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DOE STANDARD

Preparation of Safety Basis Documents for Transuranic (TRU) Waste Facilities

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Foreword

This Standard provides analytical assumptions and methods, as well as hazard controls to be used when developing Safety Basis (SB) documents for transuranic (TRU) waste facilities in the U.S. Department of Energy (DOE) Complex. It also provides supplemental technical information that is specific to TRU waste operations, so that contractors can formulate, implement, and maintain safety bases for TRU waste operations in a consistent manner that is compliant with 10 CFR Part 830, Subpart B, requirements.

Nothing in this Standard is intended to conflict with or modify the requirements for compliance with "safe harbor methods" in Table 2, Appendix A, of 10 CFR Part 830, Subpart B. In the case of an apparent conflict between this Standard and a safe harbor methodology for developing documented safety analyses, the language in the safe harbor Standard takes precedence, unless approval for an alternative methodology is requested and approved per Subpart B requirements.

The information contained in this Standard is intended for use by all Department of Energy (DOE) and National Nuclear Security Administration (NNSA) sites and all contractors for DOE-owned or DOE-leased, Hazard Category 1, 2, or 3 nuclear facilities or nuclear operations that involve handling and remediation of TRU waste containers.

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1.0 Introduction

1.1 Background

The DOE is responsible for the safe handling, packaging and ultimate disposal of TRU wastes at the Waste Isolation Pilot Plant (WIPP) located near Carlsbad, New Mexico. Much of this waste, which is a result of legacy operations supporting the U.S. nuclear weapons mission, is now stored at numerous DOE sites located across the United States. These wastes can present significant hazards to workers, the environment, and the public if not adequately controlled.

While numerous and located within multiple states, facility operations supporting the TRU waste management mission have shared similarities in terms of the hazards and scope of operations. However, facilities often employ a variety of different controls to manage the TRU wastes. Recognition of these inconsistencies led the DOE to develop this technical Standard, which lays out expectations for analyzing and controlling TRU waste hazards.

To support this effort, DOE had to overcome several challenges. Chief among them was that TRU wastes are present at both large and small sites and involve wastes ranging from very low radioactive levels to those with significant radiological hazards. A one-size-fits-all approach could be overly expensive for smaller sites and not necessarily in line with relative lower actual risks.

A second challenge was that TRU waste operations are conducted in a variety of newly designed structures and existing buildings originally intended for other DOE missions. These older facilities may not meet current facility design requirements, although they may be compliant with the code of record. Therefore, it was recognized that protective features designed into existing facilities are not always reliable or available as in new facilities. In such cases, alternative controls that include specific administrative controls may become the primary controls available. [NOTE: This does not relieve a new facility or major facility modification from DOE Order O 420.1B nuclear facility requirements.]

To support these strategies, DOE collected hazard analysis and control data from all of its major TRU waste sites. This information was used to provide a baseline against which analytical methods and proposed controls could be evaluated, compared, and selected. It also highlighted inconsistencies among TRU waste sites that warranted further guidance.

1.2 Scope

Based on the evaluation of existing SB information and input received from TRU waste operations personnel, analysts and DOE SB reviewers, the Standard focuses on topics related to hazard analysis, hazard controls, SB implementation, and the DOE review process. These topics are addressed in a level of detail that supports the existing framework of nuclear facility SB requirements and standards.

Specific topical areas covered in the Standard, and their associated Sections are as follows:

- **Section 2.0, Acronyms,** provides easy access definitions to all acronyms used in the Standard.
- **Section 3.0, Identification and Evaluation of TRU Waste Events**, discusses the types of hazards expected during TRU waste operations, defines a minimum set of accidents to be evaluated in the DSA, and addresses DSA provisions for addressing incidents that are inherent to normal operations such that operational impacts from their occurrence are appropriately minimized.
- **Section 4.0, TRU Waste Source Term Analysis**, defines analytical methods and assumptions related to unmitigated analysis, Material-At-Risk, Damage Ratios, and Airborne Release Fractions/Respirable Fractions;
- **Section 5.0, Consequence Analysis**, addresses assumptions supporting qualitative evaluations of facility workers, as well as dispersion analysis assumptions supporting quantitative evaluations of onsite worker populations and offsite receptors;
- **Section 6.0, TRU Waste Hazard Controls Selection and Standardization**, provides guidelines for standardizing the hazard control selection process and gives specific controls that are appropriate for TRU waste operations.
- **Section 7.0, SB Review and DOE Risk Acceptance**, clarifies expectations for SB review and acceptance of risks.
- **Section 8.0, Verification of SB Implementation**, describes general expectations for ensuring that new/revised SB documents are properly implemented.
- **Section 9.0 References,** provides a list of all references cited in the main body of the Standard. Additional references are provided within each appendix.

1.3 Purpose

This Standard provides detailed guidance for consistently analyzing hazards and selecting controls for TRU waste activities. The hazards analysis, accident analysis, and controls for TRU waste activities must be integrated into the overall SB documents for DOE Category 1, 2, or 3 nuclear facilities prepared in accordance with 10 CFR Part 830, Subpart B requirements (or alternate methodology where approved in accordance with the regulation).

1.4 Applicability

The information contained in this Standard is intended for use by all DOE and National Nuclear Security Administration (NNSA) sites and all contractors for DOE or NNSA owned or leased, Hazard Category 1, 2, or 3 nuclear facilities or nuclear operations that involve retrieval, handling, storage and processing of TRU waste containers. This Standard applies to Documented Safety Analyses (DSAs) complying with "safe harbor methods" in Table 2 to Appendix A of 10 CFR Part 830, Subpart B (or alternate methodology where approved in accordance with the regulation) and the associated TSRs.

This Standard is not a safe harbor method as defined in 10 CFR Part 830, Subpart B. Nothing in this Standard is intended to conflict with or modify the requirements for compliance with safe harbor methodologies listed in 10 CFR Part 830. In addition, the Standard is not intended to conflict with requirements of 10 CFR Part 830.206 related to new Hazard Category 1, 2, or 3 nuclear facilities or major modifications. In the case of an apparent conflict between this Standard and a 10 CFR Part 830, Subpart B requirements, as well as supporting "safe harbor" standards in Table 2 of Appendix A of 10 CFR Part 830, Subpart B, the language in the "safe harbor" standard takes precedence, unless approval for an alternative methodology is requested and approved per the current DOE approval process for 10 CFR 830 exemptions or interpretations.

The process used to justify deviations from methods prescribed in the standard should not be confused with the process used for exemptions from DOE nuclear safety requirements. In one case technical justifications for analytical methods or key assumptions are developed and submitted to the SB DOE Approval Authority for their approval of deviation from this Standard. Such deviations should be documented in the Safety Evaluation Report and not confused with the case where new or enhanced safety controls are needed because of a new activity or major modification, and those controls cannot meet current DOE design or other requirements. Where controls cannot meet current requirements, exemptions with appropriate compensatory measures are generally needed to authorize acceptability of not meeting the requirement. Depending on the requirement and its applicability to existing facilities, the SB DOE Approval Authority may not be the same person as the DOE authority for an exemption to current DOE Orders or other requirements. Furthermore, approval of exemptions to DOE Order requirements involving nuclear safety need concurrence of the DOE and/or NNSA Central Technical Authorities per the DOE exemption process in effect at the time of the request.

1.5 Use of the Words *Must* and *Should*

The verbs "*must*" and "*should*" are used throughout this Standard. If this Standard is listed as a contract requirement or otherwise directed by DOE for a facility or project, the DOE contractor or other organization required to meet this Standard *must* comply with all of the applicable provisions that include the word "*must*." Provisions that use the word "*should*" are not required but they are recommended, particularly for complex or hazardous activities.

2.0 Acronyms

AA	Accident analysis
AC	Administrative controls
AEGL	Acute exposure guidance level
AHJ	Authority having jurisdiction
AK	Acceptable knowledge
ANSI	American National Standards Institute
ARF	Airborne release fraction
BR	Breathing rate
CFR	Code of Federal Regulations
CH	Contact-handled
CVS	Confinement ventilation system
DBA	Design basis accident
DBE	Design basis earthquake
DCF	Dose conversion factor
DID	Defense in depth
DNFSB	Defense Nuclear Facilities Safety Board
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DR	Damage ratio
DSA	Documented safety analysis
DU	Depleted uranium
DVS	Drum venting system
EG	Evaluation guideline
EM	(DOE Office of) Environmental Management
EMHA	Emergency management hazards assessment
EPA	Environmental Protection Agency
FO	(DOE) Field Office
FR	Facility Representative
FSS	Fire suppression system
HA	Hazard analysis
HC	Hazard class
HEPA	High efficiency particulate air
HGS	Headspace gas sampling
ICRP	International Commission on Radiological Protection
IEEE	Institute of Electrical and Electronics Engineers
ISMS	Integrated Safety Management System
IVP	Implementation verification process
IVR	Implementation verification review
LCO	Limited conditions for operations
LEL	Lower explosive limit
LFL	Lower flammability limit
LMA	Line manager assessment
LPF	Leak-path factor
MAR	Material-at-risk
MOI	Maximally exposed offsite individual
NCSE	Nuclear criticality safety evaluation
NDA	Non-destructive assay

NDE	Non-destructive examination
NFPA	National Fire Protection Association
NNSA	National Nuclear Security Administration
NPH	Natural phenomena hazards
ORR	Operational readiness review
OSHA	U. S. Occupational Safety and Health Administration
PC	Performance category
PE-Ci	Plutonium equivalent curies
PISA	Potential inadequacy in the safety analysis
PMMA	Polymethyl methacrylate
POC	Pipe overpack container
PPE	Personal protective equipment
RA	Readiness assessment
RCRA	Resource Conservation and Recovery Act
RF	Respirable fraction
RH	Remote-handled
RLC	Removable Lid Canister
SAC	Specific administrative controls
SB	Safety bases
SBD	Safety basis document
SC	Safety Class
SER	Safety evaluation report
SIH	Standard industrial hazard
SME	Subject matter expert
SMP	Safety management program
SSC	Structures, systems, and components
SSO	Site Safety Office
ST	Source term
SWB	Standard waste box
TBD	To be determined
TDOP	Ten drum overpack
TED	Total effective dose
TEEL	Temporary emergency exposure level
TRU	Transuranic
TSR	Technical safety requirements
UCL	Upper confidence limit
USQ	Unreviewed safety question
UTL	Upper tolerance limit
VOC	Volatile organic compound
WAC	Waste Acceptance Criteria
WIPP	Waste Isolation Pilot Plant

3.0 Identification and Evaluation of TRU Waste Events

3.1 Purpose

This section provides guidance on identification of hazards expected during various types of TRU waste operations, as well as a minimum set of accident events that are applicable based on these hazards. The definition of Standard Industrial Hazards (SIH), as discussed in DOE-STD-3009, is also clarified to help distinguish those hazards that do not require analysis within the DSA. Finally, this section provides a distinction for certain operational events that are to be expected during the course of normal TRU waste operations.

3.2 Hazard Identification and Standard Industrial Hazard Screening

The identification of hazards inherent in TRU waste activities is necessary to provide a sound basis for identifying potential accident events and performing a hazard evaluation. The hazard identification process should result in a comprehensive list of hazardous materials and energy sources that are present in the facility or operation. This process must be conducted in accordance with the DOE-STD-3009 process for hazard identification and selection of accidents.

Hazards commonly expected for TRU waste operations are identified in Table 3.2-1. This listing provides major hazard sources and material groups that could be potential initiators for specific accident events discussed in Section 3.3. Where these hazards are present in a given TRU waste operation, analysts must evaluate the applicability of the corresponding accident event(s).

Hazards identified in Table 3.2-1 do not always result in accidental release of radiological materials or hazardous chemicals (i.e., as required to be evaluated by DOE-STD-3009). Depending on the location and specific characteristics of the hazard, it may be considered an SIH. DOE-STD-3009 defines an SIH as a hazard that is:

> . . . *routinely encountered in general industry and construction, and for which national consensus codes and/or standards (e.g., OSHA, transportation safety) exist to guide safe design and operation without the need for special analysis to design safe design and/or operational parameters.*

Examples of SIH types that are common to TRU waste operations include radiography equipment that is governed by American National Standard Institute (ANSI) standards and heavy equipment hazards regulated by the U.S. Occupational Safety and Health Administration (OSHA). Further discussion and guidance on SIHs, as well as the hazard identification process in general, is provided in DOE-HDBK-1163, *Integration of Multiple Hazard Analysis Requirements and Activities*.

It is not the intention of the DSA to provide analysis of SIH type of hazards. Rather, hazards in Table 3.2-1 are evaluated to the extent that they act as initiators and contributors to accidents that result in a radiological or chemical release. Application of a hazard screening during the hazard identification process can be helpful in distinguishing between SIH hazards and those that must be evaluated in the DSA.

Hazard screening is a simple evaluation used to identify those hazards that need no further consideration in the DSA. The screening process sorts through a comprehensive list of hazards based on the following considerations:

- Does the identified hazard have the characteristics of an SIH? Hazardous materials that are incidental to the process operation, such as those that are found in laboratories, or environmental circumstances such as the presence of insects, hanta virus, etc., can be screened from further consideration in the DSA, but should be considered in the preparation of job hazard analyses. Unique hazards cannot be screened and must be carried forward for further evaluation. In determining whether a hazard is unique, consider any variations from standard practice, the magnitude of the hazard, etc.

- Does the hazard have the potential for significant interactions with nuclear hazards? Such interactions may not be addressed by consensus standards and require more thorough evaluation than screening would afford (i.e., to verify or determine appropriate controls). Some hazards are adequately controlled, but may still serve as initiators for a nuclear accident. Electrical power is an example.

TABLE 3.2-1 Hazard Sources and Potential Events

Hazard Source and Material Groups	Potential Accidents
Electrical	Fires (Events 1-4) – In combination with combustible/flammable material Explosions (Events 5-8) – In combination with explosive material
Thermal	Fires (Events 1-4) – In combination with combustible/flammable material Explosions (Events 5-8) – In combination with explosive material Criticality (Event 19) – Increased concentration
Pyrophoric Material	Fires (Events 1-4) – Pyrophoric fire; may serve as ignition source for larger fires Explosions (Events 5-8) – In combination with explosive material
Spontaneous Combustion	Fires (Events 1-4) – May serve as ignition source for larger fires Explosions (Events 5-8) – In combination with explosive material
Open Flame	Fires (Events 1-4) – In combination with combustible/flammable material Explosions (Events 5-8) – In combination with explosive material
Flammables	Fires (Events 1-4) – In combination with ignition source
Combustibles	Fires (Events 1-4) – In combination with ignition source

TABLE 3.2-1 Hazard Sources and Potential Events - Continued

Hazard Source and Material Groups	Potential Accidents
Chemical Reactions	Fires (Events 1-4) – Fire or other thermal effect Explosions (Events 5-8) – Explosion or over-pressurization Loss of Confinement/Containment (Events 9-12) – Toxic gas generation Criticality (Event 19) – Increased concentration, precipitation of material
Explosive Material	Fires (Events 1-4) – As an ignition source Explosions (Events 5-8) – In combination with ignition source Loss of Confinement/Containment (Events 9-12) – Missiles (in combination with ignition source) Criticality (Event 19) – Loss of configuration or spacing
Kinetic Energy (Linear and Rotational)	Loss of Confinement/Containment (Events 9-12) – Impacts, acceleration/deceleration, missiles Criticality (Event 19) – Loss of configuration or spacing
Potential Energy (Pressure)	Loss of Confinement/Containment (Events 9-12) – Impacts, missiles Criticality (Event 19) – Loss of configuration or spacing
Potential Energy (Height/Mass)	Loss of Confinement/Containment (Events 9-12) – Impacts (falling objects), dropping Criticality (Event 19) – Loss of configuration or spacing
Internal Flooding Sources	Loss of Confinement/Containment (Events 9-12) – Ground/surface water runoff Criticality (Event 19) – Increased moderation
Physical	Loss of Confinement/Containment (Events 9-12) – Puncture, dropping
Radiological Material	All Events – Potentially releasable material
Hazardous Material	All Events – Potentially releasable material
Ionizing Radiation	Direct Exposure (Event 13) – Direct exposure to worker
Non-Ionizing Radiation	Direct Exposure (Event 13) – Direct exposure to worker Other – May interfere with equipment operation
Fissile Material	Criticality (Event 14)
Non-facility Events	External Initiated Event (Events 15 – 19) – These events may be similar to Events 1 – 14
Vehicles in Motion (external to facility)	External Initiated Event (Events 15 – 19) – These events may be similar to Events 1 – 14
Natural Phenomena	Natural Phenomenon Hazard (NPH) Events (Events 20 – 25) – These events may be similar to Events 1 – 14

3.3 TRU Waste Operations Minimum Set of Accidents

The following section represents the minimum set of accident events that must be addressed in the DSA hazard evaluation when the hazard identification indicates the presence of potential initiators that could lead to the accident event. If a particular event is not applicable for a facility (e.g., volcanic ash does not apply to many DOE locations), then the basis for excluding the event should be developed and discussed with the local DOE Approval Authority. The applicability of a specific accident also depends on whether it is plausible during the TRU waste activity being conducted (e.g., a vehicle accident may not be plausible during glovebox repackaging activities). The following consolidated list of general TRU waste activities has been developed to facilitate an understanding and characterization of TRU waste accident events:

- **Characterization:** Non-Destructive Assay (NDA), Non-destructive Evaluation (NDE), and Headspace Gas Sampling (HGS). These activities are those typically required for package acceptance and certification at WIPP.

- **Container Handling:** Lifting and moving TRU waste containers with forklifts, cranes, drum handlers, etc.; stacking; banding; loading and unloading from waste container arrays; overpacking; and loading on transport vehicle until ready for transport.

- **Venting and/or Abating/Purging:** Installing vents to release gases built up within the TRU waste container, allowing gases to passively vent, and purging the TRU waste container headspace. The purpose of these activities is to reduce the potential hydrogen concentration within the TRU waste container to a level at which the hydrogen no longer presents a deflagration hazard.

- **Staging and Storage:** Static conditions which may include staging (temporary storage), storage, surveillance, and maintenance. Staging and storage may take place inside a facility with features such as fire suppression and ventilation, inside temporary structures such as tents that only protect the waste container from the elements, or outside of any physical structure.

- **Retrieval and Excavation:** Excavation of buried waste and/or retrieval from original storage location.

- **Waste Repackaging:** Intrusive material handling. May include sorting, visual inspection of waste, size reduction, compaction, invasive sampling, dewatering, repackaging, consolidation, conditioning or treatment of reactive material, and absorption or solidification of liquids.

- **Type B Container Loading/Unloading:** Handling and storage/staging of Type B containers.

The minimum set of accident events presented in this Section addresses those events with the potential for consequences that could be significant enough to warrant explicit technical safety requirements (see additional discussion in Section 6). A matrix of the minimum accident events versus typical TRU waste activities discussed above is provided in Table 3.3-1. Areas of the table marked by “X’s” indicate potential applicability.

Accident events are presented according to broad categories that include fires, explosion events, loss of confinement/containment, direct radiation exposure, criticality, externally initiated events, and natural phenomena events. These events are applicable to both Contact-Handled (CH) and Remote-Handled (RH) TRU activities. The descriptions and causes of accidents may not be inclusive of certain hazards or operations that are unique to a given site. The hazard identification process, conducted in accordance with DOE-STD-3009, should identify those hazards not addressed by the standard.

When an accident is applicable based on the facility's hazard identification and the type of TRU waste activity being conducted, the accident must be covered in the DSA hazard evaluation. A subset of these accidents may also require formal accident analysis where required in accordance with DOE-STD-3009 (e.g., Hazard Category 2 facilities).

TABLE 3.3-1 Minimum TRU Waste Activity/Hazard Evaluation Event Matrix

Hazard Evaluation Event [1]	**Character-ization**	**Container Handling**[2]	**Venting &/or Abating/ Purging**	**Staging and Storage**	**Retrieval and Excavation**	**Waste Repack-aging**	**Type B Container Loading/ Unloading**
Fire Events							
Fuel Pool Fire (Event 1)		X		X	X		X
Small Fire (Event 2)	X	X	X	X	X	X	X
Enclosure Fire (Event 3)	X		X			X	
Large Fire (Event 4)	X	X	X	X	X	X	X
Explosion Events							
Ignition of Fumes Results in an Deflagration/Detonation (external to container) (Event 5)		X			X	X	X
Waste Container Deflagration (Event 6)	X	X	X	X	X		
Multiple Waste Container Deflagration (Event 7)	X	X	X	X	X		
Enclosure Deflagration (Event 8)	X		X			X	
Loss of Confinement/Containment							
Vehicle/Equipment Impacts Waste/Waste Containers (Event 9)		X	X	X	X	X	X
Drop/Impact/Spill Due to Improperly Handled Container, etc. (Event 10)		X			X	X	X
Collapse of Stacked Containers (Event 11)		X	X	X			
Waste Container Over-Pressurization (Event 12)	X	X	X	X	X		
Direct Exposure to Radiation Events (Event 13)	X	X	X	X	X	X	X
Criticality Events (Event 14)	X	X	X	X	X	X	
Externally Initiated Events							
Aircraft Impact with Fire (Event 15)	X	X	X	X	X	X	X
External Vehicle Accident (Event 16)	X	X	X	X	X	X	X
External Vehicle Accident with Fire (Combustible or Pool) (Event 17)	X	X	X	X	X	X	X
External Explosion (Event 18)	X	X	X	X	X	X	X
External Fire (Event 19)	X	X	X	X	X	X	X
NPH Initiated Events							
Lightning (Event 20)	X	X	X	X	X	X	X
High Wind (Event 21)	X	X	X	X	X	X	X
Tornado (Event 22)	X	X	X	X	X	X	X
Snow/Ice/Volcanic Ash Build-up (Event 23)	X	X	X	X	X	X	X
Seismic Event (Impact Only) (Event 24)	X	X	X	X	X	X	X
Seismic Event with Fire (Event 25)	X	X	X	X	X	X	X

[1] Transport activity accidents and control selection are done in compliance with DOE O 460.1B and 461.1.

[2] Movement of TRU waste containers (not including Type B containers) is considered "container handling," even when it is related to the completion of another type of TRU waste activity. When analyzing these events, one must consider the waste being handled as well as other stored/staged waste that may be impacted.

3.3.1 Fire Events

The magnitude of fire events provided below should be consistent with the assumptions of a facility's fire hazard analysis. Fire sizes and types are generally defined below to facilitate the selection of controls in Section 6.0. In addition, the use of the term "facility" within the fire events does not necessarily mean the evidence of a structure, i.e., fires may occur inside or outside of a structure.

3.3.1.1 Fuel Pool Fires (Event 1)

The analysis of liquid fuel fires, separate from other fires, is important because liquid fuel fires have the potential to result in pool fires that have a substantially higher source term than combustible material fires when TRU waste containers are involved in the event. Pool fires can cause rapid heating of containers. This heating can cause relatively small containers, such as 55-gal drums, to experience rapid pressure buildup, resulting in a lid failure and expulsion/ejection of material from the container. The ejected material would burn as unconfined material, resulting in a greater release than confined material.

These potential fires are associated with the ignition of pools by various ignition sources, such as thermal energy from the equipment or sparks from moving containers. The fuel pool is formed from the leaking of equipment and/or vehicle flammable/combustible liquids or the spilling of the liquids during refueling, maintenance, or an impact from equipment/vehicles used to support TRU waste operations. The potential amount of fuel is dependent on the equipment/vehicles used within the facility footprint and may range from a few gallons to thousands of gallons. If this is the case, separate small and large fuel pool fire events must be included for complete hazard evaluation and control selection. Additionally, if the fuel pool fire event is initiated by an equipment/vehicle impact and postulated to impact uncontainerized and/or containerized waste; an additional fuel pool fire must be analyzed for complete hazard evaluation and control selection.

3.3.1.2 Small Fire (Event 2)

Small fires may affect either one container during a container fire or one to several containers through exposure or direct impingement, but outside of any facility confinement enclosure (e.g., glovebox). This type of fire is limited in size and is contained within a fire zone. Additionally, the intensity of a small fire may be inadequate to result in automatic Fire Suppression System (FSS) activation. These fires, in general, will cause material in containers to burn as confined material. However, some containers (e.g., those with relatively significant quantities of liquids or reactive materials) may result in drum pressurization, lid failure, and ejection of some of the container contents. The ejected material would burn as unconfined material, resulting in a greater release than confined material.

The event covers all small fires initiated within the facility, but outside of any facility enclosures. This fire is started from the ignition of combustible and/or flammable materials within the facility as well as exposure fires from vehicles or other equipment within the facility. Fires of this type affect containers through exposure or direct impingement. Separate small fire events from hazards associated with various facility activities may be required to ensure a complete hazard evaluation. The propagation of these fires into a larger fire is addressed in a separate event (Event 4).

3.3.1.3 Enclosure Fire (Event 3)

For facilities using enclosures such as gloveboxes or hot cells, this fire is addressed separately from other small fire events to ensure a complete hazard evaluation. This fire covers all internally initiated fires. The ignition source may be from pyrophoric or spontaneous combustion reaction, chemical reaction, or other source of internal heat generation. Flammable gas inside the enclosure may also result in a deflagration, which is addressed in a separate event. Additionally, if waste treatment activities not typically associated with TRU waste operations are conducted within an enclosure (e.g., stabilization of pyrophoric material through controlled oxidation), separate events may be required for complete hazard evaluation and control selection.

3.3.1.4 Large Fire (Event 4)

This is a fire that propagates from any of the proposed smaller fire events. Propagated fires of different sizes may be proposed depending on the facility configuration (e.g., a large, multi-level facility may have a room fire, a level fire, and a full-facility fire). The size of the fire analyzed within the DSA will be dependent on assumptions addressed in the Fire Hazard Analysis (e.g., full facility fire may not be plausible because of non-combustible facility construction/design and lack of operational needs for combustible/flammable materials).

3.3.2 Explosion Events

3.3.2.1 Ignition of Fumes Results in an Explosion (external to container) (Event 5)

This event is caused by hazards external to the waste matrix such as vehicle fuel/fumes, battery explosions, welding gases, or other explosive gases used in the facility. In addition to explosion overpressures, an explosion could produce missiles that could impact containers of waste. For waste in containers, the release mechanism would essentially be an impact.

3.3.2.2 Waste Container Deflagration (Event 6)

This event is due to hydrogen or other flammable/explosive gases (e.g., off-gas from Volatile Organic Compounds [VOCs]) inside the container) in a *suspect* container. A *suspect* container is unvented (including those containers with inadequate vents, no vent, or plugged vents) and meets *at least one* of the following criteria:

1. Obvious indications of pressurization

2. Waste stream characteristics indicate a potential for generating concentrations of hydrogen or other flammable gas mixtures greater than or equal to the Lower Flammability Limit (LFL)

3. Waste stream data is either inadequate or unavailable to rule out the potential for generating concentrations of hydrogen or other flammable gas mixtures greater than or equal to the LFL

Ignition sources include sparks, heat, etc., that can ignite gases escaping the container, as well as potential ignition sources in the waste, such as metal objects, pyrophoric material, and heat-generating chemical reactions. More than one waste container deflagration event may be required depending on the number of various facility activities and the similarity of the postulated event causes and potential controls.

3.3.2.3 Multiple Waste Container Deflagration (Event 7)

This event is due to waste container deflagration propagating horizontally or vertically to initiate additional container deflagrations. This event requires two *suspect* containers (see the definition in Event 6) to be stacked, or of poor container integrity (see Section 4.4.1) to be stored or staged immediately adjacent to each other (e.g., on a pallet). This event is not required for newly generated drums (see Section 4.4.2 for further discussion).

3.3.2.4 Enclosure Deflagration (Event 8)

For facilities using enclosures such as gloveboxes or hot cells, deflagrations within the enclosure are addressed as separate events to ensure a complete hazard evaluation. This event is due to hydrogen or other flammable/explosive gases inside an enclosure or within a container that has been placed inside and opened within an enclosure. Ignition sources include sparks, heat, etc. that can ignite gases as well as potential ignition sources in the waste, such as metal objects, pyrophoric material, and heat-generating chemical reactions.

3.3.3 Loss of Confinement/Containment

3.3.3.1 Vehicle/Equipment Impacts Waste/Waste Containers (Event 9)

This event is due to operation of vehicles or equipment within the facility. These vehicles and equipment may or may not be used in close proximity to the TRU waste. The impact type will vary based on the impact source and may involve, for example, container puncture by forklift tines, or result in a stacked drum array falling.

3.3.3.2 Drop/Impact/Spill Due to Improperly Handled Container, etc. (Event 10)

This event is due to mishandling of containers or to drops/impacts caused by equipment failure. If TRU waste containers may be dropped from elevated surfaces (e.g., drums falling from third tier or higher during removal), a separate event will be required to ensure a complete hazard evaluation.

3.3.3.3 Collapse of Stacked Containers (Event 11)

This event is a collapse of a stacked array of containers. The collapse may be a failure of the containers, pallets, or other stacking media due to corrosion, defective construction, damage, or improper stacking (e.g., exceeding limits, unstable array).

3.3.3.4 Waste Container Over-Pressurization (Event 12)

This event is due to a buildup of pressure inside of a container. The pressure buildup may be due to radiolysis of water or other hydrogenous material, thermal expansion of material/gases inside the container, or chemical reactions inside the container. This is typically a slowly developing event (on the order of months), although containers with unknown material or with the potential for chemical reactions may pressurize more rapidly (on the order of hours to days).

3.3.4 Direct Exposure to Radiation Events (Event 13)

This event is caused by ionizing radiation from the waste. The exposure may be due to normal operational conditions (e.g., handling, cleaning up a spill) or due to an accident that causes the loss of shielding inherent to the container/activity. If the facility processes both CH and RH TRU waste, separate events for these waste types must be included for complete hazard evaluation.

3.3.5 Criticality Events (Event 14)

Criticality events can occur due to many different causes. These are typically evaluated in a Nuclear Criticality Safety Evaluation (NCSE) consistent with DOE-STD-3007, *Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Nonreactor Nuclear Facilities*. Events in the NCSE that require criticality controls should be explicitly presented in the DSA. Also, the NCSE events should be evaluated against other events in DSA to ensure that all potential upsets were considered in the NCSE.

3.3.6 Externally Initiated Events

3.3.6.1 Aircraft Impact with Fire (Event 15)

This event occurs when a large commercial aircraft, small general aviation aircraft, or helicopter crashes into the facility and a fire ensues. Site over-flights and nearby airports are contributors to this event.

Aircraft impact events must be evaluated where deemed credible in accordance with DOE-STD-3014.

3.3.6.2 External Vehicle Accident (Event 16)

This event is due to a vehicle, not associated with facility activities, impacting the facility/waste containers. Traffic on nearby roads contributes to this event. This event differs from the vehicle impact from operations activities previously discussed in that the vehicle may be of a different type used in the facility (e.g., fuel tanker), traveling at a greater speed, and impact more containers. Additionally, if controls are necessary, the control set for this event may be different than that for operations-related equipment.

3.3.6.3 External Vehicle Accident with Fire (Combustible or Pool) (Event 17)

This is a potential follow-on event for the external vehicle accident. After the vehicle accident, spilled combustible waste, and/or fuel from the vehicle ignite and burn.

3.3.6.4 External Explosion (Event 18)

This event is similar to the explosion due to mechanical failure with missiles occurring within the facility that was discussed earlier. The hazard is primarily from vehicles/roadways near the facility or storage location, or from nearby locations with large quantities of explosive gas (e.g., nearby gas pipeline, propane tanks, pressurized gas used for characterization or welding, etc.). In addition to explosion overpressures, an explosion could produce missiles that could impact containers of waste. For waste in containers, the release mechanism would essentially be an impact.

3.3.6.5 External Fire (Event 19)

This is a fire that begins outside of the facility and propagates to the facility. The external fire could be from wildland fires, other facilities, or another fire source. If TRU waste may be within and/or outside of a building, separate external fires must be addressed.

3.3.7 Natural Phenomenon Hazard Initiated Events

3.3.7.1 Lightning (Event 20)

For facilities with electrical systems, a lightning strike may cause fires in the electrical system (e.g., ignition of wire insulation) that could ignite nearby material. Lightning strikes that cause fires outside of the facility are addressed as external fires.

Additionally, lightning may strike a container or near stored/staged containers. The direct strike could cause rapid heating and pressurization of a container, with ejection of material. The nearby strike could cause small missiles (e.g., fragments of concrete).

3.3.7.2 High Wind (Event 21)

This event is due to high winds causing impacts to both the facility and the containers via falling objects. The falling objects may be nearby trees, pole, cranes, or parts of the facility structure.

3.3.7.3 Tornado (Event 22)

This event is due to a direct effect of a tornado, falling objects, or tornado-produced missiles causing impacts to both the facility and the containers. Missiles may be produced from various pieces of equipment or material (e.g., pallets). The falling objects may be nearby trees, poles, cranes, or parts of the facility structure.

3.3.7.4 Snow/Ice/Volcanic Ash Build-up (Event 23)

Accumulation of snow, ice, or volcanic ash may cause the roof of a facility or structure to collapse, or may cause nearby objects, such as trees, to fall and impact the waste containers.

3.3.7.5 Seismic Event (Impact Only) (Event 24)

The seismic event can cause failure of the facility structure (partial or catastrophic, depending on the facility construction), failure of equipment inside the facility, or other structure failure, which impacts the waste. Additionally, the event can cause containers to fall and spill their contents.

3.3.7.6 Seismic Event with Fire (Event 25)

The seismic event can cause failure of the facility, failure of equipment inside the facility, or failure of other structures, which impact the waste. Additionally, the event can cause containers to fall and spill their contents. The structural failure could involve damage to electrical systems that are not seismically qualified or involve other potential ignition sources (e.g., flammable materials or gas lines where present) that can ignite spilled combustible waste or other combustibles in the facility.

3.4 Expected Operational Events

A facility's DSA addresses normal, abnormal, and accident conditions as required by 10 CFR Part 830. A subset of the events evaluated in the DSA includes certain operational events that are expected to occur during the lifetime of a given TRU waste operation even with preventive controls in place. As used in this Standard, expected events are defined as planned occurrences encountered during normal operations that result from hazards inherent to the material and activities. This definition does not include events caused by personnel errors, since these causes involve a control failure that warrants some level of investigation. For example, incidental fires or reactions might be expected during retrieval and excavation of TRU wastes involving flammable/explosive atmospheres.

In cases where an expected operational event occurs, it is prudent to validate that established protective measures function as intended, and then resume operations. This is similar in concept to initiating authorized required actions when a *Limiting Condition of Operation* (LCO) condition is entered. The DOE acknowledges the potential for the event and adequacy of the protective measures through approval of the DSA. Approval of a DSA in which response actions are cited for specified "expected events" effectively authorizes work to continue once the event conditions are evaluated, reported (where necessary in accordance with DOE O 231.1A), and it is confirmed that the expected event occurred as planned and no unanticipated behavior or consequences were exhibited.

For the purposes of this Standard, an expected operational event involves known hazards that are described in the DSA, and which does not result in significant consequences to workers or the public with preventive and mitigative controls in place. In other words, the protective features provided to perform operational processes ensure consequences are within the operational standards that apply to the work. For example, worker dose is limited to criteria established in 10 CFR Part 835.

The DSA provisions for documenting expected operational events are as follows:

- The event is documented in the facility process description of the DSA
- The response actions following occurrence of the expected event are specifically documented in the DSA, although they may be as simple as evaluate and report the event to DOE (where necessary in accordance with DOE O 231.1A)
- The event is analyzed in the DSA hazard evaluation
- Worker protection measures for the operational event are identified in the DSA

A primary benefit of identifying expected operational events is to provide DOE with the means of pre-approving actions for continued operation should certain events that meet the conditions of an *Expected* event occur. Because these events are expected, appropriate protective measures and actions to ensure continuation of operations must be identified and in place prior to beginning the operation.

4.0 TRU Waste Source Term Analysis

4.1 Purpose

This section defines assumptions for unmitigated analyses and provides guidance on source term development. The Source Term (ST) is the amount of airborne respirable radioactive material released to the environment. As specified in DOE-HDBK-3010, ST is determined by:

$$ST = MAR \cdot DR \cdot ARF \cdot RF \cdot LPF$$

Where,

MAR = material-at-risk is the amount of radionuclides available to be acted on by a given physical stress.
DR = damage ratio or fraction of the MAR that is impacted by the postulated accident scenario, unitless
ARF = airborne release fraction, unitless
RF = respirable fraction, unitless
LPF = leak-path factor, unitless

4.2 Definition of Unmitigated Analysis

For the purpose of this discussion, "unmitigated" means no credit is given to preventive and mitigative controls to reduce the frequency or consequence of potential accidents. The unmitigated accident scenario is intended to represent a reasonably conservative bounding analysis of potential consequences independent of their likelihood of occurrence (as long as these are physically plausible). Based on recent implementation experience at some DOE sites, the potential for "inherently credited controls" to define the scenario and frequency considerations, and the guidance of DOE-STD-3009, Appendix A, the following general features of an unmitigated analysis are required:

1. Consider material quantity, form, location, dispersibility, and interaction with available energy sources. The unmitigated release calculation represents a theoretical limit to scenario consequences assuming that all safety features including administrative controls have failed, so that the physical release potential of a given process or operation is conservatively estimated. The unmitigated release should characterize the energies driving the release and the release fractions in accordance with the physical realities of the accident phenomena at a given facility or process.

   NOTE: It is reasonable to assume that certain hazards are not expected to be introduced in the facility (e.g., flammable gases, explosives) if supported by the DSA facility process description and hazards identification. In those cases, unmitigated analysis need not assume their presence simply to ensure a bounding analysis. However, in those cases where unplanned hazards or activities have a real potential of being introduced into the facility (e.g., due to human error and the hazard exists elsewhere on the DOE site), they may need to be analyzed or their exclusion protected with TSR controls as an initial assumption of the analysis. It is also expected that the unreviewed safety question determination process will evaluate proposed introduction of new hazards or activities before they are implemented in the facility, thus preserving the DSA assumption to not evaluate certain hazards.

2. Take no credit for active safety features such as ventilation, filtration systems, and process controls. In addition, do not credit passive safety features producing a leakpath reduction in building source term, such as building filtration.

3. Do not credit building wake in calculating the public or worker doses unless shown to yield more conservative or bounding results. There is considerable uncertainty associated with such analysis, e.g., concentration within the recirculation cavity or immediately downwind from the cavity depends on the release location from the building, size of building and structures around the facility, wind speed and direction, etc. Use of alternative dispersion methodologies than that described in Section 5.3 must have a valid basis and be discussed with and approved by the DOE Approval Authority.

4. The analysis may take credit for passive safety features where the capability is necessary to define a physically meaningful scenario. The effect of acknowledging passive features to define a meaningful accident scenario in the unmitigated analysis means that the unmitigated analysis is not necessarily a "parking lot release" expectation. In addition to those examples cited in DOE-STD-3009 Appendix A, another example for TRU waste operations is that credit may be taken for designed storage racks and fixed-aisle spacing, if these are to survive the postulated events and are not subject to change as part of the facility operations.

   It should be recognized that the presence of some design features could result in greater releases. As an example, if a facility interior contains heavy objects (e.g., equipment, concrete floors) on floors above the ground floor, the unmitigated seismic accident may have greater releases if this equipment were assumed to fall onto the ground floor than if it were assumed that no facility existed. This also applies to a postulated collapse of a concrete facility compared to the collapse of a lightweight metal type facility.

   However, it is important to note that such defining assumptions may warrant some level of safety Structures Systems and Components (SSC) designation to ensure that the assumptions remain valid in the future.

5. In general, credit must not be taken for administrative controls (e.g., combustible controls or restrictions). Based on experience within the DOE complex, an exception is application of a MAR control as an initial condition to preserve a Hazard Categorization (HC)-3 designation (e.g., for low-level waste storage) or an imposed HC-2 facility inventory.

6. The following guidance on assessing accident frequency is based on recent DOE experience:

   a. DOE-STD-3009 and 3011 caution that a frequency cutoff such as less than 10-6/yr (*Beyond Extremely Unlikely*) is not to be used as an absolute cutoff for dismissing physically credible operational accidents without any evaluation of preventive and mitigative features in hazard analysis.

b. Frequency estimates for Natural Phenomena Hazards (NPH) events generally have a lower initiating event frequency (e.g., *Unlikely*) and are based on design and evaluation criteria provided in DOE O 420.1B and its associated implementation in the DOE 1020 series of standards. Consideration should also be given to frequency of enabling events resulting from the NPH event.

c. External manmade accidents are to be evaluated if the event can occur with a frequency $>10\text{-}^{6}$/yr as conservatively estimated, or $>10^{-7}$/yr as realistically estimated. Frequency of aircraft events is determined based on DOE-STD-3014, which uses a 10^{-6} per year frequency cutoff.

d. The frequency of the unmitigated event is the product of the probabilities for independent initiating and enabling events that could cause a radiological release if preventive controls are not credited. An initiating event is the first in a sequence of detrimental events leading to an adverse consequence. Enabling events are those other intermediate events that link the initiating event with the outcome of an accident. Fortuitous circumstances, e.g., activities that are rarely performed, can be credited for the unmitigated analysis. However, failure of preventive controls, whether an active engineered safety feature or an administrative control, cannot be credited for the unmitigated analysis.

e. If the failure is caused by human error, the unmitigated annual frequency of occurrence normally should be assumed to be *Anticipated* unless a rationale for supporting lower frequencies is provided (e.g., requires multiple independent errors of commission or omission, activity is rarely performed, etc.).

f. Guidance on *Expected* operational events is provided in Section 3.4.

4.3 Bounding the Material-At-Risk

The amount of hazardous material that is assumed to be at risk from a postulated accident scenario, or MAR, will directly impact the doses to both workers and the public. An overly conservative estimate of the MAR could very well lead to an over-designation of controls that could, in some circumstances, negatively impact safety. On the other hand, an optimistic (non-conservative) analysis could lead to major impacts on operations due to the discovery of discrepant as-found-conditions, Potential Inadequacies in the Safety Analysis (PISAs), preparation of multiple Unreviewed Safety Questions (USQs), and even potentially creating conditions that could lead to accidents. Thus, there is a need to balance the level of conservatism associated with the MAR definition.

4.3.1 Data Uncertainties in Hazard and Accident Analysis

The purpose of determining MAR estimates during Hazard Analysis (HA) and Accident Analysis (AA) is to identify a bounding value for the scenario being evaluated. During HA, qualitative consequence severity categories are assigned to each of the postulated accident scenarios. Thus, there is a need for an understanding of the MAR expected to be involved. During AA, a more quantitative knowledge of the anticipated MAR is expected and is based on a quantitative assessment of the effects of the postulated release considering factors such as inventory, material form, and the energy sources involved with the release.

Data uncertainties associated with the MAR depend on many variables, such as the quality of the current inventory data, whether the data represents Acceptable Knowledge (AK) for legacy waste or newly generated waste, and whether the inventory is based on actual characterization data. Most uncertainties associated with legacy waste stem from the fact that requirements for, and formality associated with AK documentation, have changed significantly, with the requirements for the older documentation being less stringent than current requirements. Thus, uncertainties associated with characterized waste are much less significant, (e.g., intrinsic uncertainties associated with NDA and NDE).

4.3.2 Defining a Bounding MAR for TRU Operations

Table 4.3.2-1 summarizes the bounding MAR limits for TRU waste operations. The table provides an algorithm of MAR values based on the number of containers anticipated to be impacted by postulated scenarios (single container, payload, building, etc.), and inventory knowledge (e.g., whether the inventory has been partially or fully characterized). In cases where no characterization data is available, inventory estimates must be based on existing process knowledge or the use or extrapolation of characterization data from similar waste streams.

The quantities of TRU material presented in Table 4.3.2-1 follow the general algorithm that a single container scenario assumes the presence of the single maximum loaded container (including instrument uncertainty), while multiple container accident scenarios assume the presence of some combination of containers containing the maximum container value, the 99th percentile value, the 95th percentile value, and the mean value quantities of TRU material, from the population of containers being evaluated. The algorithm also accounts for the extent of characterization associated with the inventory (limited or partial characterization, and fully characterized, e.g., WIPP compliant assay). The use of an additional 20% margin is recommended for single container events in which the container is not characterized or has limited characterization (e.g., not fully WIPP compliant or otherwise acceptably characterized). The methodology in Table 4.3.2-1 provides for additional conservatism to account for the increased uncertainty when the waste containers involved in the accident are not fully characterized. For those inventory populations with only limited or partial characterization, the MAR value should be based on the non-parametric estimate of the 95% upper tolerance limit (UTL_{95}) for the specified percentiles and the 95% upper confidence limit (UCL_{95}) for the mean (arithmetic average) (See Appendix A). Container populations, for which individual container inventories have all been determined, through measurement (and documented), may be considered to be fully characterized for application of the algorithm in Table 4.3.2-1.

The MAR methodology in Table 4.3.2-1 provides a reasonably bounding approach for typical TRU waste operations. However, this approach is not intended for the following situations: (1) operations that intentionally commingle containers with the highest distribution of radioactive material in a facility's inventory (e.g., highest two or three containers in the same array that is impacted by an accident stress); (2) operations in which it can't be distinguished whether containers with the highest distribution of radioactive material are commingled in a facility's inventory (e.g., retrieval of legacy containers without data supporting such assumptions); or (3) containers that have been prepared for shipment in accordance with limits established in the WIPP waste acceptance criteria. In the first two situations, the term "commingling" is relative to the proximity of containers that are concentrated in an area that can be impacted by a single accident stress, e.g., intentionally concentrating together or segregating high-MAR drums from the general population of drums.

When using the MAR methodology in Table 4.3.2-1, assumptions regarding the scope of container movement activities should be clearly stated in the DSA. Special attention should be given to whether the scope of container activities could unintentionally concentrate problematic containers, thereby invalidating the MAR methodology. If this situation exists, an administrative control will be required to protect assumptions of the hazard analysis.

TABLE 4.3.2-1 Bounding MAR Limits for TRU Waste Operations[4]

MAR Description	Limited Characterization[1]	Fully Characterized [2]
Single Container	Maximum container +20%	Maximum container
Two Containers	One at Maximum container, one at UTL_{95} for the 99th percentile	One at Maximum container, one at 95 th percentile
Three Containers	One at Maximum container, one at UTL_{95} for the 99 th percentile, one at UTL_{95} for the 95 th percentile	One at Maximum container, one at 95 th percentile, one at mean or median[4]
Four Containers	One at Maximum container, one at UTL_{95} for the 99 th percentile, two at UTL_{95} for the 95 th percentile	One at Maximum container, one at 95 th percentile, two at mean
Greater than four containers	One at Maximum container, one at UTL_{95} for the 99 th percentile, two at UTL_{95} for the 95 th percentile, Remainder at UTL_{95} for the mean each, Or Applicable Facility/area/payload Limit [3]	One at Maximum container, one at 95 th percentile, remainder at mean each, Or Applicable Facility/area/payload Limit [3]
TRUPACT-II Payload	N/A	Fourteen containers at WIPP WAC Limit[3]

[1] Waste has limited characterization data and relies on measures such as process knowledge.

[2] Inventory is assumed to be fully characterized when contents of each container are known (e.g., meets requirements for WIPP compliant assay or other acceptable characterization of each container).

[3] Bounding MAR limit determined based on operational needs and inventory profile. If the maximum container limit to be shipped is well below the WIPP Waste Acceptance Criteria (WAC) limit, then the 14 containers must be at the maximum inventory limit.

[4] In cases where containers are intentionally grouped (e.g., separation of high or low inventory containers), statistics in this table must be applied to each grouped population of containers.

As an alternative to using a statistical MAR approach, process areas with a known throughput of inventory (e.g., TRU staging pad) may establish a bounding MAR limit that is used in the unmitigated analysis. In these cases, any subset of the full facility inventory should be justified on the basis that it contains the maximum inventory that could be impacted by an accident stress. For example, if planned activities are such that a limit of 1,000 PE-Ci is sufficient to bound the MAR based on known container loadings to be staged in a given area, then the unmitigated MAR could be established at this limit. In such a case, the limit must be protected with a specific TSR inventory control.

4.4 Damage Ratios

The DR is one of the parameters of the “five-factor formula” presented in the DOE-HDBK-3010 for estimating the airborne radiological release from an accident. The DR is defined in the Handbook as the “fraction of the MAR actually impacted by the accident-generated conditions.” However, there is a degree of interdependence between the definitions of DR and MAR. If only the MAR directly affected is used, then the DR is 1.0. If the MAR is the facility maximum operating limit, then the DR may well be less than 1.0 depending on the accident. What is important is that one convention is used consistently to avoid an obvious potential for assigning incorrect DR values.

The DR is estimated based upon engineering analysis of the response of structural materials and materials-of-construction for containment to the type and level of stress/force generated by the event. Standard engineering approximations are typically used. These approximations often include a degree of conservatism due to simplification of phenomena to obtain a useable model, but the purpose of the approximation is to obtain, to the degree possible, a realistic understanding of potential effects.

