (total) gas generation, thermal expansion of gases, and the vapor pressure of water within the cavity. In addition, the MNOP fractional contributions from sealed containers and aerosol cans will affect the internal pressure. After evacuation and backfill with an inert gas at an assumed temperature of 70 °F (21.1 °C), the TRUPACT-III is closed for transport. Temperatures are documented in Table 3.3-1, *NCT Hot Temperatures w/ SLB2 Payload*, of the TRUPACT-III SAR[3] at three different payload decay heats (20 watts, 40 watts, and 80 watts). Temperatures required to calculate pressure increases include the bulk average payload temperature ($T_{ap}$), the bulk average void volume (gas) temperature ($T_{avv}$), and the TRUPACT-III minimum inside wall temperature ($T_{minwall}$). The $T_{ap}$ is used to correct the effective G value as discussed in Section 2.3.3, *Example Calculation of Decay Heat Limit per SLB2*. The $T_{avv}$ is used to correct for the thermal expansion (i.e. heat-up) of gases. The water vapor pressure contribution is calculated based on the temperature of the coolest or condensing surface on the inner wall of the packaging, $T_{minwall}$.

[3] Packaging Technology, Inc., *Safety Analysis Report for the TRUPACT-III Shipping Package*, current revision, USNRC Docket No. 71-9305, Packaging Technology, Inc., Tacoma, Washington.

All three temperatures are approximately linear functions of decay heat and are summarized in Table 2.3-1. The relationships between temperature (°C) and decay heat (watts) are represented by the following regression equations:

$$T_{ap} = 0.52214\ Q + 48.70$$

$$T_{avv} = 0.18286\ Q + 48.40$$

$$T_{minwall} = 0.05107\ Q + 46.35$$

**Table 2.3-1** – Bounding Temperatures for Net (Total) Gas Generation Calculations

| Temperature | Symbol | Q = 20 watts | Q = 40 watts | Q = 80 watts | Slope | Intercept |
|---|---|---|---|---|---|---|
| | | Value (°C) | Value (°C) | Value (°C) | | |
| Bulk Average Payload Temperature | $T_{ap}$ | 59.0 | 69.8 | 90.4 | 0.52214 | 48.70 |
| Bulk Average Void Volume (Gas) Temperature | $T_{avv}$ | 52.0 | 55.8 | 63.0 | 0.18286 | 48.40 |
| TRUPACT-III Minimum Inside Wall Temperature | $T_{minwall}$ | 47.3 | 48.5 | 50.4 | 0.05107 | 46.35 |

**Waste Matrix (Net Gas G Values)**

The gas generation potential of a waste material is quantified by a G value, which is the number of molecules of gas generated per 100 electron volts (eV) of energy absorbed. The G value is used to convert the calculated ATGGR into a limit on decay heat per SLB2 as discussed later in this section. The G value is determined based on the bounding materials present in the SLB2. CH-TRU wastes that can be classified as solidified inorganics, solid inorganics, or solid organics based on the chemicals and materials present in the waste in quantities >1% (weight) and the list of allowable materials specified in the TRUPACT-III TRAMPAC (Table 4.3.2-1)[2] are bound by a net (total) gas G value of 8.4 (Appendix 3.2 of the CH-TRU Payload Appendices).[1] As described in Appendix 7.1.6, *Determination of Bounding Dose-Dependent Net Gas G Value for TRUPACT-III*, of the TRUPACT-III TRAMPAC, for SLB2s meeting a dose-criterion of >0.012 watt*year, a net (total) gas G value of 1.5 may be used.[2]

**Derivation of Allowable Total Gas Generation Rates**

The TRUPACT-III internal pressure at the end of the 10-day shipping period is the sum of four pressure components less an assumed atmospheric pressure, $P_{atm}$, of 1 atm (101.325 kPa). The four pressure components are as follows:

- Pressure corresponding to the moles of net (total) radiolytic gas generated during transport ($P_{rg}$).
- Pressure corresponding to the thermal expansion of gases due to heat up of gases during transport ($P_{hu}$).
- Water vapor (i.e., saturation) pressure ($P_{wv}$). The payload is assumed to contain a sufficient amount of water to reach saturation pressure. The water vapor pressure is based on the temperature of the coolest or condensing surface on the inner wall of the TRUPACT-III ($T_{minwall}$). The corresponding water vapor pressure at this temperature is simply the saturation pressure of steam obtained from the Bolton equation.[4]
- Pressure corresponding to the sum of the MNOP fractional contributions from sealed containers and aerosol cans ($P_{scac}$).

The maximum allowable TRUPACT-III internal pressure at the end of the 10-day shipping period, $P_{max}$, is equal to the MNOP. Thus, the $P_{max}$, or MNOP, may be defined in terms of the four pressure components as:

## Equation 1

$$P_{max} = MNOP = P_{rg} + P_{hu} + P_{wv} + P_{scac} - P_{atm}$$

Rearrangement of Equation 1 to solve for the net (total) radiolytic gas generation pressure contribution yields:

## Equation 2

$$P_{rg} = MNOP - P_{hu} - P_{wv} - P_{scac} + P_{atm}$$

The $P_{scac}$ term may be expressed by the following relationship:

## Equation 3

$$P_{scac} = MNOP \sum_{i=1}^{NSCAC} \pi_i$$

where,

| | | |
|---|---|---|
| $P_{scac}$ | = | Pressure corresponding to the sum of the MNOP fractional contributions from sealed containers and aerosol cans (from Step 12 of Section 2.3.1, *Compliance with MNOP*). |
| NSCAC | = | Number of sealed containers and aerosol cans within the SLB2 |
| $\pi_i$ | = | MNOP fractional contribution from sealed container or aerosol can "i". |

[4] D. Bolton, *The Computation of Equivalent Potential Temperature*, Monthly Weather Review, #108, p.p. 1046-1053, 1980.

## Thermal Expansion of Gases (Heat Up)

The pressure change due to thermal expansion of the gas is computed assuming an initial gas temperature of 21.1 °C. The pressure due to heat up is then calculated through the following relationship based on the Ideal Gas Law:

### Equation 4

$$P_{hu} = P_{atm} \frac{(T_{avv} + 273.15)K}{(21.1 + 273.15)K} \frac{101.325\ kPa}{atm}$$

where,

$P_{atm}$ = 1 atm.

Substitution of the values for MNOP and $P_{atm}$ into Equation 2 and simplifying results in:

### Equation 5

$$P_{rg} = 273.325\ kPa - P_{hu} - P_{wv} - P_{scac}$$

From the Ideal Gas Law, the allowable moles of net (total) gas that may be radiolytically generated, $N_{rg}$, is calculated as:

### Equation 6

$$N_{rg} = \frac{P_{rg}\ V_V}{(8.314\ kPa\ L\ mol^{-1}\ K^{-1})(T_{avv} + 273.15)K}$$

where,

$V_V$ = Total void volume within the TRUPACT-III CV (liters) and all unsealed layers of confinement voids. This volume is the sum of the void volume in the TRUPACT-III CV outside the SLB2 (2,354 liters), the void volume within the SLB2 surrounding the inner containers/contents, and the sum of the void volumes across all unsealed layers of confinement.

The ATGGR in units of mole/sec is calculated based on the shipping period duration, $t_{ship}$, (i.e., 10 days) as:

### Equation 7

$$ATGGR = \frac{N_{rg}}{t_{ship}\ (86{,}400 sec/day)} = \frac{N_{rg}}{(10\ days)(86{,}400\ sec/day)} = \frac{N_{rg}}{864{,}000\ sec}$$

## Derivation of the Decay Heat Limit per SLB2

The decay heat limit for the SLB2 is calculated from the ATGGR value and the effective, bounding net (total) gas G value at the bulk average payload temperature through the following expression (Equation (5) of Appendix 5.5 of CH-TRU Payload Appendices[1]):

## Equation 8

$$Q = \left[\frac{(ATGGR)(N_A)}{(G_{eff}\ \text{molecules}/100\ \text{eV})}\right][1.602E\text{-}19\ \text{watt-sec/eV}]$$

where:

| | | |
|---|---|---|
| Q | = | Decay heat limit per SLB2 (watts) |
| ATGGR | = | Allowable net (total) gas generation rate per SLB2 (mole/sec) |
| $N_A$ | = | Avogadro's number = 6.023E23 molecules/mole |
| $G_{eff}$ | = | Effective, bounding net (total) gas G value for the waste matrix at the bulk average payload temperature ($T_{ap}$); (molecules of net (total) gas formed/100 eV emitted energy). |

### 2.3.3 Example Calculation of Decay Heat Limit per SLB2

This section provides an example calculation of the ATGGR and corresponding decay heat limit for an example TRUPACT-III payload using the methodology detailed in Section 2.3.2, *Derivation of Decay Heat Limit based on MNOP*. Site implementation of this methodology may be performed either manually or through the use of a verified/validated software package.

The example assumes that the following sealed containers are present in an SLB2:

- One 5-gallon crimped lid steel bucket (16.0 psig burst pressure from Table 2.1-6)
- One 55-gallon bolted closure ring steel drum (28.2 psig burst pressure from Table 2.1-6)
- Two aerosol cans.

In addition, the SLB2 is assumed to contain several unsealed layers of confinement (that do not restrict the free flow of gases) such that the sum of the void volumes across all unsealed layers of confinement is 567 liters. Also, the example assumes that the void volume within the SLB2 surrounding the inner containers/contents is 789 liters.

**Methodology**

Using Table 2.1-1 of Section 2.1, *Pressure due to Sealed Container Deflagration*, the 5-gallon crimped lid steel bucket is assigned an MNOP fractional contribution of 0.04 (i.e., could contribute ~4% to the 25 psig (172 kPa) MNOP) and the 55-gallon bolted closure ring steel drum is assigned an MNOP fractional contribution of 0.50 (i.e., could contribute ~50% to the MNOP). Using Table 2.2-1 of Section 2.2, *Pressure due to Aerosol Can Contents Release*, the two aerosol cans are assigned an MNOP fractional contribution of 0.06 (i.e., could contribute 6% to the MNOP).

Thus, the total pressure contribution of sealed containers and aerosol cans to the MNOP may be calculated from Equation 3:

$P_{scac}$ = 172 kPa (0.04 + 0.50 + 0.06)

$P_{scac}$ = 103.2 kPa

The heat-up of gases pressure contribution, $P_{hu}$, at $T_{avv}$ = 57.0 °C is calculated from Equation 4 as 113.7 kPa. The water vapor pressure contribution, $P_{wv}$, at $T_{minwall}$ = 48.7 °C is calculated from the Bolton equation as 11.6 kPa. These temperatures are obtained through the iterative solution of Equation 4 through Equation 8.

The allowable net (total) radiolytic gas generation pressure contribution, $P_{rg}$, is calculated from Equation 5 as:

$$P_{rg} = 273.325\text{ kPa} - 113.7\text{ kPa} - 11.6\text{ kPa} - 103.2\text{ kPa}$$

$$P_{rg} = 44.8\text{ kPa}$$

From the Ideal Gas Law, the allowable moles of net (total) gas that may be radiolytically generated, $N_{rg}$, is calculated from Equation 6.

Again assumed for this example, the void volume within the SLB2 surrounding the inner containers/contents is 789 liters and the sum of the void volumes across all unsealed layers of confinement is 567 liters.

Thus, the total void volume is:

$$V_v = 2{,}354\text{ L} + 789\text{ L} + 567\text{ L}$$

$$V_v = 3{,}710\text{ L}$$

The allowable number of radiolytically generated moles of gas is thus:

$$N_{rg} = \frac{(44.8\text{ kPa})(3{,}710\text{ L})}{(8.314\text{ kPa L mol}^{-1}\text{ K}^{-1})(57.0 + 273.15)\text{K}}$$

$$N_{rg} = 60.55\text{ moles}$$

The ATGGR in units of mole/sec is then calculated from Equation 7 as follows:

$$\text{ATGGR} = \frac{60.55\text{ moles}}{864{,}000\text{ sec}}$$

$$\text{ATGGR} = 7.008\text{E–5 mole/sec}$$

## Derivation of Decay Heat Limit per SLB2

The temperature dependence of G values is approximated by the Arrhenius equation (see Appendix 3.1 of the CH-TRU Payload Appendices[1]):

$$G(T_{ap}) = G(T_{rt}) \times e^{\left[\frac{E_a}{R}\right]\left[\frac{(T_{ap} - T_{rt})}{(T_{ap} \times T_{rt})}\right]}$$

where,

$G(T_{ap})$ = Net gas G value at the bulk average payload temperature (molecules/100 eV)

$G(T_{rt})$ = Net gas G value at room temperature (8.4 molecules/100 eV) (For this example, it is assumed that the SLB2 has not met the >0.012 watt*year criterion for use of the dose-dependent G value)

$E_a$ = Activation energy (2.1 kcal/mole)

R = Gas constant (1.99E-3 kcal/mole K)

$T_{ap}$ = Bulk average payload temperature (346.4 K (73.2 °C))

$T_{rt}$ = Room temperature (294 K).

Substitution of the variables in the Arrhenius equation results in the following expression for the net gas G value at the bulk average payload temperature of 346.4 K:

$$G(346.4\,K) = 8.4\,\frac{\text{molecules}}{100\,\text{eV}} \times e^{\left[\frac{2.1\frac{\text{kcal}}{\text{mol}}}{1.99\text{E-}3\frac{\text{kcal}}{\text{mol K}}}\right]\left[\frac{(346.4\,K-294K)}{(346.4\,K\times 294K)}\right]}$$

$$G(346.4\,K) = 14.45\,\frac{\text{molecules}}{100\,\text{eV}}$$

The decay heat limit for the SLB2 is then calculated from the ATGGR value and the effective, bounding net (total) gas G value at the bulk average payload temperature using Equation 8.

$$Q = \left[\frac{(7.008\text{E-}5\text{ mole/sec})(6.023\text{E}23\text{ molecules/mole})}{(14.45\text{ molecules/100 eV})}\right][1.602\text{E-}19\text{ watt-sec/eV}]$$

Q = 46.795 watts

The decay heat limit calculated in this example was obtained through the iterative solution of Equation 4 through Equation 8 to resolve the dependence upon wattage of the various temperatures and functionally dependent pressures and G value utilized in the equations.

# 2.4 Appendix

## 2.4.1 Model for Evacuation of the TRUPACT-III

### 2.4.1.1 Introduction

After assembly in a TRUPACT-III, an SLB2 that has been certified in accordance with Section 3.0, *Payload Assembly*, undergoes the application of a vacuum as described in Section 3.2.3, *PREx Operating Controls and Conditions for Shipment*. The vacuum application is followed by backfilling with an inert gas (e.g., nitrogen, argon, or helium). The objective of the evacuation/backfill process is to reduce the concentration of oxygen (i.e., a potential oxidizer) within the TRUPACT-III CV, the SLB2, and any unsealed layers of confinement such that no flammable mixture and no possibility of a deflagration event exists within these void spaces during the shipping period.

### 2.4.1.2 Scope

This appendix describes the mathematical model for the evacuation of oxygen from all unsealed layers of confinement within the TRUPACT-III CV. A methodology has been developed that describes gas movement between void volumes during the application of a vacuum and the introduction of a backfill gas and accounts for the removal of oxygen from all unsealed layers of confinement. An allowable maximum oxygen concentration (MOC) for any unsealed layer of confinement of a TRUPACT-III package following the evacuation process has been determined as the oxygen concentration below which a deflagration cannot occur. The material balance equations are presented, along with model assumptions and model parameter definitions, including specifications for a minimum flow rate and a maximum allowable ultimate vacuum pump pressure. Based on a bounding packaging configuration for an SLB2, this appendix establishes a minimum vacuum duration as the time required to ensure that the MOC is not exceeded in any unsealed layer of confinement within the TRUPACT-III.

### 2.4.1.3 Maximum Oxygen Concentration following Evacuation and Backfill of TRUPACT-III Package

The derivation of the MOC for any unsealed layer of confinement is based on the requirements of a nationally acknowledged standard of the National Fire Protection Association (NFPA), NFPA 69, "Standard on Explosion Prevention Systems."[1] Section 4.1.1 of the NFPA 69 standard lists oxidant concentration reduction as a method to prevent combustion.[1] The standard defines "oxidant" as any gaseous material that can react with a fuel (gas, dust, or mist) to produce combustion and defines "limiting oxidant concentration" (LOC) as the concentration of oxidant below which a deflagration cannot occur.[1] Oxygen in air is the most common oxidant.