A DR of 1.0 is often assumed, either for simplicity in performing the calculations as suggested in the DOE-HDBK-3010 or based on conservatism if the final radiological consequences do not drive the need for special TSRs to prevent or mitigate the accident. Section 7.3.6.2 of the DOE-HDBK-3010 provides a very important perspective on assigning DRs:

> *In the examples in this handbook, DRs are typically bounded by assuming a value of 1.0 for the sake of simplicity. The above discussion indicates how conservative such a bound can be. It is important not to lose sight of the fact that the phenomena being examined are generally unlikely to highly unlikely. By the time a maximum MAR has been assumed, the DR has been maximized as 1.0, the bounding ARFs and RFs of this document have been applied, no leakpath is accounted for, and 95% or greater meteorology has been used for*

> *dispersion, the answer obtained is extreme. Objectivity must be retained in the evaluation process so that a rote conception does not distract available resources from areas where greater real gains in safety can be made. As previously cautioned in this handbook, answers obtained are only as good as the decisions they lead to.*

That perspective should be kept in mind when DRs are justified for any specific accident scenario, natural phenomena event, or external events. The selection of appropriate DRs must support an overall conservative analysis consistent with the DOE-STD-3009 methodology (DOE 1994b). DRs must also be selected in context with the conservatisms of the other parameters in the "five factor formula," i.e., MAR, bounding ARFs and RFs per DOE-HDBK-3010 as required by DOE-STD-3009 Appendix A, and Leakpath Factor (only for mitigated analysis).

The following subsections address container integrity, and identify bounding DRs for drum deflagrations, fires, container impacts/spills, and natural phenomena events.

4.4.1 Container Integrity

U.S. Department of Transportation (DOT) 7A or equivalent containers purchased for the packaging and storage of TRU waste provide containment of radioactive materials and minimize release of radioactive material to the public and workers. DOT 7A containers must meet the performance testing requirements specified in 49 CFR Part 173. This includes performance testing which demonstrates that the containers can withstand the following types of events:

- Water spray test
- Free drop test
- Penetration test
- Stacking test

When purchased, TRU waste containers are certified to DOT specifications. However, containers can degrade over time, and DOT certification is only effective for one year after packaging. Legacy TRU waste containers greater than one year, therefore, have lost their DOT certification, but have not stopped performing their intended function. Type 7A containers that meet DOT specifications and conditions most applicable to DOE TRU waste activities are qualified to withstand an impact from a 4-ft drop onto a hard surface without being breached.

It is not reasonable to assume that the structural capability of drums, exceeding one year, has diminished significantly or that these containers will split open upon any impact. This is supported by field experience during handling, movement and storage evolutions. Although handling activities do not subject the drums to the same loads as does an impact from a drop, these activities, along with regular inspections, do provide some evidence that most of the drums have maintained structural capability.

During storage, handling, and movement, TRU waste containers may be punctured, crushed, toppled, or dropped, causing failure of the container and release of material. Legacy container performance and the degree of damage from these accident stresses are largely dependent on the structural integrity of the container. Several individual drum drop and palletized drum drop tests have been conducted and conclude that legacy drums will maintain confinement from a 4-ft drop, because any small degradation is likely to be less than the margin of safety in the original drum design.

The WIPP CH WAC recognizes that most TRU containers are legacy and, therefore, provides an inspection checklist to document that a container meets the DOT 7A criteria. WIPP has established these criteria to address legacy drums and qualify them against new drum requirements. By applying the WIPP criteria to legacy drums, they can be deemed DOT Type 7A compliant. It is reasonable to conclude that containers that satisfy the WIPP container criteria and may be shipped as DOT compliant containers may also be credited as meeting DOT specifications during storage. The WAC states:

> *Payload containers shall meet U.S. Department of Transportation (DOT) Specification 7A, Type A, packaging requirements. Payload containers must be made of steel and be in good and unimpaired condition prior to shipment from the generator/storage sites. To demonstrate compliance with the requirement that payload containers be in good and unimpaired condition, the exterior of all payload containers shall undergo 100% visual examination prior to loading into a TRUPACT-II or HalfPACT. The results of this visual examination shall be documented using the payload container integrity checklist. A payload container in good and unimpaired condition 1) does not have significant rusting, 2) is of sound structural integrity, and, 3) does not leak. Significant rusting is a readily observable loss of metal due to oxidation (e.g., flaking, bubbling, or pitting) that causes degradation of the payload container's structural integrity. Rusting that causes discoloration of the payload container surface or consists of minor flaking is not considered significant. A payload container is not of sound structural integrity if it has breaches or significant denting/deformation. Breaching is defined as a penetration in the payload container that exposes the internals of the container. Significant denting/deformation is defined as damage to the payload container that results in creasing, cracking or gouging of the metal, or damage that affects payload container closure. Dents or deformations that do not result in creasing, cracking or gouging or affect the container closure are not considered significant.*

These criteria have been assembled into a verification checklist as provided in Table 4.4.1-1. It should be noted that the WIPP WAC and container integrity checklist criteria are subject to change based on field experience and feedback. The Table 4.4.4-1 criteria are based on DOE/WIPP-02-3122 that was in effect at the time of development of this Standard. The most current criteria must be used to determine sound structural integrity of TRU containers.

The use of damage ratios specified in the Standard that are based on containers with sound integrity (i.e., DR < 1) must meet these criteria. Application of these criteria assumes container integrity can be verified through an inspection program or process knowledge. Where this cannot be accomplished (e.g., TRU waste retrieval from a burial ground), a DR of less than 1 requires explicit justification. Additionally, in cases where a criterion is met in Table 4.4.1-1, the legacy container cannot be assumed to be of sound integrity.

TABLE 4.4.1-1 Payload Container Integrity Checklist

Container Examination		Discussion of Criteria
1.	Is the payload container obviously degraded?	Obviously degraded means clearly visible and potentially significant defects in the payload container or payload container surface.
2.	Is there evidence that the payload container is, or has been, pressurized?	Pressurization can be indicated by a fairly uniform expansion of the sidewalls, bottom or top. Past pressurization can be indicated by a notable outward deflection of the bottom or top. Verify that the drum is not warped.
3.	Is there any potentially significant rust or corrosion such that wall thinning, pinholes, or breaches are likely or the load bearing capacity is suspect?	Rust must be assessed in terms of its type, extent, and location. Pitting, pocking, flaking, or dark coloration characterizes potentially significant rust or corrosion. This includes the extent of the payload container surface area, covered, thickness, and, if it occurs in large flakes or built-up (caked) areas. Rusted payload containers may not be accepted if: • Rust is present in caked layers or deposits • Rust is present in the form of deep metal flaking, or built-up areas of corrosion products In addition, the location of rust should be noted; for example, on a drum: top lid; filter region; locking chine; top one-third, above the second rolling hoop; middle one-third, between the first and second rolling hoops; bottom one-third, below the second rolling hoop; and on the bottom. Payload containers may still be considered acceptable if the signs of rust show up as: • Some discoloration on the payload container • If rubbed would produce fine grit or dust or minor flaking (such that wall thinning does not occur)
4.	Are there any split seams, tears, obvious holes, punctures (of any size), creases, broken welds, or cracks?	Payload containers with obvious leaks, holes or openings, cracks, deep crevices, creases, tears, broken welds, sharp edges or pits, are either breached or on the verge of being breached.
5.	Is the payload container improperly closed?	Inspect the fastener and fastener ring (chine), if applicable, for damage or excessive corrosion. Check the alignment of the fastener to ensure that it is in firm contact around the entire lid and the payload container will not open during transportation.
6.	Are there any dents, scrapes, or scratches that make the payload container's structural integrity questionable or prevent the top and bottom surfaces from being parallel?	Deep gouges, scratches, or abrasions over wide areas are not acceptable. If top and bottom surfaces are not parallel, this would indicate that the container is warped. Dents should be less than ¼ inch deep by 3 inches long and between ½ inch to 6 inches wide. All other dents must be examined to determine impact of structural integrity.
7.	Is there discoloration which would indicate leakage or other evidence of leakage of material from the payload container?	Examine the payload container regions near vents, top lid fittings, bottom fittings, welds, seams and intersections of one or more metal sheets or plates. Payload containers must be rejected if evidence of leakage is present.
8.	Is the payload container bulged?	For the purposes of this examination, bulging is indicated by: • A fairly uniform expansion of the sidewalls, bottom, or top (e.g., in the case of a drum, either the top or bottom surface protrudes beyond the planar surface of the top or bottom ring,

TABLE 4.4.1-1 Payload Container Integrity Checklist--Continued

Container Examination		Discussion of Criteria
		• A protrusion of the side wall (e.g., in the case of a drum, beyond a line connecting the peaks of the surrounding rolling hoops or a line between a surrounding rolling hoop and the bottom or top ring), or • Expansion of the sidewall (e.g., in the case of a drum, such that it deforms any portion of a rolling hoop).

4.4.2 Container Deflagration Events

This section addresses the DRs for a deflagration within a container from non-fire initiating events (e.g., internal spark during material handling, impacts to drums). The accident phenomenology is described in Appendix B, "Container Deflagrations", and along with a review of the literature, establishes conservative estimates of DRs for this event. The explosion ejects the drum lid and a fraction of the contents. Radioactive material is released to the environment from three accident stresses:

- During the flexing in air
- From assumed unconfined burning of a fraction of the material ejected
- From assumed burning of the remaining materials inside the drum

Appropriate ARFs and RFs for the different contributions are described in Section 4.5. The MAR associated with a single, bounding drum or a two drum deflagration must be consistent with the recommendations in Section 4.3.

TRU wastes are actinide surface-contamination on combustible and noncombustible substrates. The contents of some drums are almost entirely combustible materials composed of cellulose and plastic substrates. The combustible materials are often found as multilayer wrapped, especially for most waste with highest potential inventory (e.g., from gloveboxes where waste, especially cellulose waste, is placed in a plastic bag and the air expelled before sealing for ease of handling and space considerations, and placed in a heavy-wall plastic sleeve during extraction from the glovebox). Other drums may be almost entirely of noncombustible items. Other forms of TRU wastes (e.g., sludge, decontaminated equipment, liquids absorbed on diatomaceous earth, etc.) are also found. There are also two categories of TRU drummed waste: “legacy” and WIPP WAC.

The radiolysis of hydrogenous materials by the alpha-activity present in TRU waste generates hydrogen gas that may accumulate in the drums. Based on drum characterization studies until recently, the oxygen content is simultaneously reduced, likely due to reaction with other materials present or hydrogen and oxygen forming water vapor, although this could be offset by inleakage past container seals due to breathing caused by barometric pressure and atmospheric temperature changes. However, recent characterization of drums at the Savannah River Site has demonstrated that sufficient levels of oxygen are present with levels of hydrogen that exceed its Lower Flammability Limit (see discussion in Appendix B). Three components are necessary for burning: fuel, oxidant, and an ignition source. Other factors will affect the ignition and combustion of hydrogen-air mixtures such as concentrations of the reactants, the location of the ignition source, presence of water vapor, etc. Typically in the DOE-complex, the ignition source is assumed to be present. The fuel and oxygen must be mixed and at a sufficient level to support the combustion.

Contained gases can explode (deflagrate or detonate) and result in loss of containment and ejection of surface-contaminated combustible and noncombustible contents. The energy release and the duration of the energy release is a function of the explosive reaction: deflagration or detonation. When the fuel and oxidant are in a gaseous state, the flammable mixtures deflagrate (fast burning), but under special conditions (such as proper concentration of the component gases, turbulent mixing, a strong ignitions source, an adequate length/diameter ratio, run-up distance, etc.), a deflagration can transition into a detonation (Deflagration to Detonation Transition). This phenomenon is addressed in Appendix B, which concludes that a deflagration in a drum will not transition to a detonation.

There are many published experimental studies on the behavior of metal drums in the literature and those that are relevant and available are reviewed in Appendix B. Appendix B summaries hydrogen and oxygen concentrations measured in legacy TRU waste drums, provides the basis for the drum deflagration DRs, and covers the factors that influence the behavior of the contents (i.e., surface-contaminated combustible and noncombustible materials) of the 55-gal metal TRU waste drums.

The Idaho drum deflagration tests discussed in Appendix B indicated that sympathetic deflagration of a drum on top of the initial deflagration occurred. However, the lower drum did not lose its lid due to the weight of the drum on top. No experimentation has been conducted nor observed on sympathetic deflagration of horizontally adjacent drums. Therefore, it is conservatively assumed that sympathetic deflagration is possible involving two suspect drums as defined by Event 7 in Section 3.3.2.3. Although additional sympathetic drum deflagrations may be possible depending on the staging configuration and other factors, modeling more than two drum deflagrations is not deemed necessary, because adequate insights from the two-drum deflagration should be sufficient to establish appropriate controls to protect the facility worker, other onsite (collocated) workers, the public, and the environment, and based on the likelihood of three or more sympathetic deflagrations being very low, this is not perceived to be a significant risk.

Sympathetic deflagrations need not be evaluated for the unmitigated analysis for TRU waste drum handling and staging/storage of newly generated drums associated with typical DOE Complex processes that generate contaminated, combustible wastes. Newly-generated drums are those generated per a site's waste packaging procedure with the intent to meet the WIPP WAC that was in effect since WIPP opened in the 1999, but may not be fully characterized as compliant to the current WIPP WAC. The assumption of not involving more than a single drum is based on the low likelihood associated with multiple upright drums, located adjacent or in nearby proximity to each other, having sufficient hydrogen-air concentration necessary for lid loss (i.e., exceeding approximately 15% hydrogen concentration with at least 7.5% oxygen, a small fraction of legacy drums based on characterization experience, and even lower chance that newly-generated drums would achieve such levels, as described in Appendix B).

The following DRs for deflagrations within a drum must be used, unless otherwise justified, for TRU wastes in metal drums:

- **Single, Bounding Drum**
    - 40% ejected = 0.4 DR based on the maximum value cited in the Idaho experiment evaluated in Appendix B. This 0.4 DR applies to the flexing-in-air release and the unconfined burning outside the drum.
        - Fraction of material that is released from the drum and burns in the ambient atmosphere as unconfined material: 0.05 DR of the mass of ejected combustibles that is ignited by heat generated by the combustion of a stoichiometric H_2-air concentration in the drum. This includes the total energy generated by the deflagration of a 30-vol% hydrogen in air (that is assumed to contain a sufficient oxygen concentration for the complete combustion of the hydrogen) and ignoring any heat transfer to other components such as waste remaining in the drum or the drum itself and the possible extinguishment during its flight (see Appendix B discussion).
    - 0.6 DR for the remainder of the material in the drum that is conservatively assumed to burn, modeled as confined materials.
- **Two-Drum Deflagration**
    - Both drums – use the values for the single, bounding drum deflagration (i.e., 40% ejected with 0.05 burn fraction), and 60% burning inside the drums, as discussed in Appendix B).

In addition, the waste form influences the amount released (e.g., all combustible waste versus some noncombustible wastes). Where an individual site may be able to justify a specific ratio of combustible to noncombustible drum contents, that justification may be credited in the analysis. Releases from combustibles are assumed to be representative of cellulosic materials and surface-contaminated plastics, as discussed in Appendix B.

Table 4.4.2-1 DRs for drum deflagrations must be used, unless otherwise justified, for TRU waste operations.

TABLE 4.4.2-1 Drum Deflagration Damage Ratios

Number of Drums Involved	Waste Form Percentage	Release Phenomenon DR	Fraction Burned Outside DR
1.A. Ejected flexing in air	n/a	0.4	n/a
1.B. Ejected combustible waste burning outside	100%	0.4	0.05
1.C. Combustible waste burning inside drum	100%	0.6	n/a

n/a – not applicable

The potential presence of prohibited items (cylinders of flammable/combustibles gases, VOCs) in legacy waste also can generate flammable gas mixtures. Appendix B concludes that the behavior of TRU waste drums filled with combustible waste containing a limited quantity of VOC is bounded by the drum behavior resulting from the deflagration of an internal stoichiometric H_2-air mixture. This applies to both the ejection fraction and the amount of combustibles that could burn outside the drum. Although the quantity of the VOC is small, under most TRU waste drum situations, larger quantities are not anticipated. Under special circumstances for drums containing liquid VOC or large quantities of cellulose wetted with solvents used to clean glove box interior that are packaged, larger quantities of VOC may be found. This situation would not be bounded by the H_2 drum deflagration due to the amount of solvent-soaked combustibles that could burn outside the drum, and the possibility that a larger fraction of wastes may be ejected. For combustible solid wastes with large quantities of VOCs, a DR of 1.0 is conservatively assumed for ejection of combustible wastes and unconfined burning due to the lack of experimental data and uncertainty of what can occur under these conditions. If the contents are radioactive flammable or combustible liquids and no combustible solid wastes, the release must be modeled per recommendations in the DOE-HDBK-3010, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities* assuming a DR of 1.0 for lid loss and subsequent burning of the liquid inside or outside the drum.

Internal deflagrations for other container sizes are addressed as follows:

- For a Standard Waste Box (SWB), lid loss will not occur for a container deflagration, because the lid is very heavy and bolted onto the body of the box.

- Lid loss will not occur for a direct-loaded RH waste container with a welded lid, or the Removable Lid Canister (RLC) for the RH-TRU 72-B cask. The RLC has a very robust lid closure mechanism using grooved tabs (like the TRUPACT-II) and lock pins in lieu of bolting.[1]

- Overpacking a metal drum of sound integrity with a larger metal drum, a SWB, or a RH canister with nested metal drums can be credited to prevent lid loss and ejection of contents.

- For the SWB, RH canister with nested metal drums, and the overpacked drum, a significant release from potential venting through the outer container seal is not expected.

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[1] See the latest WIPP procedure for more information

Any potential release from venting through the outer container would be bounded by the mechanical impact evaluations presented in Section 4.4.4 (e.g., spill-type release). Additionally, a subsequent fire will be limited by the availability of oxygen remaining after the deflagration or inleakage through damaged seals, and is bounded by the fire evaluations presented in Section 4.4.3.

- For the Pipe Overpack Container (POC), pressure testing (see Appendix C) showed that even if a hydrogen deflagration should occur, its magnitude would not be enough to damage the pipe component or significantly degrade its filter.

- For fiberglass reinforced wooden boxes of legacy TRU wastes, the Idaho test results discussed in Appendix B concluded that sufficient hydrogen buildup is not possible due to its lack of leak-tightness.

- For other containers, specific analyses are required to credit their ability to prevent lid loss and/or ejection of materials.

4.4.3 Fire Scenario Damage Ratios for TRU Waste Containers

This section addresses selection of DRs for fires in TRU waste container storage in existing facilities for the facility DSA. The technical bases, including conservative assumptions where direct experimental data are not available, for the DR values presented in this section are included in Appendix C, "Damage Ratios for Container Insults and Fires".

The most common TRU waste storage container is the open-top, 55-gallon steel drum with a bolted lid locking ring, a DOT Type A container[2]. Other drum sizes may include 15-gal, 30-gal, 35-gal, 85-gal, and 100-gal. Waste may also be stored in SWBs, special purpose, and in some unique cases, DOT Type B containers. In this section, drums are the primary focus, because they are bounding with respect to vulnerability to release. The term "drum" as used in this section means that it is a metal container of sound integrity as described in Section 4.4.1, so that it provides a confinement safety function. Although SWB lids are bolted in place and are not expected to be lost, they are evaluated for releases from seal failure. This section also addresses overpacked containers (e.g., a metal drum of sound integrity nested within a larger metal drum or a SWB, or Ten Drum Overpack [TDOP]) and POCs. The RH canister is also evaluated for lid loss (direct loaded) and seal failure (overpacked drums). Drum storage areas include rooms within buildings, transportainers, and domed structures, as well as staging or storage outdoors. Fires may also occur in drum loading and unloading areas for transportation.

For fire scenarios involving multiple drums, pallets, pads, or the inventory of a building, the general approach is to estimate DRs based on estimating the footprint of the design or evaluation bases fire to determine the area of impact of the fire (includes direct flame contact and the radiant heat and heat fluxes). From this area and the storage characteristics, the number of drums

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[2] Type A and Type B refer the robustness of the drums, as defined by meeting a series of tests (drop, fire, water, etc.) specified by the DOT. Type B is the more robust of the two, because Type B containers are required to survive a 30-min fire and 30-ft drop test. Type A containers have no requirements regarding fires and must survive only a 4-ft drop.

that could be impacted is estimated. Assumptions are made with respect to drums stacked on top of each other, to determine how they fail (i.e., seal failure venting or lid loss due to a fire). The potential for lid loss and ejection of contents is also considered.

Extensive solid waste drum fire tests were performed by Hughes Associates, Inc. for the Hanford site and reported in *Analytical and Experimental Evaluation of Solid Waste Drum Fire Performance,* WHC-SD-TRP-233, and *Solid Waste Drum Array, Fire Performance*, WHC-SD-WM-TRP-246. These results were interpreted into a protocol to model drums exposed to flammable or combustible liquid pool fires and are published in the *Fire Protection Guide for Waste Drum Storage Arrays*, WHC-SD-SQA-ANAL-501. The general methodology outlined in Section 5 of that Fire Protection Guide is an acceptable methodology for fire modeling inputs and assumptions to determine the number of drums involved, extent of lid loss with ejected contents and seal failures, and to estimate the overall source term released. As an alternative to applying this Fire Protection Guide, the following simplified approach for flammable or combustible liquid pool fires and for ordinary combustible fires has been conservatively established to determine the extent of lid loss with ejection vs. seal failures and appropriate DRs for the different ARFs and RFs. Other site-specific fire modeling approaches based on drum fire testing results can be applied if technically justified for development of the control set.

4.4.3.1 Drums Exposed by Flammable Liquid Pool Fires

Fire calculations to support the DSA analysis are required to determine the size of a pool fire or extent of sufficient radiant heat flux for non-pool fires, which in turn are used to define the number of drums involved. These calculations must be consistent with standard fire protection engineering methods for the bounding type of fires associated with the facility. DSA and fire hazard analysis modeling assumptions (e.g., pool burning characteristics and depth of an unconfined pool) must be consistent unless justified for the different objectives of the analyses (i.e., DSA unmitigated scenario versus a Maximum Possible Fire Loss scenario).

Based on fire testing of drums, fires can cause release of radioactive and other hazardous materials from metal containers in two ways. First, fires can cause lid seals to fail, allowing unfiltered out-gassing at the interface between the lid and body of the container. Second, fires can cause the lid to be forcefully ejected (lid loss), possibly with an accompanying expulsion of material from within the container. Ejected materials are subject to the unconfined burning ARF of 1E-2 with a 1.0 RF as discussed in Section 4.5. Unlike the recommendation in Section 4.4.2 regarding unconfined burning of a fraction of the ejected wastes from a drum deflagration, all wastes ejected are assumed to burn unconfined due to the external fire source. Materials remaining in drums with lid loss are subject to the confined burning ARF 5E-4 with a 1.0 RF as discussed in Section 4.5. Seal failures are also subject to the confined burning ARF and RF. Since the different drum responses involving confined and unconfined burning result in significantly different estimates of airborne releases, damage ratios need to be addressed for both situations.

To simplify the modeling approach, drum contents are assumed to be 100% combustible contaminated solid wastes. Appendix C discusses how to treat noncombustible contaminated solid wastes if the site can justify bounding estimates for the distribution of combustible vs. noncombustible waste forms.

The response of metal containers to fire depends on whether the heat transfer is through direct flame impingement or only through radiation. Lid loss can occur only if specific conditions are met (e.g., a "fast" fire growth rate, direct flame impingement, etc.). Engulfing fires are those fires in which burning liquid fuel (including melted drum liners) passes beneath the container (e.g., on a pallet) or surrounds it. These fires can cause lid loss to a fraction of the engulfed drums, which may expel a portion of the contents. From the fire testing experience described in Appendix C, not all unrestrained drums engulfed in a pool fire experienced lid loss. Twenty-five percent (25%) of the drums engulfed in the pool fire are conservatively assumed to experience lid loss and ejection of some contents, so that the analytical model more accurately represents the results of the fire tests. Some unrestrained drums adjacent to the fire that have direct flame impingement are also conservatively assumed to experience lid loss and ejection, therefore, apply the same 25% assumption. If containers are stacked, the drums on the lower layers are expected to retain their lids, as the weight of the upper layers will keep them in place. However, there are exceptions to this. In experiments with stacked drums, lid rupture was occasionally observed on levels other than the top level. In those cases, however, the lid was displaced, but not totally lost and there was little expulsion of material from within. For modeling purposes, it is sufficient to assume that lid loss occurs only on the top level, and some contents are ejected, as determined next.

For drums that experience lid loss, one-third of the contents (33%)[3] are assumed to be ejected from the drum and burn as unconfined materials. The other two-thirds of the MAR are assumed to stay inside the drum and burn as confined materials. The DR is 1.0 for each portion, or this could be thought of as a DR of 0.33 of the total MAR for the expelled portion and 0.67 for the remainder in the drum.

Those containers with direct flame impingement inside the pool or along the edge of the pool fire that do not lose their lids will most likely experience lid seal failure and experience confined material burning. If a container on the top tier in the second row outside the pool area is adjacent to a drum in the first row along the edge of the pool fire that loses its lid, seal failure and confined burning is also expected due to the likely magnitude of radiant heat flux from the pool fire and lack of shielding from the first row. Drums on lower tiers in the second row below the top tier do not experience seal failures due to assumed shielding from the first row of lower-tier drums and limited "view factor" from the flame.

This approach does not consider toppling of stacked drums and potential for additional unconfined burning of scattered wastes. Rapid pressurization is not expected to topple higher-tier drums based on the Idaho hydrogen deflagration experiment described in Section 4.4.2. The Hanford fire tests did not observe toppling, however, the drums were banded to pallets that allowed the drums to slump vertically. Failure of metal pallets is much less likely and would require a sufficiently long duration fire to cause failure, not typically associated with potential facility fires in TRU waste storage areas, and must only be evaluated in the DSA if it is evaluated

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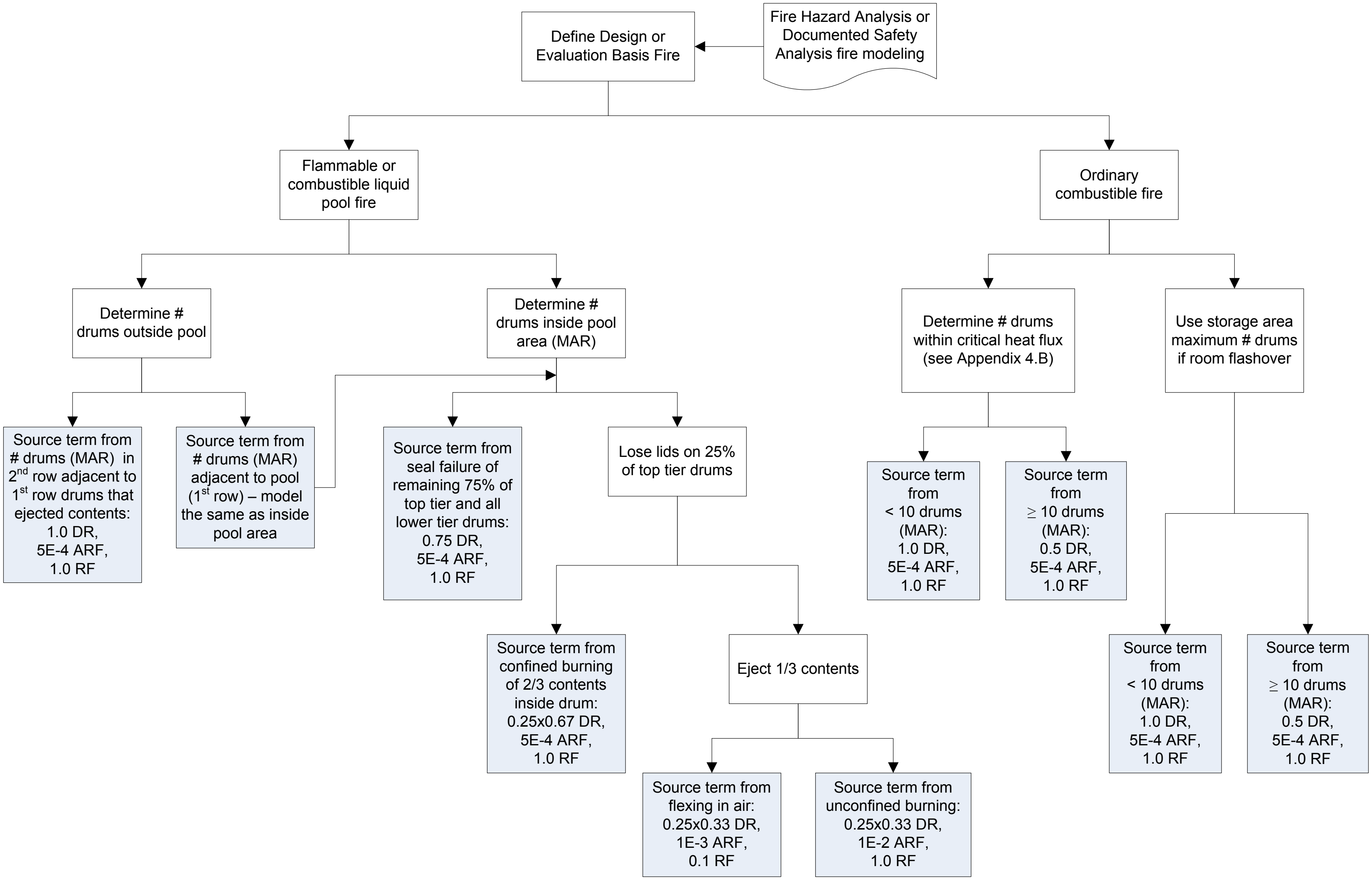
[3] See Appendix C discussion regarding how conservative this assumption is.

for the Fire Hazards Analysis based on the fixed and transient fuel loading associated with TRU waste operations. However, a fire would be expected to cause toppling of stacked drums on wooden pallets, which must be evaluated if this hazard exists at a site.

FIGURE 4.4.3-1 illustrates the above approach to estimate the source term from a pool fire. It also summarizes the approach to calculate non-pool fire source terms as presented in the next section.

FIGURE 4.4.3-1 Fire Damage Ratios (DRs) for Direct-Loaded Drums



4.4.3.1 Drums Exposed by Ordinary Combustible Fires

Non-pool fires are those that involve ordinary combustibles such as trash, wooden boxes, clothing, etc. This type of fire has a “moderate” fire growth rate. Fire experiments have demonstrated that lid loss and ejection of contents is not expected, so for modeling purposes, only seal failures are evaluated. This could include trash fires and wooden crate fires. For direct flame impingement on only one side of a container from an adjacent ordinary combustible fire, the container is not heated rapidly enough to cause lid loss and ejection of contents. When heat transfer is only through radiation, fires involving non-liquid fuel packages (e.g., trash) were determined to not result in lid loss. The heat output of the fire is insufficient to increase temperature and pressure inside the drum quickly enough to eject the lid before venting (seal failure) occurs. The container must be close enough to the fire such that it is exposed to a sufficient heat flux[4]. If room flashover is possible for the DSA unmitigated analysis, then all containers are subject to seal failures.

An additional DR consideration for seal failures to account for incomplete combustion and other factors is appropriate when more than a few drums are involved. The use of a DR for an inventory of a single drum has not been substantiated through direct experimentation. The effect of incomplete combustion of the surface-contaminated solid combustible wastes is incorporated in the DOE-HDBK-3010-94 value in the experiments performed for waste burned in cardboard containers (i.e., the 5E-4 ARF presented in Section 4.5). Because the DR was not measured in the experiment, the relationship between the ARF and DR is unknown, introducing additional uncertainty upon application to other types of containers involved such as metal drums. But, it is reasonable to assume that the release of the same material, contained in a sealed metal drum, will be reduced by some factor due to the drum's effect and vapor and particle transport. However, due to uncertainties in how much of the contents burn and extent of seal failure versus lid loss, for any event that involves 10 or more drums, an assumption of a uniform-like surface contamination is acceptable and a DR of 0.5 is considered reasonably bounding. A DR of 1.0 is assumed for less than 10 drums due to this uncertainty regarding the amount burned and whether there is uniform contamination.

Another type of fire that could cause a lid loss occurs when flammable/combustible liquid is present in the drum with other combustible solid wastes. A fire involving any type of fuel package may result in auto-ignition of flammable vapors inside the drum. For these mixed combustible wastes, based on assuming small amounts of the liquid, this phenomenon is modeled in accordance with assumptions presented in Section 4.4.2, unless otherwise justified. The Section 4.4.2 hydrogen deflagration modeling assumptions do not apply to drums of mixed wastes of combustible solid wastes with flammable or combustible liquids that exceed the small-quantity VOC assumption as described in Appendix B, "Container Deflagrations", or drums of radioactive flammable or combustible liquids. For combustible solid wastes with large quantities of VOCs, a DR of 1.0 is conservatively assumed for ejection of combustible wastes and unconfined burning due to the lack of experimental data and uncertainty of what can occur under these conditions. If the contents are radioactive flammable or combustible liquids and no combustible solid wastes, the release must be modeled per recommendations in the DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor*

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[4] See Appendix C discussion

Nuclear Facilities assuming a DR of 1.0 for lid loss and subsequent burning of the liquid inside or outside the drum.

It should also be noted that the Hanford fire tests concluded that an internal fire in a single drum is not expected to propagate to an adjacent drum[5], whether the adjacent drum is to the side or above the drum with the internal fire.[6]

4.4.3.2 Fire Damage Ratios for Other Containers

A similar DR for seal failures of SWBs is established based on physical consideration that four drums are approximately equivalent to one SWB. This results in a DR of 0.5 for more than two SWBs involved in a fire (i.e., 10 drums divided by 4 and rounded up). However, a DR of 1.0 is assumed for one or two SWBs involved in the fire.

As discussed in Section 4.4.2 on deflagration within a container, overpacking a metal drum of sound integrity with a larger metal drum, a SWB or a TDOP, can be credited to prevent lid loss and ejection of contents and modeled as seal failures. In addition to preventing lid loss, overpacked containers provide an additional level of protection from fires that allows a lower DR than those for directed-loaded drums or SWBs.

The dimensions of the SWB are nominally 5 ft long, 4 ft wide, and 3 ft tall, with rounded sides to fit within the TRUPACT-II container for shipments to WIPP. The walls are typically 10- to 12-gauge (about 0.1 in.) sheet metal, and the container is sealed with a gasket and lid with 42 bolts. The TDOP is constructed similar to a SWB and provides primary confinement to a large drum-like volume that can be loaded directly or as an overpack for 10 full 55-gal drums, up to 6 full 85-gal drums, or an SWB. Both the outer container and inner drums in an overpack assembly must have vents installed. For a radioactive material release to occur, the fire has to heat up the inside of the SWB/TDOP and also heat the inner contents of the 55-gal drums resulting in pyrolization of the drum contents and subsequent venting from both containers. The SWB/TDOP configuration presents a significant heat sink and pyrolization of drum contents would require a very long lasting fire or a very large fire. Another consideration is that the SWB/TDOP is large, therefore, it is not expected that all of the waste will be affected by a fire. Although the drum-in-drum overpack does not provide the same level of heat sink, the overpacked drum fire testing described in Appendix B.2.4, "Volatile Organic Compounds (VOCs)" concluded that the average mass loss for a drum overpacking was about a factor of five less than that of the direct-loaded drums that did not undergo "lid loss" (which only averaged about 10% mass loss). Therefore, a DR of 0.1 is assumed for overpacked drums of sound integrity whether overpacked in a larger drum, a SWB, or a TDOP. This applies to a single or multiple overpacked containers exposed to the radiant heat flux that causes seal failures. DRs presented in this section for “overpacked containers” do not apply to overpacked drums of suspect integrity, which must be modeled as a single, direct-loaded drum

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[5] *Fire Protection Guide for Waste Drum Storage Arrays*, WHC-SD-SQA-ANAL-501

[6] The heat generated by a fire within a drum and possible “torches” via seal failure were not significant enough to heat adjacent drums to cause their failure. This is different than the sympathetic deflagration discussed in Section 4.4.2.

Direct-loaded RH canisters may experience lid loss depending on the design of the lid restrain, because it is only required to be qualified as a DOT Type A container. As discussed in Section 4.4.2 for hydrogen deflagrations within a RH canister, lid loss will not occur for a direct-loaded RH container whose lid is welded, or the RLC for the RH-TRU 72-B cask. Although RH canisters with nested drums are expected to behave similar to SWBs and not experience lid loss, the SWB DRs above can be applied to overpacked RH drums in a canister. For RH canisters or drums handled outside a hot cell facility in a shielded "facility cask" or onsite shipping cask that does not meet the DOT Type B criteria[7], lower DRs may be appropriate. This can be justified based on a fire hazards analysis or DSA fire modeling to assess the extent of damage for bounding facility-specific fires or material-handling equipment fuel spills[8].

In the case of POCs**,** the containers are designed in a manner that precludes their failure during expected storage area fires. Four POCs were subjected to Type B protocol thermal tests as summarized in Appendix C. The associated 150 MW fuel pool fire caused the one outer 55-gallon drum of a POC package with a metal filter to experience lid loss[9]. This occurred within the first three minutes of the fire. Post-fire inspection showed the pipe component seal and filter gasket to be damaged. Associated leak rate testing of this POC showed a total leak rate of 24 cm^3/s at a differential pressure of 87 kPa. This leak rate was later associated with an ARF of 6E-6 for the bounding material type in POCs (i.e., powder)[10]. It should be noted that inspection of the POC packages remaining intact revealed that the POCs did not experience temperatures above 200 °F and remained leak tight. Therefore, POCs involved in storage and room fires need not be further evaluated in an accident analysis. However, engulfing fuel pool fires that last longer than 30 minutes exceed the testing conditions and may cause sufficient impact to POCs to warrant assessing the release.

4.4.4 Damage Ratios for Mechanical Insults

This section addresses DRs for the steel drums of various sizes (e.g., 55, 85, 100-gal), SWBs, RH canisters, POCs, and overpacked containers (e.g., 55-gal drum of sound integrity nested within an 85-gal drum or four drums in a SWB; the TDOP, or RH canister with nested drums). Several tests have been performed for dropping 55-gal drums from various heights and with various weights and contents, and for crushing drums. These are described in Appendix C, "Damage Ratios for Container Insults and Fires". However, there has been no testing of the SWBs with “bolted down” lids, overpacked containers, or the TRUPACT-II double-stacked seven-pack drum configuration. Therefore, engineering judgment must be used to extrapolate the available test results to these configuration and accident scenarios. The term “drum” as used in this section means that it is a metal container of sound integrity as described in Section 4.4.1, so that it provides a confinement safety function. DRs presented in this section for “overpacked containers” do not apply to drums of suspect integrity, which must be modeled as a single, direct-loaded drum.

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[7] Casks that meet current Type B criteria normally are expected to survive facility fires typical of those that may occur in the DOE Complex where TRU wastes are stored or handled, unless a facility-specific hazard or accident can cause a mechanical breach of the cask or a much longer duration of fire is possible.

[8] For example, see *Damage Assessment of Waste Containers Involved in Accidents at the Waste Isolation Pilot Plant,* PLG-1121.

[9] The other POC packages had plastic filter seals, which melted during the fire.

[10] See Appendix C discussion.

Drops and impact stresses on TRU waste containers will result in a wide range of damage depending on magnitude of these forces and condition of containers. Spills from a TRU waste container can result from severe shock and vibration stress, from impact events or dropping a container. Spills from a container can also result from the accidental falling or flowing of powders out of a confinement boundary resulting in an airborne release due to the free-fall of the powder in air. As stated in Section 4.4, the DR is that portion of the MAR that is affected by the accident stresses. For TRU waste containers, the materials are primarily contaminated combustible or noncombustible solid materials, solidified/vitrified sludges that do not contain free liquids, or may also be powders of radioactive compounds.

Containers may be punctured, crushed, toppled, or dropped, causing failure of the container and release of the material. Dispersal of the material will occur from the kinetic energy from the accident initiator and from the fall of material from the container failure point to the ground. In the case of container failure due to corrosion, the energy for dispersal is provided by the fall of the material from the container failure point to the ground. Significant release of non-dispersible wastes, such as those that have been vitrified or solidified with concrete in metal containers, would require higher energy input to release the wastes than is available from mechanically initiated spills such as container punctures, drops, or falls.

Examples of potential spill scenarios may include a spill from a metal container due to a forklift puncture or impact by a compressed gas cylinder missile, a spill of waste container(s) due to drops/falls, or a spill of waste container(s) resulting from impact with material handling equipment. Based on the Sandia, Hanford, and Rocky Flats experimental results of drum testing, each of these types of accidents are addressed in Appendix C to establish a range of DRs for various container types and waste forms. From this range of damages, DRs are established for other drop or impact events that can breach waste containers associated with heights typical of existing facilities in the DOE Complex that store and handle TRU wastes. Six broad categories were chosen to represent the range of damage ratios. Appropriate adjustments are made if the material form is contaminated solids versus sand-like material that may be free-flowing, as well as vitrified waste forms. An overview of Appendix C insights from drum and metal box testing performed by Sandia National Laboratories, Hanford, and Rocky Flats follows.

A majority of the reported drum tests were performed with DOT Type 17C drums with a rigid polyethylene liner containing bagged waste of various forms. However, generators will also ship drums that currently have the designation of Type 17H (thinner wall), and both types of drums will be shipped with and without liners. The type of drum and the presence of a liner within it cannot be readily distinguished once it is packaged. Type 17C drums are made from 16-gauge material, which have a nominal wall thickness of 0.059 inches. The Type 17H drums are made from 18-gauge material, which has a typical wall thickness of 0.039 inches. Based on simple calculations of compression stress in the wall and axial buckling performed in the PLG-1121 report, Type 17C drums are stronger than the Type 17H drums. Because both types of drums are to be handled and stored, the characterization of drum failure should be based on the more limiting case of Type 17H drums.

DOT Type A drums are only qualified for a 4-ft drop as discussed in Section 4.4.1. Drum drop testing and static axial crush tests indicated that they perform very well, but results are significantly affected by impact orientation and weight of the contents, among other variables. For example, no lid failures (and thus, no material releases) occurred for drop heights less than 44 ft (13 m) or impact velocities less than ~35 mph for the heaviest drum tested of 748 lb. However, all 1,000 lb drums landing such that the lid locking ring bolt struck the test surface failed at a drop height of 11 ft (3.4 m). Obvious (highly visible) damage to a drum is not necessarily an indicator of drum integrity. Extensive damage to the drum walls may not be indicative of container breach whereas a small amount of damage to the lid and upper sealing surface may cause lid separation and loss of container integrity. The testing concluded that drum deformation cannot be predicted by considering only the kinetic energy of the system; drum contents are important because different materials absorb various amounts of energy. The DRs are based on the amount of spillage of sand-like materials (powders) from test results increased to account for shock-vibration effects that could suspend particulates; a factor of two reduction is assumed for contaminated bulkier materials.

The SWBs are made from 10-gauge material (minimum thickness of approximately 0.128 inches) and have a bolted lid. Because there are no tests for the SWBs, some insight is available from the results of the Rocky Flats DOT 7A welded metal box drop tests. There was no apparent failure of seams or closure welds and no contents were lost from either waste box for the 15-ft drop. For the 25-ft drop test, a pinhole leak was detected. Due to the bolted lid and gasket configuration of the SWB, its performance should be similar to the welded box. However, due to the lack of direct test data and that the container is only required to meet the DOT Type A drop test for 4 ft, and its much larger load capacity (4,000 lb), DRs for drops are established based on those for the 55-gal drum. This is also based on simple compression stress in the wall and axial buckling calculation performed in the PLG-1121 report, that concluded that Type 17C drums appear to be stronger than the SWBs, which in turn are stronger than the Type 17H drums. However, the lids for the SWBs are bolted to the body of the container implying that lid separation is much less likely for the SWBs than for the drums. DRs for forklift punctures are reduced by a factor of two due to the much larger size of the container as discussed in Appendix C, and for the accident involving falls equivalent to a fourth tier of drums (about 10 feet).

The RH waste canister for a 72-B shipping cask is a 0.25 inch thick carbon steel cylindrical vessel having 26 inches outside diameter and 121 inches in overall length. Standard vessel heads are welded to each end of the cylinder, or the top may have a mechanical lid such as the RLC described in Section 4.4.2. They are designed to DOT Type A criteria. It is reasonable to assume that their performance during drop and impact events would be at least as good as SWBs, therefore, the SWB DR recommendations apply to spill events involving RH waste canisters. This is also supported by structural calculations in PLG-1305. For RH canisters or drums handled outside a hot cell facility in a shielded "facility cask" or onsite shipping cask that does not meet the DOT Type B criteria[11], lower DRs may be appropriate. This can be justified based on quantitative or qualitative arguments to credit the more robust container such as those

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[11] Casks that meet current Type B criteria normally are expected to survive facility mechanical insults typical of those that may occur in the DOE Complex where TRU wastes are stored or handled, unless a facility-specific hazard or accident is more severe than the testing requirements.

presented in the Appendix 3B of the Hanford *Solid Waste Operation Complex Master Documented Safety Analysis* (HNF-14741, 2005).

For overpacked containers, there are no test data available. For the single package drop event, a factor of two credit is believed to be a reasonably conservative estimate, because two metal containers should provide some added protection for drop events. This applies to drums of sound integrity overpacked in another drum, SWB, TDOP, or RH canister, and does not apply to overpacked containers that do not meet the Section 4.4.1 container integrity requirements.

The TRUPACT II payload configuration is a two seven-pack plastic-wrapped drum configuration. Based on the pallet drop testing, a DR of 0.5 is recommended, i.e., either the lower seven drums all breached (the more likely consequence), or half the 14 drums on either tier failed. The overall DR includes an adjustment for the type of contents which is based on test data for maximum spillage for two drums and average spillage for the other five drums, and rounding up to account for other shock-vibration effects and for conservatism. This approach is based on the concept similar to that for estimating a bounding MAR involving multiple containers as discussed in Section 4.3.

The POC consists of a sealed pipe component (Schedule 40 pipe with 6-inch diameter or Schedule 20 pipe with 12-inch diameter), contained within a Type 17C 55-gal drum. The pipe component is separated from the drum by fiberboard packing material and a plastic liner. The lids of both the drum and the pipe component have filtered vents. The robustness of the POC was assessed by Rocky Flats[12] based on data taken from reports of Type B protocol testing conducted at the Sandia National Laboratories (e.g., crush, 30-ft drop, and 30-min fire tests), pressure tests, and Finite Element computer modeling of crushing and puncturing. Rocky Flats concluded that the POC does not qualify as a DOT Type B container, because it was not subjected to the complete Type B protocol testing program and, because the pipe component is vented. However, the tests that were performed were passed and it is expected that the puncture test would also have been passed, based on computer modeling and comparison with similar containers that are certified as Type B. The POC far exceeded the DOT Type A test requirements.

For spill scenarios, POCs are vulnerable only to drops/falls from a distance of greater than 30 ft, structural collapse of substantial construction facilities (where falling structural concrete slabs impact POCs such as seismic collapse addressed in Section 4.4.5), and puncture by forklift tines. Stacked POCs could be toppled due to a forklift collision. The POCs would be expected to withstand the impact associated with the toppling of stacks of POCs, as the distance to fall is less than that in the Type B drop tests: a five-high drum-stacking configuration means that the top drum would fall a distance equal to the height of four drums plus the pallet separators – about 13 ft altogether, less than half the distance used in the drop test. Due to the fiberboard material (Celotex®) fill in the POC, the robust design of the Schedule 20 or 40 inner pipe, and the POC drop test performance, no release is expected from a cylinder missile impact, or from tornado/wind-generated missiles. The POC was determined by finite element modeling to be vulnerable to the forklift tine puncture due to the chisel design assumption and very small impact area. The frequency of a POC punctured by a forklift is Extremely Unlikely as discussed in

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[12] See Appendix B discussion.

Appendix C. This is not the case for other missiles impacting the 55-gallon POC drum with the fiberboard fill where no release is expected.

Based on extrapolations and interpretation of the test data discussed in Appendix C as well as DOE Complex precedence established for SB development, the Table 4.4.4-1 DRs for container drops or impacts must be used, unless otherwise justified, for TRU waste operations. These DR recommendations apply a gradation based on energy imparted and container robustness for the range of container breaches presented.

TABLE 4.4.4-1 Container Drop and Impact Damage Ratios

Accident Stress	Damage Ratio (DR)[d]			Comments
	Drum	SWB and RH canister	POC	
1. Stress within container qualifications	0	0	0	Containers of sound integrity per Section 4.4.1 dropped from 4 ft or less (e.g., 2nd tier[a] in stacked array).
2. Minor stress causes breach, e.g.: - Single container or unbanded palletized containers dropped from 3rd tier in stacked array - Multiple containers impacted by low-speed vehicle (e.g., less than ~10 mph in congested or tight areas) - Containers containing closed pipes or welded containers that are dropped from 4th or 5th tier in stacked array	0.01	0.01	0	Considered a “spill” event as defined in Section 4.5.3.1 for ARFs/RFs.
3. Container(s) punctured by forklift tines: - Contaminated solids - Sand-like materials	 0.1 1.0	 0.05 0.5	 0.05 0.1	See Appendix C discussion. Considered a “spill” or "low-energy impact" event as defined in Section 4.5.3.1 for ARFs/RFs. Forklift could puncture two drums.
4. Single container or unbanded[b] palletized containers dropped from 4th or 5th tier in stacked array: - Contaminated solids - Sand-like materials	 0.1 0.5	 0.1 0.25	 0 0	4th tier falls are considered a “low-energy impact” event as defined in Section 4.5.3.1 for ARFs/RFs. 5th tier falls are considered a "high energy Impact" event as defined n Section 4.5.3.2.
5. Moderate to severe stress causes breach, e.g.: - Multiple containers impacted by a vehicle whose speed may be restricted by physical layout of the facility/site and associated obstacles, but whose speed can't reasonably be assumed to be < ~10 mph - Vehicle crash affecting multiple containers, but not in the first row directly crushed by the vehicle (low or high speeds)	0.1	0.1	0	Considered a “low-energy impact” event as defined in Section 4.5.3.1 for ARFs/RFs, unless containers could be crushed as defined in Section 4.5.3.2 due to site-specific circumstances.
6.Catatrophic stress causes breach, e.g.: - Containers directly impacted by high-speed vehicle with crushing force - Container(s) impacted by compressed gas cylinder traveling long distance and/or airborne - Container(s) impacted by tornado- or wind-generated missile	1.0	1.0	0[c]	Containers crushed by > ~25% volume reduction are considered a "high-energy impact" event as defined in Section 4.5.3.2 for ARFs/RFs. Cylinder and missiles are considered a “low-energy impact” event as defined in Section 4.5.3.1 and Appendix C.

[a] Stacking height applies to 55-gallon drums stacked three or more high (i.e., typical drum height of 3 feet plus a nominal 4 inch pallet per tier).

[b] Credit a factor of 2 reduction for banding 4 drums to a pallet, as discussed in Appendix C.

[c] Use natural phenomena hazard DRs in Table 4.4.5-1 if severe crushing is possible.

[d] For vitrified/concreted wastes in metal containers, a 50% reduction in the DRs associated with the metal container is generally recommended for contaminated solids.

4.4.5 Natural Phenomena Damage Ratios for TRU Waste Container Storage

The following section addresses how to establish DRs for NPH for TRU waste container storage in existing facilities. The NPH discussion focuses on seismic events affecting existing TRU waste container storage facilities because they usually dominate the extent of potential damage and amount of material released, thus, the radiological consequences. High wind events and tornadoes may also cause extensive damage, including collapse of a structure. However, their radiological dose is much lower due to the higher winds causing dispersion of releases. The following seismic DRs can be used for the other facility-wide NPH events to the extent that the releases are caused by impact from structural debris. Other NPH events such as wind-driven or tornado-driven missiles have much smaller impacts that normally do not drive special TSRs that have common applicability to the DOE Complex. DRs for these missiles are addressed in Section 4.4.4. The technical bases for the DRs are from extrapolation of the DRs presented in Section 4.4.4 and precedence established in the DOE Complex during the development and approval of existing facility DSAs.

The general approach is to estimate DRs based on whether or not a facility structure survives the event or collapses. For collapse events, a footprint of damage is defined to determine the number of drums impacted, and effect on stacked drums. If the facility does not collapse, waste containers may be impacted and breached by falling objects (e.g., lights, fire suppression sprinkler lines) and other overhead equipment not seismically rated in the structure that are not qualified to the “Code of Record” earthquake. Toppling of stacked containers is also considered for both events if the DOE requirements for a Design Basis Earthquake (DBE)[13] is sufficiently large based on the site-specific evaluation.

During an earthquake (and shortly thereafter), portions of a facility may fall onto containers of nuclear materials, breaching some of them, and containers may topple due to the earthquake causing a container breach. Three facility construction types are defined for use in damage assessment of containers and derivation of the corresponding values of DR. These are:

- Light construction (or none) includes tents, wood frame buildings, and open storage areas with no protective structure at all.
- Medium construction includes structural steel framing with sheet metal siding and roof. This includes Butler® type buildings and cargo containers
- Substantial construction includes buildings made of concrete, cinder block, etc.

Because of the robust nature of the packaging used for containing nuclear waste materials (e.g., metal 55-gal drums and boxes), the collapse of a facility of light construction is not expected to breach the containers. Therefore, the analyst must assume DR = 0 for facilities of light construction for seismic events.

For facilities of medium and substantial construction, the extent of damage to containers depends upon the magnitude of the earthquake. Various designations have been used for earthquakes of

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[13] Or "Derivative DBE" or "Evaluation Basis Earthquake" for evaluation of existing nuclear facilities.

different sizes. A Code of Record earthquake is one that a facility was originally designed and built to withstand. Thus, it is not expected to experience any structural damage that could cause significant radiological releases. An earthquake that causes collapse of the structure is called a "Collapse Earthquake" for the purposes of this DR discussion.

During a Collapse Earthquake, 100% of the exposed packages may be assumed impacted by falling debris in a facility of substantial construction. This debris would include massive chunks of concrete from a ceiling or roof. All waste containers inside buildings are affected, because of impact from falling objects and collapsing building components such as walls, roofs, and structural I-beams, and/or toppling. For a medium construction building, the number of containers impacted by falling I-beams may be estimated by determining the I-beam area relative to the total floor area for a large size TRU waste storage building. The I-beam area for each building can be determined as follows:

%I-beam area = [I-beam width (assumed to be 1 ft) × I-beam length (feet) × number of I-beams per building] / total area of building.

Alternately, in lieu of the above calculation for a specific building design, the number of packages impacted may be conservatively assumed as 10%, based on DOE Complex-wide application of the above formula for typical TRU waste medium construction facilities.

However, as discussed next, not all impacted containers are assumed to be breached. For both medium and substantial construction facilities, the amount of damage to an impacted package depends on its construction, as follows.

- For drums, 10% of those impacted may be assumed breached (i.e., penetration of drum and internal packaging). This value is based on engineering judgment. It takes into account the strength of the drums and the types of overhead materials that may fall (i.e., they have to be heavy and fall with a sharp edge or corner hitting the package). Another interpretation as applied to a population of containers impacted by an accident, a DR of 0.1 represents: (1) 100% of the affected containers spilling 10% of their contents; (2) 10% of the affected containers spilling 100% of their contents; or (3) a combination of these two. A DR of 0.1 is considered reasonably conservative given the various mechanisms by which containers may be compromised (uplift, toppling, rolling and impact, equipment or building falling on the containers, missile strike). This value does not apply if only a couple of drums are impacted, where a 1.0 breach fraction must be assumed.

- For SWBs, the same 10% assumption as for drums applies.

- For overpacked containers, a factor of two reduction from the drum DRs may be assumed breached, i.e., 0.05. This lower value is based on the configuration of the 55-gal metal drum nested within a larger metal container (e.g., four 55-gal drums inside a SWB or the TDOP, giving additional protection). This value does not apply if only a couple of drums are impacted, where a 0.5 breach fraction must be assumed.

- POCs afford even greater protection and only 1% of those impacted may be assumed breached in a substantial construction facility. However, a DR of zero is expected in a medium construction facility, as the falling debris would not be as massive as in a substantial-construction facility. POCs are vulnerable to being crushed by a collapsing concrete building, but not prefabricated metal buildings. The Rocky Flats report[14] noted that finite element modeling of the impact of falling heavy objects was done only for the bare pipe components, not the complete POCs. Therefore, the results of these simulations can be used in either of two ways. First, the modeling results can be considered conservative, because the drum and its packing material absorb some of the impact, as was demonstrated by the Type B crush tests. For example, in the top-impact crush tests, 500 kg (1,100 lb_m) steel plates were dropped on the POCs. The drums were shortened by about 13 cm (5 inches), but the pipe components were undamaged. The side-impact test also showed that the drum and its packing material absorbs some of the impact energy.

- If direct loaded, RH canister performance should be similar to the SWB. Therefore, SWB DRs can be applied. RH canisters with nested drums must be modeled similar to overpacked containers. If the RH canister is handled outside a hot cell in a "facility cask" or onsite shipping cask that does not meet the DOT Type B criteria[15], lower DRs may be appropriate, and can be modeled similar to mechanical spills discussed in Section 4.4.4.

The NPH DR is the product of the fraction impacted times the fraction breached from the preceding discussion. For a substantial construction facility subject to a Collapse Earthquake, the NPH DR is 0.1 (i.e., 100% impacted x 10% breached) for drums and SWBs, and 0.01 (i.e., 100% impacted x 1% breached) for POCs. For a medium construction facility subject to a Collapse Earthquake, the NPH DR is 0.01 (i.e., 10% impacted x 10% breached) for drums and SWBs, and no release for POCs (i.e., DR = 0).

DRs for the Code of Record earthquake are scaled down from those for the Collapse Earthquake based on engineering judgment. They are based on the assumption of limited amount of non-seismically qualified overhead mounted equipment (e.g., suspended space heaters, electrical distributions and lighting, fire sprinklers, etc.) that could fall and impact containers. This limited amount of damage is expected to result in at least a factor of 10 reduction from the NPH DRs applicable to the Collapse Earthquake. For the Code of Record earthquake, the DRs are for the exposed containers to the falling debris. If stacked, only the top tier is considered exposed. For example, four-high stacking means that only 25% of the containers are exposed.

Stacked drums can also topple during an earthquake of sufficient magnitude. In the event that stacked drums fall during an earthquake, only those from the third tier and above could possibly rupture due to the DOT Type A qualification of the drums to withstand a 4-ft drop. For the unmitigated analysis, the DR values presented in Table 4.4.4-1 based on stacked tier height are applicable to seismic-induced toppling, e.g., 0.1 DR for all fourth-tier drums and 0.01 for all

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[14] See Appendix C.

[15] Casks that meet current Type B criteria normally are expected to survive facility mechanical insults typical of those that may occur in the DOE Complex where TRU wastes are stored or handled, unless a facility-specific hazard or accident is more severe than the testing requirements.

third-tier drums for contaminated solids (these are in addition to the above recommendations for releases from falling debris). These DRs do not consider the potential additional release from non-seismically qualified cranes that may be in TRU waste facilities. An additional evaluation of the extent of damage from the crane collapse should be performed in the DSA based on the facility-specific circumstances.

If the drum banding (four drums to a pallet) is credited for the mitigated analysis, the chances of toppling are very small. The horizontal force would have to be great enough to cause the center of gravity of the stack to be displaced at least two feet from normal for the entire stack to topple. A site-specific structural engineering analysis should be performed to determine whether toppling is possible for unbanded and banded drums for the Code of Record and/or Collapse Earthquake being evaluated in the DSA. For the mitigated analysis crediting banding on pallets, the Table 4.4.4-1 DRs can be reduced by a factor of 2 (extrapolated from the Appendix C Hanford pallet drop test results).

Based on the engineering evaluations discussed in Appendix C, stacks of SWBs, TDOPs, and TRUPACT-II payloads are not expected to topple (i.e., the DR would be zero) unless the site-specific engineering analysis determines otherwise. Finally, POCs are so robust that even if they toppled from five-high stacking, they would not be breached (DR = 0).

Table 4.4.5-1 summarizes the DRs for seismic debris impacts that must be used, unless otherwise justified, for TRU waste operations.

TABLE 4.4.5-1 Damage Ratios for Containers Impacted by Seismic Debris

Container Type	Earthquake Type	Building Construction			Toppling Containers
		Substantial	Medium	Light	
Drum	Code of Record[a]	1E-2	1E-3	0	note (b)
	Collapse[e]	1E-1	1E-2	0	note (c)
SWB	Code of Record[a]	1E-2	1E-3	0	0 [note (b)]
	Collapse[e]	1E-1	1E-2	0	0 [note (d)]
POC	Code of Record[a]	1E-3	0	0	0 [note (b)]
	Collapse[e]	1E-2	0	0	0

[a] Applies to containers exposed to falling debris. Use the "low-energy impact" ARFs/RFs from Section 4.5.3.1.

[b] Earthquake magnitude is assumed not sufficient to topple containers for the Code of Record earthquake, unless site-specific engineering analysis determines otherwise as discussed in Section 4.4.5, then note (c) applies.

[c] Use Table 4.4.4-1 DRs based on tiers and dispersible form of material.

[d] Earthquake magnitude is assumed not sufficient to topple containers for the Collapse Earthquake unless site-specific engineering analysis determines otherwise as discussed in Section 4.4.5, then note (c) applies.

[e] Use the "low-energy impact" or "high-energy impact" ARFs/RFs from Section 4.5.3 depending on facility-specific circumstances and magnitude of the debris that can cause substantial crushing of containers. For POCs, use the "low-energy impact" ARFs/RFs based on its testing performance described in Appendix C.

The impacts of NPH may also need to consider subsequent fires and explosions and associated DRs for those types of events. This is a facility-specific consideration based on the existence of fixed and transient combustibles, ignition sources, and/or presence of flammable or combustible gases and liquids.

4.5 Airborne Release Fractions/Respirable Fractions

The ARF and RF are key factors in estimating the amount of airborne materials generated from accidents involving solids, liquids, gases or surface contamination. ARF and RF values are given in DOE-HDBK-3010-94 (see the handbook for further discussion of values and assumptions referenced in the table). Pertinent values from DOE-HDBK-3010-94 as applied to TRU waste accidents are clarified in this section of the Standard.

ARF and RF values vary according to the form of material and type of accident stress. A breakdown of TRU waste forms and accident types is discussed in this section of the Standard and summarized below in Table 4.5-1. The resulting product of ARF and RF values must be used, unless otherwise justified, for TRU waste operations.

TABLE 4.5-1 ARF*RF Value Applicable to TRU Waste Accidents

Waste Form[1] (surface-contaminated)		Explosion[2]	Over-Pressure[3]	Fire[4]	Mechanical Insults	
					Spill[5]	Impact[6]
Combustible – cellulose, plastics	Ambient Atm.	(see fire)[7]	---	1E-2[7]	---	---
	In container	(see fire)	1E-4	5E-4	1E-4	1E-4/2E-3
	In-flight	1E-4	---	---	---	---
Grout – cement, concrete		3E-4[ED][8, 9]		<1E-6	7E-5	7E-4
Sludge or liquid slurries		MR[10]	1E-4	2E-3	4E-5	MR[11]
Liquid		MR[10]	2E-3	2E-3	1E-4	4E-5
Soil/Gravel, Powder, Granules		2E-4[9]	7E-2	6E-5	6E-4	1E-3
Metal, Non-Combustible materials not subject to brittle fracture		MR[10]	1E-3[12]	6E-5[12]	1E-4[12]	1E-3[12]
HEPA filters	In-package	1E-2[13]	2E-3	1E-4	5E-4	1E-3
	Un-contained				1E-2	

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[1] The event is assumed to fail any additional layers of plastic wrapping.

[2] Deflagration of H_2-air stoichiometric mixture that ejects lid and some fraction of the contents.

[3] Internal pressure that fails the container and expels some fraction of the contents at a pressure ≤500-psig.

[4] Thermal stress that ejects lid and some of the contents. Some fraction of the ejected combustible contents may burn as well as the residual contents that remain in the open drum.

[5] Some fraction of the contained powder and liquid contents are released from a location that is elevated to the equivalent of 3rd or 4th tier of stacked drums as defined in Table 4.4.4-1 and impacts a hard, unyielding surface.

[6] The container is impacted with two possible levels of force. For lower energy impacts that do not crush the container, the "Spill" ARF*RF value of 1E-4 is applicable as discussed in Section 4.5.3.1. For impacts postulated that crush the container due to falling massive debris such as during a seismic event, or an errant blow from a high-speed vehicle crash that crushes the container, the cited value of 2E-3 is applicable as discussed in Section 4.5.3.2. The phenomena in this category are complex; and, provided a defensible technical basis is developed, other ARF & RF values are allowed.

[7] For the fraction ignited from a container due to deflagration event or ejection from thermal effects that burns to completion.

[8] Applied to the volume of grout/cement affected, ED = Energy Density, J/cm^3. Note: ARF*RF values vary according to drop height and material density. The density of concrete is used to approximate ARF/RF values. A drop height of

3 m is used to bound ARF*RF values for the "Spill" category. A drop height of 4 m (roughly 5th tier of array) is used to bound values for the "impact" category.

[9] This form does not generate a combustible gas/vapor and the value only applies if this form is combined with a material that does generate a combustible gas/vapor.

[10] Steindler and Seefeldt correlation for detonation on/or contiguous to material– Mass Ratio (MR) = mass inert, kg ÷ TNT Equivalent, kg. See Table 3-6, pg 3-46, in NUREG/CR-6410 for ARF & RF values. RF limited to RF of source material-of-concern.

[11] The [ARF][RF] can be estimated by calculating the energy imparted to the slurry and assuming a free-fall and impact from the height that would insert that energy into the material.

[12] Of loose, surface-contamination present. Metal fragmentation is not anticipated.

[13] Assumes deflagration blast passes through the High Efficiency Particulate Air (HEPA) filter prior to failure of container.

4.5.1 Deflagration Events

Deflagration accidents involve several types of accident stresses. The modeling of this event, as discussed in Section 3.3 and Section 4.4.2, is conservatively assumed to involve the ejection and ignition of combustible wastes. The fraction of wastes that is ejected and burns is modeled consistent with DOE-HDBK-3010-94 values for unconfined cellulosic or plastic materials. The bounding ARF is 1E-2 and RF is 1.0.

The ejected material that is "in-flight" (i.e., traveling through the air) can shed particles due to the flexing of the substrate during the transmission. The ARF and RF cited in DOE-HDBK-3010-94 for this phenomenon are 1E-3 and 0.1. These values must be applied to the same fraction assumed to be ejected from the drum.

The surface-contaminated combustible material that remains in the open drum is also assumed to burn. The ARF and RF cited in DOE-HDBK-3010-94 for "packaged waste" are applied. The bounding values are 5E-4 and 1.0.

4.5.2 Fire Scenarios

Airborne releases due to thermal stresses are primarily influenced by the form and combustibility of TRU waste materials and whether they are packaged or loosely strewn about. Cellulosic or plastic materials that are packaged must be modeled consistent with Section 5.2.1.1 of DOE HDBK-3010-94, which assigns bounding ARF and RF values of 5 E-4 and 1.0 for packaged wastes. The original experiments supporting these values were performed on wastes packaged in plastic bags and sealed in cardboard cartons. DOE-HDBK-3010-94 states that even waste placed together in a pile without bag containment forms a loosely agglomerate package of sorts. Therefore, combustion of TRU wastes that is contained in drums or boxes, meets the definition of packaged waste, even when these containers have suffered lid degradation or loss.

Thermal stress on combustible cellulosic or plastic materials that are either ejected from containers or otherwise unconfined or packaged must assign bounding ARF and RF values from Section 5.2.1.2 of DOE-HDBK-3010-94, which are 1 E-2 and 1.0 respectively. These values must also be applied to the burning of unpackaged waste that is located in glovebox enclosures.

The ARF value for plastics in DOE-HDBK-3010-94 is 5E-2. This is based upon the maximum measured value for a pile of ball-milled Depleted Uranium (DU) oxide powder lying on granular

Polymethyl Methacrylate (PMMA). The phenomenon that suspends the particles from burning PMMA, a thermoplastic material, requires energy to melt the plastic prior to ignition and burning of the vapors. In drummed TRU waste, the contaminant is incorporated into the matrix of material that is folded with contaminant inside or high-activity material from glovebox in additional layers of plastics. The single value cited in DOE-HDBK-3010-94 for the ball-milled DU powder lying under the granular PMMA, ARF 1E-2, is most representative of the conditions here, but probably still over-estimates the airborne release.

Other plastic materials such as polystyrene, polycarbonate, and cellulose have bounding ARFs of 1E-2 with RF values less than 1.0. Thus, a more representative, but still bounding ARF for plastics under these conditions is ARF 1E-2. Because the ARF values for cellulose are 1E-2, the value is applied to all combustible material ejected from the drums that burn in the ambient atmosphere.

Other forms of TRU waste that are noncombustible may include concrete or grout form, sludge or liquids, soils/gravel/powders, or solid metal forms. Values as described in Table 4.5-1 vary from 2E-3 for sludges and liquids (assumed to be at boiling point of water) to less than 1E-6 for grout forms.

Noncombustible waste fractions of inventory that are assumed in the DSA should be conservatively assumed and supported by waste generator data. This assumption must not be used in single drum accidents due to the potential that average waste composition for an entire inventory may not be bounding for single drums.

4.5.3 Mechanical Insults

TRU waste containers can be dropped or impacted by a variety of forces (seismic, forklifts, wind, and other vehicles). Where these forces are significant, containers can be breached and the contents dispersed. Many of the experiments for freefall spills, as described in DOE-HDBK-3010, are based on a testing apparatus that dropped materials from a 10 to 12 ft distance. This distance closely approximates the height of the third tier in a stacked array of drums.

Accidents that involve container drops substantially higher than the equivalent of a 3rd or 4th tier of drums (as defined on Table 4.4.4-1), as well as high-energy accident stresses from vehicle crushing impacts or structural collapse of a concrete building during certain seismic events (see Section 4.4.5), may not be bounded by [ARF][RF] values that are based on tests using the 10 to 12 ft drop testing apparatus. Therefore, mechanical stresses are presented according to categories that consider container drops from either 3rd and 4th tier falls and low-energy impacts, labeled as “Spills”, or from higher level drops and other higher-energy mechanical insults, labeled as “Impacts.”

4.5.3.1 Spills

Cellulosic or largely cellulosic mixed wastes that become dispersed from breached containers due to a freefall spill, forklift puncture, 3rd or 4th tier falls (based on Appendix C drum drop tests), or experience lower energy impacts from falling ceiling-mounted debris but not structural collapse or other stresses (e.g., low-speed vehicle accident as defined on Table 4.4.4-1, gas cylinder or windborne missiles) that do not substantially crush the containers as discussed in Section 4.5.3.2 of this Standard, are considered to be bounded by [ARF][RF] values for the suspension of loose surface contamination from shock/impact stresses. The basis for this phenomena and assumed bounding values are given in Section 5.3.3.2 of DOE-HDBK-3010-94.

Regarding impact events, the analyst must consider two levels of impact energies to assess the airborne release from impacts to containerized TRU waste. For lower impact energy that fails the container confinement, and dents the container or simply displaces the container location, the appropriate ARF and RF values are most closely modeled by the values cited on page 5-3 in DOE-HDBK-3010-94 of ARF 1E-3 and RF 0.1. These values are based on Langer's experiments for shock-vibration of unconfined powders covered in Section 4.4.3.3.2 of the handbook, i.e., the same value that is recommended in Section 5.3.3.2 of the handbook for impact to a robust container. Although the experiments were performed on unconfined powders, some of the experiments involved powder in open cans that showed significantly smaller ARF and RF values relative to the experiments involving loose powder. This configuration is reasonably representative for the behavior of surface-contaminated waste due to shock-vibration forces and is conservative due to the additional difficulty of dislodging particles entrenched on the substrate matrix, and additional attenuation provided by the natural forces within the container that will reduce the amount of airborne particle prior to release (e.g., from deposition or agglomeration due to increased particle sizes). Higher energy impacts to containerized wastes are addressed in Section 4.5.3.2 of this standard.

The DOE-HDBK-3010-94 does not specifically recommend the 1E-4 ARF*RF for seismic debris impacting TRU waste containers. However, it does extrapolate from the Langer tests with loose powders and those in cans, which is assumed applicable to TRU waste containers, as follows:

> *There appears to be a significant decrease in the overall respirable release, due most likely to some combination of shielding of the powder and interaction between the powder and confining surfaces. As in the estimate for loose powder, there is considerable uncertainty associated with this data. If the highest ARF from the data set (1E-3 for uncontained Al_2O_3 powder) is used in conjunction with the largest RF from the contained experiments (rounded up to 0.1), the bounding values would be the same as that assessed for vibration shock of loose, clump powders, and the overall ARF x RF would be a factor of 5 greater than that measured in the experiment (1E-4 vice 2E-5). Accordingly, for powder held in cans failed by debris, an ARF of 1E-3 with an RF of 0.1 is assessed to be bounding.*

DOE-HDBK-3010-94 does not specifically address sludges, but this material form is considered to be bounded by experiments that measured ARF and RFs from the free-fall spill of slurries. The bounding ARF/RF values that are discussed in Section 3.2.3.2 of DOE-HDBK-3010-94 are 5E-05 and 0.8. The bounding [ARF][RF] for liquids is selected based on the airborne release of an aqueous liquid on impact after a freefall spill from and height less than 10 ft (2E-4 and 0.5).

No experimentally measured [ARF][RF] values are available for TRU waste that is comprised of solid metal (e.g., equipment parts). No metal fragmentation is anticipated from freefall spills. Potential releases under accident stresses are assumed to consist of loose surface contamination that is released through vibration and shock of the material substrate. These values (1E-3 and 0.1) are the same as described in Section 3.2.3.2 of DOE-HDBK-3010-94.

Nonmetallic or composite solids can be fragmented when impacted or crushed. DOE-HDBK-3010-94, Section 5.3.3.2.1 provides a calculational method based on material density and energy imparted during the impact of the material with a hard, unyielding surface. Based on the density of typical grout and a fall height that approximates a third tier of a drum array, an [ARF][RF] value of 7E-5 is given to bound this material. This does not consider the energy absorption of the metal drum that adds to the conservatism of this calculation.

The behavior of TRU waste in the form of soils or loose powders is approximated by experiments described in Section 4.4.3.1.2 of DOE-HDBK-3010. The bounding [ARF][RF] values for cohesionless powders are 2E-3/0.3. These values are applied to spills involving lower energy levels as opposed to “impacts” involving a higher distance drop of materials than 10 ft, seismically induced forces, or impacts from vehicle accidents.

4.5.3.2 Impacts

As stated in the preceding section, the analyst must consider two levels of impact energies to assess the airborne release from impacts to containerized TRU waste. Impact energy that is higher than that associated with typical spills and low-energy impacts as described in Section 4.5.3.1 is characterized by internal volume reduction of more than ~25% (i.e. crushes the drum) and failure of drum confinement. This level of crushing is based on engineering judgment from the drum drop tests described in Appendix C. The Sandia tests concluded that drum deformation cannot be predicted by considering only the kinetic energy of the system. Drum contents are important because different materials absorb various amounts of energy. The Hanford tests concluded that obvious (highly visible) damage to a drum is not necessarily an indicator of drum integrity. Extensive damage to the drum walls may not be indicative of container breach whereas a small amount of damage to the lid and upper sealing surface may cause lid separation and loss of container integrity. The 1E-4 ARF*RF for impact to a robust container, e.g., a 55-gallon metal drum, discussed in Section 4.5.3.1 is not representative for severe stresses that substantially crush the drum, since it was based on the Langer 12 ft drop tests with 2 to 5 lb rocks. Section 4.4.3.3.2 of the DOE-HDBK-3010-94 acknowledged the limitation of the data as related to seismic debris impact to loose powders, as follows:

> *The size and weight of the debris used and the fall heights appear to bound a number of phenomena in nonreactor nuclear facilities, including seismic vibration and impacts on large confinement structures such as gloveboxes. However, the size and weight of debris and the fall heights also appear to be unrealistically low for severe conditions in facilities such as a large building collapse, where large-sized debris from multiple levels may impact the released materials. In as much as the release mechanism appears to be air turbulence and shock-vibration, factors that can potentially increase with mass and size of debris and fall height. On the other hand, as the debris size increases, the impact effect is less likely to be fully concentrated in one area, and debris will provide cover for material that could limit releases.*

Since there are no experiments involving TRU waste containers under such severe stress, this phenomenon should be conservatively modeled in DOE-HDBK-3010 by suspension of bulk powders from shock impacts due to falling massive debris from structural collapse of a concrete building or external energy. It is stated in Section 4.4.3.3.2 of the handbook that "*Due to the uncertainty in the test conditions, a conservative bounding value for the ARF is assessed to be 1E-2 with an RF of 0.2"* for large debris and vibration from a seismic event. Thus, the [ARF][RF] is selected as 2E-3. This value is considered appropriate for the relatively higher levels of energy and container damage as compared to "spills." Values apply to combustible and non-combustible solids not subject to brittle fracture. It does not apply to loose TRU wastes in gloveboxes or material forms that are not applicable including liquids, sludges or grout forms.

It is recognized that the new approach for evaluating severe seismic stresses produces similar results to the traditional approach in DOE-HDBK-3010-94. Accordingly, use of the original DOE-HDBK-3010-94 basis for an ARF*RF of 1E-4 coupled with a damage ratio of 1.0 is also acceptable. This approach may also be extended to drums that will clearly be buried under a significant amount of debris as discussed in DOE-HDBK-3010-94, or drums stored outside of facilities.

For solid materials that undergo brittle fracture (e.g., grout), the [ARF][RF] values are determined by the material mass and energy as discussed in Section 5.3.3.2.1 of the handbook. Due to the numerous variables such as weight of material and impact energy, a specific [ARF][RF] value is not given. For conservatism in cases where the calculational method is not used, a value of 7E-4 may be used for impacts to grout materials. This represents a one-order magnitude increase in spill events involving these materials, which is consistent with magnitude of increase for other materials in the Spill vs. Impact categories.

Impacts on liquid-filled drums are postulated to fail the drums by compression and venting of the airborne liquid. The bounding [ARF][RF] values cited in DOE-HDBK-3010-94 for the venting of an aqueous solution at an internal pressure of ≤ 0 psig is 5E-5 and 0.8.

5.0 Consequence Analysis

5.1 Purpose

This section provides guidance for evaluating accident consequences to all receptors. For facility workers, this section addresses qualitative guidelines for assessment of consequences. Accident scenarios typically postulate a release of radioactive material that is released into the atmosphere to the collocated worker and public receptors. For these receptors, this section provides an overview of atmospheric dispersion and consequence assessment methods.

Receptors, as used in this Standard, are defined as follows:

- **Facility Worker** – An individual who is impacted by an accident and is located within the facility boundary

- **Collocated Worker** – The collocated worker is represented by a hypothetical onsite receptor located at a distance of 100 m from the point of release at which the maximum dose occurs. If the release is elevated, the onsite receptor is assumed to be at the location of greatest dose, which is typically where the plume touches down.

- **Offsite Public** – The offsite public is represented by the Maximally-Exposed Offsite Individual (MOI), a hypothetical receptor located at or beyond the site boundary at the distance and in the direction from the point of release at which the maximum dose occurs.

5.2 Facility Worker Consequences

During the performance of hazards analysis, the hazards analysis team must consider the impacts of evaluated hazards on the facility worker. For each hazardous condition evaluated for the public and collocated worker in the hazards analysis, a qualitative evaluation of unmitigated consequence to the facility worker should be included. In accordance with DOE-STD-3009, quantitative consequence analysis should not be performed for the facility worker.

The provided information is for the determination of facility worker safety-significant SSCs or Specific Administrative Controls (SACs) (i.e., meets the DOE-STD-3009 and DOE-STD-1186 "significant" criteria of prompt death, serious injury, or significant radiological or chemical exposure criteria.)

Examples of conditions where a significant consequence to the facility worker should be considered for controls include the following:

- Energetic releases of high concentrations of radiological or toxic chemical materials where the facility worker would normally be immediately present and therefore unable to take self-protective actions.

- Deflagrations or explosions within process equipment or confinement/containment structures or vessels where grievous injury or death to a facility worker may result from the fragmentation of the process equipment or failure of the confinement (or containment) in the vicinity of areas occupied by facility workers.

- Chemical or thermal burns to a facility worker that could reasonably cover a significant portion of the facility worker body where self-protective actions are not reasonably available due to the speed of the event or where there may be no reasonable warning to the facility worker of the hazardous condition.

- Exposures to radiological or toxic materials of sufficient magnitude that death or ongoing large-scale medical intervention may reasonably be expected to result.

- Leaks from process systems where asphyxiation of a facility worker normally present may result.

These and other unique conditions that may be "significant" for a specific process must be discussed by the hazard analysis team prior to initiating the hazards analysis process so that all members of the team may participate in the assessment of facility worker hazards. Lesser facility worker hazards may be evaluated and any results identified in the comments section for the hazardous condition. These lesser facility worker hazards are normally controlled through application of existing safety management programs (SMPs).

5.3 Collocated Worker and Public Consequence

Doses to the collocated workers or MOI from postulated accident scenarios depend directly on the values and assumptions made with respect to determining the doses to these receptors. Even though qualitative consequence calculations are acceptable for collocated workers in the hazard analysis, these need to be supported by scoping calculations that implement the methodology described in this Section (this could be part of the hazard analysis and included as an attachment or appendix to the DSA). In order to comply with this Standard, this methodology must be used to support quantitative evaluations performed as part of the hazard or accident analysis.

The potential doses to these receptors depend directly on the source terms from such scenarios, dispersion/transport of hazardous material, and assumptions with respect to exposure durations and release characteristics, among others. Following is a discussion of the major parameters that affect the doses to the collocated workers or MOI.

Simplistically, the dose to these receptors can be determined (assuming that the inhalation pathway is the predominant exposure pathway [this is mostly true for alpha emitters, such as plutonium]), by:

$$\text{Dose (rem)} = \text{ST} \cdot \chi/Q \cdot \text{DCF} \cdot \text{BR}$$

where:

ST = respirable source term (Ci)
χ/Q = atmospheric dilution factor (s/m^3)
BR = breathing rate (m^3/s).
DCF = inhalation dose conversion factor (rem/Ci)

The respirable source term calculation is described in Section 4.0.

The atmospheric dilution factor, χ/Q, accounts for the effects of atmospheric dispersion of material released under postulated accident conditions at a specified receptor location. It is defined as the concentration in air per unit release rate of the material from an upwind source at a particular receptor location. The value of χ/Q is a function of the type of release (elevated, buoyant, ground level, etc.), release duration, wind speed, atmospheric stability class, and distance from the source (only centerline or under-centerline, ground-level values are considered). The duration of the release is assumed to conclude within two hours or proceed for up to eight hours for more slowly developing accidents, based on accident phenomenology.

When evaluating consequences of exposure to hazardous materials, radiological and chemical consequences are evaluated differently. For radiological consequences, the analysis evaluates dose (time-integrated exposure) in units of Total Effective Dose (TED), because health effects are dose-driven. Consequences from hazardous chemicals are generally based on the concentration of the material to which an individual is exposed, rather than a time-integrated dose. For chemicals associated with TRU operations, the chemical atmospheric dilution factors are identical to those used for radiological consequence assessment (unless there are gases or vapors heavier than air).

Radiological consequence modeling must be based on the following attributes listed below (may also apply to chemical dispersion analysis where noted) for unmitigated releases. Use of alternate dispersion methodologies or attributes discussed below must have a valid basis and be discussed with and approved by the DOE Approval Authority. Dispersion attributes are as follows.

- The values of χ/Q used for radiological and chemical consequence analysis are generated using MACCS2 Computer Code (see DOE-EH-4.2.1-MACCS2-Code Guidance, *MACCS2 Computer Code Application Guidance for Documented Safety Analysis*). Use of other DOE-approved Toolbox Codes , or site-specific codes that have undergone appropriate validation and verification in accordance with DOE O 414.C requirements on software quality assurance, must be technically justified

- Worst case meteorological assumptions (i.e., 95th percentile based on local site data) for onsite radiological and chemical releases (see STD-3009, Appendix A, for offsite evaluations)

- Dry deposition velocity must be used at a value of 1 cm/s for all unfiltered, non tritium, non-noble gas species

- Wet deposition must not be modeled

- An surface roughness value of 3 cm must be assumed for radiological and chemical releases

- Building wake effects must not to be credited (modeled) unless shown to yield more conservative or bounding results.

- Plume buoyancy may only be used when modeling fires that are outdoors or venting through a large breach in the facility (use of plume buoyancy should not be credited in a non-conservative manner)

- The breathing rate value, as specified in the DOE Toolbox Codes, is 3.3×10^{-4} m^3/s. This value corresponds to the light activity breathing rate for adults and must be used in consequence assessment.

- Inhalation dose conversion factors for the MOI evaluation must be consistent with ICRP 72, *Age-dependent Dose to Members of the Public from Intake of Radionuclides: Part 5 Compilation of Ingestion and Inhalation Dose Coefficients*, and optionally may use ICRP 68, *Dose Coefficients for Intakes of Radionuclides by Workers*, for the collocated worker evaluation.

6.0 TRU Waste Hazard Controls Selection and Standardization

6.1 Purpose

This section of the Standard provides guidelines for standardizing the hazard control selection process and gives specific controls that are appropriate for the most common TRU waste accident events of concern. Section 6.2 presents evaluation guidelines that help grade the significance of accident events and safety classification of controls. Section 6.3 clarifies what is challenging to the Evaluation Guideline (EG) of DOE-STD-3009. Section 6.4 and the associated hazard control tables provide a set of preferred controls, as well as alternate controls that may be applied in certain situations.

6.2 Risk Ranking and Control Selection Guidelines

DOE-STD-3009 encourages the use of hazard evaluation ranking mechanisms as a means of identifying the higher risk accidents that may warrant quantitative analysis and TSR controls. This section provides a risk ranking process and associated control selection guidelines that collectively give a qualitative tool to facilitate discussion between cognizant Subject Matter Experts (SMEs), including facility and operational staff, to enhance the judgment process inherent to selection of hazard controls. The numerical guidelines must be followed to comply with this Standard, but dose and frequency thresholds should not be construed as risk acceptance criteria.

The risk ranking process bins the results of unmitigated hazard and accident analysis for the maximally exposed offsite individual, collocated workers onsite, and facility workers. Table 6.2-1 identifies consequence levels and evaluation guidelines for each of these receptors. High, moderate and low consequence levels are quantitatively defined for the offsite public and collocated workers. High consequence levels are qualitatively established for facility workers consistent with DOE-STD-3009 guidelines for a significant worker consequence. Moderate and low consequence levels are not established for facility workers, because qualitative analysis would not yield results that provide a meaningful comparison to a distinguishable threshold.

Table 6.2-2 identifies risk ranking bins that consider the consequence rankings from Table 6.2-1 together with the postulated accident frequency. Based on these factors, an accident is ranked as Risk Class I through IV.

TABLE 6.2-1: Consequence Levels and Risk Evaluation Guidelines

Consequence Level	Maximally Exposed Offsite Individual’	Collocated Worker (at 100 meters	Facility Worker Involved worker within facility boundary
High	Considerable offsite impact on people or the environs. CHALLENGE 25 rem TED or > AEGL-2/TEEL-2	Significant onsite impact on people or the environs. > 100 rem TED or > AEGL-3/TEEL-3	For Safety Significant designation, consequence levels such as prompt death, serious injury, or significant radiological and chemical exposure, must be considered.
Moderate	Only minor off-site impact on people or the environs. ≥ 1 rem TED or > AEGL-1/TEEL-1	Considerable on-site impact on people or the environs. ≥ 25 rem TED or > AEGL-2/TEEL-2	No distinguishable threshold
Low	Negligible off-site impact on people or the environs. < 1 rem TED or < AEGL-1/TEEL-1	Minor on-site impact on people or the environs. < 25 rem TED or < AEGL-2/TEEL-2	No distinguishable threshold

AEGL: Acute Exposure Guideline Level
TED: Total Effective Dose Equivalent
TEEL: Temporary Emergency Exposure Limit

Minimally Exposed Individual:

- Offsite consequences that challenge 25 rem must be protected with Safety Class controls independent of frequency. See Section 6.3 of this standard for further clarification of challenging the EG.
- For elevated releases use location of highest dose

Collocated Worker (at 100 meters)

- For elevated releases use location of highest dose

TABLE 6.2-2: Qualitative Risk Ranking Bins[16]

Consequence Level	Beyond[17] Extremely Unlikely Below 10^{-6}/yr	Extremely Unlikely 10^{-4} to 10^{-6}/yr	Unlikely 10^{-2} to 10^{-4}/yr	Anticipated 10^{-1} to 10^{-2}/yr
High Consequence	III	II	I	I
Moderate Consequence	IV	III	II	II
Low Consequence	IV	IV	III	III

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[16] Industrial events that are not initiators or contributors to postulated events are addressed as tndrd industrial hazards in the hazard analysis

[17] For external events, frequency of occurrence below 10^{-6}/yr conservatively calculated or 10^{-7}/yr realistically calculated are *Beyond Extremely Unlikely*.

Risk Class I events for the public must be protected with safety SSCs, SACs (where appropriately justified in accordance with DOE-STD-1186) and associated TSRs. For offsite public protection, Safety Class SSCs, SACs (where appropriately justified in accordance with DOE-STD-1186) and TSRs are required for radiological events that challenge 25 rem TED offsite (regardless of frequency) in accordance with Appendix A of DOE-STD-3009, Change Notice 3. Events resulting in high offsite radiological consequences must be moved forward into accident analysis for determination of safety classification, without consideration of frequency. Safety Significant controls may also be warranted for protection of the public.

Risk Class I events for the collocated worker or facility worker, and Risk Class II events for all receptors, must be considered for protection with Safety Significant SSCs, SACs (where appropriately justified in accordance with DOE-STD-1186) and associated TSRs. The consideration of control(s) should be based on the effectiveness and feasibility of the considered controls along with the identified features and layers of Defense In Depth (DID). Risk Class II events resulting in high offsite radiological consequence must be included in subsequent accident analysis for determination of safety classification, without consideration of frequency.

Risk Class III events are generally protected by SMPs. These events may be considered for DID SSCs in unique cases. Risk Class IV events do not require additional measures.

For facility worker protection, hazardous events with significant consequences must be considered for safety SSCs or SACs in accordance with DOE-STD-3009, Change Notice 3 and DOE-STD-1186. Activity-specific controls (e.g., Personal Protective Equipment [PPE] and hot work permit) are developed as needed based on job hazard analyses as part of the work control process, not as a specific TSR control. The TSR commitment to SMPs is relied upon to provide general worker protection. The actual implementation of work control process should be reviewed as part of the Integrated Safety Management System (ISMS) verification.

DID is a philosophy that ensures the facility is operated in a safe manner through multiple means. DID features include the entire suite of safety controls, encompassing Safety Class and Safety Significant SSCs, Administrative Controls (ACs), SMPs, and other engineered controls. Only the significant contributors to DID should warrant TSR designation. Those passive features that provide significant safety benefit are covered by the TSR Design Features section. Compensatory measures should be provided for those existing TSR Design Features that do not meet functional requirements. DOE G 423.1-1 provides additional guidance for consideration.

Many important aspects of the DID strategy are implemented through the SMPs. The holistic approach embedded in the SMPs and their effective implementation as part of the ISMS must continue to optimize the intended safety benefits. The discipline imposed by the SMPs extends beyond simply supporting the assumptions made in the hazard analysis and is an essential part of DID safety posture.

6.3 Clarification of What Challenges the Evaluation Guideline

Several DOE directives qualitatively address the issue of challenging the offsite Evaluation Guideline described in Appendix A of DOE-STD-3009. DOE G 420.1-1 and DOE O 420.1B define "challenge the Evaluation Guideline (EG)" as doses in the "rem range." These directives apply to major modifications and new nuclear facilities, in which Design Basis Accidents (DBAs) are defined, developed, and quantified to derive design requirements for engineering SSCs. Safe harbor standards identified in Table 2, Appendix A, of 10 CFR Part 830 (e.g., DOE-STD-3009, DOE-STD-1120) are primarily intended to address existing facilities and activities, and these standards do not specifically define the term "challenge the DOE EG." Most existing DOE facilities in the complex were not designed to a particular DBA. As such, any accident analysis for these facilities needs to be derived from assumptions made with respect to the operations and adequacy of the controls that may be available within these facilities (thus, the term evaluation basis accident, for these types of facilities).

The term "challenging the EG" was developed to ensure that the 25 rem value would not be used as an acceptance threshold for potential consequences to the public. According to DOE G 420.1-1, "it should emphatically be understood that 25 rem is not an acceptable criterion for safety design." There is a potential for misusing this EG, in the sense that an unmitigated dose below, but close to the EG could be interpreted as not requiring Safety Class (SC) controls.

Depending on the assumptions made with respect to source term and consequence analysis factors, uncertainties associated with dose estimates could be as high as two orders of magnitude. Thus, the key to determining whether a calculated dose "challenges" the DOE EG will depend on the conservatism in the values for each of these terms. Guidance contained in Chapters 4 and 5 ensures appropriate conservatism in the analysis to be performed for TRU waste operations, and thus results in a reasonably conservative estimate of dose consequences used for comparison to the EG. Table 6.3-1 presents the typical uncertainty associated with source term and consequence analysis factors, and summarizes recommendations addressed in the standard for each factor.

TABLE 6.3-1 Uncertainties Associated with Source Term and Consequence Analysis Factors

Variable	Typical Uncertainty	Cause of Uncertainty	Recommended Value
MAR	For accident analyses, the MAR developed in accordance with Section 4.3.2 is expected to be bounding; that is it represents a conservative accumulation of MAR in the number of containers involved in the accident scenario. This is accomplished by including the maximum drum and a number of 99th percentile and/or 95th percentile containers with the balance of the average containers. As a result, only a limited amount of uncertainty is associated with the generally conservative estimates of MAR for the containers in any accident scenario.	Characterization based on some measurements, experience, training, and process knowledge in defining AK, for both newly generated and legacy waste introduces some statistical uncertainty associated with waste characterization.	The MAR recommendations in Section 4 must be used for accident analysis; higher MAR values could be used for hazard analysis in order to ensure that no postulated scenarios are screened from further accident analysis in the DSA.
χ/Q	Standardized modeling parameters (DOE-EH-4.2.1-MACCS2-Code Guidance, *MACCS2 Computer Code Application Guidance for Documented Safety Analysis;* from hereon referred as "Tool Box Codes"), ground level release, default terrain (prairie grass), surface roughness, etc. Depending on the site, receptor location, and release characteristics, these variables could result in an uncertainty of about a factor of four.	Terrain conditions, variability in meteorological conditions, site boundary distances, release characteristics (e.g., ground vs. elevated release), surface roughness, dispersion coefficients (relevance to site), deposition velocity, etc.	Site-specific 95% based on meteorological data (DOE STD 3009) and using recommended values in the DOE Tool Box Codes (e.g., surface roughness, deposition velocity, ground release). The calculated χ/Q should be conservative, when the default or recommended values in the Tool Box Codes are used. The use of these default parameter values in determining χ/Q should be used for at least scoping calculations supporting the hazard analysis For accident analysis, alternate parameter values or assumptions can be made, if the site (complex terrain vs. flat) and the postulated release characteristics (e.g., filtered or volatile releases instead of unmitigated dispersible releases) are significantly different than those in the DOE Tool Box. Justification for values and assumptions different than those in the Tool Box Codes must be provided.

TABLE 6.3-1 Uncertainties Associated with Source Term and Consequence Analysis Factors--Continued

Variable	Typical Uncertainty	Cause of Uncertainty	Recommended Value
DCF	The derivation of DCF values are based on a complex combination of metabolic, statistical, historical exposures, experimental, and human characteristics (e.g., age, sensitivity), among others. However, since these values are regulatory driven, they are assumed to be fixed for dose calculation purposes.	N/A	The latest recommendations of the International Commission on Radiological Protection (e.g., ICRP 68, 71, 72) are recommended for use in hazard and accident analysis
BR	While 3.33E-4 m^3/s is the recommended breathing rate (BR) specified in the *Radiological Health Handbook*, some sites use values as high as 3.5E-4 m^3/s.	Values depend on the level of physical activity assumed during the accident condition.	The BR of 3.3 E-4 m^3/s must be used for both hazard and accident analysis. This value is the recommended BR specified in the *Radiological Health Handbook*.
DR	Depending on the particular accident scenario and the number of containers involved, the uncertainty associated with this variable could be as high as one order of magnitude.	Values are heavily dependent on the specific accident characteristics (e.g., type and magnitude of insult), type of containers, and model assumptions. The determination of the DR for a given accident scenario is heavily dependent on the magnitude of the scenario in question, container configuration during the accident, and number of containers involved. Results of experiments or tests have demonstrated high variability in the DRs.	The DRs provided in Chapter 4 are based on empirical or analytically supported data (where available and represents "reasonable" conservative values for accident analysis.

TABLE 6.3-1 Uncertainties Associated with Source Term and Consequence Analysis Factors--Continued

Variable	Typical Uncertainty	Cause of Uncertainty	Recommended Value
ARF*RF	Provided that bounding values from DOE-HDBK-3010 are appropriately selected, the calculated doses (for safety analysis purposes) will be sufficiently conservative for derivation of adequate controls.	Derivations of ARF/RF values reported in DOE-HDBK-3010 were based on a limited set of experiments, data gathering, and empirical correlations; thus, some uncertainty is expected. The bounding ARF/RF in the Handbook, however, represented in most cases the bounding values for the set of experiments or conditions being represented.	Bounding ARF/RF values from DOE-HDBK-3010, with exceptions as noted in Chapter 4.
LPF	TRU waste facilities are relatively simple facilities (e.g., relatively low number of operational areas, ventilation zones, and fire areas), and in most cases do not rely on active ventilation to maintain confinement during accident scenarios; thus, a LPF of 1 is expected.	For unmitigated dose estimates this represents a bounding condition, akin to a parking lot release scenario. Complex facilities, with multiple operating areas separated by different fires areas, ventilation zones, and evacuation pathways are expected to have LPFs less than 1.0, due to potential plateout, deposition, and filtration (among others) of particulates as these are transported throughout the facility, before these are released to the environment.	For unmitigated dose estimates, a LPF of 1 represents the worst or most bounding value. A lower LPF can be used in mitigated analysis, but must be established using a technically derived basis.

In many cases, having an unmitigated MOI dose less than 10 rem (<40% of the EG) based on the recommended values above (Table 6.3-1) should still represent a reasonably low risk to be public and workers (assuming an adequate set of preventive and/or mitigative controls are implemented in the operation of these facilities). Thus, it is reasonable to expect that for existing facilities using the assumptions provided in this Standard, an unmitigated MOI greater than 10 rem should be considered sufficient to challenge the EG.