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[1] NFPA 69, *Standard on Explosion Prevention Systems*, 2002 Edition, National Fire Protection Association, Quincy, Massachusetts.

Based on previous experience with the TRUPACT-II package and transuranic (TRU) waste[2], the only oxidant of concern for the TRUPACT-III is oxygen as a component in air after evacuation and backfilling with an inert gas. In addition, because the TRUPACT-III is a leaktight package, oxygen will not be re-introduced into the cavity during transport. Appendix 2.4.2, *Oxygen Generation During Transportation of TRUPACT-III Payloads*, establishes the fact that generation of oxygen by radiolysis or by any other mechanism will be negligible during the shipping period. Hydrogen is the primary flammable gas of concern that may be radiolytically generated in TRU wastes. As required by Section 5.7.2.2 of the NFPA 69 standard[1], the determination of the LOC for a system shall be based on the worst credible case gas mixture yielding the smallest LOC. Per Table C.1(a) of Annex C of the NFPA 69 standard[1], the smallest LOC for a flammable gas is for hydrogen (or carbon disulfide). This LOC is 5% (volume) oxygen when nitrogen in air is the diluent.

The NFPA 69 standard defines the requirements for systems operated below the LOC. As the oxygen concentration of the TRUPACT-III package will not be continuously monitored during the shipping period, the requirements of Section 5.7.2.7.2 of the NFPA 69 standard apply as follows:

> "The procedure of pulling a partial vacuum and then breaking the vacuum with inert gas shall be permitted without measuring the oxygen concentration if the following apply:
>
> (1) The vacuum condition is held for a time to check for leakage.
>
> (2) The vacuum level is monitored.
>
> (3) The vacuum-creating medium is compatible with the process chemistry.
>
> (4) The residual oxygen partial pressure is calculated or demonstrated by test to be at least 40 percent below the LOC.

Section 3.2.3, *PREx Operating Controls and Conditions for Shipment*, describes the operational process for loading the TRUPACT-III for transport including the implementation of the vacuum application and the introduction of a backfill gas into the TRUPACT-III CV and leakage rate testing of the TRUPACT-III CV. The MOC in any unsealed layer of confinement is conservatively limited to 40 percent of the LOC.

Thus, the MOC is:

$$MOC = 0.4 \times 5\%\ O_2$$

$$MOC = 2.0\%\ O_2 = 9.52\%\ \text{air (as air is comprised of } 21\%\ O_2 \text{ and } 79\%\ N_2)$$

While the implementation of the NFPA 69 standard results in the determination of an MOC of 2% oxygen, an additional safety factor of two will be applied such that the evacuation process and subsequent backfilling with inert gas will result in an MOC of 1% (volume) or 4.76% air within any unsealed layer of confinement. As the gas removed during the evacuation process is air, an MOC of 1% oxygen corresponds to an absolute pressure after evacuation of 0.0476 atm within any unsealed layer of confinement.

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[2] U.S. Department of Energy, Appendix 6.12, "Use of TRUPACT-II for the Shipment of High-Wattage CH-TRU Waste," *CH-TRU Payload Appendices*, current revision, U.S. Department of Energy, Carlsbad, New Mexico.

### 2.4.1.4 Mathematical Analysis of Evacuation and Backfill of Gas in TRUPACT-III

The application of a vacuum on the loaded TRUPACT-III CV is designed to reduce the concentration of oxygen within all unsealed layers of confinement within the TRUPACT-III CV to an acceptable level defined by an MOC of 1% oxygen. Subsequent introduction of a backfill gas into the evacuated TRUPACT-III CV dilutes the remaining gases. This section documents the development and use of a mathematical model describing the evacuation of oxygen and nitrogen from all unsealed layers of confinement within the TRUPACT-III by application of a vacuum. The material balance equations are presented along with model assumptions and model parameter definitions. Model results are presented for a bounding case that establishes the minimum vacuum application duration required to ensure an MOC of less than or equal to 1% oxygen after the backfilling process.

#### 2.4.1.4.1 Model Assumptions

The assumptions used in the model development are as follows:

1. All gases are ideal.
2. As specified in Section 2.4, *Filter Vents*, of the TRUPACT-III TRAMPAC, each SLB2 to be transported in the TRUPACT-III shall be vented such that the minimum total hydrogen diffusivity of 9.90E-04 mole/sec/mole fraction is met.[3]
3. The initial pressure of all unsealed layers of confinement within the TRUPACT-III CV is 1 atm. The ambient atmospheric pressure outside the TRUPACT-III remains constant at 1 atm during the evacuation and backfilling process.
4. The ambient temperature during the vacuum application and backfilling process remains constant at 294 K.
5. There are potentially three primary means of gas transport across each confinement layer boundary:
    - Diffusion
    - Permeation (bags only)
    - Convection.

    As a conservative assumption (i.e., one which will overestimate the time required for vacuum application), only the transport by pressure-induced gas flow, or convection, is considered.
6. If present, each bag does not expand more than 20% of its original void volume during the evacuation process. When the volume limits are reached, the bag becomes a constant-volume confinement layer. For purposes of the simulations, it is assumed that the bags are fully expanded during the evacuation process. As discussed in Section 2.4.1.4.3.1, *Void Volumes*, this is a conservative assumption. Bags are not damaged by expansion or contraction.

[3] U.S. Department of Energy, *TRUPACT-III Authorized Methods for Payload Control (TRUPACT-III TRAMPAC)*, current revision, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

7. As specified in Section 2.4.1.4.3.5, *Vacuum Pump Characteristics*, the maximum gas flow rate out of the TRUPACT-III CV is 11.9 standard cubic feet per minute (scfm).
8. The MOC is 1.0% oxygen or 4.76 % air, as air is comprised of 21 volume or molar % oxygen and 79% nitrogen when other small constituents of air are ignored (see Section 2.4.1.3, *Maximum Oxygen Concentration following Evacuation and Backfill of TRUPACT-III Package*). Thus, pressure within the most restrictive unsealed layer of confinement at or below 0.0476 atm corresponds to the required vacuum application time such that the MOC will be 1% oxygen after the backfilling process.

### 2.4.1.4.2 Derivation of Gas Mass Balances

Figure 2.4-1 depicts the configuration of i to N containers (unsealed layes of confinement) (denoted by subscripts i and N) within an SLB2 (denoted by subscript B) that is loaded in the TRUPACT-III CV (denoted by subscript T) prior to the evacuation/backfill process.

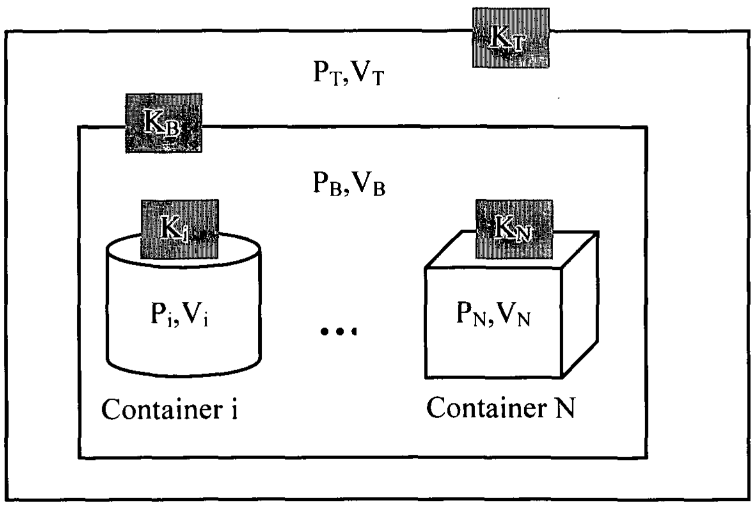


**Figure 2.4-1** – Schematic of Confinement Layers in SLB2 in TRUPACT-III

The following variables are used in the description of the mathematical model:

$n_B$ = Moles of gas in the SLB2 void volume (mole)

$n_T$ = Moles of gas in the TRUPACT-III CV (mole)

$n_i$ = Moles of gas in Container "i" void volume (mole)

$n_N$ = Moles of gas in Container "N" void volume (mole)