6.4 TRU Waste Controls

This section describes hazard controls that must be implemented for those accident events that warrant designation within the SB documents based on the results of the hazard/accident analysis and comparison to control selection guidelines presented in Section 6.2 (i.e., Risk Class I and potentially II types of events). The safety classification of controls (i.e., safety significant, safety class) is not specified in this section and is expected to vary at each DOE site depending on facility/container specific MAR and the results of consequence analysis as compared to thresholds specified in control selection guidelines.

Though some accident events may not rise to a level of significance that warrants TSR controls, it still may be prudent to apply controls established in this section. Where applicable, recommended controls should be considered for accident events with consequences below the thresholds of concern. This is considered a good practice that is consistent with the control selection criteria.

The hazard controls (Table 6.4.1-1) at the end of this section are presented according to each type of accident event. Events are identified with unique numbers that link to accident descriptions in Section 3. Where an accident event applies to multiple types of TRU waste operations, and the control set differs for each activity, the event is listed multiple times with each control set designated. If no specific TRU waste operation is designated in the accident description, then it applies to all TRU waste operations that are designated in Table 3.3-1 for the event.

Minimal control functions are identified for each accident event. Each control function must be met. "Preferred" and "Alternate" controls are listed for each function and are separated in some cases by a semicolon, in which case all of the controls are required. In other cases, controls may be separated by "or" statements indicating that either control is acceptable.

Preferred controls provide a high level of protection that gives precedence to the hierarchy of controls established in DOE-STD-3009 (i.e., passive over active, engineered over administrative, prevent over mitigate). The ordering of controls in Table 6.4.1-1 is presented in accordance with this hierarchy.

Preferred controls may not always be available in existing facilities. Modifying facilities may require substantial operational impact. In such cases, consideration may be given to the "Alternate" set of controls listed in Table 6.4.1-1. The selected control set should also include some combination of Preferred and Alternate controls, when only a portion of the

Preferred controls can be met. In cases where preferred and alternate controls aren't available or feasible to implement, other means for implementing stated control functions are acceptable if explicitly discussed and approved by the DOE Approval Authority. In those cases, technical justification for deviating from the Standard must be provided.

With respect to TSR controls, the use of Alternate controls must be substantiated by a sound technical basis that is communicated and agreed upon with the DOE SB Approval Authority. The supporting rationale for selecting Alternate controls must demonstrate that Preferred controls are either not available or not appropriate for the given facility situation. The rationale must be documented in the DSA or in the hazard analysis document supporting the DSA.

A variety of controls may be available to control a hazard that requires safety class or safety significant controls. This set of potential controls could include both engineered controls and administrative controls. Engineered controls typically provide the most robust approach to address a hazard. However, for operations in older facilities, the engineered controls may not meet the current design requirements for safety class or safety significant engineered controls.

In such cases, the tendency may be to specify an administrative control (designating it as a Specific Administrative Control) as the primary control having the safety class or safety significant function, even though the engineered features exist and are in place, and would appear to more adequately control the hazard. Where engineered controls exist that are most capable of accomplishing the needed safety function, those controls should be designated as safety class or safety significant rather than less robust administrative controls. If exemptions to requirements become necessary because of the designation, they must be obtained and appropriate compensatory measures proposed to ensure that the engineered controls provide protection commensurate with the protection warranted by the hazard. Specific Administrative Controls should not be proposed to avoid establishing an adequate set of engineered controls where it is possible to do so, and not cost-prohibitive.

Though not indicated in the control sets for all accidents identified in Table 6.4.1-1 the use of MAR inventory limits is an acceptable approach for limiting consequences. However, this is not always prudent or feasible in TRU waste operations that must accept and process legacy containers. Where this approach is not operationally limiting and is used to limit consequences within facilities or designated areas, it must be listed as an initial condition of the hazard analysis and protected as a TSR specific administrative control. This concept also applies to other important initial conditions supporting the hazard analysis.

It should be noted that some unique hazards that are limited to a single DOE site may not be covered by the controls listed in Table 6.4.1-1. Examples include highly dispersible forms of materials or unique waste treatment processes involving hazardous chemicals. Additionally, unique glovebox treatment activities beyond sorting and segregating may require consideration beyond those specified in this table (example, pyrophoric reaction fire). Consideration should be given to additional controls where these unique hazards are found.

6.4.1 TRU Waste MAR Effects on Control Selection

The distribution of TRU waste MAR inventory at some DOE sites may be such that it is dominated by a small percentage of containers when compared to the overall population of containers (i.e., a few percent of the containers have radioactivity levels that are well above the majority of the remaining waste container population). The following example illustrates a case where MAR is dominant in only a few containers:

> *Facility X has a population of approximately 4,000 containers. The drum with the highest radioactivity level contains 300 Plutonium-239 Equivalent Curies (PE-Ci). Only six containers have greater than 200 PE-Ci; 25 containers have greater than 100 PE-Ci; and less than one hundred containers have greater than 10 PE-Ci. Overall, 95% of the containers do not exceed 5 PE-Ci.*

MAR variability has been reported in finite characterized populations where the higher MAR containers are identifiable prior to handling. Conversely, it may be difficult to differentiate high MAR containers during waste excavation and retrieval operations if characterization data is not well known.

It may not be prudent to apply preferred controls to an entire population of TRU waste containers when the risk is dominated by only a few containers with higher MAR content. The following guidelines apply to control selection under these conditions:

1. If the proposed operations can be practically conducted (limited operational impact) applying the controls driven by the highest MAR containers to all containers, doing so is the preferred approach.

2. If the highest MAR containers can be identified prior to handling and the controls required for the highest MAR containers would result in significant operational impacts if applied to the entire population, then separate controls for the subpopulation of concern are appropriate as discussed further below.

3. If the highest MAR containers cannot be differentiated prior to handling, then separate controls for any subpopulation of concern should not be applied as discussed further below.

Proposed use of Guideline 2 must be justified in the DSA. In addition, limiting operational impacts as well any risk impacts, should be discussed with DOE during the DSA and TSR review and approval process.

An acceptable approach for implementing Option 2 above is the use of TSR controls that have applicability criteria defining specific limitations for when a control is applicable. Use of this approach requires that the TSR:

- Use explicit definitions that describe the terms and conditions used in the criteria
- Incorporate criteria into Limited Conditions of Operation (LCO) applicability statements (where LCOs are used)

- Provide administrative controls that formalize and describe the applicability process (including contractor verification that criteria are satisfied)

- Provide TSR bases that support established points associated with criteria

Notes for Table 6.4.1-1 Hazard Controls

1. For existing facilities, DOE may accept the risk from NPH and aircraft events based on contractor justification. The provisions for allowing some relief when applying NPH criteria to existing facilities applies to existing activities in existing structures. New operations and activities conducted within an existing structure may require an upgrade of those facilities to meet current standards. For changes to activities that require significant modifications to existing safety bases, such as the inclusion of new safety class controls, the provisions granted for existing facilities do not apply to the new controls.

2. Unique glovebox treatment activities beyond sorting and segregating may require consideration beyond those specified in this table (example pyrophoric reaction fire).

3. This table only applies to characterization, container handling, venting and/or abating/purging, staging and storage, retrieval and excavation, and waste repackaging activities. The control set for onsite transportation activities (as opposed to intra-facility movements addressed in handling) is governed by DOE Orders 460.1B and 461.1.

4. The control for all Type B container activities is the container, once TRU waste materials are located in a closed, Type B container

5. Preventive versus mitigative control functions are denoted in the table by the letters “P” or “M”.

6. The term “suspect” container as used in Table 6.4.1-1 is defined in Section 3.3.2.2.

TABLE 6.4.1-1 Hazard Controls

Accident	Minimum Control Functions	Preferred Controls	Alternative Controls	Relevant Criteria/Discussion
Fuel Pool Fire (Event 1) External Vehicle Accident with Fire (Combustible or Pool) (Event 17) If vehicle impact is the initiator of this event, controls from Vehicle/Equipment Impacts Waste/Waste Containers (Event 9) must be added	Limit fire size (P)	Automatic Fire Suppression System (FSS) OR Vehicle Fuel limit	Alternate fire protection controls approved by qualified fire protection engineer (e.g., flammables and combustibles limit)	DOE O 420.1B Note 1: FSS is not applicable to outside pool fires. Facilities with potential for indoor pool fires should consider both Preferred Controls. Note 2: These controls are expected to be supplemented by the overall Fire Protection Program suite of controls to prevent or mitigate accidents (e.g., flammable and combustible limits).
	Separate the MAR from fuel (P)	Grading and sloping; berms; vehicle barriers	Control vehicle route; stand off distance; establish refueling location;	
	Minimize releases (M)	Non-combustible containers AND	Spacing, fire breaks	
		Confinement Ventilation System (CVS)	MAR limit and/or vehicle fuel limit	CVS defined in DNFSB 2004-2 (Indoor activities only)

TABLE 6.4.1-1 Hazard Controls--Continued

Accident	Minimum Control Functions	Preferred Controls	Alternative Controls	Relevant Criteria/Discussion
Small Fire (Event 2) Characterization	Limit fire size (P)	Closed non-combustible container	Stand off; Fire Barriers	Closed means protected from direct flame exposure Note: These controls are expected to be supplemented by the overall Fire Protection Program suite of controls to prevent or mitigate accidents (e.g., flammable and combustible limits).
	Minimize releases (M)	CVS	MAR limit and/or flammables and combustible limit	CVS defined in DNFSB 2004-2 (Indoor activities only)
Enclosure Fire (e.g. Glovebox, Hot Cell) (Event 3) Waste Repackaging	Minimize fire initiators (P)	Enclosure Design- Electrical wiring designed in accordance with IEEE standards specified in DOE O 420.1B; Glovebox design criteria in accordance with DOE-STD-1066	Alternate fire protection controls approved by qualified fire protection engineer (e.g., flammables and combustibles limit)	When potential for flammable atmosphere Note: These controls are expected to be supplemented by the overall Fire Protection Program suite of controls to prevent or mitigate accidents (e.g., flammable and combustible limits).
	Limit fire size (P)	Automatic Fire Suppression System (FFS) OR Inert atmosphere	Alternate fire protection controls approved by qualified fire protection engineer (e.g., flammables and combustibles limit)	DOE O 420.1B
	Minimize fire initiators (P)	Prohibit hotwork when combustible MAR is present AND	Protect exposed combustible MAR during hotwork (e.g. fireblankets, non-combustible containers)	

TABLE 6.4.1-1 Hazard Controls--Continued

Accident	Minimum Control Functions	Preferred Controls	Alternative Controls	Relevant Criteria/Discussion
		Use non-sparking tools OR Inert atmosphere		When potential for flammable atmosphere
	Minimize releases (M)	CVS	MAR limit	CVS defined in DNFSB 2004-2
Enclosure Fire (Event 3A) Waste Repackaging Special Treatment Example: Stabilization of pyrophoric material through controlled oxidation Event: Fire from Uncontrolled Chemical Reaction (e.g. pyrophoric)	Limit fire size (P)	Automatic FSS OR Inert atmosphere	Alternate fire protection controls approved by qualified fire protection engineer (e.g., flammables and combustibles limit)	DOE O 420.1B Fire suppression media compatible with reacting materials Note: These controls are expected to be supplemented by the overall Fire Protection Program suite of controls to prevent or mitigate accidents (e.g., flammable and combustible limits).
	Minimize releases (M)	CVS	MAR limit	CVS defined in DNFSB 2004-2
	Minimize uncontrolled reaction (M)	Control oxidation rate		

TABLE 6.4.1-1 Hazard Controls--Continued

Accident	Minimum Control Functions	Preferred Controls	Alternative Controls	Relevant Criteria/Discussion
Large Fire (Event 4) If vehicle impact is the initiator of this event, controls from Vehicle/Equipment Impacts Waste/Waste Containers (Event 8) must be added If fuel pool fire is the initiator of this event, controls from Fuel Pool Fire (Event 1) must be added	Limit fire propagation (P & M)	Automatic FSS AND	Alternate fire protection controls approved by qualified fire protection engineer (e.g., flammables and combustibles limit)	DOE O 420.1B Note: These controls are expected to be supplemented by the overall Fire Protection Program suite of controls to prevent or mitigate accidents (e.g., flammable and combustible limits).
		Combustible loading requirements (e.g. spacing, fire breaks, non-combustible pallets)		
	Minimize releases (M)	Non-combustible containers	Fire area MAR limit	
		CVS	MAR limit	CVS defined in DNFSB 2004-2 (Indoor Activities Only) -2
Ignition of Fumes Results in an Explosion (Event 5) External Explosion (Event 18)	Minimize impact (M)	Separation distance	Limit quantity of potential vapor	
Waste Container Deflagration (Event 6)	Minimize release (M)	Outer container integrity	Apply *Minimize worker exposure* control set for this event	Note: Container integrity is in accordance with Sect. 4.4.1

TABLE 6.4.1-1 Hazard Controls--Continued

Accident	Minimum Control Functions	Preferred Controls	Alternative Controls	Relevant Criteria/Discussion
Multiple Waste Container Deflagration (Event 7) Characterization And Container Handling	Reduce explosive atmosphere (M)	Vent *suspect* containers		Until vented and hydrogen concentration is verified to be less than 8%, handle as suspect container. See Appendix D for a further discussion on the basis for the 8% threshold. Drums with hydrogen less than 8% concentration may still present some worker hazards. In particular, known hydrogen concentrations in the LFL range may warrant explicit Safety Management Program attributes on drum handling. All drums should be handled in accordance with industrial safety/hygiene and radiation protection controls invoked through SMPs.
	Minimize worker exposure (M)	Lid restraints on *suspect* containers; (e.g., nylon straps, netting, or other physical restraining devices) OR Impact resistant shielding meeting OSHA requirements during handling of suspect containers; (29CFR Part 1910.120 Section j)	Minimize worker contact with *suspect* container; prevent unnecessary personnel within affected area	NOTE: Alternate controls must be applied, even when Preferred controls are available

TABLE 6.4.1-1 Hazard Controls--Continued

Accident	Minimum Control Functions	Preferred Controls	Alternative Controls	Relevant Criteria/Discussion
Waste Container Deflagration (Event 6) Multiple Waste Container Deflagration (Event 7) During Venting and Hydrogen Abatement Venting and/or Abating/Purging	Reduce potential sparks and other initiators during venting (P)	Drum Venting System (DVS) with a blast-resistant chamber and containment device (e.g., HEPA filter train)	Tools must be of the type to prevent ignition (e.g., non-sparking tools; use cold drilling, speed drilling, or drum punch); grounding and bonding; control static discharge from personnel	Static discharge from personnel may be controlled by separation distance or specific controls on static discharge Note: TBD as specified by design parameters
	Minimize worker exposure during venting (M)	DVS with a blast-resistant chamber and containment device (e.g., HEPA filter train); prevent unnecessary personnel within affected area	Blast resistant enclosure; prevent unnecessary personnel within affected area OR Remote activation; personnel exclusion area	
	Reduce potential sparks and other initiators during hydrogen abatement (P)	Isolate/segregate container after venting until hydrogen concentration is below 8%; minimize container movement		See Appendix D, *Criteria for TRU waste Drums Requiring Venting/Purging Due to Elevated Internal Hydrogen Concentrations*
	Minimize worker exposure during hydrogen abatement (M)	Minimize worker contact with container; prevent unnecessary personnel within affected area		
	Limit interaction between containers during hydrogen abatement (M)	No stacking containers		

TABLE 6.4.1-1 Hazard Controls--Continued

Accident	Minimum Control Functions	Preferred Controls	Alternative Controls	Relevant Criteria/Discussion
Waste Container Deflagration (Event 6) Staging and Storage	Minimize worker exposure (M)	Minimize worker contact with *suspect* container or containers with potential VOC concentration greater than LFL; prevent unnecessary personnel within affected area		
Waste Container Deflagration (Event 6) Retrieval and Excavation	Minimize worker exposure (M)	Impact-resistant shielding meeting OSHA requirements during handling of *suspect* containers or containers with potential VOC concentrations greater than the LFL (29CFR Part 1910.120 Section j)	Minimize worker contact with container; prevent unnecessary personnel within affected area	NOTE1: Impact resistant shielding may be designed into excavation equipment (i.e., as opposed to portable shielding) when performing excavation operations NOTE 2: Alternate controls must be applied, even when Preferred controls are available NOTE 3: Once waste is retrieved, any subsequent movement is considered under the activity definition of "Container Handling" and therefore subject to the controls for Event 6 "Container Handling"

TABLE 6.4.1-1 Hazard Controls--Continued

Accident	Minimum Control Functions	Preferred Controls	Alternative Controls	Relevant Criteria/Discussion
Enclosure Deflagration (Event 8) Enclosure examples include glovebox and hot cell	Reduce Explosive Atmosphere (P)	Concentrations of hydrogen and VOCs are verified to be less than Lower Flammability Limit prior to opening a container.	Explicit personnel restrictions to opening an unvented drum (e.g., remote contained facility, inert atmosphere, protective shielding, blast resistant enclosre)	This control only applies to operations in which TRU waste containers are opened (i.e., repackaging)
	Minimize release (M)	Enclosure designed to mitigate deflagration pressure wave		This design feature will protect for over pressurization as well
		CVS	MAR limit	CVS defined in DNFSB 2004-2
	Minimize ignition sources (P)	Enclosure designed in accordance with IEEE/NFPA standards AND Remove inner operationally restricted waste items from the enclosure upon discovery	Alternate fire protection controls approved by qualified fire protection engineer (e.g., flammables and combustibles limit)	When potential for flammable atmosphere Note: Operationally restricted waste items are those that are analyzed to be present within the waste but are not allowed to be processed within the design parameters of the enclosure.
		Prohibit hotwork when combustible MAR is present	Protect exposed combustible MAR during hotwork (e.g. fireblankets, non-combustible containers)	
		Use non-sparking tools OR Inert atmosphere		When there is a potential for flammable atmosphere
	Limit fire size (M)	Automatic FSS OR Inert atmosphere	Alternate fire protection controls approved by qualified fire protection engineer (e.g., flammables and combustibles limit)	DOE O 420.1B

TABLE 6.4.1-1 Hazard Controls--Continued

Accident	Minimum Control Functions	Preferred Controls	Alternative Controls	Relevant Criteria/Discussion
	Minimize worker exposure (M)	Minimize worker contact with container; prevent unnecessary personnel within affected area		
Vehicle/Equipment Impacts Waste/Waste Containers (Event 9) External Vehicle Accident (Event 16)	Minimize material release (M)	Robust waste container	Waste array MAR limit	
	Minimize vehicle/equipment impact (P)	Protect waste arrays with physical barriers	Control vehicle/equipment access OR Control vehicle/equipment route	
Drop/Spill Due to Improperly Handled Container, etc. (Event 10)	Minimize material released (M)	Outer container integrity	Limit container lift height OR Limit MAR handled at one time	
Collapse of Stacked Containers (Event 11)	Minimize material released (M)	Outer container integrity AND Pallet structural integrity	Stack limitation (e.g., height limit, weight limit, MAR distribution limit) OR Alternate structural enhancement	

TABLE 6.4.1-1 Hazard Controls--Continued

Accident	Minimum Control Functions	Preferred Controls	Alternative Controls	Relevant Criteria/Discussion
Waste Container Over-Pressurization (Event 12)	Minimize release (M)	Outer container integrity		
	Reduce over-pressurization (M)	Vent pressurized containers		Until vented handle with minimize worker exposure controls
	Minimize worker exposure (M)	Lid restraints on pressurized containers (e.g., nylon straps, netting, drum overpacks, or other physical restraining devices) OR Impact-resistant shielding meeting OSHA requirements during handling of pressurized containers (29CFR Part 1910.120 Section j)	Minimize worker contact with pressurized container; prevent unnecessary personnel within affected area	NOTE: Alternate controls must be applied, even when Preferred controls are available
Direct Exposure to Radiation Events (Event 13)	Minimize immediate life-threatening worker exposure (M)	Specific shielding distance, and/or time, requirements in accordance with Radiation Protection Requirements		Prevention of the initiating exposure event must also meet other accident event controls as applicable (i.e., whether radiation exposure event is because of drum impact with associated spill/impact, seismic event, etc).
Criticality Events (Event 14)	Minimize potential for criticality event (P)	Specific controls evaluated in accordance with site requirements		These controls are event and site specific and generic controls cannot be established

TABLE 6.4.1-1 Hazard Controls--Continued

Accident	Minimum Control Functions	Preferred Controls	Alternative Controls	Relevant Criteria/Discussion
Aircraft Impact w/ Fire (Event 15)	Minimize material release (M)	Facility designed to withstand aircraft impact event	MAR distribution (e.g. less MAR in impact footprint)	As deemed applicable by DOE-STD-3014 For existing facilities, DOE may accept the risk based on contractor justification
External Fire (Event 19)	All controls from Event 4			
	Limit fire growth (M)	Non-combustible facility construction AND Fire breaks (e.g. vegetation control)	Alternate fire protection controls approved by qualified fire protection engineer (e.g., flammables and combustibles limit)	
Lightning (Event 20)	All controls from Event 4			
	Minimize impact of lightning (M)	Facility designed to withstand lightning	Alternate fire protection controls approved by qualified fire protection engineer (e.g., flammables and combustibles limit)	For existing facilities, DOE may accept the risk based on contractor justification
		Operational restrictions during inclement weather		Outdoor handling and transport
High Wind (Event 21) Tornado (Event 22)	Minimize impact of NPH event (M)	Facility designed to withstand NPH event	Specific engineered protective enclosures	DOE-STD-1020 For existing facilities, DOE may accept the risk based on contractor justification

TABLE 6.4.1-1 Hazard Controls--Continued

Accident	Minimum Control Functions	Preferred Controls	Alternative Controls	Relevant Criteria/Discussion
Snow/Ice/Volcanic Ash Build-up (Event 23)		Operational restrictions during inclement weather		Outdoor handling and transport
Seismic Event (Impact Only) (Event 24)	Minimize impact of seismic (M)	Facility and SSC designed to withstands seismic event	Specific engineered protective enclosures/controls	DOE-STD-1020 For existing facilities, DOE may accept the risk based on contractor justification
Seismic Event w/ Fire (Event 25)	All controls from Event 4			
	Minimize impact of seismic	Facility and SSC designed to withstands seismic event	Specific engineered protective enclosures/controls	DOE-STD-1020 For existing facilities, DOE may accept the risk based on contractor justification

7.0 Safety Basis Review and DOE Acceptance

7.1 Purpose

Analysis of hazards for the operation of DOE nuclear facilities is regulated through requirements and "safe harbor" provisions defined within the 10 CFR Part 830, Subpart B. The guidance provided within this section is not intended to revise or expand requirements described within the regulation, but rather clarifies expectations for DOE's review and acceptance of the SB and measures established for protection of workers, the public, and the environment.

7.2 Assurance of Adequate Protection

The SB defines the safety analysis and hazard controls that provide assurance that a DOE nuclear facility can be operated in a manner that adequately protects workers, the public, and the environment. The risks posed by hazards described within a facility's SB are reviewed and accepted by the DOE Approval Authority as documented in the DOE Safety Evaluation Report (SER). DOE uses the SER to document the criteria and bases for the DOE approval of the SB, which includes reasonable assurance of protection. The SB Approval Authority is responsible for ensuring the SER represents a defensible review of a facility's SB.

Where new or enhanced safety controls are needed because of a new activity or major modification, those controls must meet current DOE design or other requirements. Where controls cannot meet current requirements, exemptions with appropriate compensatory measures are generally needed to authorize acceptability of not meeting the requirement. Depending on the requirement and its applicability to existing facilities, the approval authority for the SB may not be the same person as the DOE approval authority for the exemption to current DOE Order or other requirements. Furthermore, approval of exemptions to requirements involving nuclear safety need concurrence of the DOE and/or NNSA Central Technical Authorities per the DOE exemption process in effect at the time of the request.

7.2.1 Assurance of Adequate Public Protection

Reasonable assurance of adequate public protection is provided through analysis of postulated facility accidents that could lead to significant offsite consequences. DOE-STD-3009 defines an EG concept where unmitigated accidents with the potential to challenge this EG trigger a review for the need of safety-related controls. The EG is compared to the unmitigated accident dose estimate of a maximally-exposed individual assumed to stand at the site boundary for two to eight hours. DOE-STD-3009 clearly states that it is inappropriate to apply the EG as a hard pass/fail design criterion. Where the unmitigated accident dose estimate is judged to challenge the EG, public protection is assured through safety related controls that prevent and/or mitigate these consequences. The accident is then evaluated to ensure that the controls sufficiently ameliorate the risk through a reduction of consequence and/or likelihood of occurrence. If this reduction in risk is adequate, DOE accepts proposed SB controls thru approval in an SER. However, if DOE does not find the reduction in risk acceptable, alternate strategies will need to be sought out, such as additional controls prior to approval. Additionally, given the nature of certain operations, it is not possible to apply additional controls without a cost that outweighs the benefit (for example, seismic upgrades to a facility with a limited operational life left). In this case, DOE may choose to accept the significant risk that is left after available controls are in place. If DOE chooses to accept significant risk, this risk should be clearly identified in the SB and explicitly discussed and accepted in the SER.

It should be noted that the evaluation of the mitigated case (i.e., accident with controls applied) discussed above may range from a qualitative evaluation to a formal recalculation of doses. To some extent, this will be driven by the nature of the accident and the nature of the facility/activity. When reevaluating dose consequences, caution is urged to not overestimate the credit given to particular controls without proper justification (i.e., data). Note that the SB controls identified to ensure the offsite EG is no longer challenged would be safety class. If additional significant defense in depth is warranted, these significant defense in depth controls would be safety significant.

Thus, analysis of postulated accidents leads to an end state that assures adequate public protection for events that could lead to significant offsite consequences. When unmitigated dose estimates are judged to challenge the EG, there is no “hard” or absolute definition for how low mitigated results must be before adequate assurance of protection is received. However, one factor in determining whether an unmitigated accident consequence challenges the offsite EG or in determining whether a mitigated accident consequence no longer challenges the offsite EG is the overall conservatism in the accident progression and the dose calculation parameters (e.g., MAR, ARF, RF, meteorology assumed, etc.). In general, the more conservative the offsite dose calculation that is performed, the higher the radiological dose could be and not “challenge” the offsite EG of 25 rem (see Section 6.3 for rationale justifying 10 rem).

7.2.2 Assurance of Adequate Worker Protection

Thresholds related to adequate worker protection are not quantitatively defined with DOE directives. Workers, particularly those in close proximity to operations, are exposed to hazards from the release of materials during operational upsets and facility accidents. Radiological consequences of operational upsets such as spills or leaks, and design basis events are difficult to model and predict. The difficulty in estimating a worker’s dose lies primarily in defining how and where hazards are released within the facility and the proximity of those hazards to the facility worker. Small changes (or uncertainties) in these assumptions can significantly affect calculated results. For example, how long would it take workers to recognize a TRU container drop or deflagration had occurred? The answer to this question drives how long the worker breathes air contaminated with materials released from the damaged container.

The sensitivity of results to changes in these variables is one of the primary reasons DOE-STD-3009 discourages the practice of quantitative evaluation of worker consequences and does not require formal accident analysis of worker impacts. Such sensitivity (in calculation results) gives rise to the temptation to reevaluate until the results no longer indicate an unacceptable level of hazard exists. DOE-STD-3009 requires analysis of accident scenarios for derivation of controls that provide reasonable assurance of adequate public protection, and limits derivation of worker protection controls to the HA process. Worker HA is a qualitative process to establish the need for controls to protect facility workers. Although this process is often supported with quantitative analyses to guide decision making, these supporting quantitative analyses are not normally expected to be as complex or detailed as the accident analyses for public hazards.

Many sites have used an analytical process to evaluate hazard significance to collocated workers. In this case, a 100 m evaluation criteria (analogous to the public EG concept) is often chosen to assess the significance of potential unmitigated radiological/toxicological exposure to workers collocated to the subject facility. An unmitigated event with the potential to challenge this evaluation criteria triggers a review for the need of safety-significant controls for worker protection. Section 6.2 of this Standard contains guidance on control selection, which uses an onsite evaluation point to establish controls for workers. While the Standard makes the point that the guidance is to be used for control selection and does not represent risk acceptance guidelines, the concepts presented in this Section 6.2 are useful in understanding selection and evaluation of controls to ameliorate accident consequences.

7.2.3 Public Accident Analysis versus Worker Hazard Analysis

Design basis accident analyses represent an extensive and costly process employed to analyze conditions that could pose a significant hazard to the public. The DBA analysis is insensitive to many of the variables that would make a accident analysis unnecessarily prescriptive for the worker population. For example, offsite dispersion of a plume released from a TRU container explosion is fairly insensitive to the location within the facility. The DBA analyses would model the deflagration as a point source release at the facility wall and disperse the resulting plume to the site boundary. On the other hand, a worker hazard analysis is very dependent upon the location of such a deflagration within the facility. A bounding (i.e., worst case) "worker accident analysis" for such a deflagration would require an evaluation of each room with a set of assumptions concerning the location of workers, facility ventilation flows, and how long workers breathed the contaminated air. The resulting detail set of "worker accident analyses" would define proscriptive conditions that would likely result in numerous USQ determinations as new information is identified.

This Standard encourages derivation of worker protection controls, both for the facility worker as well as the collocated worker, through use of the HA process. Consistent with DOE-STD-3009, the DSA contains a summary level discussion of facility worker hazards and worker protection measures necessary to protect workers. Quantitative dose estimates to the collocated workers provides insights into the significance of overall worker consequences. TRU facilities can be expected to reduce costs by avoiding the unnecessary use of accident analysis for the worker population. This cost avoidance would be better invested in risk reduction associated with accelerating cleanup activities.

7.2.4 Reasonable and Adequate Assurance

Given the wide range of DOE nuclear operations, it is not possible for the 10 CFR Part 830, Subpart B, and its associated safe harbor provisions implementation guidance to provide detailed discussion on what is reasonable or adequate when assuring public, worker, and environmental protection. However, some of these documents (e.g., DOE O 420.1B and associated guides, DOE-STD-1120-2005, etc.) along with DOE-STD-1104 do provide discussion that is useful in understanding DOE's approval basis for the SB. Accordingly, the SB Approval Authority must assure that the control scheme selected to address accidents is adequate to provide public and worker protection.

DOE-STD-1104 guides DOE analysts during the preparation of SERs. In reviewing and approving a SB document, DOE-STD-1104-96 has the Approval Authority consider the extent to which the SB meets requirements established within 10 CFR Part 830 and satisfies the provisions of safe harbor methodologies used to prepare the SB. This consideration is based upon five general bases for approval:

- Base information
- Hazard and accident analyses
- SSCs
- Derivation of technical safety requirements
- Safety management program characteristics

DOE determination as to whether safety related hazard controls provide reasonable assurance of adequate protection is based upon the totality of the documented review rather than any specific element or criteria considered during the SB review.

The Nuclear Safety Rule and DOE-STD-3009 infer such judgment and discretion would be based upon an understanding of the facility hazards, complexity of operations, effectiveness of safety related controls, remaining operational lifetime, and degree to which DID is ensured.

7.3 DOE Review

DOE review of the SB submitted for operation on a Hazard Category 2 or 3 TRU facility determines whether the controls established provide adequate protection. When issues are identified during this review, the Approval Authority maintains the authority to determine which are significant in terms of assuring adequate protection (reference DOE STD 1104, Section 1.4). Reviewers involved in the preparation of SERs must recognize that assurance of adequate protection involves some assumption of risk by DOE. As discussed above, any significant risk needs to be discussed in the DSA (with appropriate justification) and explicitly accepted in the SER.

When evaluating the risk posed by nuclear operations, the Approval Authority (and to a lesser extent the DOE reviewers) must consider factors such as the degree of DID, remaining facility life (i.e., time at risk), worth of controls (i.e., how reliable and effective), safety margins, and relative risk posed by alternatives (e.g., risk tradeoff between faster TRU characterization and shipment to WIPP as compared to the risk of leaving TRU wastes on site for a longer period of time). There is no single solution using this approach to determining reasonable assurance of adequate protection. Sound and prudent application of judgment and discretion must be applied when evaluating options under this approach.

In general, 10 CFR Part 830, Subpart B, and its safe harbor methodologies rely upon informed assessment for making safety decisions. The complexity, level of rigor, and prescriptive nature of this informed assessment increases as the risk of events to the public and workers increases. Hazard Analyses and DBAs should clearly define the estimated likelihood and consequence of facility hazards. Within the SER, hazard analysis results should be characterized in terms of DID, worker protection, and environmental protection. Assumed risk (hazard likelihood and consequence) is then based upon providing effective controls with sufficient DID. The degree of effectiveness (e.g., reliability) and layers of DID are then tailored to the risks. High risk hazards are then addressed with controls that provide more layers of defense and higher reliability as compared to lower risk hazards.

The SB derives the hazard controls necessary to ensure adequate protection and demonstrates the adequacy of those controls to eliminate, limit, or mitigate those hazards (DOE G 421.1-2, Section 1). Risks associated with these hazards are expected to be analyzed using the inputs, assumptions, and controls defined within this Standard as part of an informed assessment approach. Sites are expected to use the inputs, assumptions, and controls defined within this Standard. DOE reviewers are encouraged to make use of tools such as review guides, procedures, or checklists to ensure applicable information contained within this Standard was considered during development of the TRU facility DSA.

This Standard establishes an appropriate level of rigor in the hazard analysis and control selection. However, it must be understood that no control can be 100% reliable or effective. Operational upsets (e.g., dropped pallet of TRU drums) and other events (e.g., pyrophoric reaction within a TRU container) may occur despite the rigor of analysis and applied controls. When these events occur, any decision related to the adequacy of HA and controls should be based upon a careful review of the facility condition/event. The review should investigate whether the occurrence and its initiator were identified within the HA; whether defined controls functioned as credited within the DSA to prevent or mitigate the event. Where applicable, the review should also determine whether DSA provisions discussed in Section 3.4 were followed. No control is assumed to be completely effective and reliable, and attention should be given where controls were relied upon for hazard prevention, particularly when these controls are administrative in nature.

A properly documented and implemented DSA should not require an extended reexamination of the DSA analysis when anticipated events are realized with the facility as analyzed and protective measures function as designed (see Section 3.4 for conditions acceptable for "*Expected* events"). Once facility management has carefully reviewed/critiqued circumstances related to the occurrence, determined hazards were addressed by events in the HA, and confirmed associated controls functioned as relied upon in the DSA, it can be reasonably concluded there is no need to revise the bounding analyses of the DSA. It may then be appropriate to resume operations once any clean up or recovery actions have been completed. Recurring events, although possibly evaluated at an anticipated frequency within the DSA, should be closely scrutinized to assess the need for additional preventive measures or layers of DID.

7.4 Summary

- The HA and AA information described within this Standard is intended for use during an informed assessment approach to evaluating TRU facility hazards and associated risks.

- Qualitative evaluation of facility worker hazards (with insights from dose consequence calculations at the 100 meter evaluation point) and derivation of associated controls should be addressed within the HA process rather than defining bounding worker DBAs within the DSA. This represents a more cost-effective approach to reasonable assurance of adequate worker protection.

- The DSA Approval Authority maintains the authority to determine what level of risk is significant in terms of providing reasonable assurance of worker and public protection. Sound and prudent application of judgment and discretion by the Approval Authority is expected when evaluating HA and AA results.

- When events anticipated by the DSA occur, decisions related to the adequacy of Hazard and Accident Analyses should be based upon a careful review of the facility condition/event. Additional, guidance on expected events is provided in Section 3.4 of this Standard.

8.0 Verification of SB Implementation

8.1 Purpose

This section describes general expectations for ensuring that new/revised Safety Basis Documents (SBDs) are properly implemented whether or not the readiness process in DOE O 425.1 is applicable. The expectations and guidance herein do not replace the processes described in DOE O 425.1, but can be used by line management (contractor and/or DOE) prior to the contractor and/or DOE readiness assessment/operational readiness review (RA/ORR) to ensure the facility/activity is verified "ready" prior to the RA/ORR being initiated. These processes can also be used where a new SB is being implemented in an existing facility where covered activities are currently operational and an ORR or RA is not required. This includes instances where covered activities in the facility are ongoing but there are changes in controls in the new SB.

8.2 Implementation Verification Process

In addition to readiness review processes required by DOE O 425.1, there are two levels of review activities that help ensure requirements and controls of the DSA and TSR appropriately flow into contractor procedures, training, and activities. The Implementation Verification Process (IVP) is the overall process used by line management to ensure SBDs are properly implemented. The IVP always includes a line manager assessment (LMA) and sometimes, depending on type/scope of SBD involved, may include an Independent Verification Review (IVR).

The LMA is a process that a line manager (typically the Facility Manager) uses to ensure all (i.e., 100% vs. a sample) of the activities (e.g., hardware modifications, procedure changes, training, etc.) necessary to properly implement the requirements in the new/revised SBD are completed prior to declaring the SBD implemented.

The IVR is a process used by the contractor, when deemed appropriate, as well as DOE line management (i.e., the DOE manager providing oversight of the facility/activity) to provide a level of independence in verifying the new/revised SBD is properly implemented. Normally, the IVR is based on verifying that a sampling of new/revised SBD requirements has been properly implemented. The sampling size (up to 100% if needed) should be based on factors such as the magnitude and complexity of the new/revised SBD requirements, past performance in line management readiness verification, and adequacy of continued implementation of existing SBD requirements.

The following guidelines address how to apply the IVP and sub-tier reviews discussed above:

1. Scope and detail of DOE and contractor IVP are expected to be based on a graded approach (complexity of changes, type/extent of hardware modifications, facility/contractor interface requirements, etc.).

2. DOE Field Offices (FOs) and contractors develop and maintain documents/procedures defining the IVP (responsibilities, etc.).

3. For activities falling under DOE O 425.1, approval authorities are already defined. For activities not under DOE O 425.1, the Approval Authority for permission to “startup” (i.e., make the new/revised SBD “effective”) is usually the contractor. If special circumstances dictate the DOE FO being the Approval Authority, this determination is expected to be part of the DOE transmittal of the SER approving the new/revised SBD and subsequently incorporated into the contractor IVP plan (also need to consider impacts to the Startup Notification Report under DOE O 425.1).

4. Contractor is expected to maintain configuration control over both the currently implemented SBDs through the USQ process and SBDs under development, review, and implementation. Contractor must identify any changes to the new/revised SBD needed prior to implementation of changes. This includes any Conditions of Approval, or Directed Changes, identified in the DOE SER approving the SBD. Any Conditions of Approval, or Directed Changes, must also be verified to be properly implemented via the IVP.

5. Implementation Schedule, Implementation Plans, and Reports
   All new/revised SBDs must be implemented 90 days or less (especially if the scope of the new/revised SBD is not extensive). If more than 90 days is required, the contractor is expected to submit detailed justification.

6. FO determines the level of DOE IVR and documentation warranted, including whether a DOE IVR plan is warranted. The degree of formality of the plan should consider the complexity of the SBD revision/change. Note: Determining the complexity of the SBD revision/change may consider items/issues such as health and safety consequences of the failure to implement new/revised controls, nature of the new/revised controls, depth/breadth of changes to the DSA/TSR including new analysis/events and extent of implementation actions such as numbers and types of procedure changes and personnel training.

7. FO determines whether DOE IVR will be conducted before or after the contractor has made the new/revised SBD “effective” based on such considerations as complexity of SB changes, type/extent of hardware modifications, facility/contractor interface requirements, past contractor performance, and duration since last DOE IVR conducted. If FO determines the DOE IVR will be conducted prior to new/revised SBD being made “effective,” FO expected to ensure contractor IVP plan for the SBD recognizes this schedule/logic tie.

8. FO determines the DOE IVR team based on a graded approach. Depending on the scope and complexity of the SB changes, the team may range from oversight from a Facility Representative (FR) and/or Site Safety Office (SSO) engineer up to a designated team consisting of Team Leader, FR, SSO engineer, SB staff, DOE Project Managers, and other SMEs).

9. FO determines method of documenting DOE IVR results (e.g., a separate IVR Report versus part of routine Technical Assessment Program documentation). .

10. Contractor must notify DOE:
    a. Upon commencement of contractor's LMA and IVR.
    b. Upon completion of contractor's LMA and IVR.
    c. Upon declaration of when SB changes have been implemented and complete (i.e., made "effective").

11. Emergency Management Hazards Assessment (EMHA) document updates are managed in accordance with DOE O 151.1. Thus, EMHA updates are not addressed as part of IVP unless the SBD change necessitates a change to the EMHA. The contractor and DOE IVP for a specific new/revised SBD are expected to determine whether the IVP for the SBD warrants verification of appropriate Emergency Management Program impacts prior to making the SBD "effective."

12. Authorization Agreements are expected to be maintained consistent with SBD changes.
    a. If the Authorization Agreement is affected, contractor must submit to DOE and obtain DOE approval of any revision prior to making the new/revised SBD "effective."
    b. DOE approval letter of new/revised SBD should address whether the Authorization Agreement is affected.

13. IVP typically focuses on implementation of TSR (or equivalent) controls. For facilities that rely heavily on SMP, IVPs need to consider adequacy of SMPs to provide control of hazards when specific TSR controls (SL, LCO, SACs, detailed ACs, design features) are not defined. If the SMP has been validated at the site level (e.g. during Annual ISMS re-verification, etc), then the facility specific aspect invoked by the DSA or any changes to the site SMP that may have occurred that are relevant to the implementation should be considered.

9.0 References

Code of Federal Regulations

10 CFR Part 71, *Packaging and Transportation of Radiological Material*

10 CFR Part 830, *Nuclear Safety Management*

29 CFR Part 1910.20, *Access to Employee Exposure and Medical Records*

49 CFR Part 173, *Shipper's--General Requirements for Shipments and Packaging*

DOE Directives

DOE O 151.1C, *Comprehensive Emergency Management System*

DOE O 420.1B, *Facility Safety*

DOE G 423.1-1, *Implementation Guide For Use In Developing Technical Safety Requirements*

DOE O 425.1C, *Startup and Restart of Nuclear Facilities*

DOE O 460.1B, *Packaging and Transportation Safety*

DOE O 461.1A, *Packaging and Transfer or Transportation of Materials of National Security Interest*

DOE Standards

DOE-HDBK-1163-2003, *Integration of Multiple Hazard Analysis Requirements and Activities*

DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*

DOE-STD-1020-2002, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*

DOE-STD-1066-99, *Fire Protection Design Criteria*

DOE-STD-1104-96, *Review and Approval of Nuclear Facility Safety Basis Documents (Documented Safety Analysis and Technical Safety Requirements)*

DOE-STD-1120-2005, *Integration of Environment, Safety, and Health into Facility Disposition Activities*

DOE-STD-1186-2004, *Specific Administrative Controls*

DOE-STD-3007-2007, *Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Nonreactor Nuclear Facilities*

DOE-STD-3009-94, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis*

DOE-STD-3011-2002, *Guidance for Preparation of Basis for Interim Operation (BIO) Documents*

DOE-STD-3014-96, *Accident Analysis for Aircraft Crash into Hazardous Facilities*

Other Documents

DOE/WIPP-02-3122, *Contact-Handled Transuranic Waste Acceptance Criteria for the Waste Isolation Pilot Plant* (most current version)

HNF-14741, Revision 3, *Solid Waste Operation Complex Master Documented Safety Analysis*, Fluor Hanford Company (2005)

ICRP 68, *Dose Coefficients for Intakes of Radionuclides by Workers* (1994)

ICRP 70, *Basic Anatomical and Physiological Data for use in Radiological Protection: The Skeleton*

ICRP 72, *Age-dependent Dose to Members of the Public from Intake of Radionuclides: Part 5 Compilation of Ingestion and Inhalation Dose Coefficients*

NUREG/CR-6410, *Nuclear Fuel Cycle Facility Accident Analysis Handbook* (1998)

PLG-1121 Rev.1, *Damage Assessment of Waste Containers Involved in Accidents at the Waste Isolation Pilot Plant*, Westinghouse Government Environmental Services Company (2000)

PLG-1305, *Remote Handled Transuranic Waste Container (RH-TWC) Structural Analyses for Postulated Handling Accidents*, Westinghouse Government Environmental Services Company (2000)

SAND 97-0368, *Testing in Support of On-site Storage of Residues in Pipe Overpack Container* (1997)

Shleien and Terpilak, *The Health Physics and Radiological Health Handbook* (1985)

WHC-SD-TRP-233, *Analytical and Experimental Evaluation of Solid Waste Drum Fire Performance*, Westinghouse Hanford Company (1995)

WHC-SD-WM-TRP-246, *Solid Waste Drum Array, Fire Performance*, Westinghouse Hanford Company (1995)

WHC-SD-SQA-ANAL-501 *Fire Protection Guide for Waste Drum Storage Arrays*, Westinghouse Hanford Company (1996)

Appendix A

Results of Analysis of Plutonium Equivalent Curies (PE-Ci) Data for Transuranic (TRU) Waste Containers from Multiple DOE Sites in Support of US DOE Environmental Management Programs

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A.1 Analysis Results

Container TRU PE-Ci data were provided from six DOE laboratory sites, Hanford-Richland (RL), Idaho (INL), Los Alamos (LANL), Lawrence Livermore (LLNL), Oak Ridge (ORNL) and Savannah River (SRS). In most cases the provided data reflects the values entered into the individual site database at the time the container was loaded and/or placed in storage. In some cases the data reflects more recent assay results from programs instituted to segregate low-level waste from TRU waste and to confirm high-activity drums among the TRU population. Although most of the data are not derived from formally certified assay processes such as used for the Waste Isolation Pilot Project TRU waste disposal program, the provided data reflect each site's best assessment of its potential MAR-associated population at the time.

Over 120,000 positive-valued data points were included in the raw data submissions as shown in the following table. Common statistics that may be immediately derived from the data, including the average (Mean PE-Ci), the Median (center-most value in an ordered sample), several of the higher percentiles, and the maximum reported value for PE-CI are also included for information. Many containers were reported with zero, negative, or blank PE-Ci values. These data points were discarded as not applicable to TRU waste and to avoid biasing the analysis results low. In addition to those data, two sites (RL and INL) included certain anomalous container values that appeared to be only "default" or "place holder" values in that they demonstrated significant departures from the distributional characteristics of the remaining data points and cannot be validly included in the analyses for these two sites. The anomalous nature of these data is illustrated in the initial histograms and dot-plots shown in the analysis enclosures for the sites. Also, as these data values fell relatively lower in the value distribution range, their exclusion tended to introduce a slightly conservative effect in the upper-percentile estimation process. Two data counts are listed for each of these two sites; the first raw count includes all positive values and the second "validated" count reflects the positive value data after exclusion of the two anomalous data values. Because the data are strongly right-skewed for all sites, it was necessary to take the natural, or napernian, logarithms (Ln or Log_e) to remove the skewness characteristic and detect such anomalous values that would otherwise have been masked in the raw data graphics. For consistency and clarity of interpretation, all calculations were based in and reflect non-transformed data and associated units.

TABLE A-1 Summary Data

Site	RL	INL	LANL	LLNL	ORNL	SRS	Total
Number of Containers Reported with Positive PE-Ci Values	13,747 (10,976 validated)	71,171 (70,703 validated)	23,172	992	3,943	11,238	123,789 (121,024 validated)
Mean PE-Ci	7.952	1.554	10.66	2.558	2.572	46.923	8.108
Median PE_Ci	1.257	0.095	0.556	0.875	0.059	3.439	0.209
90th %tile	19.24	4.229	15.79	7.321	3.335	160.56	11.50
95th %tile	30.93	7.550	32.65	10.74	5.883	248.49	25.53
99th %tile	58.83	18.65	178.86	23.44	65.70	434.30	181.62
Max PE-Ci	1290.5	329.00	1234.8	34.44	308.94	1832.5	1832.5

When dealing statistically with quantitative measures such as PE-Ci where the greatest interest or concern lies in values near the upper limits of the underlying population distribution, a preferred and commonly used statistic is the β-content upper tolerance limit (UTL). The β-content UTL is estimated from the available data such that at least $\beta\times100\%$ of the represented population is expected to fall at values less than the UTL with probability $(1-\alpha)$. That is, one may have at least $(1-\alpha)\times100\%$ confidence that at least $\beta\times100\%$ of the population is less than the UTL. Often, a default α value of 0.05 is implied and UTL's are simply referenced in terms of the desired $\beta\times100\%$ value, i.e., "UTL-98" when discussing the upper tolerance limit yielding 95% confidence that at least 98% of the related population exhibit values less than the UTL value.

To yield valid results, the usual parametric UTL procedure requires at least near-normality in value distribution. However, neither data set nor the combined aggregate approximated a normal probability distribution. Logarithmic data transformation produced only marginally normal-like data distributions. Therefore, the more robust, nonparametric (distribution free) 95% Upper Tolerance Limits ($UTL_{95/\beta\times100\%}$) should be used for each site and for the combined data. The $UTL_{95/\beta\times100\%}$ estimates are shown in the following table for several $\beta\times100\%$ values ranging from 90-to-99.5%.