$P_B$ = Gas pressure inside the SLB2 void volume (atm)

$P_T$ = Gas pressure inside the TRUPACT-III CV void volume (atm)

$P_i$ = Gas pressure inside Container "i" void volume (atm)

$P_N$ = Gas pressure inside Container "N" void volume (atm)

$P_P$ = Ultimate vacuum pump pressure during vacuum application (50 mtorr = 6.58E-5 atm) and during the backfilling process (1 atm)

$K_T$ = Flow coefficient across the Swagelok Quick-Connect QC-8 fitting assumed to be used between the pump and the TRUPACT-III CV during the evacuation and backfill process (mole $sec^{-1}$ $atm^{-1}$)

$K_B$ = Flow coefficient across the filters installed on the SLB2 (mole $sec^{-1}$ $atm^{-1}$)

$K_i$ = Flow coefficient across the filter(s) installed on Container "i" (mole $sec^{-1}$ $atm^{-1}$)

$K_N$ = Flow coefficient across the filter(s) installed on Container "N" (mole $sec^{-1}$ $atm^{-1}$)

$V_B$ = Void volume within the SLB2 (liters)

$V_T$ = Void volume within the TRUPACT-III CV (liters)

$V_i$ = Void volume within Container "i" (liters)

$V_N$ = Void volume within Container "N" (liters)

$t$ = Time (sec)

$R$ = Gas law constant (0.082056 atm L $mole^{-1}$ $K^{-1}$ )

$T$ = Absolute ambient temperature (294 K)

$P_o$ = Absolute ambient system pressure (1 atm) and initial pressure inside all void volumes.

**Gas Mass Balance in Container "i" Void Volume:**

## Equation 1

$$\frac{dn_i}{dt} = -K_i(P_i - P_B)$$

Note that the product of the flow coefficient and the pressure difference across the filter(s) on Container "i" is equal to convection rate of gases across the filter(s). Applying the Ideal Gas Law and assuming that the void volume and temperature remain constant yields:

## Equation 2

$$\frac{V_i}{RT}\frac{dP_i}{dt} = -K_i(P_i - P_B)$$

Rearranging terms yields the following equation representing the mass balance on gas within the Container "i" void volume:

## Equation 3

$$\frac{dP_i}{dt} = -\frac{K_i RT(P_i - P_B)}{V_i}$$

**Gas Mass Balance in Container "N" Void Volume:**

## Equation 4

$$\frac{dn_N}{dt} = -K_N(P_N - P_B)$$

Applying the Ideal Gas Law and assuming that the void volume and temperature remain constant yields:

## Equation 5

$$\frac{V_N}{RT}\frac{dP_N}{dt} = -K_N(P_N - P_B)$$

Rearranging terms yields the following equation representing the mass balance on gas within the Container "N" void volume:

## Equation 6

$$\frac{dP_N}{dt} = -\frac{K_N RT(P_N - P_B)}{V_N}$$

**Gas Mass Balance in SLB2 Void Volume:**

## Equation 7

$$\frac{dn_B}{dt} = \sum_{i=1}^{N} K_i(P_i - P_B) - K_B(P_B - P_T)$$

Applying the Ideal Gas Law and assuming that the SLB2 void volume and temperature remain constant, yields:

## Equation 8

$$\frac{V_B}{RT}\frac{dP_B}{dt} = \sum_{i=1}^{N} K_i (P_i - P_B) - K_B (P_B - P_T)$$

Rearranging terms yields the following equation representing the mass balance on gas within the SLB2 void volume:

## Equation 9

$$\frac{dP_B}{dt} = \sum_{i=1}^{N} \frac{K_i RT(P_i - P_B)}{V_B} - \frac{K_B RT(P_B - P_T)}{V_B}$$

**<u>Gas Mass Balance in TRUPACT-III CV Void Volume:</u>**

## Equation 10

$$\frac{dn_T}{dt} = K_B (P_B - P_T) - K_T (P_T - P_P)$$

Applying the Ideal Gas Law and assuming that the TRUPACT-III void volume and temperature remain constant yields:

## Equation 11

$$\frac{V_T}{RT}\frac{dP_T}{dt} = K_B (P_B - P_T) - K_T (P_T - P_P)$$

Rearranging terms yields the following equation representing the mass balance on gas within the TRUPACT-III CV void volume:

## Equation 12

$$\frac{dP_T}{dt} = \frac{K_B RT(P_B - P_T)}{V_T} - \frac{K_T RT(P_T - P_P)}{V_T}$$

If a filtered container contains additional unsealed layers of confinement, gas mass balances for those layers and associated volumes may also be derived and included in the system of differential equations. For example, if a container has waste packaged in sequential bag layers, the collection of bags may be treated as a single layer by calculating the effective flow coefficient for flow in series. The vacuum application time will be a maximum if the sum of the multiple bag void volumes is assumed to be located within the innermost unsealed layer of confinement as air must pass through all layers, which corresponds to a maximum total resistance value for the collection of confinement layers. Assuming that the bags are within the previously defined Container "i", the gas mass balance on the multiple bags void volume becomes:

## Equation 13

$$\frac{dP_{ICL}}{dt} = -\frac{K_{bags}RT(P_{ICL} - P_i)}{V_{ICL}}$$

where,

$K_{bags}$ = Effective flow coefficient for all bags in series (mole $sec^{-1}$ $atm^{-1}$)

$P_{ICL}$ = Gas pressure within the innermost unsealed layer of confinement void volume of Container "i" (atm)

$V_{ICL}$ = Void volume within the innermost unsealed layer of confinement void volume of Container "i" (liters).

Then, Equation 3 is replaced by:

## Equation 14

$$\frac{dP_i}{dt} = \frac{K_{bags}RT(P_{ICL} - P_i)}{V_i} - \frac{K_iRT(P_i - P_B)}{V_i}$$

where, the definitions of $P_i$ and $V_i$ are revised as follows to indicate that the void volume refers to the container headspace void volume (i.e., volume outside the bags and within Container "i"):

$P_i$ = Gas pressure inside the Container "i" headspace void volume (atm)

$V_i$ = Void volume within the Container "i" headspace void volume (liters).

### 2.4.1.4.3 Parameter Values

The parameters that effect the required duration of the evacuation process include the following:

- Available void volumes within each unsealed layer of confinement (drums, containers, bags, cans, etc.)
- Available void volume within the SLB2
- Available void volume within the TRUPACT-III with an SLB2
- Ultimate vacuum pump pressure
- Temperature
- Container filter flow coefficients (i.e., unsealed layers of confinement with filters)
- Other unsealed layer of confinement flow coefficients
- SLB2 filter flow coefficient.

#### 2.4.1.4.3.1 Void Volumes

Void volumes are required to solve the transient mass balances on gas within each unsealed layer of confinement, the SLB2, and within the TRUPACT-III CV. The TRUPACT-III CV void

volume of 2,354 liters is calculated as the difference between an empty TRUPACT-III (10,019 liters, accounting for interior protruding features and ancillary handling equipment) and the external volume of the SLB2 (7,665 liters) (Appendix 7.1.5, *Determination of Void Volumes for TRUPACT-III Payload*, of the TRUPACT-III TRAMPAC).[3] The void volume within the SLB2 will be based on waste characterization data or a conservative estimate of the waste void fraction. An empty SLB2 has an internal volume of 7,394 liters (Appendix 7.1.5, *Determination of Void Volumes for TRUPACT-III Payload*, of the TRUPACT-III TRAMPAC).[3]

A bounding packaging configuration in the SLB2 is defined to determine the longest required vacuum application duration. A bounding configuration for evacuation duration is established by Appendix 6.12 of the CH-TRU Payload Appendices[2]. As detailed in Appendix 6.12 of the CH-TRU Payload Appendices, Content Code SQ 154A describes waste that is packaged in a maximum of four layers of inner plastic bags. Bagged out items are placed in a 55-gallon drum lined with a maximum of two plastic liner bags. Thus, there are a total of six plastic bag layers. All bag closures are by the twist-and-tape method. The 55-gallon drum is lined with a rigid liner with a lid that is punctured with a ≥0.3-inch diameter hole, and the drum is vented with a filter with a hydrogen diffusivity value of 3.70E-06 mol/s/mol fraction.

An estimate of the void volumes in a 55-gallon drum containing solid organic waste is established in Appendix 3.7 of the CH-TRU Payload Appendices[2]. The multiple bag void volume is 107 liters, the void volume within the rigid liner is 20.4 liters, and the 55-gallon drum headspace (annular) void volume between the rigid liner and the drum is 28.0 liters. The calculated vacuum application time will be a maximum if the sum of the multiple bag void volumes is assumed to be located within the innermost unsealed layer of confinement. The bags will expand when exposed to a vacuum and contract when the cavity pressure is equilibrated through backfilling after applying a vacuum. Of the 48.4 liters of void volume outside the bags, 28 liters is outside the rigid liner. Thus, it is assumed that bags do not expand beyond 20.4 liters, approximately 20% of their original volume. The rigid liner lid with a minimum 0.3-inch diameter hole will offer virtually no resistance to convective-induced flow of gases and is not considered in the determination of total resistance. Thus, two volumes within the drum will be modeled: (1) the 127-liter void volume within the innermost unsealed layer of confinement and (2) the 28-liter drum headspace (annular void volume). Given that a 55-gallon drum has an external volume of 236 liters, the theoretical maximum number of 55-gallon drums that may fit inside an SLB2 is 31 (7,394 liters / 236 liters). The actual number that could fit inside an SLB2 is lower because of geometric considerations. The required vacuum application duration is calculated for two cases: (1) a single 55-gallon drum in the SLB2 and (2) thirty 55-gallon drums in the SLB2 for the purpose of evaluating the impact of multiple containers on the vacuum application time.

#### 2.4.1.4.3.2 Pressure

The ambient pressure is assumed to be isobaric and equal to one atmosphere (1 atm). The initial gas pressure within each void volume is also assumed to be atmospheric (1 atm). During the evacuation process, the maximum allowable ultimate vacuum pump pressure is 50 millitorr (mtorr) or 6.58E-5 atm (Section 6.12.9.2.4, *Gas Flow Rate Across ICV*, of Appendix 6.12 of the CH-TRU Payload Appendices[2]). The required vacuum application time corresponds to the length of time following the start of vacuum application when the pressure within the innermost unsealed layer of confinement drops to or below 0.0476 atm. This gas pressure corresponds to

an MOC of 1% oxygen after the backfilling process (see Section 2.4.1.3, *Maximum Oxygen Concentration following Evacuation and Backfill of TRUPACT-III Package*).

#### 2.4.1.4.3.3 Temperature

Temperature affects the rate of diffusion and the corresponding flow coefficient through the filter(s) on the containers within the SLB2 and on the SLB2. A constant ambient room temperature of 70°F (21°C, 294 K) will be used in all calculations. This is the temperature corresponding to the time when the TRUPACT-III CV is loaded with the SLB2 and the vacuum application and backfilling process is initiated.

#### 2.4.1.4.3.4 Flow Coefficients

Flow resistance across a filter has been measured where the flow rate across is directly proportional to the pressure drop across the filter (Section 6.12.9.2.3, *Flow Coefficients*, of Appendix 6.12 of the CH-TRU Payload Appendices[2]). The minimum flow coefficient across filters with an average hydrogen diffusion coefficient, $D_{ref}$, approximately equal to 3.70E-6 mol/s/mol fraction, $K_{ref}$, was 2.8E-2 mol $s^{-1}$ $atm^{-1}$.

### Equation 15

$$K_{ref} = \left\{\frac{(27-4)\text{slpm}}{[(10-1)\text{psi}]}\right\}\left\{\frac{14.7}{(22.4*60)}\right\} = 2.8\text{E-2 mol s}^{-1}\text{ atm}^{-1}$$

where,

slpm = standard liters per minute.

The flow coefficient, $K_{filter}$, across any filter with a diffusivity value, $D_{filter}$, can then be calculated assuming that it is proportional to the hydrogen diffusivity as:

### Equation 16

$$K_{filter} = K_{ref}\left(\frac{D_{filter}}{D_{ref}}\right)$$

Or

### Equation 17

$$K_{filter} = 2.8\text{E-2 mol s}^{-1}\text{ atm}^{-1}\left(\frac{D_{filter}}{3.70\text{E-6 mol/s/mf}}\right)$$

The drum is assumed to be fitted with a filter that has a hydrogen diffusion coefficient, $D_{filter}$, of 3.70E-6 mol/s/mol fraction. Thus, the flow coefficient, $K_{filter}$, across the filter(s) installed on a 55-gallon drum is calculated to be 2.8E-2 mole $sec^{-1}$ $atm^{-1}$. The total minimum hydrogen diffusivity of the filter(s), $D_{filter}$, on the SLB2 is 9.90E-4 mol/sec/mol fraction. Thus, the flow coefficient across the filter(s) installed on the SLB2 is calculated to be 7.5 mole $sec^{-1}$ $atm^{-1}$.

For a bag, the flow coefficient is similarly calculated as:

## Equation 18

$$K_{bag} = K_{ref}\left(\frac{D_{bag}}{D_{ref}}\right)$$

The flow coefficients for a small inner bag (sb) and drum liner bag (lb) closures have previously been established in Section 6.12.9.2.3, *Flow Coefficients*, of Appendix 6.12 of the CH-TRU Payload Appendices[2] based on diffusion coefficients through the closure only as:

$K_{sb}$ = 2.8E-2 (5.6E-7/3.70E-6) mol $s^{-1}$ $atm^{-1}$ = 4.2E-3 mol $s^{-1}$ $atm^{-1}$

$K_{lb}$ = 2.8E-2 (1.0E-6/3.70E-6) mol $s^{-1}$ $atm^{-1}$ = 7.6E-3 mol $s^{-1}$ $atm^{-1}$

For the bounding configuration there are 4 small inner bags and 2 drum liner bags. The effective flow coefficient from the six bags in series is calculated as:

$K_{bags}$ = 1 / (4/4.2E-3 + 2/7.6E-3) mol $s^{-1}$ $atm^{-1}$ = 8.2E-4 mol $s^{-1}$ $atm^{-1}$

If sites have waste packaging configurations with other unsealed layers of confinement (e.g., without known release rates), testing or analysis can be used to establish that the packaging configuration with unsealed layers of confinement is bound by the packaging configurations analyzed.

The flow coefficient across the Swagelok Quick-Connect QC-8 fitting is quantified in Section 2.4.1.4.3.5, *Vacuum Pump Characteristics.*

### 2.4.1.4.3.5 Vacuum Pump Characteristics

The vacuum pump performance or the flow resistances across fittings connecting the vacuum pump with the TRUPACT-III CV limit the maximum gas flow rate out of the cavity. A minimum flow rate (at ambient pressure) of 11.9 scfm is used in the evaluation based on the flow rating of the Swagelok® Quick-Connect QC-8 fitting to be used during TRUPACT-III loading/unloading procedures. This fitting is considered the most restrictive point to gas flow between the vacuum pump and TRUPACT-III CV. The double-end shut-off fitting is rated for air at a flow rate of 81 scfm at a pressure differential of 100 psi (Section 6.12.9.2.4, *Gas Flow Rate Across ICV*, of Appendix 6.12 of the CH-TRU Payload Appendices[2]). Assuming a linear relationship between air flow and pressure differential, at a pressure differential of 14.7 psi (assuming initial system pressure of 1 atm), the initial air flow rate at zero vacuum in the TRUPACT-III CV is 11.9 scfm [81 scfm (14.7 psi / 100 psi) = 11.9 scfm].[2]

A flow coefficient across the fitting, $K_{fit}$ is defined in terms of the gas flow rate, F, at a particular pressure differential, ΔP:

## Equation 19

$$K_{fit} = \frac{F}{\Delta P}$$

At standard pressure and temperature, 1 mol of gas occupies 22.4 liters. Thus, the minimum flow coefficient for any fitting is defined in terms of the Swagelok Quick-Connect QC-8 fitting previously used[2] in applying a vacuum on a TRUPACT-II ICV:

$$K_{fit} = (81 \text{ scfm} / 100 \text{ psi})(14.7 \text{ psi} / \text{atm})(1000 \text{ L} / 35.3145 \text{ ft}^3)(\text{mol} / 22.4 \text{ L})(\text{min} / 60 \text{ s})$$

$$= 0.25 \text{ mol s}^{-1} \text{ atm}^{-1}$$

A linear relationship between air flow (scfm) and the pressure differential across the fitting is assumed. A similar relationship between gas flow and intake pressure is observed in oil-free roughing pumps. Direct-drive, oil-sealed vacuum pumps designed to operate at lower ultimate pressures generally maintain a constant gas flow until the intake pressure approaches the ultimate pressure; therefore, a linear relationship between gas flow and intake (CV) pressure is considered to be conservative. The maximum allowable ultimate vacuum pump pressure is 50 mtorr or 6.58E-5 atm.