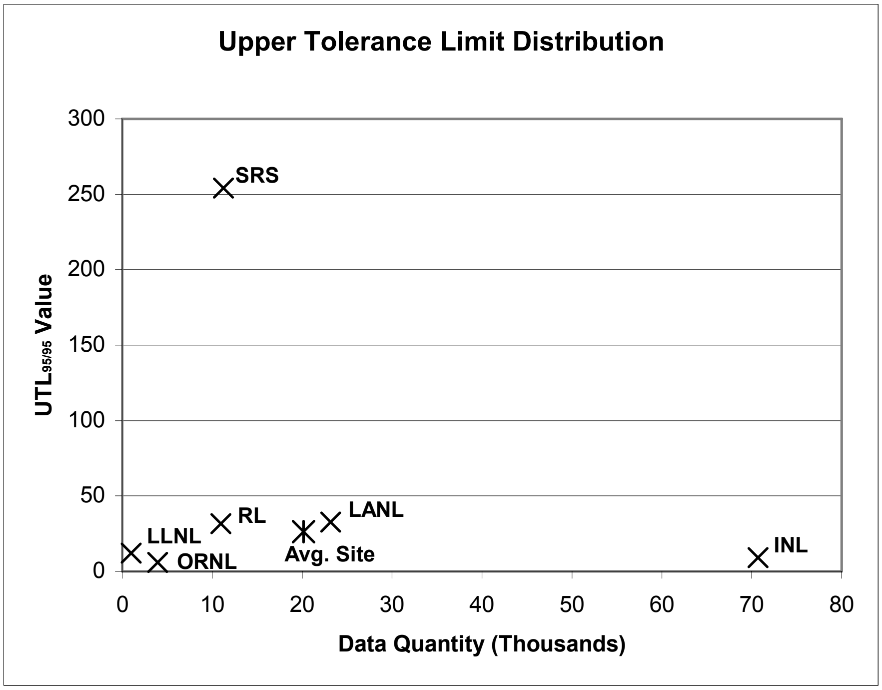
TABLE A-2 $UTL_{95/\beta\times100\%}$ Estimates

Site:	RL	INL	LANL	LLNL	ORNL	SRS	All Sites Combined
$UTL_{95/90}$	20.00	5.43	16.28	8.24	3.70	166.02	11.77
$UTL_{95/95}$	31.68	9.12	32.65	12.13	6.02	254.11	26.36
$UTL_{95/98}$	54.33	15.34	96.48	19.95	38.18	374.13	88.86
$UTL_{95/99}$	60.88	22.27	202.45	27.13	83.68	460.18	187.07
$UTL_{95/99.5}$	130.30	32.51	438.91	28.89	135.63	731.11	291.35

It may be seen from Table A-2 and Figure A-1 that most of the site UTL values varied only moderately from site to site while one contributor site, Savannah River (SRS), exhibited significantly higher UTL values. This could be related to a systemic difference in site mission and/or TRU waste production processes or reflect a difference in data collection and reporting.

Data analysis was performed using the most current (July 14, 2006) release of the NCSS®-2004 Statistical Analysis software package {Hintze, J. (2006). *NCSS, PASS, and GESS*. NCSS, Kaysville, Utah. www.ncss.com.} The output from the applicable statistical analyses in this package are included in the attached pages. The output has been edited to reduce and/or eliminate extraneous/low-value information and improve readability where possible. No computational results were changed except to round off most numbers to no more than four decimal places or five significant digits.

FIGURE A-1 Upper Tolerance Limit Distribution



A.2 Analysis of TRU Waste Pe-Ci Data

The following figures depict data from each of the TRU waste sites.

A.2.1 Hanford (Richland) Site

Database Hanford MAR RL_PE_Ci.S0Z Filter None

**FIGURE A-2 Hanford Site Raw Data
Histogram & Dot Plot**

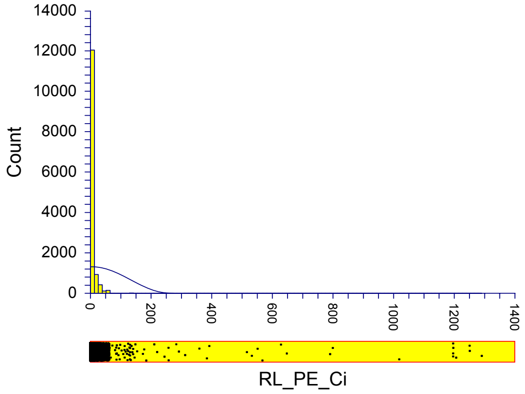
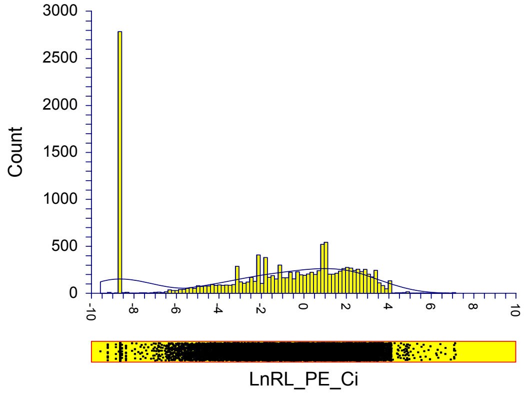


**FIGURE A-3 Logarithms of Hanford Site Data
Histogram & Dot Plot**



The 2771 containers reported with PE-Ci value = 0.000175723 {Ln(PE-Ci) = -8.6466} are suppressed for the analysis. [The next most-frequent value = 0.119195787 {Ln(PE-Ci) = -2.1270} for 294 containers.]

Database Hanford MAR RL_PE_Ci.S0Z Filter ValFreq<2770

**FIGURE A-4 Filtered Hanford Site Raw Data
Histogram & Dot Plot**

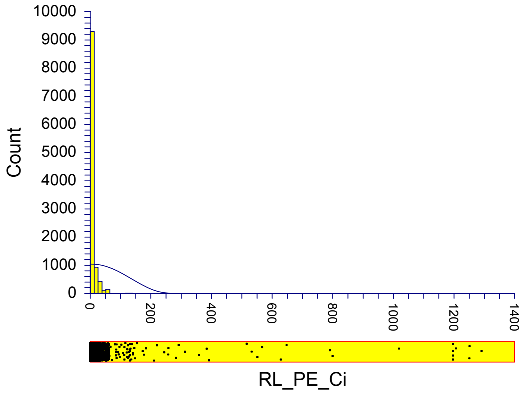
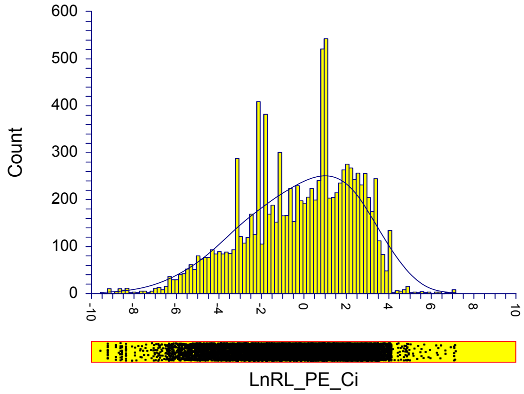


**FIGURE A-5 Logarithms of Filtered Hanford Site Data
Histogram & Dot Plot**



RL_PE_Ci (Hanford Site PE_Ci)

Descriptive Statistics Report Filter ValFreq<2700

Count	**Mean**	**Standard Deviation**	**Standard Error**	**Minimum**	**Maximum**	**Range**
10976	7.9515	41.29871	0.394198	0.000069	1290.524	1290.524

Parameter	**Mean**	**Median**	**Geometric Mean**	**Skewness**	**Kurtosis**
Value	7.9515	1.257139	0.8493796	23.12873	628.6501
99% LCL	6.936113	1.161519	0.7970991		
95% LCL	7.178886	1.17005	0.8092986		
95% UCL	8.724114	1.405626	0.8914456		
99% UCL	8.966887	1.417914	0.9050891		

Note: The geometric mean confidence interval assumes that the ln(y) are normally distributed.

Percentile	**Value**	**99% LCL**	**95% LCL**	**95% UCL**	**99% UCL**	**Exact Conf. Levels**	
99.5	112.1160	62.1365	63.1302	130.7045	138.1518	95.083	99.011
99	58.8277	57.6020	57.7788	61.1328	61.4554	95.104	99.052
98	50.7472	44.0297	45.5950	54.7341	54.9977	95.210	99.046
95	30.9295	29.7003	30.0510	31.8098	31.9838	95.127	99.025
90	19.2403	18.2547	18.4508	20.1650	20.3835	95.148	99.004

Upper One-Sided 95% Tolerance Bounds of RL_PE_Ci (UTL$_{95/x\%}$)

Percent of Population Less Than Bound	**Parametric Upper Tolerance Bound**	**Nonparametric Upper Tolerance Bound**
99.5	115.6847	130.3000
99	105.2817	60.8849
98	93.9180	54.3334
95	76.8812	31.6773
90	61.7567	20.0030

Notes: The parametric (normal-based) limit assumes that the data follow the normal distribution.
The nonparametric (distribution-free) limit makes no special distributional assumption.

A.2.2 Idaho National Lab Site

Database IdahoNL.S0Z

Filter None

FIGURE A-6 Idaho NL Site Raw Data Histogram & Dot Plot

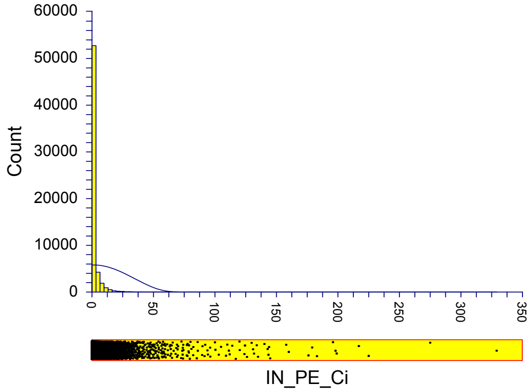
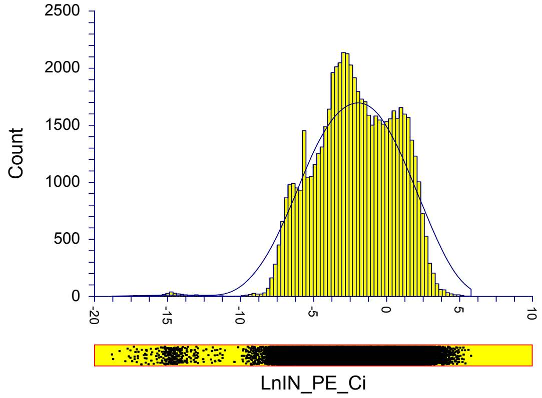


FIGURE A-7 Logarithms of Idaho NL Site Data Histogram & Dot Plot



The 468 containers reported with PE-Ci value = 0.003495893 {Ln(PE-Ci) = -5.6562} are suppressed for the analysis. [The three next most-frequent values applied to only four containers each.]

Database IdahoNL.S0Z Filter ValFreq<460

FIGURE A-8 Filtered Idaho NL Site Raw Data Histogram & Dot Plot

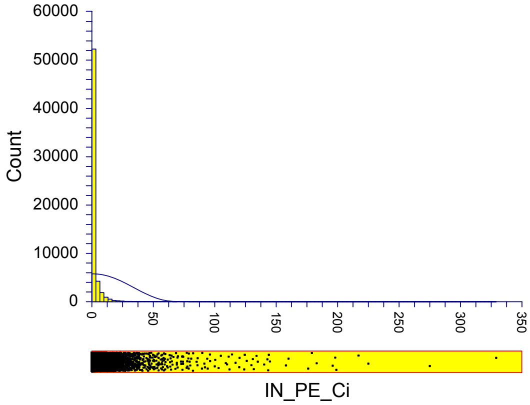
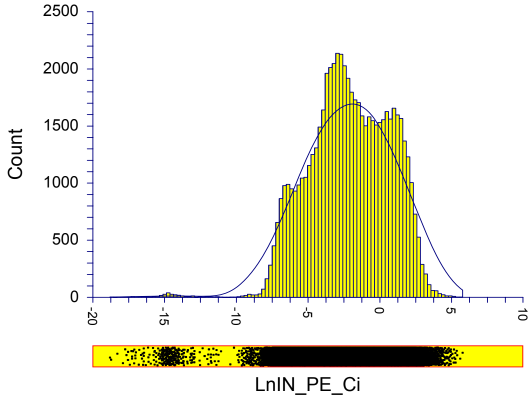


FIGURE A-9 Logarithms of Filtered Idaho NL Site Data Histogram & Dot Plot



IN_PE_Ci (Idaho NL Site PE_Ci)

Descriptive Statistics Report Filter ValFreq<460

Count	Mean	Standard Deviation	Standard Error	Minimum	Maximum	Range
70703	1.5536	5.6423	0.0212	6.8301E-09	329	329

Parameter	Mean	Median	Geometric Mean	Skewness	Kurtosis
Value	1.5536	0.0978	0.1079	17.4677	554.178
99% LCL	1.4989	0.0945	0.1051		
95% LCL	1.5120	0.0954	0.1058		
95% UCL	1.5952	0.1004	0.1101		
99% UCL	1.6082	0.1011	0.1109		

Note: The geometric mean confidence interval assumes that the ln(y) are normally distributed.

Percentile	Value	99% LCL	95% LCL	95% UCL	99% UCL	Exact Conf. Levels	
99.5	26.7374	25.0696	25.3503	28.4139	28.9520	95.156	99.032
99	18.6528	17.8378	18.0054	19.6779	19.9104	95.067	99.039
98	13.1805	12.7569	12.8692	13.5235	13.6484	95.013	99.010
95	7.5502	7.3220	7.3839	7.7389	7.8003	95.084	99.012
90	4.2288	4.1097	4.1399	4.3261	4.3585	95.022	99.001

Upper One-Sided 95% Tolerance Bounds of IN_PE_Ci ($UTL_{95/x\%}$)

Percent of Population Less Than Bound	Parametric Upper Tolerance Bound	Nonparametric Upper Tolerance Bound
99.5	18.1237	32.5119
99	16.5580	22.2740
98	14.8474	15.3411
95	12.2821	9.1195
90	10.0038	5.4316

Notes: The parametric (normal-based) limit assumes that the data follow the normal distribution.
The nonparametric (distribution-free) limit makes no special distributional assumption.

A.2.3 Los Alamos National Lab Site

Database LANL.S0 Filter None

FIGURE A-10 Los Alamos Site Data Histogram & Dot Plot

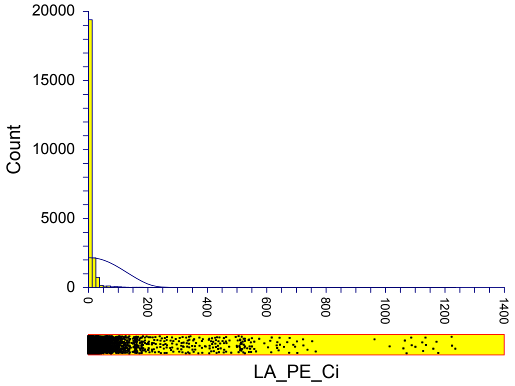
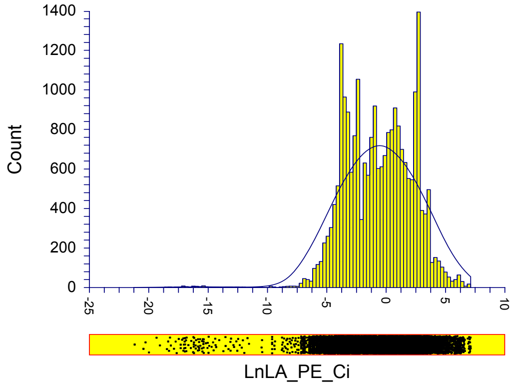


FIGURE A-11 Logarithms of Los Alamos Site Data Histogram & Dot Plot



LA_PE_Ci (Los Alamos NL Site PE_Ci)

Descriptive Statistics Report

Count	Mean	Standard Deviation	Standard Error	Minimum	Maximum	Range
23172	10.6620	52.8121	0.3469	6.271E-10	1234.818	1234.818

Parameter	Mean	Median	Geometric Mean	Skewness	Kurtosis
Value	10.6620	0.5563	0.5408	12.6162	207.7858
99% LCL	9.7683	0.5341	0.5151		
95% LCL	9.9820	0.5414	0.5211		
95% UCL	11.3419	0.6160	0.5612		
99% UCL	11.5556	0.6201	0.5678		

The geometric mean confidence interval assumes that the ln(y) are normally distributed.

Percentile	Value	99% LCL	95% LCL	95% UCL	99% UCL	Exact Conf. Levels	
99.5	408.6259	333.8182	343.4209	451.2727	463.1577	95.502	99.100
99	178.8629	160.5263	160.7766	213.1578	224.0062	95.244	99.002
98	89.5048	77.8796	80.2631	98.2894	100.0299	95.132	99.015
95	32.6531	31.8827	32.1429	32.6531	32.6531	95.167	99.005
90	15.7895	15.4985	15.4985	16.4791	16.7519	95.126	99.024

Upper One-Sided 95% Tolerance Bounds of LA_PE_Ci (UTL$_{95/x\%}$)

Percent of Population Less Than Bound	Parametric Upper Tolerance Bound	Nonparametric Upper Tolerance Bound
99.5	147.8872	438.9091
99	134.6240	202.4545
98	120.1346	96.4769
95	98.4084	32.6531
90	79.1158	16.2815

Notes: The parametric (normal-based) limit assumes that the data follow the normal distribution.
The nonparametric (distribution-free) limit makes no special distributional assumption.

A.2.4 Lawrence Livermore National Lab Site

Database LLNL.S0 Filter None

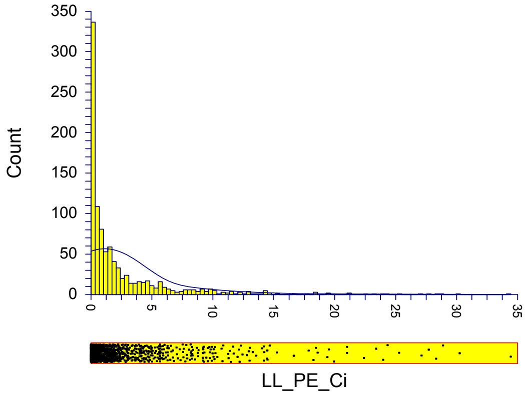


FIGURE A-2 Lawrence Livermore NL Site Data Histogram & Dot Plot

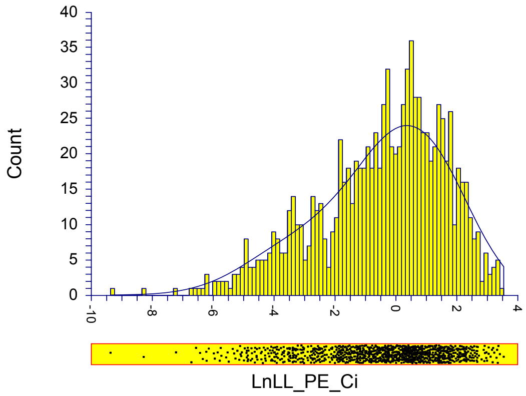


FIGURE A-13 Logarithms of Lawrence Livermore NL Site Data Histogram & Dot Plot

LL_PE_Ci (Lawrence Livermore NL Site PE_Ci)

Descriptive Statistics Report

Count	Mean	Standard Deviation	Standard Error	Minimum	Maximum	Range
992	2.55797	4.288204	0.1361506	8.511728E-05	34.44009	34.44001

Parameter	Mean	Median	Geometric Mean	Skewness	Kurtosis
Value	2.55797	0.874592	0.618509	3.279683	16.68486
99% LCL	2.207269	0.7154716	0.5204744		
95% LCL	2.29112	0.7465357	0.5423988		
95% UCL	2.82482	1.032796	0.7052991		
99% UCL	2.908671	1.111215	0.735009		

Note: The geometric mean confidence interval assumes that the ln(y) are normally distributed.

Percentile	Value	99% LCL	95% LCL	95% UCL	99% UCL	Exact Conf. Levels	
99.5	27.7297	21.0104	23.3972	34.4401	34.4401	96.303	99.125
99	23.4379	18.2565	18.5897	28.3216	28.8871	96.460	99.077
98	17.9156	13.2707	14.0515	21.0104	23.9794	95.903	99.113
95	10.7350	9.2577	9.5960	12.4374	13.0521	95.120	99.144
90	7.3211	5.8209	6.0177	8.3370	8.7886	95.589	99.057

Upper One-Sided 95% Tolerance Bounds of LL_PE_Ci ($UTL_{95/x\%}$)

Percent of Population Less Than Bound	Parametric Upper Tolerance Bound	Nonparametric Upper Tolerance Bound
99.5	14.0864	28.8871
99	12.9807	27.1266
98	11.7738	19.9509
95	9.9663	12.1339
90	8.3647	8.2359

Notes: The parametric (normal-based) limit assumes that the data follow the normal distribution.
The nonparametric (distribution-free) limit makes no special distributional assumption.

A.2.5 Oak Ridge National Lab Site

Database Oak Ridge.S0 Filter None

**FIGURE A-14 Oak Ridge NL Site Data
Histogram & Dot Plot**

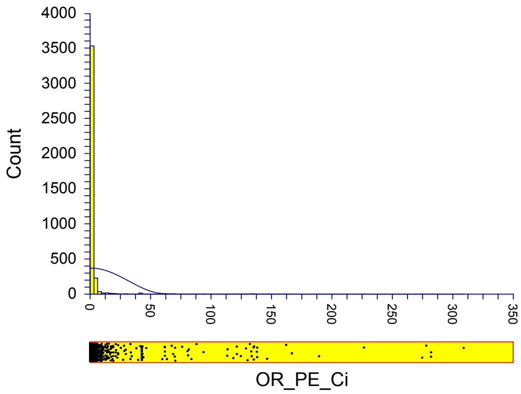
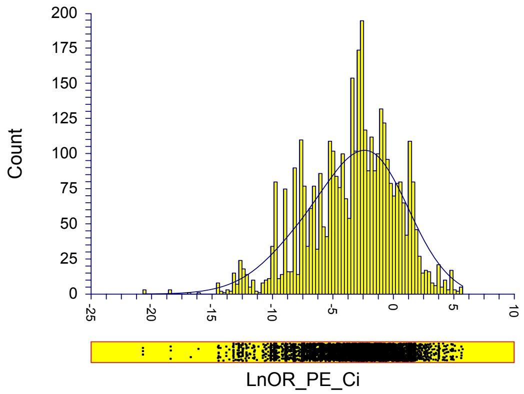


**FIGURE A-15 Logarithms of Oak Ridge NL Site Data
Histogram & Dot Plot**



OR_PE_Ci (Oak Ridge NL Site PE_Ci)

Descriptive Statistics Report

Count	Mean	Standard Deviation	Standard Error	Minimum	Maximum	Range
3943	2.5724	15.8726	0.2528	1E-09	308.9394	308.9394

Parameter	Mean	Median	Geometric Mean	Skewness	Kurtosis
Value	2.5724	0.0588	0.0325	11.76839	170.8977
99% LCL	1.9213	0.0463	0.0279		
95% LCL	2.0770	0.0490	0.0290		
95% UCL	3.0679	0.0620	0.0365		
99% UCL	3.2235	0.0627	0.0379		

Note: The geometric mean confidence interval assumes that the ln(y) are normally distributed.

Percentile	Value	99% LCL	95% LCL	95% UCL	99% UCL	Exact Conf. Levels	
99.5	130.7383	80.9718	87.9859	138.1367	162.0566	95.845	99.101
99	65.6974	42.6968	42.6974	93.7702	121.2946	95.488	99.202
98	23.0764	14.6624	16.4356	42.6868	42.6968	95.386	99.127
95	5.8830	5.2911	5.4314	6.1836	6.6194	95.161	99.056
90	3.3347	2.4620	2.6477	3.7799	3.9147	95.055	99.073

Upper One-Sided 95% Tolerance Bounds of OR_PE_Ci ($\text{UTL}_{95/x\%}$)

Percent of Population Less Than Bound	Parametric Upper Tolerance Bound	Nonparametric Upper Tolerance Bound
99.5	44.3298	135.6342
99	40.3056	83.6848
98	35.9105	38.1837
95	29.3287	6.0226
90	23.4833	3.6992

Notes: The parametric (normal-based) limit assumes that the data follow the normal distribution.
The nonparametric (distribution-free) limit makes no special distributional assumption.

A.2.6 Savannah River Site

Database	SRS.S0	Filter	None

FIGURE A-16 Savannah River Site Data Histogram & Dot Plot

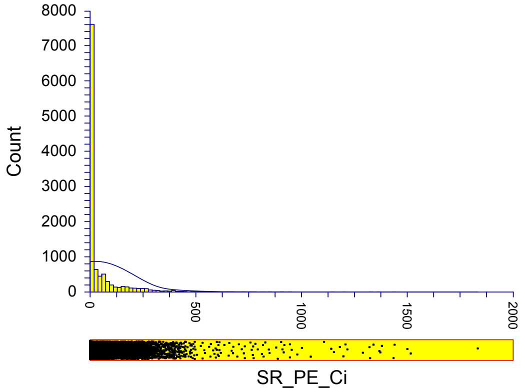
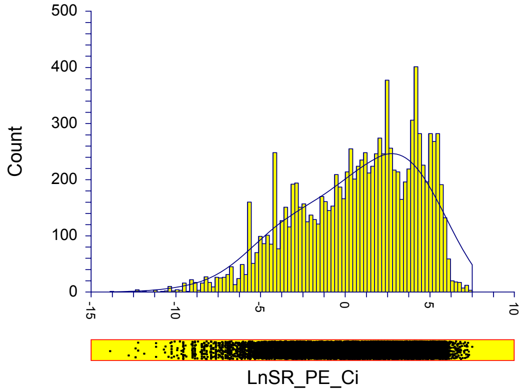


FIGURE A-17 Logarithms of Savannah River Site Data Histogram & Dot Plot



SR_PE_Ci (Savannah River Site PE_Ci)

Descriptive Statistics Report

Count	Mean	Standard Deviation	Standard Error	Minimum	Maximum	Range
11238	46.9229	108.5805	1.02425	0	1832.526	1832.526

Parameter	Mean	Median	Geometric Mean	Skewness	Kurtosis
Value	46.9229	3.4390	2.1402	5.3597	49.8088
99% LCL	44.2846	3.1268	1.9619		
95% LCL	44.9154	3.2249	2.0031		
95% UCL	48.9304	3.8395	2.2867		
99% UCL	49.5612	3.9535	2.3347		

Note: The geometric mean confidence interval assumes that the ln(y) are normally distributed.

Percentile	Value	99% LCL	95% LCL	95% UCL	99% UCL	Exact Conf. Level	
99.5	631.1199	505.0768	542.4899	768.5273	792.4094	95.565	99.109
99	434.2976	404.5919	411.5441	472.6521	480.1347	95.378	99.098
98	358.6606	332.1971	338.2767	376.3134	382.3930	95.328	99.055
95	248.4931	236.6846	239.5997	255.6561	258.7740	95.114	99.062
90	160.5646	151.9921	153.5496	168.6707	170.9745	95.064	99.008

Upper One-Sided 95% Tolerance Bounds of SR_PE_Ci (UTL$_{95/x\%}$)

Percent of Population Less Than Bound	Parametric Upper Tolerance Bound	Nonparametric Upper Tolerance Bound
99.5	330.1276	731.1143
99	302.7795	460.1810
98	272.9059	374.1310
95	228.1184	254.1051
90	188.3575	166.0206

Notes: The parametric (normal-based) limit assumes that the data follow the normal distribution.
The nonparametric (distribution-free) limit makes no special distributional assumption.

A.2.7 All Sites Combined

Database Combined Data.S0Z Filter Val Freq < 460

FIGURE A-18 Filtered Combined Site Data Histogram & Dot Plot

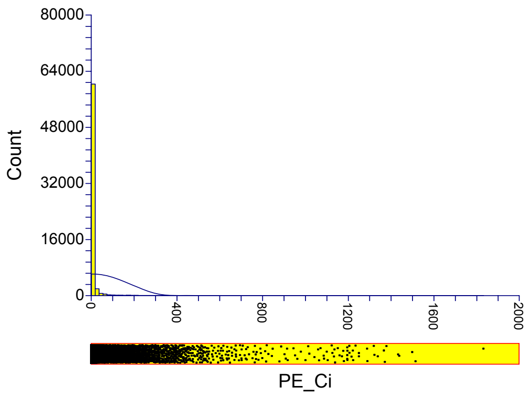
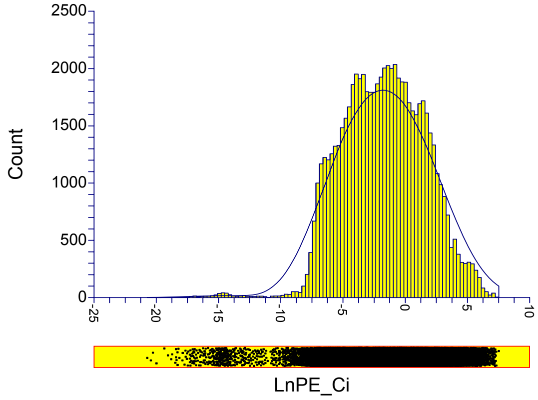


FIGURE A-19 Logarithms of Filtered Combined Site Data Histogram & Dot Plot



PE_Ci (All Sites Combined PE_Ci)

Descriptive Statistics Report

Count	Mean	Standard Deviation	Standard Error	Minimum	Maximum	Range
121024	8.1079	44.4880	0.1279	1E-09	1832.526	1832.526

Parameter	Mean	Median	Geometric Mean	Skewness	Kurtosis
Value	8.1079	0.2090	0.2271	14.5907	315.5744
99% LCL	7.7780	0.2013	0.2220		
95% LCL	7.8569	0.2035	0.2232		
95% UCL	8.3589	0.2157	0.2311		
99% UCL	8.4377	0.2178	0.2324		

Note: The geometric mean confidence interval assumes that the ln(y) are normally distributed.

Percentile	Value	99% LCL	95% LCL	95% UCL	99% UCL	Exact Conf. Levels	
99.5	279.2875	264.2727	267.2305	291.8000	293.8486	95.224	99.046
99	181.6242	173.0356	174.6364	189.0920	192.2097	95.085	99.038
98	85.2916	79.5028	80.3636	89.5732	91.8188	95.043	99.013
95	25.5352	24.4443	24.7091	26.5009	27.0408	95.016	99.018
90	11.4957	11.1786	11.2469	11.7981	11.8564	95.025	99.001

Upper One-Sided 95% Tolerance Bounds of SR_PE_Ci ($UTL_{95/x\%}$)

Percent of Population Less Than Bound	Parametric Upper Tolerance Bound	Nonparametric Upper Tolerance Bound
99.5	123.1398	291.3545
99	112.0087	187.0654
98	99.8471	88.8561
95	81.6077	26.3575
90	65.4062	11.7736

Notes: The parametric (normal-based) limit assumes that the data follow the normal distribution.
The nonparametric (distribution-free) limit makes no special distributional assumption.

Appendix B

Container Deflagrations

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LIST of TABLES

B.1 Introduction

This appendix establishes the technical bases for the Damage Ratios (DRs) for a deflagration within a Transuranic (TRU) waste container as presented in Section 4.4.2, "Container Deflagration Events". The accident phenomenology is described, and along with a review of the literature, establishes conservative estimates of DRs for this event. The container response is different for waste containers other than drums. For metal drums, the explosion ejects the lid and a fraction of the contents. Radioactive material is released to the environment from three accident stresses: (1) during the flexing in air, (2) from assumed unconfined burning of a fraction of the material ejected, and (3) from assumed burning of the remaining materials inside the drum. Appropriate Airborne Release Fractions (ARFs) and Respirable Fractions (RFs) for the different contributions are described in Section 4.4.5, "Airborne Release Fractions/ Respirable Fractions". The Material-at-Risk (MAR) associated with a single, bounding drum or a two drum deflagration must be consistent with the recommendations in Section 4.3, "Bounding the Material-at-Risk". All of these source term parameters are put into perspective with the applicable DR values that are summarized in Section B.3.

TRU wastes are actinide surface-contamination on combustible and non-combustible substrates. The contents of some drums are almost entirely combustible materials composed of cellulose and plastic substrates. The combustible materials are often found as multi-layer wrapped, especially for most waste with highest potential inventory (e.g., from glove boxes where waste, especially cellulose waste, is placed in a plastic bag and the air expelled before sealing for ease of handling and space considerations, and placed in heavy-wall plastic sleeve during extraction from the glove box). Other drums may be almost entirely of non-combustible items. Other forms of TRU waste (e.g., sludge, decontaminated equipment, liquids absorbed on diatomaceous earth, etc.) are also found. There are also two categories of TRU drummed waste – those being processed to meet the Waste Isolation Pilot Plant's (WIPP) Waste Acceptance Criteria (WAC) and "legacy" waste. "Legacy" waste is contained TRU waste that does meet the WIPP WAC, and may contain prohibited items.

The radiolysis of hydrogenous materials by the alpha-activity present in TRU waste generates hydrogen gas that may accumulate in the drums. The radiolysis of TRU waste can produce flammable hydrogen (H_2) concentrations in 55 gallon, unvented storage drums. There are many aspects to the formation, avenues for generation (e.g., metal/solution reaction), and accumulation of the gas that are not well defined. The concern is the combustion of the H_2 in the drums and the potential loss of confinement of the TRU waste and the activity present. However, DOE Complex experience has demonstrated that the oxygen content is usually reduced by reaction with other materials present or combined with hydrogen generated to form moisture. For combustion to occur, three components are necessary for burning – a combustible-flammable vapor, oxidant in a gaseous form, and an ignition source. Other factors will affect the ignition and combustion of H_2-air mixtures such as concentrations of the reactants, the location of the ignition source, presence of water vapor, etc. Typically, for the purposes of an unmitigated hazard or accident analysis, the ignition source is assumed to be present, although the configuration of the waste and drums (presence of a plastic liner that may be of substantial thickness requiring destruction for heat transfer and is a barrier for the transmission of electrical charges) may be resistant to the introduction of an ignition source. The presence of air in the drums is a given due to the packaging of the material in an air atmosphere (typically 20- to 21-vol% O_2). But the generation of H_2 may affect the O_2 concentration by combination of H_2 and O_2 to form water vapor; and, furthermore, O_2 can combine with various components of the waste and packaging materials. The potential presence of prohibited items (e.g., cylinders of flammable/combustibles gases, Volatile Organic Compounds), in "legacy" waste also can generate flammable gas mixtures.

The fuel and oxygen must be mixed and at a sufficient level to support the combustion. The Lower Flammable Limit (LFL) for a gas is the concentration that will support combustion. In the case of hydrogen, the LFL is about 4 volume percent (vol%), and at this concentration the flame "sparkles" through the mixture in an upwards direction. A slightly higher H_2 concentration (~ 5 vol%) is necessary to form a continuous flame front in an upwards direction. Larger concentrations are necessary for a flame front to travel in the horizontal or downwards directions for confined gases. An even greater concentration is required for the flame front to achieve a deflagration velocity, as will be shown in the experimental studies cited later in this appendix.

Contained gases can explode and result in loss of containment and ejection of surface-contaminated combustible and non-combustible contents. An explosion of a flammable gas can be either a detonation or a deflagration. A detonation is combustion fronts traveling at or above sonic[18] speeds relative to the unburned gases, with large overpressures. A deflagration is combustion fronts traveling at subsonic speeds relative to the unburned gases, typically much less than sonic, with overpressures much less than detonations. The energy release and the duration of the energy release is a function of the explosive reaction – deflagration or detonation. When the fuel and oxidant are in a gaseous state, the flammable mixtures deflagrate (fast burning) but, under special conditions such as proper concentration of the component gases, turbulent mixing, a strong ignitions source, an adequate Length/Diameter (L/D) ratio, run-up distance, etc. a deflagration can transition into a detonation (Deflagration to Detonation Transition [DDT]). This phenomenon is also addressed in this appendix, which concludes that a deflagration in a drum will not transition to a detonation.

There are many published experimental studies on the behavior of metal drums in the literature and those that are relevant and available are reviewed in this appendix. This appendix provides the basis for the drum deflagration DRs, and covers the factors that influence the behavior of the contents (i.e., surface-contaminated combustible and non-combustible materials) of the 55-gallon, metal TRU waste drums.

The reader should bear in mind the significance of the following factors when assessing the experimental studies cited in this appendix. Some of the factors that have a substantial affect the combustion of hydrogen-air mixtures are:

- Hydrogen concentration;

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[18] Speed of sound (sonic velocity) is ~346 m/s at 25° C at 14.7 psia.

- Oxygen concentration;
- Strength and location of ignition source;
- Direction of flame propagation;
- Size of enclosed volume;
- Presence of obstacles that allow flow through/around them; and,
- Presence of water vapor.

The remainder of this introduction provides background information on prevalence of hydrogen and oxygen in TRU waste drums.

B.1.1 Hydrogen Measurements in TRU Waste Drums

Various DOE sites have attempted to determine the accumulation of H_2 in TRU waste drums by experimentation and measurements of the H_2 and O_2 concentrations in stored unvented TRU waste. A summary of this data was extracted from a Hanford report, HNF-19492, *Revised Hydrogen Deflagration Analysis* (Fluor-Hanford 2004). That report summarized a 1982 study performed by the Savannah River Site as reported in DP-1604, *Radiogenic Gas Accumulation in TRU Waste Storage Drums*, which measured generation rates as a function of several variables, including the radionuclide strength (note: the moisture content was not measured). Three drums that were filled with a typical waste from a plutonium-238 (^{238}Pu) processing facility were prepared and the hydrogen and oxygen concentrations monitored. The results were:

- Inventory 37-Ci – peak H_2 concentration ~5-vol% at Day-900 (~2.5-yr), O_2 concentration reduced to 2- to 7-vol%.

- Inventory 113-Ci – peak H_2 concentration 50-vol% at Day-1280 (~3.5-yr), O_2 concentration reduced to 1- to 5-vol%.

- Inventory 47.5-Ci – peak H_2 concentration 4-vol% at Day 1420 (~3.9-yr), O_2 concentration
  <4-vol%.

The Hanford report also tabulated results from H_2 concentration measurements reported from various DOE sites. These are summarized in Table B-1.

TABLE B-1. Fraction of Stored TRU Waste Drums Containing Flammable Hydrogen Concentrations

Site	Total Drums	Drums with >15-vol% H_2	Percentage	Drums with >5-vol% O_2	Percentage
Savannah River	10,169	797	7.8%	N	---
INL	210	6	2.8%	1	0.5%
LANL	13,000	175	1.3%	N	---
Rocky Flats	298	5	1.7%	1	0.3%

N means No Data

The DOE Complex-wide limited data appears to indicate that <8% of the drums contain hydrogen concentrations that could deflagrate, but only the drums at the lowest hydrogen level appear to contain an O_2 concentration that could support the combustion of the H_2 present.

The report demonstrates that:

- Although, the H_2 concentration varies with time and activity level, the data is limited and no reasonable trend based on either parameter can be deduced. On the assumption the initial atmosphere in the drums is air (~21 vol% O_2), the O_2 concentration decreased significantly and appears to be less than required to support the complete combustion of the H_2 present except for the lowest concentration, 4 vol% (the LFL for H_2). The fraction of TRU waste drums that can attain the range of H_2 concentrations that can be deflagrate is small, less than 8%. This ignores the need for an O_2 concentration that would support complete combustion (lesser O_2 may support incomplete combustion resulting in reduced pressure generation).

- The O_2 concentrations appear to decrease significantly with increasing H_2 level and are not adequate to support complete combustion of the H_2 present (>½ the vol%). It is postulated that the hydrogen atoms generated by radiolysis are reactive with the O_2 molecules present and result in the formation of water. The greater the O_2 concentration, the greater the probability of the two materials to react. As the H_2 concentrations increase, the probability of the interaction decreases but still continues.

B.1.2 Recent Savannah River TRU Waste Drum Hydrogen Measurements

A more recent tabulation of the H_2 and O_2 concentrations in stored TRU waste drums was reported by the Savannah River Site (SRS) (WSRC 2007). The tabulation did not include the previous measured concentrations for that organization cited in Table B-1. SRS is retrieving TRU waste drums stored in concrete culverts. Culverts may contain up to 14-drums stacked 2-high. Many culverts have drum activities <20 Pu-239 equivalent Curies (PE-Ci) but a large number of drums have much higher activities, > 100 PE-Ci. Some drums have a "0" waste generator reported activity, however, in some cases, SRS has found the reported "0" PE-Ci to be in error once new assays have been performed. After retrieval from the culverts, the initial processing step is venting containers using the Drum Venting System (DVS) that punctures the drum and liner and extracts a sample of the headspace gas in the 90-mil, rigid, HDPE liner and installs a filtered vent. The DVS is an automated system that vents the drum, extracts a sample of the headspace gases, analyzes the headspace gas, purges drum with N_2, and installs a filtered vent in lid. H_2 and O_2 in headspace gas samples are analyzed by gas chromatograph. The uncertainty of the method is: H_2 ±9%, O_2 ±20%.

Over 700 drums have been retrieved from culverts and vented during the period January 2006 to January 2007. The waste in drums was packaged in several layers of plastic inside a 90-mil HDPE liner. Container integrity was observed to be in very good condition with little evidence of corrosion.

Attachment 1 to the report, "*Hydrogen and Oxygen Data for SRS, January 2006 through January 2007*", provides information on the individual drums tested:

- 705 drums were assayed
- H_2 concentrations range - 57.78-vol% (± 5.20-vol%) H_2 with 0-vol% O_2 for an inventory of 88 PE-Ci to 0.0307-vol% H_2 (± 0.00276-vol%; the Lower Detection Limit for analysis not given in paper) with 16.98-vol% (± 3.40-vol%) O_2 for an inventory of 14 PE-Ci
- O_2 concentration range – 0-vol% for 8.3 PE-Ci to 21.8-vol% (±4.35-vol%) for 57 PE-Ci.

The information from the Attachment was segregated into three categories for the purposes of this appendix:

- Drums with a H_2 concentration >13.65-vol% (15.0 ± 1.35-vol%)
- Drums with a H_2 concentration of >7.28-vol% (8.0 ± 0.72-vol%)
- Drums with a H_2 concentration of >3.64-vol% (4.0 ± 0.36-vol%).

Table B-2 summarizes the SRS data showing the number and percentages of drums with H_2 concentrations >4-, >8- and >15-vol%. All drum totals include the uncertainty in estimating the concentrations (i.e., >3.64-vol%, >7.28-vol%, and >13.65-vol%). The number of drums and percentages >8- and >15-vol% H_2 are included in the >4-vol% H_2 total, and likewise, the number of drums and percentages included in the >15-vol% are included in the >8-vol% total. The listing also shows the number of drums and percentages that have O_2 concentrations >5-vol% (4-vol% with the uncertainty considered).

TABLE B-2. Unvented Culvert Drum Initial Headspace Gas Results

Initial H_2 Concentration	Unvented Culvert Drums Exceeding H_2 Concentration		Unvented Culvert Drums >5-vol% O_2[1]	
	Number	% Drums	Number	% Drums
>15-vol%	39	5.5%	6	0.85%
>8-vol%	64	9.1%	12	1.7%
>4-vol%	86	12.2%	22	3.1%

[1] Fraction of drums with stated H_2 concentration.

The hydrogen data shows approximately 12% of the unvented culvert drums contain > 4-vol% hydrogen, and about one-quarter of these drums (3.1% of the total assayed) also have an oxygen concentration exceeding 5-vol%, the concentration that is necessary for flaming combustion. However, Table B-3 shows the percentage of drums that have sufficient O_2 for complete combustion of the H_2, i.e., at least 50% O_2 concentration for the stated H_2 concentration. It should also be noted that although the number of drums used in this analysis represents a significant percentage of the total culvert drum inventory, this drum population is not necessarily a representative sampling of the various waste generators and PE-Ci values. For this reason, as additional culvert drums are vented, the percentages in Tables B-2 and B-3 may change and could either increase or decrease.

TABLE B-3. Fraction of Culvert Drums Capable of Complete Combustion with > 5-vol% O_2 and at least 50% of the Corresponding H_2 Concentration

Initial H_2 Concentration	Unvented Culvert Drums with Sufficient O_2 for Complete Combustion (O_2 concentration is > 5-vol% and ≥ 50% of H_2 concentration)	
	Number	% Drums
>15-vol% H_2	1	0.1%
>8-vol% H_2	7	1.0%
>4-vol% H_2	17	2.4%

There were 39 drums (5.5% of the total assayed) in the first category > 15-vol% H_2, as listed on Table B-4. Of these:

- 1 drum (0.1% of the total 705 assayed, or 2.6% of this subset) has a sufficient concentration of O_2 to allow complete combustion and could result in “lid-loss” and ejection of a fraction of the contents based on the results from the INL experiments that is covered in a subsequent portion of this appendix.

- 3 drums (0.4% of the total assayed, or 7.7% of this subset) have an O_2 concentration that would allow flaming combustion but the combustion could be incomplete and not release the Adiabatic Isochoric (constant volume) Complete Combustion (AICC) heat release value (discussed later in this appendix); therefore, are assumed not to undergo “lid-loss”.

- 2 drums were cited with an inventory of 0 PE-Ci but were assayed to have 19.649 ± 1.768-vol% H_2 and 16.617 ± 1.496-vol% H_2, respectively.

- 24 drums (3.4% of the total assayed, or 62% of this subset) were found to have 0-vol% O_2.

**TABLE B-4. Drum H_2 Concentration >15.0-vol%
(> 14.65-vol% with uncertainty), 39 drums**

Drum #	Years Storage[1]	PE-Ci	Vol% H_2	Vol% O_2
SR515034	25	88	57.775 ± 5.2	0
SR515037	25	97	43.389 ± 3.905	0
SR515009	25	42	43.079 ± 3.877	0
SR515002	25	107	42.906 ± 3.862	0
SR515010	25	32	40.110 ± 3.61	0
SR515032	25	33	40.075 ± 3.607	2.83 ± 0.57
SR515205	25	15	38.145 ±3.433	0
SR506734	27	40	34.92 ± 3.14	0
SR512682	25	13	32.474 ± 2.927	0
SR515004	25	82	32.11 ± 2.89	0
SR505995	27	6	31.871 ± 2.868	0
SR504287	30	3	31.662 ±2.85	0
*SR506731	27	22	31.65 ± 2.89	4.912 ± 0.982
SR513221	26	6	26.513 ± 2.386	0
SR512685	29	31	25.451 ± 2.291	4.156 ± 0.831
SR504051	29	31	25.451 ± 2.291	4.156 ± 0.831
SR513727	26	1	24.556 ± 2.21	0
*SR503919	29	3	24.444 ± 2.20	8.018 ± 1.60
SR512730	26	11	23.294 ± 2.096	0
*SR503701	30	6	21.530 ± 1.938	8.045 ± 1.61
SR503645	29	110	21.471 ± 1.903	0
SR506732	28	54	20.704 ± 1.863	0
SR503681	30	4	20.558 ± 1.850	2.019 ± 0.40
SR520501	27	0	19.649 ± 1.768	0
SR515035	25	82	18.856 ± 1.70	2.20 ± 0.44
SR512653	25	29	18.848 ± 1.696	0
SR504265	29	1	18.60 ± 1.674	1.604 ± 0.321
SR515006	25	25	18.599 ± 1.674	2.104 ± 0.421
SR504595	30	10	18.532 ±1.668	0
SR501725	30	4	17.566 ± 1.581	0
SR515012	25	41	17.298 ± 1.597	2.376 ± 0.48
SR512691	25	1	17.062 ± 1.536	0
**SR512676	25	22	16.633 ± 1.50	7.332 ± 1.47
SR504261	29	0	16.617 ± 1.496	0
SR503926	29	3	16.515 ± 1.486	4.292 ± 0.858
SR514787	25	7	16.111 ± 1.50	0
SR504288	29	2	15.458 ± 1.391	0
SR512710	26	3	14.350 ± 1.292	3.953 ± 0.791
Sr501771	26	2	14.149 ± 1.273	0.746 ± 0.0149

[1] Approximate duration between date of generation and sampling.
* May burn but combustion incomplete.
** Potential to burn to completion.

Table B-5 summarizes the 24 drums (3.4% of the total assayed) in the H_2 concentration range between 7.28-vol% (8- ±0.72-vol%) and 13.65-vol% (15.0- ± 1.35-vol%):

- 6 drums (0.9% of total assayed, or 25% of this subset) have sufficient O_2 for complete combustion, but the energy release (AICC value) does not result in "lid-loss" based on INL experimental data.

- 1 drum has a reported H_2 concentration of 11.065 ± 0.996-vol% but with an inventory of 0 PE-Ci.

- 3 drums (0.4% of the total assayed, or 13% of this subset) were assayed with an O_2 concentration of 0-vol%.

TABLE B-5. Drum H_2 Concentration Between 8- to 15-vol% (7.28- to 13.65-vol% with uncertainty), 24 drums

Drum #	Years Storage[1]	PE-Ci	H_2, vol%	O_2, vol%
SR515011	25	59	13.576 ± 1.222	0.235 ± 0.047
SR506337	29	31	13.514 ± 1.216	3.612 ± 0.722
SR501730	30	1	13.512 ± 1.216	0
Sr517544	25	148	13.130 ± 1.171	3.171 ± 0.634
**SR513222	25	12	13.010 ± 1.171	7.427 ± 1.485
SR513732	26	41	12.934 ± 1.164	3.457 ± 0.691
SR506181	28	2	12.874 ± 1.159	0.310 ± 0.062
SR501728	30	25	12.866 ± 1.158	0
SR514788	25	4	12.098 ± 1.089	2.126 ±0.452
SR514785	25	4	11.825 ± 1.064	2.364 ± 0.473
SR514784	25	8	11.555 ±1.040	0.410 ± 0.082
SR520502	23	1	11.410 ±1.027	0
SR503730	30	0	11.065 ± 0.996	2.527 ± 0.505
SR506341	29	1	10.348 ±0.932	3.221 ± 0.644
SR501505	31	2	10.089 ± 0.908	3.123 ± 0.625
**SR504373	29	21	9.888 ± 0.890	16.185 ± 3.237
**SR506704	29	55	9.558 ± 0.860	10.023 ± 2.005
**SR504184	31	1	9.473 ± 0.826	10.023 ± 2.005
SR513728	26	4	9.442 ± 1.888	3.364 ± 0.673
SR503588	30	1	9.341 ± 0.841	0
**SR503912	31	20	8.919 ± 0.803	9.719 ± 1.944
**SR501799	31	2	8.319 ± 0.749	8.547 ± 1.709
SR506008	29	1	8.140 ± 0.733	2.067 ± 0.413
SR504263	31	2	8.129 ± 0.732	1.6211 ± 0.3242

[1] Approximate duration between date of generation and sampling.