### 2.4.1.4.3.6 Calculational Results

The required vacuum application time was calculated for the following two cases:

- A single 55-gallon drum in the SLB2 with 6 layers of bags (4 small inner bags and 2 drum liner bags)
- Thirty 55-gallon drums in the SLB2 each with 6 layers of bags (4 small inner bags and 2 drum liner bags).

The times for each case were calculated by numerically solving the appropriate system of gas mass balance differential equations with initial conditions. The results of the calculations are summarized in Table 2.4.1-1.

The calculation results summarized in Table 2.4.1-1 demonstrate that additional containers have minimal impact on the calculated vacuum application time. Based on the results, a bounding minimum vacuum duration of 6.5 hours is established as the time required to ensure an internal vacuum pressure of less than or equal to 0.0476 atm in any confinement layer. This assumes a vacuum pump with a minimum flow rate (at ambient pressure) of 11.9 scfm and a maximum allowable ultimate vacuum pump pressure of 50 mtorr. The internal vacuum pressure of less than or equal to 0.0476 atm (36 torr) ensures an MOC of less than or equal to 1% oxygen after the backfilling process.

**Table 2.4.1-1** – Required Vacuum Application Times

| Case | Required Vacuum Application Time (hrs) |
|---|---|
| SLB2 contains 1 filtered 55-gallon drum with 6 plastic bag layers (4 small inner bags and 2 drum liner bags). | 6.13 |
| SLB2 contains 30 filtered 55-gallon drums each with 6 plastic bag layers (4 small inner bags and 2 drum liner bags) | 6.35 |

## 2.4.2 Oxygen Generation During Transportation of TRUPACT-III Payloads

### 2.4.2.1 Summary

Oxygen generation in TRUPACT-III payloads will be insignificant during transportation, given the largely inert nature of the waste that minimizes thermal, biological, and chemical activity. Radiolysis will most likely result in the consumption of oxygen, given that the payloads are primarily organic or inorganic debris materials or large bulky equipment. In addition, while the maximum shipping period is 10 days, the actual transport time is expected to be only a few days, minimizing the time period the payload is sealed within the TRUPACT-III CV.

### 2.4.2.2 Purpose and Scope

The purpose of this appendix is to establish that the TRUPACT-III and SLB2 void spaces and unsealed layers of confinement will remain non-flammable during the shipping period (limited to 10 days). This appendix documents that any potential oxygen generation during the shipping duration is insignificant and will have no impact on the evacuation/backfill methodology for reducing oxygen concentrations in unsealed layers of confinement in TRUPACT-III payloads.

### 2.4.2.3 TRUPACT-III Payload Analysis with Respect to Potential Oxygen Generation

As described in the Appendices 6.1, 6.5, and 6.6 of the CH-TRU Payload Appendices[1], gas generation due to chemical, biological, and thermal mechanisms is insignificant during transport (these mechanisms in most cases result in oxygen consumption). Radiolysis is the primary mechanism for potential gas generation for the CH-TRU wastes that comprise the TRUPACT-III payload. Appendix 3.1 of the CH-TRU Payload Appendices[1] presents a detailed summary of the literature on the radiolysis of materials that could be present in CH-TRU wastes. For the TRUPACT-III, these CH-TRU payload materials are primarily solid organic and inorganic materials. Examples are debris materials such as paper, plastic, cellulose, etc., resulting from decontamination and decommissioning or laboratory activities, and inorganics such as glass, metal, equipment, etc. Potential gas generation from solid inorganic materials could be from the plastic bags used to package the waste.

In general, radiolysis results in the generation of free radicals and oxygen readily reacts with these free radicals, resulting in its consumption.[1] Several experiments with materials like polyethylene and cellulose, which are common materials in CH-TRU wastes, consistently demonstrate net oxygen consumption. For example, irradiation of commercial samples of high-density polyethylene and low-density polyethylene in air resulted in all of the oxygen in the sample tubes being consumed.[2] Similar results were seen by other researchers with polyethylene

[1] U.S. Department of Energy (DOE), *CH-TRU Payload Appendices*, current revision, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

[2] Bersch, C. F., et al., *Effect of Radiation on Plastic Films*, Modern Packaging 32, pp. 117-168, 1959.

irradiation resulting in the depletion of oxygen.[3] Irradiation of cellulosic materials like paper and Kimwipes® also resulted in the rapid depletion of the oxygen initially present.[3,4]

Oxygen generation in specific configurations of high nitrate compounds and solutions like nitric acid or high nitrate sludges has been observed[5,6]; however, these materials are not present in any significant amounts in the CH-TRU material to be transported in the TRUPACT-III. For example, aqueous sludges with high nitrate concentrations have been shown to generate oxygen, but the gas generation decreased as the water content of the sludge and the nitrate content decreased. The TRUPACT-III payloads applicable to the PREx are debris materials, including cellulose and plastic materials, that have been shown to consume oxygen due to radiolysis. Free liquids are not expected to be present in TRUPACT-III payloads and are also restricted as described in the TRUPACT-III TRAMPAC.[7]

As discussed in Appendix 2.4.1, *Model for Evacuation of the TRUPACT-III*, the evacuation backfill process ensures that oxygen in all unsealed layers of confinement, the SLB2, and the TRUPACT-III CV is reduced to well below its limiting oxidant concentration (1% versus a limiting oxidant concentration of 5% below which a deflagration cannot occur). While the maximum shipping period is 10 days, based on data from more than 4,500 CH-TRU waste shipments made to date in the TRUPACT-II and HalfPACT packagings, the typical shipping time for waste in a TRUPACT-III is expected to be less than three days.

Given the nature of the waste, the short shipping time, and the potential mechanisms of gas generation and consumption, no viable mechanism for other than negligible oxygen generation exists during transportation.

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[3] Kazanjian, A. R. and A.K. Brown, *Radiation Chemistry of Materials used in Plutonium Processing*, The Dow Chemical Company, Rocky Flats Division, RFP-1373, December 1969.

[4] Kosiewicz, S. T., *Gas Generation from Organic Transuranic Wastes. I. Alpha Radiolysis at Atmospheric Pressure*, Nuclear Technology 54, pp. 92-99, 1981.

[5] Bibler, N.E., *Curium-244 Radiolysis of Nitric Acid. Oxygen Production from Direct Radiolysis of Nitrate Ions*, J. Phys. Chem. 78, pp. 211-215, 1974.

[6] Lewis, E. L., *TRU Waste Certification: Experimental Data and Results*, Monsanto Research Corporation, Mound Laboratory, MLM-3096, September 1983.

[7] U.S. Department of Energy, *TRUPACT-III Authorized Methods for Payload Control (TRUPACT-III TRAMPAC)*, current revision, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

# 3.0 PAYLOAD ASSEMBLY

This section presents an overview of the control procedures that shall be used by the sites in order to assemble a payload qualified for transport in the TRUPACT-III. The parameters described in this document and in applicable sections of the TRUPACT-III TRAMPAC[1] shall be evaluated for selection of the payload. If any of the limits are not met by the SLB2, it shall be rejected from transport (subject to mitigation or repackaging), marked, and segregated.

## 3.1 Requirements

The TRUPACT-III payload shall be authorized for shipment by the site Transportation Certification Official (TCO) by completing and signing the PREx Payload Transportation Certification Document (PPTCD)

The shipping records shall be maintained by the shipper for a minimum period of three years after the shipment is made.

[1] U.S. Department of Energy (DOE), *TRUPACT-III Authorized Methods for Payload Control (TRUPACT-III TRAMPAC)*, current revision, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

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# 3.2 Methods of Compliance and Verification

## 3.2.1 Procedure for Certification of Individual Payload Containers

Sites shall qualify an SLB2 for transport in the TRUPACT-III by verifying that the container meets the parameter requirements/limits of this document summarized in Table 3.2-1, *PREx Payload Transportation Certification Document (PPTCD).* The information in Table 3.2-1 must be completed for each SLB2. Table 3.2-1 may be reformatted for site use. All parameters noted on the form must be included in modified versions. Data on the parameters shall be obtained by methods outlined in this document or the TRUPACT-III TRAMPAC.[1] Table 3.2-1 shall be completed as follows (section numbers in parentheses refer to sections in this document or the TRUPACT-III TRAMPAC that provide requirement information for the transportation parameter described):

Identification Parameters

- SLB2 ID # (Section 2.3 of the TRUPACT-III TRAMPAC): The site-specific identification (ID) number is unique to each container of waste and provides a means for tracking data records and package history. These records on the properties of the container are referred to as the data package. The container ID number assigned to the container appears on a label affixed to the payload container and can be read for visual verification or for electronic retrieval (i.e., bar codes). This ID number may be used to track data necessary for payload container compliance determinations.
- Certification Site: This is the location at which transportation certification takes place.
- Payload container specifications are met (Section 2.8.1 of TRUPACT-III TRAMPAC and Appendix 1.5.1, *Payload Container General Arrangement Drawings*): Compliance with the payload container specifications of Section 2.8.1 of the TRUPACT-III TRAMPAC and Appendix 1.5.1, *Payload Container General Arrangement Drawings*, shall be ensured.
- Filter specifications of Section 2.4 of the TRUPACT-III TRAMPAC are met: Compliance with the filter specifications in Section 2.4 of the TRUPACT-III TRAMPAC shall be ensured.

Transportation Parameters

Compliance information for the transportation parameters shall be obtained from the data package for the container. The following criteria shall be met:

- Criteria:
  - Residual liquids are <1% of the payload container volume. (Section 2.5 of the TRUPACT-III TRAMPAC)
  - Sharp/heavy objects are blocked/braced/suitably packaged. (Section 2.6 of the TRUPACT-III TRAMPAC) This requirement is met if blocking, bracing, or

[1] U.S. Department of Energy (DOE), *TRUPACT-III Authorized Methods for Payload Control (TRUPACT-III TRAMPAC)*, current revision, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

packaging is ensured within the payload container or if sharp/heavy objects are not present.

- Radioactive pyrophorics are ≤1% (weight). (Section 4.1 of the TRUPACT-III TRAMPAC)
- Nonradioactive pyrophorics are not present or have been reacted. (Section 4.1 of the TRUPACT-III TRAMPAC)
- Explosives are not present. (Section 4.2 of the TRUPACT-III TRAMPAC)
- Corrosives are not present. (Section 4.2 of the TRUPACT-III TRAMPAC)
- Compressed gases (e.g., compressed air cans/cylinders) are not present. (Section 4.2 of the TRUPACT-III TRAMPAC). Note: Pressurized containers (i.e., aerosol cans and sealed containers >4 liters) are allowed per the methodology described in Section 2.1, *Pressure due to Sealed Container Deflagration*, Section 2.2, *Pressure due to Aerosol Can Contents Release*, and Section 2.3, *MNOP Compliance Methodology*.
- Beryllium and/or beryllium oxide are ≤1% of waste weight (Section 3.1 of the TRUPACT-III TRAMPAC)
- Machine-compacted waste is not present (Section 3.1 of the TRUPACT-III TRAMPAC)

- Weight Limit (Section 2.2 of the TRUPACT-III TRAMPAC): The loaded weight of each SLB2 is obtained from its data package. The SLB2 weight plus error shall be compared to the maximum allowable weight limit of 10,500 pounds.
- Fissile Mass Limit (Section 3.1 of the TRUPACT-III TRAMPAC): The Pu-239 fissile gram equivalent (FGE) of the payload container shall be recorded. The Pu-239 FGE plus two times the error (i.e., two standard deviations) of the payload container shall be compared to the applicable FGE limit per payload.
- Decay Heat Limit (Section 2.3, *MNOP Compliance Methodology*): Compliance with the MNOP shall be by compliance with the decay heat limit per SLB2. The decay heat of the SLB2 shall be determined as described in Section 3.1 of the TRUPACT-III TRAMPAC. The decay heat plus error (i.e., one standard deviation) shall be compared to the decay heat limit determined for the SLB2 in accordance with the methodology described in Section 2.3. Each SLB2 qualified for TRUPACT-III shipment as described in this document must be shipped as a controlled shipment in accordance with the controls specified in Appendix 7.1.3 of the TRUPACT-III TRAMPAC and Section 3.2.4, *Controlled Shipments*. Table 3.2-2 must be completed as described in Section 3.2.4.
- Activity Limit (Section 3.3 of the TRUPACT-III TRAMPAC): The total payload container activity shall be less than or equal to $10^5$ $A_2$ curies.
- Radiation Dose Rate Limit (Section 3.2 of the TRUPACT-III TRAMPAC): The measured radiation dose rate at the surface of the payload container shall be ≤200 mrem/hour.

If the above requirements are met, proceed to Section 3.2.2, *Procedure for Certification of a TRUPACT-III Package*.

### 3.2.2 Procedure for Certification of a TRUPACT-III Package

Compliance with the SLB2 requirements ensures compliance with the TRUPACT-III package requirements, except for the weight and dose rate measurements for the loaded package. No additional controls, other than certifying the SLB2 and meeting the weight and dose rate requirements of Section 2.2 and Section 3.2 of the TRUPACT-III TRAMPAC, are needed for certifying the package for shipment. Compliance with the dose rate limits for the loaded package shall be documented in accordance with site-specific procedures.

- TRUPACT-III Body ID No.: Record the ID number of the TRUPACT-III body.
- Shipment No.: Record the shipment number of the trailer.
- Weight of Payload Loading Pallet and Roller Floor (Section 2.2 of the TRUPACT-III TRAMPAC): The total weight of the pallet and roller floor is recorded. If the weight is determined through a single measurement of the payload assembly, indicate the weight of the pallet and roller floor is not applicable (e.g., "NA").
- Total Weight (Section 2.2 of the TRUPACT-III TRAMPAC): The sum of the payload container weight plus the weight of the pallet and roller floor shall be recorded.
- Total Weight plus Error Less Than or Equal to Payload Assembly Limit (Section 2.2 of the TRUPACT-III TRAMPAC): The payload container weight plus the weight of the pallet and roller floor plus the weight error shall be less than or equal to 11,409 lbs.
- Transportation Certification Official: The site TCO shall verify that all of the requirements for the above transportation parameters are met as stated in this document. The site TCO shall sign and date the PPTCD upon verifying that the TRUPACT-III PREx and applicable portions of the TRUPACT-III TRAMPAC transportation requirements are met, thereby authorizing the payload for shipment in accordance with Section 3.2.3 and Section 3.2.4. If the requirements are not met, the payload is rejected (payload may be reconfigured and reevaluated against the payload requirements in this document).

### 3.2.3 PREx Operating Controls and Conditions for Shipment

Loading the TRUPACT-III for transport involves (1) qualification and approval of an SLB2 payload container in accordance with this document, (2) loading the prepared SLB2 payload container into the TRUPACT-III, (3) applying a vacuum to evacuate the TRUPACT-III containment vessel and then backfilling with an inert gas, and (4) leakage rate testing of the TRUPACT-III. The process of loading the TRUPACT-III and leakage rate testing the containment boundary O-ring seals is detailed in Section 7.1 of the TRUPACT-III SAR. The implementation of the vacuum application and the introduction of an inert backfill gas into the TRUPACT-III containment vessel are controlled using the procedures delineated in Section 7.1 of the TRUPACT-III SAR with the following modifications and/or additions.

3.2.3.1 If pre-shipment leakage rate testing is performed per the requirements of Section 8.2.2.2 or 8.2.2.3 of the TRUPACT-III SAR, then during testing

a. Evacuation of the payload cavity shall be performed utilizing a vacuum pump with the minimum specifications of a) minimum flow rate (at ambient pressure) of 11.9 scfm and (b) an ultimate vacuum pump pressure of less than or equal to 50 mtorr.

b. Evacuation of the payload cavity shall be performed for a minimum of 6-1/2 hours until the containment vessel internal vacuum pressure is less than or equal to 0.0476 atm (36 torr).

c. After evacuation of the payload cavity, proper tooling and valving shall be employed to ensure that the evacuated payload cavity is backfilled with helium only and that atmospheric air is not allowed to pass back into the payload cavity.