** Potential to burn to completion.

Table B-6 summarizes the 22 drums (3.1% of the total assayed) in the H_2 concentration range between 3.64-vol% (4- ± 0.36-vol%) and 7.28-vol% (8- ± 0.72-vol%):

- 10 drums (1.4% of the total assayed, or 45% of this subset) have sufficient O_2 for complete combustion and would release the AICC value for heat energy that is insufficient for "lid-loss" based on the INL experimental data.
- 6 drums (0.9% of the total assayed, or 27% of this subset) have a reported inventory of 0 PE-Ci.

TABLE B-6. Drum H_2 Concentration Between 4- to 8-vol%-(3.64- to 7.28-vol% with uncertainty), 22 drums

Drum #	Years Storage[1]	PE-Ci	H_2, vol%	O_2, vol%
**SR504041	31	2	7.163 ± 0.645	6.227 ± 1.245
SR501727	30	9	6.978 ± 0.628	0.738 ± 0.148
**SR514786	25	2	6.912 ± 0.622	5.150 ±1.03
SR515036	25	34	6.727 ± 0.605	1.439 ± 0.288
**SR506161	29	2	6.554 ± 0.590	5.215 ± 1.043
**SR501732	30	2	6.055 ±0.545	10.853 ± 2.171
SR510497	27	1	5.983 ± 0.538	0.880 ± 0.176
SR506705	29	43	5.908 ± 0.532	1.622 ± 0.324
SR503676	30	3	5.736 ± 0.516	1.400 ±0.28
SR515044	25	56	5.729 ± 0.516	3.546 ±0.709
**SR504048	29	6	5.671 ± 0.510	16.789 ± 3.358
**SR501116	29	3	5.623 ± 0.506	17.458 ± 3.492
SR504994	30	1	5.582 ± 0.502	1.852 ± 0.370
SR517136	23	0	4.945 ± 0.445	3.603 ± 0.721
SR520550	23	0	4.907 ± 0.442	0
Sr520523	23	0	4.826 ± 0.434	0.202 ± 0.040
**SR515206	25	13	4.520 ± 0.407	10.615 ± 2.123
**SR501769	30	1	4.284 ± 0.386	14.710 ±2.942
**SR503922	29	7	4.008 ± 0.361	11.874 ±2.375
**SR512687	25	0	3.936 ±0.354	15.727 ± 3.145
SR520505	23	0	3.836 ± 0.345	1.260 ± 0.252
SR520521	26	0	3.665 ± 0.330	0

[1] Approximate duration between date of generation and sampling.
** Potential to burn to completion.

In summary, there does not appear to be any obvious correlation between inventory level (PE-Ci) or duration of storage and the H_2 or O_2 concentrations. In addition, the above data shows there is only a small fraction of legacy drums with sufficient H_2 and O_2 concentrations to cause lid loss upon an internal deflagration. The presence of H_2 with 0 PE-Ci inventories raises the question if radiolysis is the only H_2 generation mechanism, e.g., from metal/solution reaction, or whether the legacy assay results reported by the waste generator are suspect as recent assays have demonstrated. Furthermore, the presence of zero (2 of 39 drums, ~5%, of the drums with >15-vol% H_2) to very low O_2 raises the question of the behavior of the O_2 (e.g., preferential release, chemical reaction with other components of the drummed waste, etc.).

B.2 Review and Evaluation of Pertinent Experiments and Literature of Internal Deflagration in TRU Waste Containers

B.2.1 Idaho Drum H_2 Explosion Tests

An experiment was performed by EG&G Idaho in 1983 to investigate the explosion potential of hydrogen-air mixtures deflagration within a 55-gallon steel drum (EG&G 1983). It was initiated to address the hazard of H_2 gas generation in stored TRU waste, which was recognized since retrievable TRU waste storage was started. However, it was generally believed that amount of α-emitters were insufficient to generated enough H_2 to pose a problem. But in 1980, a Rocky Flats first-stage sludge drum was discovered with a bulged lid. In addition to this sludge waste, combustible waste (e.g., plastics) is the other most likely form to generate flammable gas. A program was initiated to estimate the number of drums capable of accumulating flammable concentrations and to postulate a maximum credible hydrogen explosion in TRU waste drum retrieval at the Radioactive Waste Management Complex. It also included tests to determine whether Fiberglass Reinforced Plywood (FRP) boxes and M-III bins were capable of accumulating gas.

The Idaho tests characterized H_2 explosions in DOT 17C (55 gal metal) drums tests by:

1. Overpressure (compressed air injected into drum with lid attached per specifications; also established maximum internal pressure that could be used for explosion tests)

2. Ignition of two H_2-air mixtures (maximum observed in drums and calculated “worst case”). Two ignition sources, near the top of the drum, were used for explosions:

    - Soft spark from sparkplug (20 mJ)
    - Hard spark from electro-chemical squib (5 J)

3. Drum dropped 12 ft onto hard, unyielding surface

4. Diving a puncturing device into drum; and

5. Sympathetic explosions (i.e., explosion induced in the donor drum initiates an explosion in the recipient drum stacked on top of the donor drum).

DOT 17C drums with 90 mil polyethylene liners and simulated wastes were used. The drum was penetrated through drum and liners in three places at:

- Bottom of drum;
- Gas inlet; and,
- Exhaust lines.

Table B-7, presents the purpose of each test and initial conditions. Results are presented in Table B-8.

TABLE B-7. Purpose and Initial Conditions for Each Test

Test	Purpose of Test	Ignition Source[a]	Internal Pressure	Waste Matrix	Void Volume[b]	Gas mixture	Ever Observed? [c]	2000 Prediction [d]
1	Determine hazards from over-pressurization without flammable gas.	None	22 psig	none	7.6 ft^3 @10 psig	Air	NA	NA
2	Determine the effects of the "worst observed" H_2-O_2-N_2 mixture in INEL TRU waste ignited by soft spark" ignition.							
2A	Sludge	Soft spark	10 psig[e]	Simulated sludge	4.8 ft^3	11% H_2, 50% O_2, 31% N_2 [f]	Yes	NA
2B	Combustibles			Simulated combustibles plus metal	7.3 ft^3	6% H_2, 8% O_2, 86% N_2 [f]	Yes	NA
3	Determine the effects of the "worst projected" H_2-O_2-N_2 mixture ignited by "soft spark" ignition.							
3A	Sludge	Soft spark	10 psig[e]	Simulated sludge	4.9 ft^3	14% H_2, 62% O_2, 24% N_2[g]	No	868 (1st stage sludge)
3B	Combustibles			Simulated combustibles plus metal	6.0 ft^3	30% H_2, 15% O_2, 55% N_2 [g]		271 (plastics)
4	Determine the effects of the "worst projected" H_2-O_2-N_2 mixture ignited by "hard spark" ignition.							
4A	Sludge	Hard spark	10 psig[e]	Simulated sludge	4.3 ft^3	14% H_2, 62% O_2, 4% N_2[7]	No	868 (1st stage sludge)
4B	Combustibles			Simulated combustibles plus metal	6.5 ft^3	30% H_2, 15%		271 (plastics)

TABLE B-7. Purpose and Initial Conditions for Each Test--Continued

Test	Purpose of Test	Ignition Source[a]	Internal Pressure	Waste Matrix	Void Volume[b]	Gas mixture	Ever Observed? [c]	2000 Prediction [d]
4C	Combustibles (effects of less dense waste)			Kimwipes	7.7 ft^3 [h]	O_2, 55% N_2 [g]		
4D	Combustibles (effects of exploding a drum on its' side)			Simulated combustibles plus metal	6.5 ft^3			
5	Determine if dropping a drum would ignite gas mixture	Impact	10 psig[e]	Simulated combustibles plus metal	---	30% H_2, 15% O_2, 55% N_2 [g]	No	271 (plastics)
6	Determine if puncturing a drum would ignite gas mixture	Puncture						
7	Determine sympathetic explosion effect (if any)	Hard spark						

[a] A spark plug was used for the soft spark ignition source (~20 mJ); a squib (chemical spark) was used for the hard spark ignition source (~5 J).

[b] Void volume was measured by comparing the pressure change of the drum (plus 90 mm polyethylene liner) with the pressure change of the mixing chamber (a known volume).

[c] Has this gas concentration been actually observed in waste drums?

[d] If not observed, the number of drums that could have this concentration in the year 2000.

[e] This is the maximum level to which drums could consistently be pressurized during the tests without significant leakage.

[f] This gas mixture was the "worst" gas mixture observed in the sampled drums containing this type of contents.

[g] These gas mixtures were the worst gas mixtures calculated to be reasonably expected in drums containing the listed contents without excessively over-pressurizing the drums.

[h] The value of 7.7 ft^3 for the void volume is not a typographical error, and is 0.1 ft^3 higher than the volume measured for an empty drum plus liner (attributed to experimental error).

TABLE B-8. Idaho Drum Deflagration Tests Results

Test #	Container Type	Container Contents	Void Volume[a]	Gas Mixture	Pressure	Initiation Method	Results[b]
1	17C 55 gal drum with 90 mil liner (upright)	Empty	7.6 ft^3 @ 10 psig	Air	22 psig (max)	None	Pressure relieved by leakage around gasket. Drum lid did not blow off.
2A	17C 55 gal drum with 90 mil liner (upright)	Simulated sludge[c]	4.8 ft^3	11% H_2, 58% O_2, 31% N_2[d]	10 psig[e]	Soft spark[f]	Drum lid remained on the drum and there was no release of the contents. [Don't know if the gas mixture ignited]
2B		Combustible plus metal[g]	7.3 ft^3	6% H_2, 8% O_2, 85% N_2[d]			
3A	17C 55 gal drum with 90 mil liner (upright)	Simulated sludge[c]	4.9 ft^3	14% H_2, 62% O_2, 24% N_2[h]	10 psig[e]	Soft spark[f]	Drum lid remained on the drum and there was no release of the contents. [Don't know if the gas mixture ignited]
3B	17C 55 gal drum with 90 mil liner (upright)	Combustible plus metal[g]	6.0 ft^3	30% H_2, 15% O_2, 55% N_2[h]	10 psig[e]	Soft spark[f]	Drum lid was blown ~130 ft into the air, some of the contents were blown by the wind more than 950 ft away, and a smoldering fire developed in the contents that burned 30 min. before being extinguished by water. Ejection fraction was 27%.
4A	17C 55 gal drum with 90 mil liner (upright)	Simulated sludge[c]	4.3 ft^3	14% H_2, 62% O_2, 24% N_2[h]	10 psig[e]	Hard spark[f]	Drum lid remained on the drum and there was no release of the contents. Smoke was observed from the smoldering liner when the lid was removed.
4B	17C 55 gal drum with 90 mil liner (upright)	Combustible plus metal[g]	6.5 ft^3	30% H_2, 15% O_2, 55% N_2 [h][i]	10 psig[e]	Hard spark[f]	Drum lid was blown about 175 ft into the air, some of the contents were blown away by the wind ~35 ft away, and a flaming fire developed in the contents following a second explosion that occurred after the lid has blown off [could have been due to burning of residual H_2 when contacted oxygen in air]. Ejection fraction 14%

TABLE B-8. Idaho Drum Deflagration Tests Results -- Continued

Test #	Container Type	Container Contents	Void Volume[a]	Gas Mixture	Pressure	Initiation Method	Results[b]
4C	17C 55 gal drum with 90 mil liner (upright)	Kimwipes	7.7 ft^3	30% H_2, 15% O_2, 55% N_2[h]	10 psig[e]	Hard spark[f]	Drum lid was blown ~50 ft into the air, some of the contents were blown by the wind ~260 ft away. No fire developed. Ejection fraction 7%.
4D	17C 55 gal drum with 90 mil liner (on its side)	Combustible plus metal[g]	6.5 ft^3	30% H_2, 15% O_2, 55% N_2[h]	10 psig[e]	Hard spark[f]	Drum lid was blown horizontally traveling ~ 200 ft away, some of the contents traveled ~35 ft away, and a flaming fire developed in the contents which burned for ~15 min. before self-extinguishing. Ejection fraction was 41%. The bottom weld failed in several places but the drum bottom was not blown off.
5	17C 55 gal drum with 90 mil liner (upright)	Combustible plus metal[g]	---	30% H_2, 15% O_2, 55% N_2[h]	10 psig[e]	Drop 12 ft	Drum made 180° turn, landing on its' lid when dropped. No ignition took place, and there was no release of contents. The drums held pressure following impact.
6	17C 55 gal drum with 90 mil liner (upright)	Combustible plus metal[g]	---	30% H_2, 15% O_2, 55% N_2[h]	10 psig[e]	Puncture	Drum was punctured by a sharpened drill bit near the middle of the drum. Gas escaped through the hole, and no ignition took place.
7	17C 55 gal drum with 90 mil liner (upright) with 3 adjacent drums. Top drum also contained a flammable gas mixture	Combustible plus metal[g]	---	30% H_2, 15% O_2, 55% N_2[h]	10 psig[e]	Hard spark in bottom drum	Bottom drum gases were ignited. Lid of bottom drum was not blown off. Gases in the top drum ignited, the top drum lid was blown 182 ft into the air; some of the contents traveled 63 ft away in a slight wind, and a small fire resulted in the top drum. Ejection fraction was 16%.

Footnotes Table B-8

[a] Void volume was measured by comparing the pressure change of the drum with the pressure of the mixing chamber (a known volume)
[b] Explosion overpressures were not measured.
[c] Sludge was simulated by diatomaceous earth moistened with ~5 gal water.
[d] The gas mixtures were the worst observed in sampled drums containing those types of contents.
[e] This is the maximum reasonable pressure that drums could be expected to maintain without significant leakage.
[f] A spark plug was used for the soft spark ignition source (~20 mJ); a squib (chemical spark) was used for the hard spark ignition source (~5 J).
[g] The combustible material (e.g. cellulose of various forms, type of plastic such as Poly-vinyl Chloride [PVC], Poly Ethylene [PE], polypropylene, etc.) and the size/weight of the individual pieces were not specified.
[h] These gas mixtures were the worst gas mixtures calculated to be reasonably expected in drums containing those contents (without over-pressurizing the drum).
[i] Handwritten notation, 3.5 mol H_2?

Observations and conclusions from the Table B-8 results are:

- Drum lid not blown off by 22 psig of internal pressure from compressed air, but this is not representative of pressure increase due to an internal deflagration
.
- All the gas mixtures were ignited by a hard spark (5 J is 250 times more energetic than the soft spark, 20 mJ).
- The drums tested contained the pressure generated by the burning of H_2-air mixtures up to 14 vol% H_2 with both hard and soft spark ignition. Uncertain if gas mixture was ignited by soft spark, or burned to completion. If those tests that stated "drum lid not blown off" are assumed to have ignited but generated insufficient internal pressure to blow lid off, then need >14% H_2 to generate sufficient internal pressure to dislodge lid.
- All 5 drums with 30% H_2 + 15% O_2 (a stoichiometric[19] mixture) deflagrated and generated sufficient internal pressure to blow-off lid.
- Of the drums that blew off their lids and contained "combustibles and metal", the ejection fraction (i.e., the materials ejected from the drum, which were called the "release fraction" in the report) were 27%, 14%, 7%, 41%, & 16%. This results in a bounding value of 41% (due to the only drum that was located horizontally) and average value of 21%. If the one horizontal drum is excluded, the bounding value for upright drums is 27% and the average is 16%.
- Fires were observed in the combustibles, but ejected contents did not sustain a fire. Only one drum had to be extinguished.
    - For the single upright drum containing "kimwipes" (tissue), the ejection fraction was 7% for a stoichiometric concentration, and no subsequent burning occurred outside the drum.
    - At H_2 concentration >14 vol% in air with a hard spark ignition, a reaction was noted by the smoldering polyethylene liner.

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[19] Composition of different gases in accordance with the Law of Definite Proportions.

- Test 7 demonstrated that more than one drum can explode in a given scenario. Based on the one test involving two stacked drums with H_2-O_2 stoichiometric concentrations, only the top (recipient) drum is expected to eject the its lid and partial contents in the scenario. The lid from the bottom (donor) drum was not displaced due to the weight of the drum on top, but venting occurred. The top drum lid was blown 182 ft and ~16% of its contents was ejected and blown 63 ft. Fire was observed in the drum residue material. Indicates that sympathetic deflagration can occur for stacked drums.

- No significant shrapnel danger was apparent other than from drum lids. Test 5 demonstrates that impact from a 12 ft fall that rotated 180 degrees did not cause a shock induced ignition or sparking of metal wastes to ignite the stoichiometric H_2 concentration. Therefore, impact from a displaced lid is not likely to cause a sympathetic deflagration, but this conjecture is based on a single test.

- Drum with a stoichiometric H_2 concentration in air punctured by a sharpened drill did not ignite (Test 6). This may be partially due to the presence of a 90 mil polyethylene liner.

- The two adjacent drums to the bottom (donor) drum did not contain a flammable concentration, so no conclusions can be drawn regarding sympathetic deflagrations to horizontally adjacent drums with flammable concentrations due to lid/locking ring/bolt impact, shock induced ignition, or vented hot gases heating an adjacent drums to its auto-ignition temperature.

Impact on Single Drum Deflagration Recommendation

Based on the Idaho measured values of amount of material ejected, a bounding value of 40% is assumed for a single-container deflagration. This value must be used in conjunction with other bounding assumptions presented in Appendix Section B.3, "Container Deflagration Recommendations". The hydrogen concentration must exceed 14 vol% to cause lid loss and ejection of contents. The ejection fraction is based on the most conservative orientation of a drum lying on its side (e.g., during retrieval from a burial site), based on the Idaho maximum ejection fraction. This value is conservatively assumed to bound deflagrations from a single upright drum.

The ejected fraction of materials experience two release stresses during the flight through the air and impact with the ground, and from subsequent burning of unconfined wastes. The wastes remaining in the drum are assumed to burn as confined wastes. Section 4.5 provides guidance on the applicable release parameters. Unconfined and confined burning release parameters are further discussed in Appendix Section B.2.3, "Burning of Ejected Wastes ". For the flight through air and impact, the values for suspension from shock-vibration of 1E-3 ARF and 0.1 RF are conservative and applicable.

Impact on Sympathetic Drum Deflagrations

The Idaho drum deflagration tests indicated that sympathetic deflagration of a drum on top of the initial deflagration occurred; however, the lower drum did not lose its lid due to the weight of the drum on top. No experimentation has been conducted, nor observed, on sympathetic deflagration of horizontally adjacent drums. Therefore, it is conservatively assumed that sympathetic deflagration is possible involving two unvented drums for TRU waste being retrieved from burial sites. Although additional sympathetic drum deflagrations may be possible depending on the retrieval staging configuration and other factors, modeling more than two drum deflagrations is not deemed necessary since adequate insights from the two-drum deflagration should be sufficient to establish appropriate Technical Safety Requirements (TSR) controls to protect the facility worker, other onsite (collocated) workers, the public, and the environment, and based on the likelihood of three or more sympathetic deflagrations being very low.

Based on the Idaho measured values of amount of material ejected, a bounding value of 25% per drum could be assumed. This value is rounded from the 27% maximum for upright drums and 21% average of upright and horizontal drums, since the two drums would need to be staged adjacent to each other, or in nearby proximity (i.e., the 40% ejection fraction was based on a drum lying on its side). However, as further discussed in Appendix Section B.2.3, "Burning of Ejected Wastes", the combined effect with the fraction burned outside the drum does not significantly change the overall release estimate. Therefore, for a two-drum deflagration, the same assumptions as for a single, bounding drum above should be applied, i.e., 40% ejection.

Sympathetic deflagrations need not be evaluated for the unmitigated analysis for TRU waste drum handling and staging/storage of newly generated drums associated with typical DOE Complex processes that generate contaminated, combustible wastes. This is based on the low likelihood associated with multiple drums, located adjacent or in nearby proximity to each other, having sufficient hydrogen-air concentration necessary for lid loss (i.e., exceeding approximately 15% hydrogen concentration with at least 7.5% oxygen, a small fraction of legacy drums based on characterization experience, and even lower chance that newly-generated drums would achieve such levels).

B.2.2 SRS Drum H_2 Explosion Tests

Tests were conducted by the E.I. DuPont Explosion Hazards Laboratory for the Savannah River Site (SRS) to determine a minimum concentration of H_2 for "lid loss" of a 55 gal drum (WSRC 1990). Secondary objectives were to obtain the maximum pressure and rate of pressure rise vs. hydrogen concentration. Preliminary tests were performed for the secondary objectives with a small-scale pressure vessel to establish the concentration range over which a drum lid loss might occur, and as a baseline for comparison with the drum measurements. Mixing tests were also performed to determine the equilibration time for two H_2-air mixtures in a drum. Observations and results are summarized as follows.

Pressure Vessel Tests and Results

- 1.7 liter vessel filled to slightly above ambient pressure (by pulling an initial vacuum) with 5 to 50 vol% H_2 concentration[20] and ignited

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[20] oxidant gas not specified, air?

- Maximum pressure and pressure rise rate were determined to be highly dependent on H_2 concentration, as shown in Table B-9 (see Figures 7 and 8 in WSRC 1990)

- Third-order polynomial was determined to be good fit to data

- Maximum pressure and pressure-rate rise occurred at slightly greater than stoichiometric H_2-air mixture. The maximum pressure measured was 268 psig for a 45 vol% H_2 concentration at an initial pressure of 12.03 psig (near 2 atmospheres). The greatest pressure measured for a 30 vol% H_2 concentration (slightly less than stoichiometric for the experimental conditions) was 240.1 psig.

- Results are consistent with basic combustion theory, i.e., as the stoichiometric H_2 concentration is exceeded, oxygen becomes the limiting reagent and H_2 would be in excess. Under non-ideal conditions, with a limited supply of oxygen, excess H_2 would be required for complete combustion to achieve the AICC pressure generated from this reaction (see later discussion).

TABLE B-9. Pressure Vessel Test Data

H_2 Concentration, vol%	Initial Pressure, psig	Maximum Pressure, psig	Δp/Δt, psi/s
5	0.77	1.8	0.1
		20.5	229.2
		1.5	0.1
10	1.63	45.3	368.8
		45.3	329.8
15	2.59	78.9	4012
		76.8	3755
20	3.68	121.5	13039
		119.8	13645
25	4.9	186.4	30592
		189.1	34051
30	6.3	240	44132
		236	46444
		240.1	42188
35	7.92	253.5	51153
		250.8	51102
40	9.8	260.5	51780
		251.5	47344
45	12.03	268	49774
		258.3	47344
47	13.04	263.6	46444
50	14.7	252	39995
		185	22784

Drum Mixing Tests and Results

- Standard 55 gal drum with rigid PE liner was modified to plug the drum vent and to install one inlet and three sampling ports
- Five and twenty five vol% H_2 added (by pulling an initial vacuum) in middle of drum
- Equilibrated by natural convection
- Caused some initial stratification along the drum length, but the air and hydrogen become well mixed within 60 minutes, and 50 minutes was determined to be adequate for the drum explosion tests.

Drum Explosion Test and Results

- Standard 55 gal drum[21] was modified to plug the drum vent and to install one inlet through the side of the drum in the middle. Sealed and closed according to established procedure.

- H_2 equilibrated by natural diffusion for at least 50 minutes;

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[21] Not stated if drum filled with waste or its' composition, if filled. Presumed that drums were empty.

- Concentration verified prior to ignition by hot wire;

- Eighteen tests were performed over a H_2 concentration range of 13 to 36 vol% (by pulling an initial vacuum). During the first eight tests, successful ignition was achieved only twice, resulting in one lid loss. The experiment was modified for the next 10 tests to install a shorter hot wire so the H_2 would reach the auto-ignition temperature. For the modified tests # 9 – 18, nine of the 10 resulted in successful ignition. Results are shown on Table B-10.

  - Lid-loss occurred for 4 tests >17 vol% H_2
  - Lid loss did not occur for 5 tests < 17 vol% H_2 – drum bulged at top and bottom. Concluded that data suggests an explosive mixture up to 15 vol% of H2 can be contained in a 55 gal TRU drum without lid loss.
  - Empirical relationship for maximum pressure and pressure rise within drums could not be established due to limited number of data and the variability in drum lid sealing and retaining ring closure.

TABLE B-10. Drum Explosion Data

Test #	H_2 Concentration, vol%	Maximum Pressure, psig	Observations
14	13.3	70	Bulged
18	13.9	69	Bulged
12	14.1	138	Bulged
11	14.9	69	Bulged
13	16.5	121	Bulged
10	16.95 (~ 17.0)	137	Lid blown
17	18.0	211	Lid blown
16	22.7	320	Lid blown
9	35.3	105	Lid blown

Impact on Single Drum Deflagration Recommendation

The SRS experiments results show that "lid loss" occurred when exceeding ~ 17 vol%, and less than that caused the drum to bulge at the top and bottom, but with no loss of containment. This supports the 1983 Idaho conclusion that more than 14 vol% was needed for lid loss. The maximum pressures measured in the SRS experiment are also noteworthy regarding rapid depressurization that can cause ejection of some contents.

B.2.3 Burning of Ejected Wastes

The Idaho experiment demonstrated that combustible wastes could be ignited within the drum, but that ejected wastes did not sustain a fire, if it was ignited by the deflagration. Due to the limited testing performed to date, burning of ejected wastes cannot be definitively ruled out, so conservative assumptions are made to account for this possibility. A technical argument for establishing an estimate on the amount of material burned outside is presented in HNF-19492, *Revised Hydrogen Deflagration Analysis*, developed for the Hanford site (Fluor Hanford 2004). That basis is provided here and calculations are revised based on a higher stoichiometric concentration than the Hanford "worst-case" concentration.

The stated intent of the Hanford document is to remove "excess conservatism" in the analysis for an accident involving a single drum during handling and transport within a facility. It reviewed published literature on the growth of hydrogen concentrations during long-term storage and the measured hydrogen concentration in stored drummed TRU waste at various DOE sites. It noted the reduction of O_2 levels with H_2 growth, and that drums with H_2 concentrations that are adequate for deflagration have O_2 concentrations that are not adequate to support complete combustion. The selected "worst-case" based on the conditions at Hanford were established as a 20 vol% H_2 based on measured values from stored drummed TRU waste at Hanford and an assumed O_2 concentration of > 10 vol%(i.e., the O_2 required for complete combustion of the H_2).

The fraction of the ejected waste that is ignited is based on the assumption that the total heat generated during the combustion of a 20 vol% H_2-air mixtures goes into the ejected waste. It is that portion that is heated to the ignition temperature upon which the fraction of ejected waste ignited is based. The heat transferred to the material remaining in the drum, and to the drum itself, is ignored, which is contrary to the actual experience of the Idaho tests that resulted in burning inside the drum but not outside. Therefore, the assumption that all the heat goes to igniting ejected wastes, and that no burning would result inside the drum, is very conservative, and double-counts the heat generated during the deflagration.

The calculation of the possible ignition is based upon the ignition temperature of paper that has the smallest ignition energy of the combustible materials considered. The possible extinguishment during flight from the air velocity over the ejected materials and by contact with the cooler ground is also ignored.

Relevant excerpts from HNF-19492 are as follows:

> ***3.3 Conclusion that Ejected Waste Burns***
>
> *Calculations performed in Section 2.3 with the worst-case drum show that it is unlikely that the ejected waste will be heated to ignition temperatures. Previous discussions in this document show that ejected waste is unlikely to continue burning, especially in light of the weaker ignition source from the worst-case drum conditions, as was the case in the INEEL tests.*
>
> *However, as Section 3.2 shows, numerous unknowns and uncertainties cannot be resolved. As a result, it is assumed that waste ejected from the worst-case drum (Appendix A, Case 4 as discussed in Section 2.2) could ignite and burn. This assumption is made because these conditions are such that, as shown in Section 2.3, ignition and burning are marginally possible. Given that these conditions also represent the worst-case drum, the assumption is conservative. The assumption is considered to be reasonable given the few "knowns" and all of the "unknowns" and "uncertainties."*
>
> ***3.4 Calculation of the Damage Ratio***
>
> *Because the deflagration and ejection create turbulence, which can extinguish a flame that has been ignited or cool the surface such that ignition will not occur (or continue), and because the ejected waste likely is dispersed over an area larger than the drum, it is reasonable to assume that not all of the waste will burn. To be conservative, a value of 0.18 is calculated for the damage ratio (DR). The basis is as follows. The DR will be based on the quantity of waste that*

can be heated to ignition by the radiant energy from the deflagration divided by the quantity of waste ejected. Appendix A, Case 4 is used for the worst-case drum:

$$q = 4.3 \times 10^4 \text{ cal}$$

The specific heat is the value for paper. This value is less than almost all of the values for plastics. The value is the same as that used in the SFPE Handbook of Fire Protection Engineering discussion in Section 2.3. The ignition temperature is taken to be 280 °C, the average ignition temperature from Section 2.3. The mass heated to ignition is found from:

$$\begin{aligned} m &= q/(C_p \Delta T) \\ &= (4.3 \times 10^4 \text{ cal})(4.187 \text{ J/cal})/[(1340 \text{ J/kg-K})(553 \text{ K} - 298 \text{ K})] \\ &= 0.53 \text{ kg.} \end{aligned}$$

The net energy release of 4.3×10^4 cal was based on adding 1.06 moles of H_2 in the 20 vol% H_2-air concentration. For a stoichiometric concentration of 30 vol% H_2 in air, Case 3 in the HNF-19492 calculates the net energy released as 9.5×10^4 cal from 2.14 moles of H_2 and a 50% void fraction that was assumed above. This results in an increase factor of $(9.5 \times 10^4) / (4.3 \times 10^4) = 2.2$ for the amount of combustibles that can burn outside the drum. The calculated value shows that there is sufficient heat generation from the deflagration to ignite 0.53 kg of paper for 20 vol% H_2 in air, so 1.2 kg of combustibles could burn outside from the 30 vol% H_2 deflagration.

To determine the burn fraction for the 30 vol% H_2-air stoichiometric concentration, the mass of ejected wastes that burns is divided by the mass of wastes ejected. According to the HNF-19492, the contents of the average drum weigh 57.2 kg[22]. For the 40% ejection fraction recommended in Appendix Section B.2.1 as a bounding value for a single drum deflagration, the ejected portion weighs

$$0.4 \times 57.2 \text{ kg} = 22.9 \text{ kg}$$

The burn fraction for a single drum deflagration is then:

$$1.2 \text{ kg} / 22.9 \text{ kg} = 0.05$$

For the 25% ejection fraction discussed in Appendix Section B.2.1 for a sympathetic deflagration of two horizontally adjacent, upright drums, the mass ejected from each drum is 14.3 kg (0.25 x 57.2 kg). The amount of mass that can burn from each drum is 1.2 kg, due to the conservative assumption that it is also at the stoichiometric H_2-air concentration. The burn fraction for each drum in a sympathetic deflagration is then:

$$1.2 \text{ kg} / 14.3 \text{ kg} = 0.08$$

The combined effect of the 25% ejection with 0.08 burn fraction is the same as the 40% ejection with 0.05 burn fraction, i.e., a product of 0.02 due to rounding of the individual values. Considering the other two release phenomena of flexing in air and burning in the drum and their different ARFs and RFs, the impact on the overall effective release fraction is not that great. This is also true whether the donor drum is assumed to be 40% ejection with 0.05 burn fraction and the recipient drum is assumed to be 25% ejection with 0.08 burn fraction. Therefore, the

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[22] This value is approximately half of the average weight of a drum received at the WIPP site as of 2006. Using the higher average drum weight would result in a smaller DR for burning of ejected wastes and less conservatism.

recommendation is to apply the 40% ejection with 0.05 burn fraction to both drums. The impact of this recommendation is presented in Appendix Section B.3, "Burning of Ejected Wastes".

Section 4.5 provides guidance on the applicable release parameters. For the combustibles ejected that burn unconfined, an ARF and RF of 1E-2 and 1.0, respectively, is applicable. This is higher than confined burning (5E-4 ARF and 1.0 RF) that is assumed to still occur inside the drum. As stated earlier, this is double-counting the energy of the deflagration to cause ignition of both ejected wastes and wastes remaining inside the drum.

B.2.4 Volatile Organic Compounds

A study of the potential to breach a drum due to a VOC explosion was performed for the Solid Waste Management Facility TRU Waste Drums at the Savannah River Site and the calculation was documented in Reference 9 of the position paper (WSMS 2006) that is discussed further in Appendix Section B.2.5.5, "Drum DDT Position Paper". The results of the study showed that ignition of VOCs mixed with air are not sufficient to eject the lid of a drum. The calculation then evaluated a mixture of VOCs, hydrogen, and air to determine what level of this mixture would be a concern for lid ejection. This evaluation concluded that a VOC ignition with a hydrogen concentration at 4% by volume would not eject the lid of a drum. Higher concentrations of hydrogen with the VOCs were required for lid loss.

The Lawrence Livermore National Laboratory (LLNL) conducted fire tests on metal drums to “provide information on the fire performance of 55 gallon metal waste drums used for dry waste storage” (LLNL 1993). Drums with combustible wastes were seeded with 100 cm^3 of isopropyl alcohol in fires. This behavior reflects deflagration of VOC and the conclusion that it is bounded by a deflagration of stoichiometric H_2-air mixtures in drums.

LLNL conducted six tests using three different types of drums. The first tests involved an empty drum heated in a furnace according to ASTM E119 time-temp curve. The remaining five tests used various drum configurations filled with 10 kg [22 lb] class “A” combustibles exposed to a 60 ft diameter pool fire. Table B-11 shows the types and weights of combustibles loaded into drums. All drums except overpacks were loaded with the material described. Some tests included overpacked drums (drum nested within drum). Internal pressure and temperature were monitored, as well as the mass loss determined.

TABLE B-11. Description of Combustibles Loaded into Drums

Number of Items	Description	Wt, Item, g	Total Wt., g
25	Small polyethylene bags	~140	~3,500
25	Tyvek® coveralls, white, with zipper	~120	~3,000
25	3M Dust & Mist Respirator	~7.6	~190
50	Dura-fit shoe covers	~8.5	~425
50	9 oz. Cotton gloves	~21.8	~1,090
25	Cap, Disposable, non-woven material	~3.6	~90
Boxes*	Soft-tech wipes		

* The number of wipes was varied to obtain the desired weight of 10 kg.

For the ASTM E-119 fire exposure test of the empty drums, the failure criterion of an internal temperature >325° F (163° C) was reached in 140 seconds (s). The internal temperature closely tracked the furnace temperature. Commonly used auto-ignition temperature for the type of waste material in drums is 500° C in ~ 400 s (~ 6.7 min). The pressure peaked at 16 psig with seal failing ~ 330 s (~ 5.5 min).

Isopropyl alcohol was used as the fuel for the pool fire. Drums were placed in a 6 ft diameter (28.25 ft^2 total surface area) metal pan, but the drum occupied a significant area of the pan (around half). WDPAN1-3 tests used 10 gallons of isopropyl alcohol, depth ~0.75 in. WDPAN4 and 5 tests used 12 gallons to account for additional space and to maintain the same depth. The pool fire burned for about 5 minutes. The heat release rate was estimated to be 0.5- to 1.0 MW.

Notes and observations from the report include:

- WDPAN1. Calibration burn using 4 DOT-17C epoxy coated drums. Ignition temperature for contents in 3 of 4 drums in ~400 seconds (s), 4th drum followed fire temperature. All drums vented in 300 s indicated by sudden decrease in pressure. Fire duration ~10 min. No violent failure of drums. Lid buckled or sidewall bulged. Contents burned or charred.

- WDPAN2 and 3. 2 identical tests. 5 drums each test. 3 DOT 17C drums, 1 overpack (with inner drum), and 1 drum TRU with liner (PVC bag).

- WDPAN2 Events. Drum 1-4 vented [“seal-failure”] in 194 s. Drum 1 blew its’ lid emitting fire-ball and loud noise [not then typical drum behavior, “lid-loss” after “seal-failure”], and possibly due to isopropyl alcohol vapors deflagration at auto-ignition temperature and material ejected. Contents burned except for drum #1, fire out ~960 s [~16 min] but ejected material continued to burn. Drum #1 extinguished.

- WDPAN2 Results. Drum #1 vented at ~ 205 s with total loss of pressure @ 275 s. Max internal temperature 480° C. Drum #2 vented @ ~ 180 s with temperature of 400° C. Drum #3 started to vent @ 180 s with total pressure loss @ 280 s, temperature 280° C. Drum #4 (filtered vent) pressure oscillated between 0 to 1 psig; pressure constantly relieved, maximum temperature of 700° C. Drum #5 (inner drum) vented @ 550 s pressure just under 11 psig internal temperature ~ 350° C. Maximum temperature Drums #1, #4, and #5 ~ 700° C; drums #3 and #5 ~440° C and 480° C, respectively. Drum #1 "lid-loss" (was flipped upside down on drum, indicating that it did not have sufficient energy to travel far), drum #2 lid buckled.

- WDPAN3 Events. Drum #2 vented ("seal-failure") 170 s. Drum #1 lid buckled @ 170 s drum "seal-failure" @283 s. Drum #1 "lid-loss". Fuel fire out ~ 960 s – debris from drum #1 continued to burn (later extinguished)). Drum # 2 stopped venting @ 1333 s. Drum #? (1 in bung hole) stopped venting @ 1753 s. TRU drum stopped venting @ 21030 s.

- WDPAN3 Results. Drum #1 initial vented @ 130 s, pressure increased to 12.5 psig and again vented @ 185 s, total loss of pressure@ 250 s, maximum temperature of 450° C ("lid-loss"). Drum #2 vented @ 75 s temperature of 300° C. Overpacked drum vented @ 150 s temperature 150° C. TRU drum slow pressure increase to ~ 2.75 psig, dropped to < 2 psig @ 260 s. Inner drum of overpack vented @ 390 s temperature 220° C. Max internal temperature of drum 400° to 600° C. Drum #4 (TRU drum) liner and contents in drum.

- WDPAN4&5. 2 identical tests. 3 drums in triangular configuration – 2 55 gal & 1 overpack (#3 overpack and #4 inner). No TRU drum. Each drum had a 10 mil PE liner (bag).

- WDPAN4 Events. Drum 1 lid buckled @ 226 s, do not know if drum vented at this time but flames visible @ 953 s ("seal-failure), flame out @ 1553 s. Fuel fire ceased @ 1013 s. Drums 1 & 2 lids buckled but no "lid-loss".

- WDPAN4 Results. Drum #1 initially vented @ 220 s (pressure 13.3 psig, temperature of 100° C; continuously venting for 240 s. Drum #2 initially vented @ 150 s (pressure 14.2 psig, temperature 300° C) venting continuously for 225 s. Overpack vented @ 150 s (temperature ~ 190° C, pressure 7 psig); inner drum vented @ 560 s (pressure 15.5 psig, temperature 500° C).

- WDPAN5 events. Drum #2 "lid-loss" @ 203 s ejecting some of its contents, masked by drum #1 and could not see if it vented prior to event, fire continued after fuel fire out and extinguished. Drum #1 vented @ 232 s "seal-failure', buckling noted @ 245 s. Fuel fire diminished @ 785 s but flames from vents continued.

- WDPAN5 Results. Drum #1: vented @ 240 s. Drum #2 – vented @ 200 s, temperature probe lost and stopped recording at ~ 400° C, Overpack #3, vented @ 130 s, temperature 550° C; inner drum, #4, vented @ 475 s, temperature 400° C.

Mass loss (see Table B-12) indicates significant amount of contained material was released during burning. The greatest loss was from drums that experienced "lid-loss". Average weight loss from DOT-17C drum that did not undergo "lid-loss" was about 1 kg (i.e., about 10% of the loaded mass). Average weight loss from WDPAN2 and 3 was about 1½ kg. Although the filtered vent provided some pressure relief, "seal-failure" occurred. Average weight loss for the inner drum was 0.2 kg; this was minimized (shielded) by the overpack.

TABLE B-12. Summary of Mass Loss

Test ►	WDPAN1				WDPAN2				
Drum #	1	2	3	4	1	2	3	4	5
Drum Wt., kg	27.0	26.9	27.0	27.0	26.9	27.0	35.0	38.6	27.0
Load Wt, kg	10.0	10.0	10.0	10.1	10.0	10.1	N/A	10.5	10.4
Total Wt, kg	37.0	36.9	37.0	37.0	36.9	37.1	N/A	49.0	37.5
Post test Wt, kg	35.8	36.0	36.3	36.2	28.1	36.0	N/A	47.4	37.1
Wt Loss, kg	1.2	0.9	0.7	0.8	8.8	1.1	N/A	1.6	0.4
Total Wt Loss, Kg	3.6				11.9				

Test ►	WDPAN3					WDPAN4			
Drum #	1	2	3	4	5	1	2	3	4
Drum Wt., kg	27.0	27.0	34.9	38.7	26.9	27.0	27.0	35.0	27.0
Load Wt, kg	10.0	10.1	N/A	10.1	10.1	10.0	10.0	N/A	10.0
Total Wt, kg	37.0	37.1	N/A	48.8	37.0	37.0	37.0	N/A	37.0
Post test Wt, kg	27.9	35.9	N/A	47.3	36.7	35.9	36.4	N/A	36.9
Wt Loss, kg	9.1	1.2	N/A	1.5	0.3	1.1	0.6	N/A	0.1
Total Wt Loss, Kg	12.1					9.1			

Test ►	WDPAN5			
Drum #	1	2	3	4
Drum Wt., kg	27.0	27.1	34.8	26.9
Load Wt, kg	10.0	10.0	N/A	10.0
Total Wt, kg	37.0	37.1	N/A	36.9
Post test Wt, kg	36.2	29.0	N/A	36.7
Wt Loss, kg	0.8	8.1	N/A	0.2
Total Wt Loss, Kg	9.1			

The document demonstrates that:

- Heat transfer through drum sidewall is almost un-impeded.
- Only DOT-17C with lids that have a 1 in "bung" hole (plastic plug) failed completely (4 tested). All standard DOT-17C drums failed by lids buckling on side facing flame.
- Average time from start of fire until the lids blew off for the 3 drums was < 5 minutes. One of the lids that blew off flipped and landed on the drum upside down showing that this reaction is of limited energy.
- "Seal-failure" releases toxic and/or radioactive materials, smoke, and combustible gases.
- A TRU waste drums containing VOC (quantities >100 cm^3 are not anticipated) behave like H_2-air deflagration, although, not as violently (lid ejected did not travel as far as those in the Idaho test but only flipped over).
- The material ejected from drums did continue to burn outside the drum. This is not a valid observation for the purpose of internal drum deflagrations from a flammable

concentration due to “seeding” of waste with isopropyl alcohol.

- Quantity of ejected wastes was not measured, but the total mass loss, which includes burning inside the drum, was on the order of the 10% of the combustible wastes.

- The internal pressure required for “lid-loss” was 8 - 13 psig, indicating that overpressure from an external fire is about an order of magnitude less than that associated with an internal H_2 deflagration as determined by the SRS tests.

Impact on Drum Deflagration Recommendation

The behavior of TRU waste drums filed with combustible waste containing a limited quantity of VOC is bounded by the drum behavior resulting from the deflagration of an internal H_2-air mixture. This applies to both the ejection fraction and the amount of combustibles that could burn outside the drum. Although the quantity of the VOC is small, under most TRU waste drum situations, larger quantities are not anticipated. Under special circumstances for drums containing liquid VOC or large quantities of cellulose wetted with solvents used to clean glove box interior that are packaged, larger quantities of VOC may be found. This situation would not be bounded by the H_2 drum deflagration due to the amount of solvent-soaked combustibles that could burn outside the drum, and the possibility that a larger fraction of wastes may be ejected. For combustible solid wastes with large quantities of VOCs, a DR of 1.0 is conservatively assumed for ejection of combustible wastes and unconfined burning due to the lack of experimental data and uncertainty of what can occur under these conditions. If the contents are radioactive flammable or combustible liquids and no combustible solid wastes, the release must be modeled per recommendations in the DOE-HDBK-3010, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities* assuming a DR of 1.0 for lid loss and subsequent burning of the liquid inside or outside the drum.

The low failure pressures determined in the ASTM test and the combustible waste tests are not indicative of those achieved during a H_2 deflagration. The total mass loss both inside and outside the drum was on the order of 10%.

B.2.5 Hydrogen Combustion and Deflagration-to-Detonation Transition (DDT)

The DDT phenomenon is addressed in this section. It is concluded that a H_2 deflagration in a drum will not transition to a detonation. Various experiments are discussed, along with a review of H_2 combustion and flame propagation behaviors, and other literature papers on this topic.

Regarding hydrogen combustion, in a review of published literature on H_2 concentrations in air to burn in various directions, Los Alamos National Laboratory (LANL) quoted the following (from the McKinley 1980 reference in LANL 2002):

> *4 vol% H_2 (LFL) for upwards propagation produces an average flame temperature of <350^o C, whereas the ignition temperature of H_2 in air is 585^o C …can be understood from observation that the flame in the mixture rises as luminous balls that consuming only part of the hydrogen … fresh hydrogen diffuses into the burning ball and yields higher effective concentrations of hydrogen than initially present. It has been observed that not all the hydrogen is consumed in*

> *upward propagation in a 2 in. diameter tube until a concentration of 19 vol% H_2 was present. Similar experiments with horizontal tube resulted in a LFL of 6.5 vol% in air; downward propagation requires ~9 vol% H_2 in air.*

B.2.5.1 Electric Power Research Institute (EPRI) Hydrogen Tests

The EPRI performed experiments to evaluate hydrogen combustion and the effect of steam. The study is published in *Large-Scale Hydrogen Combustion Experiments, Volume 1: Methodology and Results*, NP-3878 (EPRI 1988). A sphere, 2.3 m (8 ft) diameter, and a large vessel (sphere, 160m [52 ft] diameter (surface-to volume ratio 0.39) resembling a reactor containment vessel with some equipment was filled with H_2 concentrations from 5.3 vol% to 13.2 vol;% in air with various concentrations of water vapor (4.2 to 38.7 vol%). Temperatures and pressure were measured at various locations and the completeness of combustion measured. Fans and obstructions (e.g., work platform, etc.) created turbulence in some experiments. Active igniter locations included the bottom, center, and top of the spherical vertical axis and along the equator walls. The AICC was computed. Test conditions and results are shown in Table B-13[23].

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[23] Suspect data were excluded; probably from water accumulation and boil-off in pressure sensing tubes.

TABLE B-13.EPRI Test Conditions and Results

	Initial						Test Results			
#	H_2, vol%	H_2O, vol%	Ign Loc.[1]	Fan/Spray	T, °C	Pres, psia	Δ_P, psi	T_{Max}, °C[2]	T_{Max}, °C[3]	% Burn
P-1	5.3	4.2	B	---	29.7	14.5	7.1	290	640	32
P-7	5.5	14.3	2E	F	52.2	14.0	9.4	325	630	37
P-2	5.8	14.3	C	S	51.1	13.2	15.3	470	658	61
P-3	5.8	14.4	C	F	52.7	14.2	11.2	365	659	44
P-6	6.0	13.7	T	---	50.0	13.1	0.0	50	677	0
P-6’	6.0	13.7	T	F	50.0	13.1	11.2	380	677	54
Sco	6.6	4.5	B	30.0	13.7	16.8	16.8	435	734	66
P-4	7.7	4.8	B	---	32.2	14.5	31.9	765	842	100
P-5	7.8	31.3	B	---	67.8	13.1	21.8	750	829	100
P-8	11.1[4]	27.2	B	F	75.0	19.5	53.2	1130	1128	100
P-22	5.2	14.5	1E	S	52.6	13.9	5.0	195	601	31
P-9	6.1	4.2	B	---	28.8	13.7	11.1	320	684	60
P-9’	6.0	4.6	B	---	29.7	13.3	8.8	305	674	53
P-11	5.8	4.9	T	S	31.6	13.9	7.8	368	655	58
P-12’	6.9	28.3	B	---	66.7	13.8	26	440	753	58
P-18	7.0	27.7	T	---	69.2	15.8	0.0	70	766	8
P-18’	6.6	27.3	T	S	69.2	15.7	17.2	480	730	69
P-13	7.8	4.4	[5]	---	30.6	NA	NA	NA	681	100
P-13’	7.8	4.4	B	---	30.9	14.4	31.0	740	851	100
P-14	8.1	38.7	B	---	74.1	13.9	16.0	600	847	92
P-15	9.9	4.2	B	---	30.4	14.9	40.6	950	1-5-	100
P-16	10.1	29.5	B	---	69.7	15.1	32.4	915	1033	100
P-20	12.9	27.8	B	---	69.0	15.6	43.7	1195	1274	100
P-21	13.2	27.4	B	F&S	68.3	15.3	43.6	1145	1297	100

[1] Igniter Location: (B) bottom, (C) center, (T) top, or (E) ---on wall at the equator
[2] Maximum gas temp recorded using 0.008 dia. thermocouple.
[3] Calculated AICC complete combustion value based on actual test conditions.
[4] Volume average value based on integrated mass flow of hydrogen, actual concentration may have been higher.
[5] Inadvertent ignition, prior to high-speed data recording.