3.2.3.2 If pre-shipment leakage rate testing is performed per the requirements of Section 7.4 of the TRUPACT-III SAR, then prior to testing

a. Evacuation of the payload cavity shall be performed utilizing a vacuum pump with the minimum specifications of a) minimum flow rate (at ambient pressure) of 11.9 scfm and (b) an ultimate vacuum pump pressure of less than or equal to 50 mtorr.

b. Evacuation of the payload cavity shall be performed for a minimum of 6-1/2 hours until the containment vessel internal vacuum pressure is less than or equal to 0.0476 atm (36 torr).

c. After evacuation of the payload cavity, proper tooling and valving shall be employed to ensure that the evacuated payload cavity is backfilled with helium, nitrogen, or argon and that atmospheric air is not allowed to pass back into the payload cavity.

### 3.2.4 Controlled Shipments

Compliance with the 10-day shipping period is administratively controlled in accordance with the conditions of Appendix 7.1.3 of the TRUPACT-III TRAMPAC, and through the following steps. These steps must be completed by the site Transportation Certification Official, or designee, and the designated receiving site operations personnel, as applicable.

Loading Time

The loading time begins with the completion of the TRUPACT-III payload cavity evacuation process and ends with the departure of the shipment from the site. The loading time is limited to a maximum of 24 hours. The following steps must be completed to ensure compliance with the 24-hour loading time:

3.2.4.1 Record the date and time that the TRUPACT-III payload cavity evacuation process was completed. Record date and time on Table 3.2-2. Table 3.2-2 may be reformatted for site use provided that the same information is recorded.

3.2.4.2 Note date and time that the shipment containing the loaded package is scheduled to depart the site. Record date and time on Table 3.2-2.

3.2.4.3 Review dates and times recorded in Steps 3.2.4.1 and 3.2.4.2 to calculate total loading time. If total loading time is less than or equal to 24 hours, proceed to Step 3.2.4.4. If total Loading Time exceeds 24 hours, the package must be vented and the evacuation and backfill with inert gas process must be repeated. Return to Step 3.2.4.1 above.

3.2.4.4 Indicate compliance with the 24-hour loading time by signature on Table 3.2-2.

Transport and Unloading Time

The transport and unloading time begins with the departure of the shipment from the shipping site and ends with the venting of the package at the receiving site. The maximum transport and unloading time is 9 days. The following steps must be completed to document compliance:

3.2.4.5 Review Table 3.2-2 to determine the date and time that the package was scheduled to depart from the shipping site. Record this date and time on Table 3.2-3. Table 3.2-3 may be reformatted for site use provided that the same information is recorded.

3.2.4.6 Using the date and time recorded in Step 3.2.4.5, ensure that the package is vented within 9 days of the departure of the shipment from the shipping site by implementing the site unloading procedures specific to controlled shipments. Record date and time to show compliance.

3.2.4.7 Indicate compliance with the 9-day transport and unloading time by signature on Table 3.2-3.

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# Table 3.2-1 – PREx Payload Transportation Certification Document (PPTCD)

**IDENTIFICATION PARAMETERS**

SLB2 ID #: ______________________ Certification Site: ____________________

Container Designated for Controlled Shipment?① ☑ Yes

Payload container specifications are met.

Filter specifications of Section 2.4 of TRUPACT-III TRAMPAC are met.

**TRANSPORTATION PARAMETERS**

**Criteria:**

- Residual liquids are <1% of payload container volume
- Sharp/heavy objects blocked/braced/suitably packaged
- Radioactive pyrophorics are ≤1% (weight)
- Nonradioactive pyrophorics are not present or have been reacted
- Explosives are not present
- Corrosives are not present
- Compressed gases are not present (e.g., compressed air cans/cylinders)
- Beryllium and/or beryllium oxide are ≤1% of waste weight
- Machine-compacted waste is not present

**Weight Limit:**

| Value (pounds) | Error | Value + 1X Error (pounds) | Limit (pounds) |
|---|---|---|---|
| | | | 10,500 |

**Fissile Mass Limit:**

| Value (Pu-239 FGE) | Error | Value (Pu-239 FGE) + 2X Error | Limit |
|---|---|---|---|
| | | | ______ Pu-239 FGE |

**Decay Heat Limit:**

| Value (watt) | Error | Value + 1X Error (watt) | Limit (watt)② |
|---|---|---|---|
| | | | |

**Activity Limit:** Activity less than or equal to $10^5$ $A_2$ curies

| | |
|---|---|
| **Radiation Dose Rate Limit:** ③ | Payload container surface radiation dose rate is ≤200 mrem/hr |

**TRUPACT-III PACKAGE**

TRUPACT-III Body ID No. ______________ Shipment No.: ______________________

Weight of Payload Loading Pallet and Roller Floor: ______________ lbs.

Total Weight: ______________ lbs. Total Weight plus Error ≤**11,409** lbs.

**APPROVED FOR SHIPMENT**

I certify that the above TRUPACT-III package meets the requirements for transport.

______________________________

Transportation Certification Official

______________________________

Date

① Payload container must be designated for controlled shipment. Table 3.2-2 must also be completed for the shipment as specified in Section 3.2.4, *Controlled Shipments*.

② Decay heat plus error must also comply with the TRUPACT-III design limit of ≤80 watts.

③ In addition, compliance with the dose rate requirements for the TRUPACT-III package (Section 3.2 of the TRUPACT-III TRAMPAC) shall be by survey of the loaded package.

## **Table 3.2-2** – PREx Shipping Site Control Checklist for Controlled Shipments①

Shipment No. ____________________ Packaging No.____________________

**To be completed by Shipping Site Transportation Certification Official, or designee, for each package designated as a controlled shipment:**

| TRUPACT-III PREx Section No. | Activity | Recorded Date | Recorded Time | Completion of Activity (Indicate by checkmark [√]) |
|---|---|---|---|---|
| 3.2.4.1 | Record date and time of completion of the TRUPACT-III payload cavity evacuation process | | | |
| 3.2.4.2 | Record date and time the shipment containing the loaded package is scheduled to depart from the site | | | |
| 3.2.4.3 | Calculate and record total **Loading Time** [Limit = 24 hours] | | | |
| | *Total Loading Time ≤1 day, proceed to No. 3.2.4.4.* *Total Loading Time > 1 day, **STOP**. Vent package and repeat payload cavity evacuation process.* | | | |
| 3.2.4.4 | I certify that the above data is accurate and compliant with the Loading Time limit of 24 hours, as specified in Section 3.2.4 of the TRUPACT-III PREx. ____________________ / ________ TRANSPORTATION CERTIFICATION OFFICIAL (OR DESIGNEE) DATE | | | |

① Controlled shipments (10 days) shall be made in accordance with the conditions specified in Appendix 7.1.3 of the TRUPACT-III TRAMPAC and Section 3.2.4, *Controlled Shipments*. This table may be reformatted for site use provided that the same information is recorded.

## **Table 3.2-3** – PREx Receiving Site Control Checklist for Controlled Shipments①

Shipment No. ____________________ Packaging No.____________________

**To be completed by designated Receiving Site Operations Personnel for each package designated as a controlled shipment:**

| TRUPACT-III PREx Section No. | Activity | Recorded Date | Recorded Time | *Completion of* Activity (Indicate by checkmark [√]) |
|---|---|---|---|---|
| 3.2.4.5 | Record the date and time that the package was scheduled to depart from the shipping site | | | |
| 3.2.4.6 | Vent package within 9 days of date and time recorded above and record vent date and time | | | |
| 3.2.4.7 | I certify that the above data is accurate and compliant with the Transport and Unloading Time limit of 9 days, as specified in as specified in Section 3.2.4 of the TRUPACT-III PREx.<br><br>______________________________ / ____________<br>RECEIVING SITE OPERATIONS PERSONNEL DATE | | | |

① Controlled shipments (10 days) shall be made in accordance with the conditions specified in Appendix 7.1.3 of the TRUPACT-III TRAMPAC and Section 3.2.4, *Controlled Shipments.* This table may be reformatted for site use provided that the same information is recorded.