Observations from the tests include:

- Large vessels inherently provide more vigorous combustion conditions than small vessel, particularly for lean mixtures. Fireball rises from point of ignition and accelerates through the first ⅔ of its upward travel. The rising buoyant plume draws air down the sides of the vessel to the bottom to replace the air rising up the center. This effectively promotes turbulence and mixing throughout the test volume. This self-induced turbulence is more effective in a large vessel that provides a longer vertical path for the rising plume to start the unburned gases in motion. Furthermore, one might expect this scale effect to be most significant with bottom ignition.

- For lean mixture tests having a H_2 concentration < 8 vol%, the report notes that the quiescent flame speeds generated as the flame front propagated away from the ignition site were augmented by the buoyant rise of hot gases. This caused the flame front to only accelerate in the upward direction with little lateral growth during the initial period following ignition. During the upwards inverse of the vessel, the growing flame front displaced cooler gases from the upper region of the test vessel. When the flame reached the top of the vessel, the momentum of the plume was able to drive the flame front downwards along the vessel wall with final combustion occurring in the lower region of that vessel. In these cases, incomplete combustion occurred, i.e., burn fraction ranged from 30% to 70%".

- In attempts to ignite quiescent lean mixture at 0.5 m (1.5 ft) below top of vessel, only minimal combustion occurred in the local region above the igniter. The initial upward flame propagation impinged on dome surface and quenched. There was insufficient vertical height above the igniter for full development of rising plume and global propagation throughout vessel was precluded.

- For H_2 concentration > 8 vol%, flame propagation was more spherical as H_2 increased from 8 to 13 vol%. For the Test P-20 with a H_2 concentration of 12.9 vol%, the initial flame front was essentially spherical.

- Hydrogen burn completion ranged from 0% to 100%. Fig 4-12, "*Burn Completeness s a Function of Hydrogen Concentration*" in EPRI 1988, shows complete combustion for H_2 concentrations > 7.7 vol% and up to 30 vol% steam (all bottom ignition). Top ignition under quiescent conditions resulted in very low burn completions due to quenching of flame at dome surface.

- Variations in peak pressure ratios with H_2 concentrations were highly non-linear (see Fig 4-5 in document), particularly for lean mixtures. Pressure ratio began to depart significantly from AICC values at H_2 concentrations < 8 vol%. Maximum temperature ranged from essentially ambient to 1102^{o} C.

Impact on Drum Deflagration Recommendation

The scale effect for small volume vs. large volume combustion of hydrogen showed that the large vessel inherently provides more vigorous combustion conditions than small vessel, particularly for lean mixtures. Therefore, hydrogen combustion inside void spaces of metal drums may also result in limited combustion efficiency. This was demonstrated in the attempts to ignite a quiescent lean mixture at 1.5 ft below top of vessel, which resulted in only minimal combustion in the local region above igniter and that the initial upward flame propagation impinged on the dome surface and quenched. This is an important observation for TRU waste drums that are ½ full of waste and the distance to the top is ~1.5 ft for lean mixtures (< 8 vol%). However, for richer mixtures > 12.9%, the initial flame front was essentially spherical, so this may support the lid loss observation of the Idaho and SRS tests in the 14 to 17 vol% range.

B.2.5.2 Sandia Hydrogen Tests

The Sandia National Laboratories performed research on flame acceleration and DDT for hydrogen-air mixtures in their FLAME facility (Sandia 1989). Flame acceleration and DDT can generate high peak pressures that may cause reactor containment failure. FLAME is a ½-scale model of the upper plenum of ice condenser for a pressurized water reactor to evaluate the explosive hazard associated with a hydrogen leak.

Deflagrations are combustion fronts traveling at subsonic speeds relative to the unburned gases; typically much less than sonic. Pressures are nearly uniform throughout containment and peak pressures are bounded by the AICC pressure; can be computed with high accuracy by thermodynamic calculations. At most, the AICC pressure is 8 times the pre-combustion pressure for H_2-air or H_2-air-steam mixtures. At deflagration, flame speed accelerated to >100 m/s, shock waves and peak instantaneous pressures are much higher. If accelerated to a fast enough speed, a deflagration may transition into a detonation – combustion fronts traveling at supersonic speed relative to the unburned gases. Peak reflected pressure for a detonation is considerably greater than AICC, up to 35 times the pre-combustion pressure. Obstacles in the path of an expanding flame front promotes/accelerates by enlarging the burning surface and increasing the local burning rate. A limited set of obstacle configurations were tested.

The FLAME facility is a large rectangular channel, 1.83 m (6.0 ft) wide, 2.44 m (8.0 ft) high, and 30.5m (100 ft) long. This translates to a L/D of ~ 25.6 (based on converting the cross sectional area into a hydraulic diameter). The channel was closed at the ignition end and open at the far-end. H_2 was inserted via 3 penetrations (1 at either end and 1 in the middle), mixed by 2 air-driven fans (1 at the ignition end and 1 near the exit). The ignition system had three independent ignition methods – bridge-wire, spark plug, and glow plug. All tests were conducted using single point bridge-wire ignition (capacitive firing set used to provide high-amplitude current to vaporize the bridge-wire). Test variables included:

- H_2 mole fraction tested ranged from 12% - 30%;
- Degree of transverse venting (by moving steel, top plate): 0%, 13%, and 50%; and,
- The absence or presence of certain obstacles in the channel: 0 to 33% blockage ratio.

Results are summarized in Table B-14.

TABLE B-14. Summary of the Test Parameters and Some Test Results

#	Top Vent, %	H_2 Mol Fraction, %	Peak Overpressure, kPa	Peak Equivalent Planar Flame Speed, m/s	Comment
Tests with no obstacles					
1	50	12.4	*	7	---
2		19.7	2.8	54	---
3		20.8	*	65	---
4		28.0	20	125	---
5		12.6	0.9	4(12)[1]	Top sheet restraint
6		15.5	3.4	19	---
7	0	12	1.2	15	---
8		18.4	25	170	---
9		6.9	*	1.2[2]	Limited burn.
10		12.3	2.5	17	---
11		12.9	4.5	30	---
12		24.7	95/1100[3,4]	374	DDT near exit.
13		12.0	---	---	All data lost.
14		30.0	250/2100[3,4]	932	DDT near exit.
15	15	15.4	3.1	50	---
16		17.6	10	75	---
17		14.9	---	---	Some data lost.
18		18.1	36	136	---
19		24.8	65/850	160	DDT at ⅓ length.
20		20.7	78	483	---
Tests with obstacles[5]					
21	0	10-15	650	580	No mixing fans.
22		15.0	3100	700	DDT near exit.
23		14.5	1200	540	---
24	50	15.5	*	45	---
25		19.7	1500	890	DDT near exit.
26		28.5	2000	1860	Box obstacle, DDT.
27		13.1	9	15	---
28		14.9	9	33.4	---
29		18.5	23	1430	---

[1] Plastic top sheet restraint gave faster values early in test.
[2] Indicates horizontal propagation velocity of thin layer below roof.
[3] 1st pressure refers to deflagration, the 2nd to detonation.
[4] Based on dynamic pressure transducer, somewhat uncertain.
[5] Obstructions that allow flow around them.

Observations and conclusions from the tests are:

- The hydrogen mole fraction is the most important variable. Reactivity of the mixture is determined by hydrogen concentration. For very lean mixtures, there is no significant flame acceleration and no DDT.

- Summary of tests with no venting or obstacles:
    - The flame speed and pressure increased with increasing H_2 concentration.
    - Flame acceleration is evident for H_2 mole fraction of 18 vol% and above, but not at 12 vol%.
    - DDT first occurred at H_2 mole fraction between 18.4 vol% and 24.7 vol% near the exit.
    - The initially convex flame shape became slightly-to-strongly concave.

- DDT occurred under the following conditions:
    - No obstacles and venting: at 24.7 and 30.0 vol% H_2 in air (none noted at 18.4 vol% H_2 in air);
    - No obstacles and 15% venting: at 24.8 vol% H_2 in air;
    - No obstacles and 50% venting: did not occur;
    - Obstacle and no venting: at 15.0 vol% H_2 in air.
    - Obstacle and 50% venting: at 19.7 and 28.5 vol% H_2 in air.

- Obstacles greatly increased flame speed, overpressure, and tendency for DDT. Different obstacle configurations could have greater or lesser effect on flame acceleration and DDT. DDT observed at 15 vol% H_2 with obstacles and no top venting.

- Obstacles lower minimum mole fraction necessary for DDT. Even if there is no detonation, deflagrations accelerated to 500 to 700 m/s (sonic velocity ~330 m/s) and generate high pressure pulses.

- A large degree of transverse venting reduces flame speed, overpressure, and the possibility of DDT. For reactive mixtures >18 vol% H_2, the effect of turbulence from venting is greater than from venting out of channel. Small degrees of transverse venting reduce flame speed and overpressure for less reactive mixtures but increase them for more reactive mixtures.

Impact on Drum Deflagration Recommendation

The detonation results are not directly applicable to drums due to the large L/D of 25.6 to allow acceleration of the flame front to sonic speeds. The observation that flame acceleration is evident for H_2 mole fraction of 18 vol% and above, but not at 12 vol%, is in the same range as the Idaho and SRS lid loss conclusions of between 14 to 17 vol%. The effect of obstacles or transverse venting is not applicable to TRU drums.

B.2.5.3 Rockwell Atomics International (AI) Hydrogen Tests

The Rockwell AI experimental study was a part of an effort to obtain information on Loss-of-Coolant Accident (AI 1973). Known water droplets were dispersed in combustible mixtures of H_2-air to limit combustion or detonation. This study used a shock-tube to determine flame and detonation initiation and propagation characteristics.

The test conditions were:

- H_2 gas concentration: 4 to 28 vol% in air (dry basis);
- Initial pressure levels: 1, 1.5, 2 atm (abs).
- Initial temperature: ambient
- Water spray 0 or 72 gpm
- Detonation source: spark-gap; for stoichiometric of H_2-O_2 driver-section
- Ignition sources for flame tests: Continuous sparking across 0.050-in spark gap of 16 vol% H_2-air mixture in driver section creating flame from ruptured diaphragm.
- Test apparatus was a 16 in diameter x 40 ft long (L/D = 30) shock tube, oriented in horizontal direction.

Detonation initiation Tests. Two series of experiments were conducted at H_2 concentrations from 4 to 28 vol% in air and pressures ranging from 0.5 atm (7.4 psi) to 2 atm (29.4 psi). Initial test performed at local ambient pressure (13.7 psi). Stoichiometric H_2-O_2 was added to the driver section. A detonation wave was established in driver section to initiate subsequent detonations of H_2-air mixtures in the shock tube. Results are summarized in Table B-15.

TABLE B-15. Detonation Test Results

#	P_i, psia	H_2, vol%[a]	Maximum Pressure[b]					Remarks
			1	2	3	4	5	
1	13.8[c]	0						System check-out
2		4						No detonation observed
3		8.7						No detonation observed
4		12						No detonation observed
5		16						No detonation observed
6		20	178	160	---	---	---	Partial detonation observed
7								Water spray
8		24	158	160	132	133	135	Partial detonation observed
9								Water spray
10		28	245	325	302	278	198	Detonation observed
11								Water spray
12								Water spray
13			130	---	---	---	150	Dry test
14	22	16	180	---	---	--	---	No detonation observed
15								Water spray
16		20	270	200	---	---	---	Partial detonation
17								Water spray
18	29.4	16	240	---	---	---	---	No detonation observed
19		20	250	---	---	---	---	No detonation observed
20								Water spray
21	13.8[c]	7	---	---	---	---	---	No detonation observed
22		9	---	---	---	---	--	No detonation observed

[a] Dry basis
[b] At photocon locations noted in FIGURE 2 of source document
[c] Local ambient pressure

No detonation propagation was observed at H_2 concentration < 16 vol% in air and 1, 1.5, and 2 atm pressure and combustion wave propagation. Published literature supports this finding. Partial detonation propagation was found at 20 and 24 vol% (dry basis) in air and combustion wave propagation. Short-duration, non-reflected pressure of 325 psig recorded with a well-established detonation propagation at 28 vol% (dry basis) in air.

Flame Tests. 26 experiments were conducted with H_2 concentrations ranging from 5 to 16 vol% (dry basis) and initial pressures from 1 to 2 atm. One additional test was performed at 28 vol% H_2 in air at initial pressure 0.5 atm. In Tests 1-18, both driver and shock tube filled with H_2-air and ignited by spark plug (no diaphragm separation). In Tests 19-26, the driver was filled with 16 vol% H_2-air ignited by spark plug (effective flame ignition source). Driver reaction produces highly turbulent flame (temp 2100°F/1379°C) that ruptured the diaphragm and jetted out into the shock tube. An automotive spark plug (0.050 in spark gap) and a high voltage cell were used as an ignition source.

The flame test results are summarized in Table B-16. There was no initiation at 5 vol% even using a well-establish flame. With the same initiators, 7 vol% with water spray did not ignite; partial burning without water spray. More substantial combustion was obtained at 9 vol% but combustion was incomplete. Ignition and flame propagation occurred even with water spray at 11, 12, and 16 vol% in air.

TABLE B-16. Flame Tests Data Summary

#	H_2 Concentration, vol%[a]	Pressure, psia Initial	Maximum	Final	Remarks
1	5.0	14.7	14.7	14.7	No ignition
2	7.0	14.7	14.7	14.7	No Ignition
3	9.3	14.7	14.7	14.7	No ignition
4	12.0	14.7	28.9	12.9	
5					Water spray
6					Water spray
7	16.0	14.7	48.8	12.2	
8					Water spray
9	9	22.0[b]	22.0	22.0	No ignition
10	12.0	22.0[b]	54	19.2	
11					Water spray
12	16.0	22.0	70	18.0	
13					Water spray
14	12.0	29.4[c]	64	25.3	
15					Water spray
16	16.0	29.4[c]	85	23.7	
17					Water spray
18	28.0	7.4[d]	28.5	5.0	
19	5.0[e]	13.7	15.0[f]	13.6	No ignition.
20	7.0[e]	13.6	15.6	13.25	20% to 40% complete.
21	9.0[e]	13.6	20.1	13.0	30% to 50and complete.
22	7.0[e]	13.6	15.3	13.5	10% to 20% complete.
23	5.0[e]	13.7	15.0[f]	13.7	No ignition.

TABLE B-16. Flame Tests Data Summary--Continued

#	H_2 Concentration, vol%[a]	Pressure, psia			Remarks
		Initial	Maximum	Final	
24	7.0[e]				Water spray
25	9.0[e]				Water spray
26	11.0[e]				Water spray

[a] Dry basis.
[b] 22.0-psi ÷14.7-psi/atm = 1.497 atm = ~1.5 atm
[c] 29.4-psi ÷14.7-psi/atm = 2.0 atm
[d] 7.4-psi ÷14.7-psi/atm = 0.503 atm
[e] 16 vol% H_2 in air in driver section.
[f] Short duration spike.

The Report shows that:

- No detonation was maintained at H_2 concentration < 16 vol%. This finding is supported by the published literature

- Flame propagation in a horizontal direction resulted in a partial detonation at 20 and 24 vol% H_2 in air; complete detonation requires 28 vol% H_2 in air.

- Combustion wave propagation (burning) at ≥ 7 vol% (dry basis) - the H_2 concentration that may deflagrate, continued with varying degrees of completion.

- Complete burning was not propagated for H_2 in air concentrations < 12 vol%.

- The behavior was similar for the tests with water vapor present.

- Values reported for burning in a horizontal direction may be high for burning in upwards direction and low for downwards direction. If shock tube is oriented in vertical direction with ignition source at lower end, burning fraction for < 9 vol% H_2-air would increase significantly. If flame direction downward, <9 vol% H_2 in air probably would not sustain flame.
- Initial pressure (more fuel and oxidant available) affects burning and (deflagration) maximum pressures.

Impact on Drum Deflagration Recommendation

The detonation results are not directly applicable to drums due to the large L/D of 30 to allow acceleration of the flame front to sonic speeds. However, the burning characteristics indicate that H_2 concentrations must exceed more than twice the 4 vol% LFL to sustain vertical flame propagation. The behavior was similar for the tests with water vapor present; an important factor due to the presence of some level of moisture (relative humidity and potential water formation during radiolysis in TRU waste drums filled with hydrogenous materials).

B.2.5.4 ARROW-PAK™ DDT Test

New Mexico School of Mining Technology, Energetic Materials Research and Testing Center (EMRTC) performed tests to evaluate the performance of ARROW- PAK™ to contain a stoichiometric hydrogen-air mixture deflagration (EMRTC 2002). ARROW- PAK™ is designed to fit into the TRUPACT-II. The container has drum-like internal dimensions (e.g., small L/D and "run-up" distance as described in Section B.2.5.5).

ARROW- PAK™ was tested to meet all the DOT CFR Part 49 paragraph 173.465 Type A packaging test requirements for free-drop, penetration, compression, and water spray. The EMRTC test design evaluated three operating conditions for defense in-depth against accident release of radioactive material was addressed the following:

- 1st test to demonstrate equipment can withstand < 3.5-psi absolute (at this pressure O_2 concentration will not support combustion at LFL).
- 2nd Test – 150 psi applied simulating pressure from H_2 buildup by high-wattage TRU
- 3rd test – Structural strength.
    - 1,248 lb drum filled with inert material and sealed in ARROW- PAK™, total weight 1,804-b, dropped 4 ft onto unyielding surface …
    - 9,100 lb steel plate placed on ARROW- PAK™ for 24-hr to demonstrate structural integrity 3” diameter metal rod dropped on side of ARROW- PAK™

For the deflagration test, an electric match was inserted through the sidewall in the middle. H_2 injected to 6.2 psig (2:1 H_2-O_2 ratio in air). A piezoelectric pressure sensor was used (sampling rate 20,000/s). Video camera (high-speed camera @10,000 frame/s) and microphone to indicate deflagration has occurred.

Observations from the test are:

- Pressure from deflagration was 75 psig.
- Vessel remained closed for one hour after deflagration and internal pressure remained 1.5 psi below atmospheric validating integrity of system.
- Post-test pressurized to 100 psig and held for 30 min to check equipment integrity; slowly increased pressure to 125 psig/139.7 psia) and held for 30 min (139.4 to 142.0 psi); slowly increased to 150 psig (164.7 psia) and vessel maintained integrity

Impact on Drum Deflagration Recommendation

A stoichiometric H_2-air mixture was ignited in the equipment and no DDT was observed. Document findings confirm that H_2-air mixtures do not transition into a detonation due to small L/D and insufficient “run-up” distances in the container.

B.2.5.5 Drum DDT Position Paper

This section summarizes a technical paper, “Position Paper on the Potential for Explosions in Transuranic Waste Drums at the Melton Valley Solid Waste Storage Facilities in Oak Ridge, Tennessee", developed to specifically address the potential of a DDT within a DOT 55 gal metal TRU waste-filled drum (WSMS 2006). Based on a literature review of experiments, such as the Idaho experiment summarized in Appendix Section B.2.1 and the SRS experiment summarized in Appendix Section B.2.2, other hydrogen and VOC explosion reports, and other relevant reports, the paper presents arguments to conclude that a DDT in a TRU drum is not credible (i.e., "not physically possible" rather than meaning an incredible frequency of occurrence). The paper also concludes that the appropriate type of explosion event for SB for TRU waste drums is a deflagration with lid loss, not a detonation that produces catastrophic failure of the drum with shrapnel and collateral damage. Some of those arguments are summarized in this section.

Absent a very large ignition source, for a detonation to occur, a deflagration must initially occur, and then it transitions to a detonation, which requires specific, specialized conditions. One of the key parameters is the L/D ratio of the enclosure. The paper cites literature values that are typically in the range of a 60 L/D if not pre-pressurized. A pre-pressure of 4.5 atm (~66 psig) reduces the L/D to about 10. DOT-7A Type A packaging are designed for pressures to 11 psig. TRU waste drums are leaky and the data indicates cannot hold pressure greater than 11 to 14 psig, and typically start to bulge at 6 psig. The L/D of an empty 55 gal drum is about 1.4 (ID 22.5 in, 32 in inner height). Since the empty TRU drum L/D is much less than the L/D of 10 for high pre-pressurization, a DDT would not occur.

Other factors are the "run-up" distance (distance from ignition point to transition) and contents of drum:

- Run-up distance in the literature is in the range of 10 m. TRU drums have an insufficient run-up distance due to the inner height of 32 in (0.8 m). The distance available in a drum is about an order-of magnitude less than that necessary for a DDT.

- The TRU waste content reduces the free volume of a drum, thereby shortening the run-up distance and lowering the L/D, which reduces opportunity for DDT.

- Solids contents that do not compress (e.g. metal, glass, etc.) would not undergo radiolysis and contribute to H_2 generation in drums, thus lessening the likelihood to achieve sufficiently high H_2 concentrations to support a detonation.

For DDT without transition, a strong energy source is required, on the order of ~ 4,000 J. Energies have been reported as low as 1 - 10 J under ideal conditions for stoichiometric conditions of pure H_2 and O_2 that do not exist for waste drums. A value closer to 4,000 J is required for TRU waste drums. The energy associated with movement, venting, and storage (e.g., static electric discharge is about 100 mJ, however, experiments have demonstrated that ~ 0.019 mJ can initiate the deflagration). These levels do not approach the high energy required for a DDT.

Impact on Drum Deflagration Recommendation

The DDT in a TRU waste drum is not possible, therefore, a deflagration with lid loss and ejection of contents is the appropriate bounding accident to be evaluated for a DSA.

B.2.6 Drum Response to Internal Pressures

Los Alamos National Laboratory evaluated the response of metal and plastic drums to internal pressurizations. Although not directly applicable to a H_2 deflagration in a metal drum, it provides insights into container strength and failure modes. Information on the strength of plastic drums is not presented.

LANL reported that there were 123 incidents between 1992 and 1998 involving pressurization of drums due to mixing of incompatible chemicals. Pressurization of drums presents personnel hazards: injury from debris; exposure to hazardous contents; and exposure to pyrophoric[24], flammable, and combustible materials. Hazmat teams have little or no training on how to respond to bulging drums. There is no quick, inexpensive method to determine pressures inside drums. LANL studied the effect of pressure on new, closed- and open-head 55 gal metal and plastic drums and 30 gallon metal and plastic drums, 20 gallon plastic pails, and 8 gallon overpacks. Objectives were to determine at what pressures drums fail, to quantify deformation, determine if data supports development of instrumentation to determine internal pressure, and to conduct a statistical analysis of mean failure pressure for 55 gallon drums.

Three sizes of metal drums (30, 55, and 85 gal) and two head closure designs were pressurized from 0 psig to failure in 5 psig increments. Open-head drums are like typical TRU waste drums with a locking ring. Closed-head drums have the top lid fastened to the drum (e.g., welded seam). Liner deformation along centerline and top and bottom were measured. Pressure increase allowed 30 s to stabilize. Table B-17 summarizes the test parameters.

TABLE B-17. Drum Capacities, Specifications, and Tests Conducted

Capacity and Description	UN/DOT/HM181 Specification	# Tested	Test Conducted
30 gal Metal, Closed-Head	1A1/Y1.8/300	2	A
30 gal, Metal, Open-Head	1A2/Y1.5/150	2	A
55 gal, Metal, Open-Head	1A2/Y1.5/150	12	B
55 gal, Metal, Open-Head, Cement-Fill	1A2/Y1.5/140	6	B
55 gal, Metal, Closed-Head	1A1/X1.8/300	14	B
55 gal, Metal-Plastic-Lined	6HA1/Y1/100	1	A
85 gal, Metal, Open-Head Overpacks	1A2/X440/S	6	B

A Failure Pressure-Characteristics
B Failure Pressure-Characteristics, Deformation

<u>55 gallon Metal Drum Tests</u>. Thirty-three tests of two types of drums were performed:

UN/1A1 – (closed-head) pressurized and observed under 3 treatments:

- ½ full of water;
- ¾ full of water; and,
- empty

---

[24] Material that spontaneously ignite at ambient temperature and pressure. For the purposes of these analyses, materials that ignite at elevated temperatures exposed to air.

UN/1A2 – (open-head) pressurized and observed under 3 treatments:

- ½ full of water;
- ¾ full of water; and,
- cement spun (partially-filled with cement and spun in a machine similar to a centrifuge to simulate waste packaging).

Retaining rings of empty and water-filled open-head drums were tightened with impact wrench and sledge hammer to within 1 cm of ring end meeting. Retaining ring of cement-filled open-head drum tightened to 40 lb torque. These closure techniques are not representative of TRU waste packaging procedures. They were pressurized to failure in 5 psig increments. Deformation was measured.

<u>85 gallon Metal Overpack Tests</u>. Two empty drums were tested to failure. Top deformation was measured.

<u>30 gallon Metal Drum Tests</u>. Four metal drums were tested to failure – two open-head and two closed head. Deformation was not measured because the device was not designed for this type of measurement. They were slowly pressurized to failure or stopped at what was perceived to be a dangerously high pressure.

55 gallon Metal Drum Results. Observations for new closed- and open-head 55 gal metal drums are:

<u>55 gallon Metal, Open-Head Drums</u>:

- Drums appear to vent immediately adjacent to nut and bolt fastener on ring, causing a crease in the metal at that location. (FIGURE 2 in the LANL report shows a bulged lid and metal crease near the bolt.)
- Pinging was noticeable between 15 and 20 psig.
- 100% of the drums tested vented at pressures at or below 32 psig.
- The 55-gallon metal open-head drums appear to bulge at only top and bottom ends.
- Body seam (top and bottom) experienced no visible distortion or apparent weakening.

<u>55 gallon Metal Closed Head Drums</u>:

- 95% of the drums failed explosively.
- Of the catastrophic failures, 68% failed at the bottom end, making the entire drum a projectile.

- 100% of the drums tested failed at the top or bottom.

- When filled with liquid (½ or ¾ full), bottom failures appear to be increasingly violent with increasing water level to ¾ full.

- ~ 5 psig before catastrophic failure, a significant amount of distortion of the drum chime is apparent (illustrated in Figure 3 in the reference document)

- The 55-gallon metal closed-head drums appear to bulge at only the top and bottom ends.

- Body seam (top to bottom) experience no visible distortion or apparent weakening.

- Pinging was noticeable between 15 and 20 psig, and increased dramatically immediately before drum failure.

- T-test indicates a probability of failure will occur above 48.7 psig. Observations indicate that bulging drums, especially closed-head, are extremely dangerous. There is a noticeable difference in behavior under pressure between open- and closed-head drums.

85 gallon Overpack Results. Six were tested and failed at 16 psig or less. Failure mode was self-venting at the nut and bolt closure. Like 55 gal drums, they bulged only at top and bottom end.

30 gallon Metal Drum Results. Two open- and two closed-head drums were tested. A significant hazard was created when pressurized.

30 gal Metal Open-Head Drums.

- Of 2 tested, 1 failed explosively and 1 self-vented.
- Both maintained < 50 psig.
- Bulged at top and bottom only but did not ping.

30 gal Metal, Closed-Head Drums:

- Extremely high pressures are possible (>120 psig) without venting.
- Fail catastrophically and violently.
- Bulged at top and bottom only but did not ping.

The report shows that:

- 55 gal and 85 gal metal, open-head, drums (TRU waste containers) are capable of retaining higher pressures than previously reported

- Drums fail by self-venting at nut and bolt closure
- 55 gal visibly deform (bulge) in 5- to 25 psig range at top and bottom, and, all failed at <32 psig
- The closure technique employed in these tests (sledge-hammer and torque wrench to ensure closure of retaining ring, nut and bolt ends within mm's) far exceeds the typical closure technique, and is not representative of actual TRU waste packaging practices.

Impact on Drum Deflagration Recommendation

This experiment does not have a direct impact on the drum deflagration recommendations. It does demonstrate the structural capability of metal drums to slow, internal pressurization, e.g., due to chemical reactions of incompatible wastes. The low failure pressures are not indicative of those achieved during a H_2 deflagration.

B.2.7 Drum Response to External Pressures

DOT 55 gal metal drums used to store surface-contaminated TRU waste have considerable strength. Extensive full-scale, ¼-scale, and 1/8-scale testing of 55 gal drums were performed by the Sandia National Laboratories (Sandia 1983). The drums used for the study were typical DOT 17-H drum (roughly equivalent to a DOE-17C drum with 20% loss of wall thickness) with a rigid PE liner and plastic bag. Tests include static crush tests, single-drum dynamic impact due to free-fall and lateral impact, and side impact of an eight-stack of drums. Static crush forces were measured and crush energies calculated. Scale model tests were performed using food pack can. Drum deformation and lid behavior are reported. Two computer techniques for calculating response of stacked drums are presented. Scale model testing demonstrated that in some aspects scale models are a reasonable model for full-scale drums. Both models tested show that they may be used with some care.

Results and observations from the tests are:

- Axial crush force: A peak force of ~88,800 N (20,000 lb) was required to initiate buckling of an empty drum, no lid separation observed. Combustible-filled drums withstood a crush force of 355,000 N (80,000 lb), four times the force for an empty drum. Sludge-filled drums exhibited almost identical responses to the combustible-filled drums. No complete "lid loss" occurred.
- Lateral static force: The lid separated (lid pulled out of sealing band) 5.3 to 6.1 cm (2.1 to 2.4 in) at a static crush force level of 17,500 to 21,500 lb. Drums containing combustible are stiffest and empty drums softest. Lateral crush force ~80,000 N (18,000 lb) sufficient to result in visual initiation of loss of leak-tightness (i.e., some lid separation). Drum interior liner prevented spillage of materials.

- Single Drum Impact Tests: Single empty and drums containing light density and heavy density sludge were dropped from 36.5 m (120 ft). Did not test drums filled with combustible materials. All tests were performed for lateral (side) impact. Impact velocities ranged up to 94 km/hr (58 mph). Dropped onto a rigid target (10 cm [4 in] thick armor plate backed by 250-tons concrete).

- Drum content had a significant influence on single drum drop test results. Worst drum deformation resulted from Test #31 for the heaviest drum (340 kg/748 lb) and highest impact velocity (71 km/hr/44 mph). Empty drums exhibited less deformation for same impact velocity than sludge-filled drums; the difference in deformation was small for kinetic energy difference. Differences between the original diameter and reduction by tests ranged from 1.24 to 7.27 cm (0.49 to 2.87 in). In some tests, the inner plastic bag was broken, but only for Test #31 was some loss of contents observed.

- Two 8-drum stacks were drop-tested. Impact velocity for the 1st test was 48.5 km/hr (30 mph) – stack remained vertical. The impact velocity for the 2nd test was 46.9 km/hr (29 mph) that used PE pad to mitigate effects. The stack tipped over after impact and foamed crushed. Results show drums withstand very significant impact without loss of contents.

- The drums behave differently under dynamic conditions. Static test indicate greater deformation than for dynamic impact. Static forces are difficult to convert to dynamic impact such as free-fall.

- Lid-displacement does not necessarily mean loss of contents – rigid PE liner and PE bag provide additional containment.

Impact on Drum Deflagration Recommendation

Although the data is not directly applicable to the response of TRU waste drums undergoing an internal deflagration, the data does provide information on the strength of the drums and their response if toppled during an event. Test results indicate that 55 gal DOT drums filled with TRU waste can withstand significant lateral external forces such as impact by a vehicle or deflagrations that may occur near the drums. Applicability of the results is limited since only sludge-filled drums were tested for lateral impacts, and an oblique impact on the ring closure was not assessed. The lid separation was defined as any displacement of the retaining ring and is not equivalent to “lid-loss” for drums involved in fires or H_2 deflagrations.

B.2.8 Other Waste Container Considerations

Internal deflagrations for other container sizes are addressed in this section. These conclusions are based primarily on engineering judgment, since there has been limited explosion testing of the SWB, overpacked containers, Remote Handled (RH) waste containers, and the Pipe Overpack Container (POC).

- For the SWB, lid loss will not occur for a container deflagration because the lids are very heavy and bolted onto the body of the box.
- Lid loss will not occur for a direct loaded RH waste container whose lid is welded, but may occur for other types of lid restraints if not similar to the bolted SWB configuration.
- Overpacking a metal drum of sound integrity with a larger metal drum, a SWB, or a RH canister with nested metal drums can be credited to prevent lid loss and ejection of contents.
- For the SWB, RH canister with nested metal drums, and the overpacked drum, a significant release from potential venting through the seal is not expected and is bounded by the mechanical impact evaluations presented in Section 4.4.4. Additionally, a subsequent fire will be limited by the availability of oxygen remaining after the deflagration or inleakage through damaged seals, and is bounded by the fire evaluations presented in Section 4.4.3.
- For the POC, pressure testing (Sandia 1998) showed that even if a hydrogen deflagration should occur, its magnitude would not be enough to damage the pipe component or significantly degrade its filter.

The Idaho test of hydrogen deflagration in drums described in Appendix Section B.2.1 also included testing other containers, but not for actual deflagrations. It tested the leak tightness of other types of containers and addressed the hydrogen buildup hazard. That test is described in the following section. The LLNL tests described in Appendix Section B.2.4 are somewhat relevant, but these involved the flammable-liquid-soaked combustible wastes, and are not repeated in this section – see results on the WDPAN4 and WDPAN5 tests involving drums # 3 and #4.

B.2.8.1 Idaho Testing of Boxes and Bins

Idaho performed two types of tests on the FRP wooden box, TX-4 box, and M-III metal bin that were used for TRU waste storage in the 1970s (EG&G 1983). These were:

- Leak tests to investigate the pressure retention characteristics; and,
- Tests to determine if H_2 gas would diffuse out of containers; and, if so, to measure the rate of diffusion. Helium gas with diffusion characteristics similar to H_2 used to alleviate safety concerns.

Helium was injected into container via center tube, air vented out bottom tube. Valves closed after predetermined amount helium injected. Vacuum pumps used to evacuate and purge sample cylinders. Initial sample verified sufficient helium injected to obtain a concentration of 25 vol% and was also used as initial sampling point. Subsequent periodic samples were taken until concentration decreased to < 4 vol% (i.e., LFL for H_2), recording the time required.

The recorded average pressure decrease/min (% of initial pressure) was:

- TX-4 box = 100[0.2 psig / 1.0 psig] ÷ 24 min. = 0.83%/min.
- M-III bin = 100[0.15 psig / 0.5 psig] ÷ 24 min. = 1.25%/min.
- FRP box could not be pressurized – its' leak rate exceeded the capacity of the injection system.

The document provides some information that is potentially useful for other types of TRU containers. The utility is limited by the lack of detailed information on the container tested. In summary:

- FRP boxes do not contain the gaseous materials in the container – very porous. Thus, this type of container would not be expected to accumulate large concentrations flammable/combustible gases/vapors generated by the contained materials.

- Metal bins (M-III) are leaky but are capable of containing up to 0.5 psig overpressure and still retain 70% of the initial pressure after 1 day.

- Vented metal bins (TX-4) demonstrated that they may hold greater than 1 psig overpressure and retain 80% of the initial pressure after 1 day.

B.3 Summary and Recommendations for Deflagration Release Parameters

Based on the experimental data and the analyses reviewed in the preceding sections, the following values for the [MAR][DR][ARF][RF][LPF] factors used to estimate the source term from an internal deflagration are recommended. For the unmitigated analysis, the LPF is always 1.0, i.e., no credit. Although the primary purpose of this appendix is to address the various DRs for drum deflagrations, the other source term parameters are also presented to put them into perspective with the applicable DR values.

The concept of "reasonably bounding" is applied and is defined as "the majority of parameters used to evaluate value are conservative”. This is similar to the "reasonable worst-case" concept presented in the hazard analysis guidance in Appendix B of the 1994 issuance of DOE-STD-3011-94, *Guidance for Preparation of DOE 5480.22 (TSR) and DOE 5480.23 (SAR) Implementation Plans*. It stated that "Unlike 'worst-case,' 'reasonable worst-case' does not consider every parameter to be in its most unfavorable state." The intent is to define values that can be applied over the entire DOE complex to establish a "reasonably bounding" estimate of the source term for an unmitigated analysis per the guidance in DOE-STD-3009 Appendix A.

A. Assumptions

Single Drum. Assumptions for modeling the deflagration within a single drum are:

- The drum contains only surface-contaminated, combustible waste (i.e., various forms of cellulose and thermoplastic materials).

- The event analyzed is the unmitigated, bounding event.

- The free volume of the drum contains a mixture of 30 vol% H_2 and > 15 vol% O_2 (if the O_2 concentration is less, the combustion is incomplete and the energy generated may not be sufficient to achieve the postulated response);

- The drum is on the highest tier of an array or is staged in a one-high array so that the drum lid movement is unrestrained by the weight of drum resting on the lid. The ejection fraction is actually based on the most conservative orientation of a drum lying on its side (e.g., during retrieval from a burial site), based on the Idaho maximum ejection fraction. This value is conservatively assumed to bound deflagrations from upright drums.

- Three release phenomena occur due to the ejection of a fraction of the contents that experience flexing in air and impact with the ground, partial unconfined burning outside the drum, and confined burning inside the drum.

Multiple Drums. There is considerable sentiment in many sites that this type of event cannot occur or is "beyond extremely unlikely". The values are cited to assist those situations where this type of event is considered. In some facilities, drums containing greater than some specific H_2 concentration are segregated and, thus, drums with known H_2 concentrations maybe located next to each other. Under this situation, more than a single drum containing elevated H_2 levels maybe involved in an event. EG&G 1983 has shown that drums that contain stoichiometric H_2-air concentrations sitting on top of drums that deflagrate may have a sympathetic explosion. The experimental data did not test adjacent drum containing stoichiometric H_2-air concentrations and, therefore, it is uncertain whether a sympathetic explosions will occur for that configuration.

The Idaho drum deflagration tests indicated that sympathetic deflagration of a drum on top of the initial deflagration occurred; however, the lower drum did not lose its lid due to the weight of the drum on top. No experimentation has been conducted, nor observed, on sympathetic deflagration of horizontally adjacent drums. Therefore, it is conservatively assumed that sympathetic deflagration is possible involving two unvented drums for TRU waste being retrieved from burial sites. Although additional sympathetic drum deflagrations may be possible depending on the retrieval staging configuration and other factors, modeling more than two drum deflagrations is not deemed necessary since adequate insights from the two-drum deflagration should be sufficient to establish appropriate TSR controls to protect the facility worker, other onsite (collocated) workers, the public, and the environment, and based on the likelihood of three or more sympathetic deflagrations being very low.

Sympathetic deflagrations need not be evaluated for the unmitigated analysis for TRU waste drum handling and staging/storage of newly generated drums associated with typical DOE Complex processes that generate contaminated, combustible wastes. Newly-generated drums are those generated per a site's waste packaging procedure with the intent to meet the WIPP WAC that was in effect since WIPP opened in the 1999, but may not be fully characterized as compliant to the current WIPP WAC. The assumption of not involving more than a single drum is based on the low likelihood associated with multiple upright drums, located adjacent or in nearby proximity to each other, having sufficient hydrogen-air concentration necessary for lid loss (i.e., exceeding approximately 15% hydrogen concentration with at least 7.5% oxygen, a small fraction of legacy drums based on characterization experience, and even lower chance that newly-generated drums would achieve such levels).

B. Material-at-Risk

The MAR associated with a single, bounding drum or a two drum deflagration must be consistent with the recommendations in Section 4.3, "Bounding the Material-at-Risk (MAR)". This depends on whether the containers meet the "limited characterization" or "fully characterized" assay.

C. Damage Ratio

The following DRs for deflagrations within a drum must be used, unless otherwise justified, for TRU wastes in metal drums:

Single, Bounding Drum:

- 40% ejected = 0.4 DR based on the maximum value cited in the Idaho experiment as described in Section B.2.1. This 0.4 DR applies to the flexing in-air release and the unconfined burning outside the drum.
    - Fraction of material that is released from the drum and burns in the ambient atmosphere: 0.05 DR based on the mass of the ejected combustibles that is ignited by heat generated by the combustion of a stoichiometric H_2-air concentration in the drum, as described in Appendix Section B.2.3. This includes the total energy generated by the deflagration of a 30 vol% hydrogen in air (that is assumed to contain a sufficient oxygen concentration for the complete combustion of the hydrogen) and ignoring any heat transfer to other components such as waste remaining in the drum or the drum itself and the possible extinguishment during its flight
- 0.6 DR for the remainder of the material in the drum that is conservatively assumed to burn, modeled as confined materials.

Two-drum deflagration:

- Both drums – use the values for the single, bounding drum deflagration (i.e., 40% ejected with 0.05 burn fraction, and 60% burning inside the drums).

In addition, the waste form influences the amount released, e.g., all combustible waste versus some noncombustible wastes. If the DOE site can justify a particular distribution of combustible versus noncombustible contents of drums, that can be credited in the analysis. For example, if a site does not segregate combustible and noncombustible wastes, a sufficiently conservative estimate may be 70% surface-contaminated combustible (i.e., various forms of cellulose and thermoplastic materials) and 30% surface-contaminated non-combustible materials (e.g., metal, glass, etc.). These fractions can be applied as additional DRs and associated with the appropriate release fractions for combustible and noncombustible wastes.

D. Airborne Release Fraction and Respirable Fractions

Appropriate ARFs and RFs for the different contributions are described in Section 4.4.5, "Airborne Release Fractions/ Respirable Fractions". A summary of the appropriate ARFs and RFs follows:

- During Flight through air: The values for suspension from shock-vibration of ARF 1E-3, RF 0.1 in DOE-HDBK-3010-94 are conservative and applicable.

- Fraction of Material that is released from the drum and burns in the ambient atmosphere: 1E-2 ARF and 1.0 RF for cellulose, contaminated plastics.

- Materials that Remain in Drum and Burns (0.6): ARF 5E-4

- Non-combustible Material Ejected from or Remaining in the Drum: Although this class of material releases a fraction of its surface contaminant during flight (i.e., from the 1E-3 ARF and 0.1 RF), no significant release is expected from its exposure to the ambient atmosphere. The resuspension rate for the suspension of surface-contaminant is for loose material that is already assumed to be released by shock-vibration during flight. This supports an ARFxRF of <1E-6. However, since it is likely to remain in the drum the 6E-3 x 0.01 ARFxRF for heating of noncombustibles should be applied.

E. Overall Effective Release Fraction

The impact of the above recommendations for DR, ARF and RF is calculated in Table B-18. For the 100% combustible single bounding drum deflagration, the overall effective release fraction is 5.4E-4. This value is applied to the MAR as described above for the single, bounding drum, or the two-drum combination.

TABLE B-18. Overall Drum Effective Release Fraction

Release Phenomenon	Fraction Ejected or Remaining	Waste Form Fraction	Outside Burning Fraction	ARF	RF	Effective Release Fraction
1. Flexing in air	0.40			1E-3	0.1	4.0E-05
2. Ejected combustibles burning	0.40	1.0	0.05	1E-2	1.0	2.0E-04
3. Burning combustibles inside drum	0.60	1.0		5E-4	1.0	3.0E-04
Overall effective release fraction =						**5.4E-04**

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Appendix C

Damage Ratios for Container Insults and Fires

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LIST of TABLES

This appendix provides the technical justifications for the Damage Ratios (DRs) presented in Section 4.4.3, "Fire Scenarios Damage Ratios for TRU Waste Containers", and Section 4.4.4, "Damage Ratios for Mechanical Insults".

C.1 Fire Scenarios Damage Ratios for TRU Waste Container

Section 4.4.3, "Fire Scenarios Damage Ratios for TRU Waste Containers" present guidelines for selection of DRs for fires in Transuranic (TRU) waste container storage in existing facilities for the facility Documented Safety Analysis (DSA). This section of the appendix provides the basis for the conservative assumptions used to establish the simplified alternate DR approach presented in Section 4.4.3, and does not repeat all of that discussion. It addresses insights from previous drum fire testing, lid loss versus seal failure considerations, and the ejection fraction for lid loss and unconfined burning.

As stated in Section 4.4.3, the general methodology outlined in Section 5 of the *Fire Protection Guide for Waste Drum Storage Arrays*, WHC-SD-SQA-ANAL-501 (Westinghouse Hanford 1996) is another acceptable methodology for fire modeling inputs and assumptions to determine the number of drums involved, extent of lid loss and seal failures, and to estimate the overall source term released. The Hanford methodology is sensitive to drum arrangement, pool size and what is burning, and is not summarized in this appendix. Some assumptions are deliberately more conservative than the Hanford Fire Protection Guide methodology in order to simplify the alternate approach.

C.1.1 Waste Container Fire Testing Insights

Section 7.3.9.2.B of the DOE-HDBK-3010 provides a source term calculation example for solid waste containers involved in fires, addressing combustible vs. noncombustible wastes, confined vs. unconfined burning of wastes, selection of appropriate release fractions, etc.. A summary of drum fire testing from that example is reproduced in this section[25]. Fire modeling for Fire Hazards Analyses (FHAs) and nuclear facility DSAs have evolved since the DOE-HDBK-3010 example, based on drum fire testing results and application of computer models and fire protection engineering handbook-type calculations that are now available.

Estimation of fire releases in drum storage must consider the issue of drum pressurization. A summary of drum fire testing follows to support the DR recommendations presented in Section 4.4.3. Many of the fire properties used in the fire analyses are based on results of small-scale specimens in over-ventilated conditions. Therefore, the results of these tests are conservative upon application to the postulated larger-scale scenarios (i.e., fire involving arrays of TRU drums).

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[25] The reader may want to review the complete source term example for a general understanding to estimate releases from drum fires.

Tests of drums under extreme fire conditions have been performed. Sandia National Laboratories (reference SNL, 1979, as cited in DOE 1994) performed experiments where drums with and without liners were placed in square burn pans holding diesel fuel. In one test, close rings were not used on five drums in the flame zone, so these drums were not actually sealed. The lids lifted on all of these drums. In another test, no lifting of lids was observed, most likely due to stacking drums on top of the bottom layer of drums that were exposed to the most intense heat.

In the Sandia large-scale test, 12 drums were sealed and placed in the diesel-soaked (190 liter) salt bed without stacking. Three of these drums were unlined, and four had 1/8-inch-diameter vents drilled through the center of their lids. The fire burned for 45 minutes, with the majority of the visible flame zone centering on four drums due to wind conditions. Of these four maximally affected drums, the vented and unlined drum blew its lid 7 minutes into the burn, scattering burning debris over the area. Flaring was observed around the lid of a lined, unvented drum, and a flame torch emanated from the side of the upper lid of a lined, vented drum. The remaining lined, unvented drum experienced a rupture of the bottom seam on one side. In general, polyethylene liners in drums melted and badly pyrolyzed. However, it is possible the insulation provided by the liners prevents as rapid a buildup of temperature and pressure as in the unlined drums.

The dislodgement of drum lids or lack thereof is a function of the rate of pressure rise. A rapid pressure rise is more likely to blow off a drum lid than a slow pressure rise, which will cause localized failure at seal and seam edges followed by emission of a torch of pyrolyzed gases. Tests at Lawrence Livermore National Laboratory (LLNL) (reference Hasegawa, Staggs, and Doughty, July 1993, as cited in DOE 1994) used sealed 55-gal metal drums without a vent plug, loaded with combustible materials and "salted" with isopropyl alcohol. These drums were placed in an isopropyl alcohol flow flame and violently ejected their lids in some instances. The test configuration (drums in a pan with isopropyl alcohol) and the fuel are extreme. However, even in those instances where lids blew off, the filmed record showed bulk waste landing on the ground, where it proceeded to burn. There was no fragmentation of the drum or instantaneous combustion of significant quantities of waste.

Sealed 55-gal metal drums, containing a mixture of combustible materials, did not lose their lids when placed in a wooden structure that was burned to the ground with combustibles purposefully stacked around the drums to produce a high fuel loading and associated heat flux (reference Greenhalgh, Demiter, and Olson, May 1994, as cited in DOE 1994). These drums exhibited a more typical phenomena of lid seal failures producing torch flames from pyrolysis gases generated in the drums. After the fire consumed the entire building, examination of the drums revealed the majority of the contents to be uncombusted (i.e., provides some justifications for a DR < 1.0 for seal failures as discussed later).

The most recent drum fire tests were performed by Hughes Associates, Inc. for the Hanford site and reported in *Analytical and Experimental Evaluation of Solid Waste Drum Fire Performance,* WHC-SD-TRP-233 (Westinghouse Hanford 1995b) and *Solid Waste Drum Array, Fire Performance*, WHC-SD-WM-TRP-246 (Westinghouse Hanford 1995c). These results were interpreted into a protocol to model drum fires for the Hanford site and published in the *Fire*

Protection Guide for Waste Drum Storage Arrays, WHC-SD-SQA-ANAL-501 (Westinghouse Hanford 1996). Numerous FHAs throughout the DOE Complex have subsequently evaluated waste container storage configurations based on the general methodology outlined in Section 5 of the Hanford guide for specific fire modeling inputs and assumptions. An example of how this is applied for the DSA is presented in *Solid Waste Operations Complex Master Documented Safety Analysis* (Fluor Hanford 2005), based on their site-specific FHA evaluation.

However, numerous site-specific modifications of that methodology have also been justified over the past decade. One example is the approach developed for the Rocky Flats Environmental Technology Site as published in their *Safety Analysis and Risk Assessment Handbook* (SARAH) (Kaiser-Hill 2002). The SARAH approach is based on a letter report from J. Mishima to Kaiser-Hill Company, *Applicable Airborne Release Fractions (ARFs) and Respirable Fraction (RFs) for Surface-Contaminated, Combustible Waste in 55-Gallon Metal Drums During Fires* (Mishima 2001). The Mishima letter report provides an extensive review of the Hanford fire tests and the other experiments mentioned earlier. Based on this review, it recommends a protocol to evaluate pool and ordinary combustible fires involving drums. The final methodology approved for FHA and DSA development at Rocky Flats with example applications was documented in the *Applicable Airborne Release Fractions (ARFs) and Respirable Fractions (RFs) for Surface-Contaminated, Combustible Waste in 55-Gallon Metal Drums During Fires*, NSTR-008-01 (Kaiser-Hill 2001), and summarized in SARAH[26]. The Mishima 2001 reference and NSTR-009-001 results are the primary basis for the DR guidelines recommended in Section 4.4.3 for the alternate methodology to the Hanford Fire Protection Guide.

C.1.2 Lid Loss and Ejection Fraction

Based on the review of the fire tests, the Mishima 2001 reference provides the following basis for recommending that 25% of drums within a pool fire, or adjacent to a pool fire, are assumed to experience lid loss with the potential to eject some contents:

> *There does not appear to be any established correlation between fire generated conditions (e.g. wall temperature, heat energy flux impacting drums) and "lid loss" and "seal failure". Consequently, the criteria used to predict these responses tend to be very conservative (tend to over-estimate their effect). Under the most rigorous test conditions (a flammable liquid fire engulfing combustible filled 55-gallon metal drum with liquid flammable fuel in the drum or fire that can transfer heat to all surfaces of the drums), less than 25% of the drums exhibited "lid loss". The "lid loss" is postulated to occur due to the auto-ignition of the flammable fuel vapor resulting in a very rapid increase in pressure, pyrolysis of solid combustible under intense heating conditions, or for long durations. Similar responses resulted from the explosion of hydrogen gas with its flammability limits in solid combustible 55-gallon metal drums (5 of 18 drums = 28%). In other tests in engulfing fires (Haecker et al., Sept. 1995), "lid loss" occurred from 0% for trash fires to 25% in a combustible fuel fire with drum containing solid combustible and non-combustible materials and a liquid hydrocarbon fuel. For a Pallet Storage Array (the storage configuration used within the DOE Complex), a predictive model proposed based on the previous test, over-predicted "lid loss" by a factor of 5.2 (94 lid failures predicted, 18 lid failures*

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[26] Not all recommendations of the Mishima 2001 report were adopted. For example, the graded application of MAR estimates based on number of containers involved was not adopted.

> *experienced). Of the 24 drums in the flames and 30 drums adjacent to the flames in the experimental Pallet Storage Array fire, only 2 drums (~3.7%) suffered "lid loss"; these were not in the top tier. The terminology describing the drum responses changed in the middle of the document revealing that the term lid loss/failure include both lid rupture (that does not physically remove the lid from the drum) and lid loss (lid physically removed from the drum). Based on this re-definition, the predictive model over-estimated "lid loss" by a factor of 47 (94 predicted vs. two with "lid loss", a factor of 18/2 = 9 smaller than drums with "lid failure").*

Each of the experiments mentioned in the previous section were critically reviewed in order to establish the 25% estimate of lid loss with ejection of contents that reflects the experimental record. Mishima noted that the different experiments did not use the same definition for lid loss, so interpretations of the results are somewhat subjective regarding whether contents were ejected. For the purpose of these guidelines, lid loss includes ejection of some contents. Lid rupture where the lid was deformed but not displaced from the drum is considered to be the same as seal failures for the purpose of these guidelines.

To establish a bounding estimate, the 25% of drums that experience lid loss is applied with a second DR adjustment that one-third of the contents (33%) is assumed to be ejected from the drum with the exception of heavy forms of waste (e.g., contaminated pieces of a glovebox). This bounding recommendation is based on a single datum during the drum fire experiments (Westinghouse Hanford 1995a) which indicated that ~1/3 of the combustible contents were ejected during a violent "lid loss" event (Mishima 2001).

Use of 33% ejected is recognized as the most bounding assumption. For a 30% hydrogen deflagration in a vertical drum with combustibles the ejection fraction is 7% to 27%[27]. The amount ejected is a function of the pressure at which the drum lid comes off which, in turn, is a function of the rate of change of pressure. Both are much greater in a hydrogen deflagration than in a fire. WHC-SD-WM-TRP-233 (Westinghouse Hanford 1995b), Section 3.3 shows that for fire testing done at various DOE locations, the peak internal pressure is 28 psig. This occurs 93 seconds after the fire starts (2.1 m JP-5 pool fire, Drum 30-D1). The pressure at which the drum lid fails for a hydrogen deflagration is around 90 to 100 psig. Therefore, the amount ejected from a fire should not be anywhere near that of hydrogen. However, a notation in the comments section for drum 31-D4, which had a maximum pressure of 13 psig, a fairly low value of dP/dt, was that “1/3 of contents were ejected.” The major difference between this drum and an actual drum is that the simulated waste was layered in the drum using individual pieces e.g., rubber sheet 6 in. by 12 in. by 0.125 in., 6-mil plastic bag cotton towels, etc. (See pg 2-6 and 2-7 of the reference). Actual TRU waste is bagged, although legacy drums may have degraded inner packaging. The void volume of the drum in the fire test appears to be similar to that in the hydrogen deflagration tests. However, most of the hydrogen that burns is above the waste, where in the fire test the pressurized air exists throughout the drum. When the lid lifts, the pressurized air can more easily eject the waste. So there is a potential reason why a fire can eject more waste than a hydrogen explosion. On the other hand, in the test, each barrel is surrounded by at least 0.3 m of flames. The drums burn as individual drums in a fire not as drums in an array (See FIGURE 16 of reference) where for the worst case drum, only one side is burning.

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[27] compared to the 40% ejection fraction for a horizontal drum that is used for a bounding assumption for the drum deflagration DR in Section 4.4.2 and Appendix B.

Because the drums are in a close packed array not widely spaced and because the waste is packaged, not present as individual sheets, 33% ejected may be overly conservative. Therefore, although the Hanford Fire Protection Guide recommends considering a 33% ejection fraction for a more conservative analysis, the application of this guide for Hanford DSAs assumes a 10% ejection fraction (which is applied to 100% of unrestrained drums in a pool fire and some lower-tier drums depending on toppling considerations). The 100% of the drums that experience lid loss but with 10% ejection (Hanford model) is about the same as assuming 25% of the drum population that experience lid loss with 33% ejection (alternate approach). Either approach results in the same level of consequences and bases for derivation of TSR controls, and is acceptable for a conservative estimate.

C.1.3 Seal Failures

For the "fast" fire growth rate associated with the pool fires, those drums engulfed in the pool or along the edge of the pool that do not experience lid loss are assumed to experience seal failure. This DR is the remaining 75% fraction of drums involved.

For “moderate” fire growth rates (e.g., ordinary combustibles such as trash or wooden pallets and crates), lid loss and ejection of contents is not expected based on the drum testing results, so for modeling purposes, seal failures only are evaluated. For direct flame impingement on only one side of a container from an adjacent ordinary combustible fire, or when heat transfer is only through radiation, fires involving non-liquid fuel packages (e.g., trash) were determined to not result in lid loss. The heat output of the fire is insufficient to increase temperature and pressure inside the drum quickly enough to eject the lid before venting (seal failure) occurs. The container must be close enough to the fire such that it is exposed to a sufficient heat flux[28]. If room flashover is possible for the DSA unmitigated analysis, then all containers are subject to seal failures.

An additional DR consideration for seal failures to account for incomplete combustion and other factors is appropriate when more than a few drums are involved. The use of a DR for an inventory in a single drum has not been substantiated through direct experimentation. The effect of incomplete combustion of the surface-contaminated solid combustible wastes is incorporated in the DOE-HDBK-3010-94 value in the experiments performed for waste burned in cardboard containers (i.e., the 5E-4 ARF presented in Section 4.5 already includes the effect of a 0.5 DR). Since the DR was not measured in the experiment, the relationship between the ARF and DR is unknown, introducing additional uncertainty upon application to other types of containers involved such as metal drums. Another factor is that the contamination may not be uniformly distributed throughout the combustible wastes in a single drum. Therefore, for fires involving seal failures involving a few drums, no additional DR should be applied. This is based on the following interpretation from Mishima 2001:

> *If a DR is applied, the "bounding" ARF/RF values cited in DOE (1994) must be corrected for the incomplete combustion during the experiments and an assumption provided to ensure uniform*

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[28] A conservative criterion (Kaiser-Hill 2000) is at least one third of the container is exposed to a heat flux exceeding 15.9-kW/m^2 based on interpretations from the Hanford fire tests (Westinghouse Hanford 1995b and 1995c).

> *concentration of the surface-contamination. Since the unburned fraction has not been quantified, any value has a considerable uncertainty associated with it. The unburned fraction during the experimental study used to establish the values cited in DOE-HDBK-3010-94 are estimated to be less than 50%. Use of a mass loss for DR must be coupled with some assurance of a relatively uniform distribution of the surface-contamination. Such an assumption can be valid for a number of drums with random surface-contamination distributions. With an adjustment in the "bounding" ARF/RF values for incomplete combustion during the experimental study, use of a fractional mass loss (DR) for an array of drums with a uniform distribution of surface-contamination on its contents is reasonable. Previously cited results of experimental studies of drums involved in fires indicate the DR (mass loss) values range from 10% during intense fire of short duration to 25% during cellulose fueled fire for a 2-hour duration.*

But it is reasonable to assume that the release of the same combustibles as in the cardboard container experiment, contained in a sealed metal drum, will be reduced by some factor due to the drum's effect and vapor and particle transport. For example, a 0.06 DR was measured from the mass loss in the Hanford drum fire tests discussed earlier, and is incorporated into the Fire Protection Guide methodology. Another perspective is provided by the U.S. General Service Administration recommended factors[29] for derating fire loads in an office occupancy, which is a conservative assumption for applying to TRU waste drum storage areas. It depends on the ratio of the weight of combustibles enclosed in metal desks or steel filing cabinets to the total weight of all combustibles, include the enclosed combustibles, free combustibles in the room, and 75% of combustibles in 5-sided open metal bookcases (which will be ignored for the examples cited next). The largest derating factor is 0.1 for exceeding a ratio of 0.8, i.e., 80% of the combustibles in the room are completely enclosed. The least derating factor is 0.4 for a ratio under 0.5, i.e., half of the combustibles are completely enclosed. A derating of 0.2 is assigned for ratios between 0.5 to 0.8. This mid-range derating factor was selected at Rocky Flats as a sufficiently conservative estimate of a 0.2 DR for seal failures of TRU waste drums in designated storage areas (Kaiser-Hill 2000; Kaiser-Hill 2001, Kaiser-Hill 2004). Due to uncertainties in how much of the contents burn and extent of seal failure versus lid loss, for any event that involves 10 or more drums, an assumption of a uniform-like surface contamination is acceptable and a DR of 0.5 is considered reasonably bounding for the alternate methodology (Mishima 2001). This is based on a DR of 0.25 for the mass loss of the substrate by pyrolysis of the surface-contaminated combustibles divided by the DR of 0.5 already incorporated into the "bounding" ARF/RF value (Mishima 2001). A DR of 1.0 is assumed for less than 10 drums due to this uncertainty regarding the amount burned and whether there is uniform contamination.

A similar DR for seal failures of direct-loaded Standard Waste Boxes (SWBs) is established based on a physical consideration that four drums are approximately equivalent to one SWB. This results in a DR of 0.5 for more than two SWBs involved in a fire (i.e., 10 drums divided by 4 and rounded up). However, a DR of 1.0 is assumed for one or two SWBs involved in the fire.

As discussed in Section 4.4.2 on deflagration within a container, overpacking a metal drum of sound integrity within a larger metal drum, a SWB or a Ten Drum Overpack (TDOP), can be credited to prevent lid loss and ejection of contents and modeled as seal failures. In addition to

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[29] as reported in Chapter 6, "Confinement of Fire in Buildings", in Section 6, "Confining Fires", of the *NFPA Fire Protection Handbook* (NFPA 1991)

preventing lid loss, overpacked containers provide an additional level of protection from fires that allows a lower DR than those for directed-loaded drums or SWBs. The dimensions of the SWB are nominally 5 ft long, 4 ft wide, and 3 ft tall, with rounded sides to fit within the TRUPACT-II container for shipments to Waste Isolation Pilot Plant (WIPP). The walls are typically 10- to 12-gauge (about 0.1 in.) sheet metal, and the container is sealed with a gasket and lid with 42 bolts. The TDOP is constructed similar to a SWB and provides primary confinement to a large drum-like volume that can be loaded directly or as an overpack for 10 full 55-gal drums, up to 6 full 85-gal drums, or an SWB. Both the outer container and inner drums in an overpack assembly must have vents installed. For a radioactive material release to occur, the fire has to heat up the inside of the SWB/TDOP and also heat the inner contents of the 55-gal drums resulting in pyrolization of the drum contents and subsequent venting from both containers. The SWB/TDOP configuration presents a significant heat sink and pyrolization of drum contents would require a very long lasting fire or a very large fire. Another consideration is that the SWB/TDOP is large, therefore, it is not expected that all of the waste will be affected by a fire. Although the drum-in-drum overpack does not provide the same level of heat sink, the overpacked drum fire testing described in Section B.2.4, "Volatile Organic Compounds (VOCs)" concluded that the average mass loss for a drum overpacking was about a factor of five less than that of the direct-loaded drums that did not undergo "lid loss" (which only averaged about 10% mass loss). Therefore, a DR of 0.1 is assumed for overpacked drums of sound integrity whether overpacked in a larger drum, a SWB, or a TDOP. This applies to a single or multiple overpacked containers exposed to the radiant heat flux that causes seal failures.

C.2 Mechanical Insults (Impact and Spills)

This section of the appendix addresses DRs for the 55-gallon steel drum, SWBs, Pipe Overpack Containers (POCs), and overpacked containers (e.g., 55-gallon drum nested within an 85-gallon drum or a SWB, or the TDOP). This appendix provides the technical justifications for the DRs presented in Section 4.4.4, "Damage Ratios for Mechanical Insults".

DOT Type A packaging (DOT 1997) is required to pass tests as described in Section 4.4.1, "Container Integrity". Drops and impact stresses on TRU waste containers will result in a wide-range of damage depending on the magnitude of these forces, type of containers, and condition of containers. The estimates of the DR for contact-handled (CH) TRU waste containers are based primarily on interpretations of tests that have been performed for waste containers of the types to be shipped to the WIPP. Axial crush and impact tests were performed for DOT 7A drums of the types that will be shipped to WIPP for emplacement, and for a metal box but not the SWB. In general, the available test data represent waste container configurations during storage and handling unique to specific generators, e.g., single drums and multiple drums in a stack configuration. Unfortunately, none of the reported tests were performed for waste drums or SWB configurations specific to loading and unloading the TRUPACT-II container for shipping to WIPP (e.g., plastic-wrapped stack of two seven-pack drum configurations). Therefore, the reported tests must be considered as indirect evidence that must be evaluated using engineering judgment in order to be introduced in the application of existing test data for these other container configurations.

A majority of the reported drum tests were performed with DOT Type 17C drums with a rigid polyethylene liner containing bagged waste of various forms. However, generators will also ship drums that currently have the designation of Type 17H (thinner wall), and both types of drums will be shipped with and without liners. The type of drum and the presence of a liner within it cannot be readily distinguished once it is packaged. Type 17C drums are made from 16-gauge material, which have a nominal wall thickness of 0.059 inches. The Type 17H drums are made from 18-gauge material, which has a typical wall thickness of 0.039 inches. The SWBs are made from 10-gauge material (minimum thickness of approximately 0.128 inches) and have a bolted lid, which makes them less susceptible to separation from the container upon impact. Based on simple calculations of compression stress in the wall and axial buckling, Type 17C drums appear to be stronger than the SWBs, which in turn are stronger than the Type 17H drums (WIPP, 2000). However, the lids for the SWBs are bolted to the body of the container implying that lid separation is much less likely for the SWBs than for the drums. Because both types of drums are to be handled and stored, the characterization of drum failure should be based on the more limiting case of Type 17H drums.

C.2.1 Container Test Results

The WIPP site performed an evaluation of the container drop and impact test data to establish DR estimates. This is reported in PLG-1121, *Damage Assessment of Waste Containers Involved in Accidents at the Waste Isolation Pilot Plant* (WIPP, 2000). It is based on the following three tests:

- "Sandia test", as documented in SAND80-2517, *Analysis, Scale Modeling, and Full-Scale Tests of Low Level Nuclear Waste Drum Response to Accident Environments*, (Sandia 1983)
- "Hanford test", as documented in WHC-SD-WM-TRP-231, *Drum Drop Test Report*, (Westinghouse Hanford 1995a)
- "Rocky Flats test", as documented in WPS 88-001, *Full-Scale Drop-Impact Tests with DOT Specification 7A Waste Containers*, (Rockwell 1988).

The discussions that follow are primarily focused on drop test results rather than the axial loading tests. It is based on selected extracts[30] from the WIPP report PLG-1121 that summarized the experiments and test conclusions. Test information is also presented on POC.

C.2.1.1 Drum Drop Tests

Sandia Drum Drop Tests

Sandia drop-tested DOT Type 17C drums (Sandia 1983). Twelve static crush tests (eight with drums in the lateral configuration [sideways] and four with drums in the longitudinal direction [axial or upright]) and 17 drop tests (all involved lateral impact). The response of the containers was reported in terms of drum deformation and lid behavior. The DOT-17C drums were obtained from the Rocky Flats facility and contained a rigid polyethylene liner and lid. In addition, the "payload" was placed in a light polyethylene plastic inner bag, providing three layers of confinement. Most of the tests involved drums that contained various forms of waste (combination waste and simulated sludge). However, four of the crush tests and six of the drop tests were performed with empty drums.

The metal drum lid is held in place with a clamping ring secured with a nut and bolt. The Rocky Flats procedure for packaging TRU waste at the time was as follows. Waste material is first loaded into the polyethylene bag and placed inside the liner. The top of the bag is then gathered and taped shut. The bag is then checked for contamination and if none is found the liner lid is installed. The liner lid snaps into place after an adhesive has been applied and is then banded with a circumferential stainless steel strap. The metal drum head is then installed using a gasket and adhesive. The clamping ring is positioned and secured with a nut and bolt.

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[30] Minor editing of the extracted information was performed for presentation in this document. The PLG-1121 report should be consulted for the entire discussion and interpretation of the test data.

The results of the Sandia single drum drop tests for DOT-17C drums are:

- The 17 full-scale drop tests were conducted with single drums in a lateral configuration. No tests were conducted in the axial configuration. The worst damage occurred with the heaviest drum (748 lb) and the highest impact velocity (this was the only case in which the inner plastic bag was broken and the only test in which contents were lost). No lid failures (and thus, no material releases) occurred for drop heights less than 44 ft (13 m) or impact velocities less than ~35 mph. No lid failures occurred for kinetic energies less than 29,413 ft lb. Empty drums exhibited less deformation for the same impact velocity.

- Four lid failures occurred in the 17 drop tests but only one test (involving the heaviest [748 lbs] drum tested) resulted in a "slight loss of contents". Although only a qualitative description of this loss was provided, PLG-1121 assumed less than 5% of the contents were lost.

- Sandia concluded that drum deformation cannot be predicted by considering only the kinetic energy of the system. Drum contents are important because different materials absorb various amounts of energy.

Hanford Drum Drop Tests

Westinghouse Hanford Corporation (WHC) performed drop tests with six drums (Westinghouse Hanford 1995a). Three of the tests were performed with Type 17C drums and three were performed with Type 17H drums. All of the single drum drop tests were conducted with the drums having a gross weight of 1,000 lbs (the maximum drum weight allowed by the WIPP Waste Acceptance Criteria [WAC]) and tilted 45° to horizontal, landing such that lid locking ring bolt struck the test surface. Sand and lead bricks were utilized in the tests to simulate waste. It should be noted that the simulated waste was placed directly in the drum. No liner or bags were utilized. The presence of a sealed drum liner and polyethylene bag will reduce the extent of spills. All of the drums used in the tests were new and undamaged. No corrosion or other visible deterioration of the drums was observed prior to the tests. The locking ring bolts were torqued to 40 ft lb.

The results of the Hanford single drum drop tests for DOT-17C and DOT-17H drums are:

- WHC concluded that single 1,000-lb drums dropped from 11 ft and impacting the locking ring at 45° to horizontal are likely to spill some of their contents. For Type 17C drums, the maximum spill was 250 lbs (27% of the drum contents) and the average for three tests was 103 lbs (11% of the drum contents). The Type 17C test with the smallest void volume produced the greatest spill. For Type 17H drums, the maximum spill was 500 lbs (53% of the drum contents) and the average was 170 lbs (18% of the drum contents). All Type 17H tests and the remainder of the Type 17C tests had initial void volumes of 10%. The lid stayed attached to the drum in each of the six single drum tests.

- Container breach occurred at the drum/lid-sealing surface in all tests.

- Obvious (highly visible) damage to a drum is not necessarily an indicator of drum integrity. Extensive damage to the drum walls may not be indicative of container breach whereas a small amount of damage to the lid and upper sealing surface may cause lid separation and loss of container integrity.

- Material larger in size than that which was tested would not have been ejected from the drum. The simulated waste was selected because of its density and ease of handling, not because it was representative of actual solid waste materials.

C.2.1.2 Pallet Tests

Sandia Pallet Tests

Two drop tests with stacks of eight drums arranged laterally (each drum contained roughly 700 lbs of simulated waste) were also conducted by Sandia (1983). The bottom of the stack was 30 ft from the target surface when dropped. One test was performed with a foam block at the bottom of the stack for energy absorption. Impact velocities were approximately 30 mph in both tests. As was the case for the single drum tests, all drums were obtained from the Rocky Flats facility and were of Type 17C, and contained a rigid polyethylene liner, and the "payload" was placed in a light polyethylene bag.

The results of the Sandia pallet drop tests with DOT-17C drums are that most of the individual drums underwent rather severe deformation, including the test with the foam block. After testing, the compressed stack height was approximately 70% of the undeformed height. The lower six drums sustained approximately the same deformation; i.e., approximately 60% of their original height. The top drum experienced only minor deformation, almost undetectable. Lid separation or loss of contents was not reported for these tests.

Rocky Flats Pallet Tests

A full-scale drop test of an array (four high by three across) of 12 DOT Type 17C 55-gallon drums used at Rocky Flats was performed by Rockwell International (Rockwell 1988). All drums contained a rigid 90-mil polyethylene liner with the lid held in place with the closure ring. Inside the rigid liner was a 10-mil Poly-vinyl Chloride (PVC) liner that was sealed with tape. The test was performed with the drums in a lateral alignment and they were dropped 15 ft.

The test configuration was designed to maximize the lateral crushing force to the lowest weight drums with the largest free volume. The three drums in the bottom of the array weighed from 116 lbs to 135 lbs. The upper two rows of drums weighed from 643 lbs to 666 lbs. The second row of drums (from the bottom) weighed from 321 lbs to 586 lbs.

The results of the Rocky Flats pallet drop tests with DOT-17C drums are:

- For the stacked array of drums, the drum with the lowest weight (bottom row) showed the most significant damage. Both the drum lid and liner lid remain attached but the lids creased to produce a large lid-to-drum gap. The 10-mil bag was not breached.

- The drum drop test indicated that loss of the drum lid-to-body seal, primarily due to crushing by adjacent drums, is the failure mode.

- Four (all in the bottom two rows) of the 12 drum lids were opened at impact.

- None of the 12 drums lost any of their contents

- Six of the drums (those in the bottom two rows that were expected to be more severely damaged) contained a red chalk dust inside the 10-mil polyethylene bag. One of the four drums in the array whose lid opened upon impact and contained sharp pieces of scrap metal had some evidence of chalk dust outside the bag. Trace amounts of the dust were on the lid of the 90-mil rigid liner. No chalk dust was present outside the drum. Close examination of the bag revealed two small puncture holes, apparently caused by the sharp pieces of metallic scrap placed in the drum.

PLG-1121 noted that it is apparent that a fraction of the contents in those drums whose lids opened on impact would have lost some of their contents had they not had a rigid liner and inner bag.

<u>Hanford Pallet Tests</u>

In the Hanford pallet tests (Westinghouse Hanford 1995a), the pallet load consisted of 4 drums (initially aligned in the vertical direction). Two of the drums weighed 500 lbs and the other two weighed 175 lbs. Metal banding was used to secure the drums to the pallet. The simulated waste was placed directly in the drum; i.e., the drum did not contain a polyethylene liner and no polyethylene bags were utilized. The payload consisted of sand and lead bricks.

The intent of the tests was to allow the dropping of one edge of the pallet to simulate a situation where the pallet was either pushed off the top of a stack or where the edge was tilted causing motion. Preliminary tests indicated that the pallet rotated 90° and landed on its side; i.e., the drums impacted in the lateral orientation. However, this was not the case for every test as drum pallets also rotated 180°, landing on the lid, and 135°, landing on the edge. The banding on one pallet slipped, scattering the drums at impact. The test plan specified that the drums be aligned so that the heavier drums fall onto the lighter drums. In addition, the lighter drums were also aligned on the pallet so that their lid locking ring bolts would strike the test surface first.

A total of six pallet tests were performed. Three of these tests were performed with Type 17C drums and the remainder were performed with Type 17H drums. All tests were performed with the bottom of the drums initially resting 11 ft from the test surface.

The results of the Hanford pallet drop tests with DOT-17C and DOT-17H drums are:

- For the four drums banded to a pallet that dropped 11 ft, spilled material occurred in only one of six drop tests (of 24 drums). Only one of the 175-lb drums spilled part of its contents (< 5 lbs or < 4.3%). In this test, the 175-lb drum landed on its edge. The average spill for 175-lb drums was < 0.42 lbs (or < 0.24%). The average spill for 500-lb drums was 0.0 lbs (mostly cushioned by the lower drums).

- Obvious (highly visible) damage to a drum is not necessarily an indicator of drum integrity. Extensive damage to the drum walls may not be indicative of container breach whereas a small amount of damage to the lid and upper sealing surface may cause lid separation and loss of container integrity.

- The bottom drums in a multiple (pallet) drum drop cushion the upper drums.

- The landing configuration of palletized drums is unpredictable.

- Container breach occurred at the drum/lid-sealing surface in all tests.

C.2.1.3 Metal Waste Box Tests

Standard waste boxes are DOT Type A containers used in TRUPACT II shipments. The only test data available for waste boxes are the full-scale drop tests performed by Rockwell International (Rockwell 1988) for DOT 7A steel boxes used at Rocky Flats. These tests involved two steel waste boxes stacked end-on-end. All seams, including the closure on both boxes were welded, rather than the SWB bolted lid configuration. One of the steel boxes (designated Test Container A) was lined with a fiberboard liner, 10-mil PVC liner and filled with coarse sand to a gross weight of 5,980 lbs. Five empty 55-gallon steel drums were placed in the waste box to permit filling the entire box with sand without exceeding the 6,000 lbs gross weight limit imposed by Rocky Flats for DOT 7A steel waste boxes. The second box (designated as Test Container B) was lined with a fiberboard liner, 10-mil PVC liner, and a 0.75-inch plywood liner on all interior surfaces. Pieces of stainless and mild steel and other metal fixtures were loaded into the lined waste box. The gross weight of this container was 3,480 lbs. No effort was made to "pad" the jagged edges of the metal scrap.

Two drop tests were performed. In the first test, the two steel boxes were stacked side-on-side with Test Container A (the heavier container) on top of Test Container B. This configuration maximizes the crushing force to the lower package. The distance from the bottom of Test Container B to the test surface was 15 ft.

The steel boxes used in the 15-ft test were also used for the second test. The two boxes were again stacked side-by-side but for this test, Test Container B (the lighter box) was placed on top of Test Container A. The distance from the bottom of Test Container A to the test surface was 25 ft.

The results of the Rocky Flats DOT 7A welded metal box drop tests are:

- For the 15-ft drop test, both boxes deformed as a result of the impact. However, there was no apparent failure of seams or closure welds. No contents were lost from either waste box.

- For the 25-ft drop test, the lower package (Test Container A) was substantially deformed and a pin hole leak was detected in Test Container B. The leak was located at a corner of the waste box, adjacent to a lifting loop. No loss of contents was apparent.

C.2.1.4 Pipe Overpack Container Testing

The POC was designed and developed at the Rocky Flats Environmental Technology Site for interim storage of certain TRU wastes, and was subsequently approved for shipping to WIPP. It consists of a sealed pipe within a 55-gallon (0.21 m^3) steel drum, with packing material between them. The packing material consists of a rigid drum liner (110 mil plastic adjacent to the steel drum) and fiberboard material (Celotex®) to separate the pipe from the liner; layers of Celotex® also separate the pipe from the drum lid and from the bottom of the drum (the pipe component rests on a disk of plywood, which rests on the Celotex®). Two pipe diameters are used: 15.2 cm (6 inch), made of Schedule 40 steel pipe, and 30.5 cm (12 inch), made of Schedule 20 steel pipe. The nominal wall thickness of the 6-inch pipe is 0.71 cm (0.28 inch) and that of the 12-inch pipe is 0.635 cm (0.25 inch). The inside length of the pipe is about 63.5 cm (25 inches) for either pipe diameter. The bottom of the pipe has either a formed (molded) end or a welded end, about 1.91 cm (0.75 inch) thick for either type of end. The top of the pipe has a welded flange, 2.54 cm (1 inch) thick, with a removable lid, 2.54 cm thick, fastened by bolts to the flange, sealed with an O-ring, and vented with a 2.54-cm (1-inch) diameter sintered-stainless-steel-medium High-Efficiency Particulate Air (HEPA) filter in a stainless-steel housing. The filter efficiency for particulates in the size range of 0.3 to 0.5 μm is rated at 99.97%. The pipe vent is to prevent pressure build-up within the pipe component, such as by hydrogen gas formed by the interaction of alpha radiation with plastic that may be in the waste or packaging, or by gases formed during a fire.

POCs were initially used for stabilizing and repackaging residues from the Rocky Flats plutonium processing mission. They included dry ashes, salts, fines, and similar materials; most are granular (including powders) but some are chunky. At Rocky Flats, waste was not placed directly into the pipes. One configuration for the secondary containers called for the residue material to be placed into a small metal can with a slip-lid, which is placed into one or possibly two plastic bag-out bags. This combination is then placed into a larger metal can with a screw-on lid, which is then placed in the pipe component. This combination is called “an interior package” below. The POC will hold from one to three interior packages. Other DOE sites have also used POCs for their TRU wastes that have higher alpha activity concentrations compared to the fissile concentration limit.

The robustness of the POC was assessed by Rocky Flats (RMRS 2000) using data taken from reports of Type B protocol testing conducted at the Sandia National Laboratories (e.g., crush, 30-ft drop, and 30-min fire tests), pressure tests, and Finite Element computer modeling of crushing and puncturing. While Rocky Flats concluded that the POC does not qualify as a DOT Type B container (because it was not subjected to the complete Type B protocol testing program and because the pipe component is vented);the tests that were performed were passed and it is expected that the puncture test would also have been passed, based on computer modeling and comparison with similar containers that are certified as Type B. The POC far exceeded the DOT Type A test requirements.

Sandia performed DOT Type B protocol testing on POCs and documented results in the following reports:

- *Testing in Support of On-Site Storage of Residues in the Pipe Overpack Container*, SAND97-0368 (Sandia 1997)

- *Analysis in Support of Storage of Residues in the Pipe Overpack Container*, SAND98-1003 (Sandia 1998).

The first set of Type B protocol tests is summarized in the Certificate of Compliance for the TRUPACT-II container (NRC 1997); these included assorted drop tests and one side-impact test. The second set of Type B protocol tests is summarized in the Sandia (1997) report; these included crush, drop, and thermal tests. These two sets of tests were solely for the purpose of qualifying the POC for interim storage, not for certifying that it qualifies as Type B package. No immersion tests were done, as they are precluded by the vents in the 55-gallon drums and the pipes. No spray, stacking, or penetration tests were done on the drum overpack as the POC already qualifies as a Type A package. None of the secondary (inner) containers were included in the SNL tests as they were not needed for the testing. Results for the crush and drop tests are as follows:

- Crush Tests: A POC was placed on an essentially unyielding flat, horizontal surface in an upright position. A flat steel plate, of area 1 m^2 (10.8 ft^2) and of mass 500 kg (1,100 lbm), was dropped onto the POC. The drop was initially guided until just above the POC, then released to free-fall the remaining distance; the height of the drop was greater than the 9 m (30 ft) required by Type B testing to allow for the friction along the guide wires. The velocity upon impact was the required 13.3 m/s (30 mph).[31] Four crush tests were performed, two with the 6-inch pipes and two with the 12-inch; both the formed and welded bottom ends were tested. Although the 55-gallon drums suffered damage, being shortened about 13 cm (5 inches), no pipe component was damaged. All of the pipes tested as leak-tight both before and after the crush tests.
- Drop Tests: Two sets of drop tests were performed. In the first set (NRC 1997), three configurations of POCs were dropped from 9 m. (For each test, two POCs were strapped together end-to-end to simulate the configuration in the TRUPACT-II container. In one test, the two POCs contained 6-inch pipes; in the second, 12-inch pipes; and in the third, one 6-inch and one 12-inch pipe.) For the second set of drop tests (Sandia 1997), two *bare* pipes, one 6-inch and the other 12-inch, both with welded bottoms, were dropped from a height of 10 ft (3.05 m) onto a flat, horizontal, essentially unyielding surface. The pipes were dropped with the bolted ends down, to achieve maximum damage. Although some of the lid bolts loosened during both sets of tests (even when the pipes were within

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[31] For a free-fall, the velocity after a drop of nine meters is $(2gh)^{½} = (2 \times 9.8\ m/s^2 \times 9\ m)^{½} = 13.3\ m/s$.

the 55-gallon drums), the pipe lids still remained fastened tightly enough that they continued to be leak tight after the drop test. In the first set of drop tests, a side-impact test was also performed on a TRUPACT-II container filled with 14 POCs. The TRUPACT-II container normally has both inner and outer containment vessels separated by crushable foam, but for this test only the inner containment vessel was used (i.e., without the foam or outer containment vessel). The pipe components were undamaged in this test; all of the pipes were shown to be leak tight following the side-impact test.

Because no Type B protocol puncture testing was done on the POCs, finite element modeling was performed to simulate an accident involving the collision of a forklift tine with the POC. Modeling was also done to simulate the falling of heavy objects (such as roof members) onto the POC, progressively increasing the energy of the impact until failure occurred. Impacts were modeled with POCs having both the 6-inch and 12-inch pipe components.

The forklift-tine impact was modeled with a forklift traveling at 4.5 m/s (10 mph); the forklift weighed 12,250 lb (5,670 kg mass). The drum was assumed to be against a rigid wall. The tine was modeled very conservatively, having a squared-off end with sharp corners and being made of an extremely dense material in order to simulate the momentum of the forklift. (Real tines have blunt ends without sharp corners and are made of steel with density about the same as that of the drum material.) This scenario represents a more severe accident than does the Type B protocol puncture testing, which uses a cylindrical rod of 15 cm (6 inches) diameter with beveled edges and a momentum corresponding only to that of the container, not that of the forklift; however, the impact velocity modeled is the same as for the Type B test, i.e., 4.5 m/s (10 mph).

The drum elements were defined to fail (tear) in this model when the equivalent plastic strain (fractional deformation) reached 20%; the wall of the pipe component was defined to fail when the equivalent plastic strain reached 80%. These strain limits were considered by the modelers to be representative of the materials used. The steel of the 55-gallon (0.21 m^3) drum was found to offer little resistance to the tine impact; the packing material (the Celotex®) offered essentially no resistance, although its presence added enough stiffness behind the steel of the drum to allow the tine to penetrate the steel quickly rather than bend it significantly. The resistance offered by the drum slowed the tine speed from 4.5 m/s (10 mph) to 4.2 m/s (9.4 mph).

The finite element modeling results are:

- The 12-inch pipe component was able to stop the tine and cause it to rebound. The strain in the wall, however, exceeded the 80% limit at the square corners of the tine, resulting in small tears at these corners. Had the corners of the tine been blunt, as they really are, it is probable that the 80% limit would not have been reached at these corners, or anywhere else. This simulation was for a dead-center impact of the tine onto the pipe.

- The 6-inch pipe component was also able to stop the tine but it suffered considerably more damage than did the 12-inch pipe component; the larger wall-thickness-to-diameter ratio (compared to the 12-inch pipe) means that it is stiffer, which decreases the amount of bending and increases the amount of tearing. The tine was able to penetrate the 6-inch pipe but the tear remained localized. This simulation was for a dead-center impact of the tine onto the pipe. Another impact was also modeled, in which the tine struck the pipe off-center, to see if the tear would be worse; it wasn't. In this simulation, the pipe was dented but it moved away from the tine, to the side and into the packing material, and no tear occurred.

- POCs are vulnerable to being crushed by a collapsing concrete building, but not prefabricated metal buildings. The Rocky Flats report (RMRS 2000) noted that finite element modeling of the impact of falling heavy objects was done only for the bare pipe components, not the complete POCs, therefore, the results of these simulations can be used in either of two ways. First, the modeling results can be considered conservative because the drum and its packing material absorb some of the impact, as was demonstrated by the Type B crush tests. For example, in the top-impact crush tests, 500 kg (1,100 lb_m) steel plates were dropped on the POCs; the drums were shortened by about 13 cm (5 inches) but the pipe components were undamaged. The side-impact test also showed that the drum and its packing material absorbs some of the impact energy. Alternatively, the kinetic energy of the falling steel plate ($\frac{1}{2}mv^2 = 0.5 \times 500 \text{ kg} \times (13.3 \text{ m/s})^2 = 4.4\times10^4 \text{ J} = 4\times10^5$ inch-lb), which was absorbed by the drum and its packing material, can be added to the kinetic energy assumed in the modeling to arrive at an estimate of the total kinetic energy involved in the simulation.

Although the POC was determined by finite element modeling to be vulnerable to the forklift tine puncture due to the chisel design assumption and very small impact area, the frequency of a POC puncture by a forklift should be assumed to be Extremely Unlikely. This is based on the following argument presented in the Rocky Flats *Hazard Category 2 Waste Management Facilities Documented Safety Analysis* (Kaiser-Hill 2004):

> *The puncture of the POC 55-gallon drum is considered an anticipated event. However, NSTR-001-97 (NSTR, 2000a) states that the likelihood of a POC pipe component puncture is extremely small, but credible. It also states that the forklift tine type of accident is not only quite unlikely (the conditions have to be exactly right) but corresponds to an accident more severe than the puncture test for Type B containers. For a pipe component puncture to occur the finite element modeling assumed that: (1) the forklift was traveling 10 miles per hour (mph) (the storage configuration does not lend itself to traveling 10 mph and the maximum speed of most electric forklifts is 10 mph), (2) the forklift weighed 12,250 lbs. (most of the forklifts used inside waste storage facilities are closer to 8,000 lbs.), (3) the drum was against a rigid wall (many facilities have sheet metal walls), (4) the forklift tine had a squared-off end with sharp corners (real tines have blunt ends without sharp corners), (5) the forklift tine was made of an extremely dense material (real tines are made of steel with density about the same as the drum material), and (6) a dead-center impact occurred between the tine and the pipe component (the storage configuration does not lend itself to being impacted dead-center). These are all conservative assumptions. Therefore, due to all of the conditions that must occur, the frequency of this accident scenario is probably closer to beyond extremely unlikely but is qualitatively evaluated as an extremely unlikely event. In addition, due to all of the conditions required for a POC puncture, it is assumed that only one POC is punctured in the accident scenario.*

C.2.2 Impact and Drop Accidents

C.2.2.1 Single Container Drops

The Sandia drop-test of DOT-17C drums from varying heights resulted in four lid failures occurring in the 17 drop tests. This is equivalent to a DR of about 0.25 (i.e., 4 failures / 17 tests). However, only one test resulted in a “slight loss of contents”. The worst damage occurred with the heaviest drum (748 lb) and the highest impact velocity (this was the only case in which the inner plastic bag was broken and the only test in which contents were lost). Although only a qualitative description of this loss was provided, the PLG-1121 DR evaluation (WIPP, 2000) assumed less than 5% of the contents were lost, thus a DR of 0.05 for sand-like contents with inner plastic bags. No lid failures (and thus, no material releases) occurred for drop heights less than 44 ft (13 m) or impact velocities less than 35.55 mph. That drum experienced lid failure but not loss of contents at 44 ft, although two other drums with similar weights (678 & 687 lb) survived higher drops (68 & 57 ft).

Some of the limitations of the Sandia test related to establishing conservative DRs include:

- Drums were dropped in a lateral configuration. Impact at an oblique angle with the lid, and especially impacting the bolts on the locking ring, was not tested. An axial impact to top and bottom was also not tested.
- Heavier drums up to the 1,000 lb shipping limit for 55-gallon drums were not tested.
- Other material forms may behave substantially different than the sand that was a surrogate for TRU wastes. The surrogate form was “high-density sludge” that is a sand and water mixture. Other TRU waste forms were not tested.
- DOT-17H drums were not tested.

The results of the Hanford drop tests for DOT-17C and DOT-17H drums concluded that all six single 1,000-lb drums dropped from 11 ft and impacting the locking ring at 45° to horizontal resulted in drum failure and spillage of some contents. Container breach occurred at the drum/lid-sealing surface in all tests. Obvious (highly visible) damage to a drum is not necessarily an indicator of drum integrity. Extensive damage to the drum walls may not be indicative of container breach whereas a small amount of damage to the lid and upper sealing surface may cause lid separation and loss of container integrity. For Type 17C drums, the maximum spill was 250 lbs (27% of the drum contents) and the average for three tests was 103 lbs (11% of the drum contents). For Type 17H drums, the maximum spill was 500 lbs (53% of the drum contents) and the average was 170 lbs (18% of the drum contents). For maximally loaded drums of sand-like contents with no inner packaging and based on the most limiting container (DOT-17H), this implies a 0.5 DR based on the maximum amount spilled.

Although over-packed drums were not tested and would be expected to perform much better than the Type 17H drum, a conservative DR of 0.25 is chosen based on the Type 17C results for maximally loaded drums of sand-like contents with no inner packaging (i.e., 27% or 250 lbs were spilled).

However, most TRU waste drums are not loaded near the 1,000 lb shipping limit. The Hanford drum test report noted that less than 1% of the Hanford waste drums at that time exceeded 1,000 lbs and that more than 97% of the WHC drums weighed less than 500 lbs[32] (Westinghouse Hanford 1995a). A search of the WIPP data base showed that the maximum weight of a 55-gal drum was 360-kg/793-lb, the 90th percentile weight was 213-kg/433-lb, and the average weight was 133-kg/203-lb. The most limiting release from the Sandia 17 drop tests with Type 17-C drums and inner packaging that resulted in slight loss of contents was for a drum weighing 748 lb containing waste in 90-mil liners dropped from 44 ft. Although the amount of "slight" spillage of the simulated sludge was not measured, a DR of 0.1 is chosen as a conservative estimate to bound releases from 55-gallon containers of contaminated materials dropped for the fourth or higher tier of stacking, considering the weaker DOT Type 17-H drum. This also reflects that impact could occur at an oblique angle on the locking ring failing these lighter containers, as implied by the 11 ft drops of 1,000 lb drums. This applies to 55-gallon drums stacked four or more high (i.e., a 10-foot fall based on a typical drum height of 3 feet plus a nominal 4 inch pallet per tier). For sand-like TRU wastes, a DR of 0.5 is assumed to account for more spillage of contents, which is about an order of magnitude more conservative than the "slight loss of contents" from the 44-ft drop. The ARF and RF associated with a 4th tier fall are based on the "low-energy impact" stress described in Section 4.5.3.1, however, a 5th tier fall is based on the "high-energy impact" ARFs/RFs.

Second tier drums are not deemed vulnerable to a spill if dropped or knocked off the lower tier (approximate 3.3 ft) due to their DOT Type A 4-ft qualification, i.e., DR = 0. For falls from a third tier (approximately 6.7 ft), the drums would not likely fail due to their 4-ft qualification requirement and the discussion above regarding drop testing results. However, since this is a fall with impact energy greater than that to which the drum is qualified, assuming no release would be non-conservative. Therefore, a factor of 10 less release than that from a fourth tier fall is recommended, i.e., a DR of 0.01. This is believed to be sufficiently conservative because: (1) the Sandia tests concluded that no lid failures (and thus, no material releases) occurred for drop heights less than 44 ft; and (2) the worst damage occurred with the heaviest drum (748 lb) and the highest impact velocity, but this was the only case in which the inner plastic bag was broken and the only test in which a minor amount of sand-like TRU wastes contents was lost, e.g., estimated to be less than 5%, and for contaminated wastes, even less release is expected. The ARF and RF associated with this magnitude of breach are based on the "spill" stress described in Section 4.5.

A DR of 0.01 is also recommended for a low-speed vehicle crash into multiple containers, since the Sandia tests concluded that no lid failures (and thus, no material releases) occurred for drum impact velocities less than ~35 mph. A vehicle traveling at "low-speeds" is interpreted to mean less than ~10 mph typically associated with traveling in congested or tight areas around drum storage sites. For vehicles whose speed may be restricted by physical layout of the facility/site and associated obstacles, but whose speed can't reasonably be assumed to be less ~10 mph, a DR

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[32] The average drum weight is approximately 127 lb (Fluor Hanford 2004a)

of 0.1 is recommended based on assumed impact energy similar to falling from the fourth tier of stack drums (i.e., this is considered to be a "moderate to severe" stress). At speeds greater than ~35 mph, a DR of 1.0 (i.e., "catastrophic stress") is assumed for those drums directly crushed, but a DR of 0.1 can be assumed for those adjacent drums that could be breached by the crushing forces from directly-impacted drums (Fluor Hanford 2004).

For overpacked containers, there are no test data available. For the single package drop event, a factor of two credit is believed to be a reasonably conservative estimate, e.g., a DR of 0.05. The involvement of 5% of a waste container inventory is judged to be conservative because two metal containers should provide some added protection for drop events.

Standard waste boxes are approximately four feet high; therefore boxes may be susceptible to drops/falls that could result in a radioactive release if they are stacked above the second tier, just like 55-gallon drums (i.e., DR = 0 for second-tier SWB fall). Since there are no tests for the SWBs, some insight is available from the results of the Rocky Flats DOT 7A welded metal box drop tests. There was no apparent failure of seams or closure welds and no contents were lost from either waste box for the 15 ft drop. For the 25-ft drop test, a pin hole leak was detected in Test Container B. The leak was located at a corner of the waste box, adjacent to a lifting loop. No loss of contents was apparent. Due to the bolted-lid and gasket configuration of the SWB, its performance should be similar to the welded box. However, due to the lack of direct test data and that the container is only required to meet the DOT Type A drop test for four feet, and its much larger load capacity (4,000 lb), a DR of 0.1 is recommended for "moderate to severe" accident stresses and falls from a fourth tier (i.e., this exceeds the fourth-tier drum fall height of about 10 ft), the same as for the 55-gallon drum with contaminated items. This is also based on simple compression stress in the wall and axial buckling calculation performed in the PLG-1121 report (WIPP, 2000) that concluded that Type 17C drums appear to be stronger than the SWBs, which in turn are stronger than the Type 17H drums. However, the lids for the SWBs are bolted to the body of the container implying that lid separation is much less likely for the SWBs than for the drums. For moderate-to-severe stress on SWBs with sand-like TRU wastes, the drum DR of 0.5 is reduced by a factor of 2 to a DR of 0.25 due to the much larger volume of the SWB that would provide self-shielding of the contents such that not all of contents could experience the energy from the impact. For SWB falls from the third tier and for "minor stress" impacts, the SWB DR is assumed to be the same as for drums, i.e., DR = 0.01.

There are no drop experiments with welded or closed pipes nested within steel drums (often used with remote handled wastes). Therefore, a DR of 0.01 for a fall from a fourth tier is recommended based on the same DR for a minor stress for the 55-gal drum fall from a third tier, and no release for shorter falls.

C.2.2.2 Palletized Drum Falls

A pallet of drums may be dropped or knocked off a stacked storage array. A payload of drums could also be dropped during loading of a shipping container with a crane. Both events could result in significant damage of up to the total number of drums on the pallet or in the payload with release of the contents. The Material-at-Risk (MAR) is assumed to be the maximum content of a drum multiplied by the number of drums on a pallet or shipping payload. For example, this could involve four 55-gallon drums on a pallet, three 85-gallon overpacked drums on a pallet, or 14 plastic-wrapped drum configurations for the TRUPACT II shipping container.

The following evaluation of dropping the TRUPACT-II payload was performed for the WIPP site based on the palletized drum drop tests (WIPP, 2000)[33]. Selected excerpts from the PLG-1121 report are presented next. This is used to then recommend reasonably conservative DRs. From this evaluation, DRs for palletized drums are then recommended.

Scenario CH2 involves a crane failure that results in the drop of a TRUPACT II pallet consisting of up to two layers of drum seven-packs or two SWBs from a height of approximately 10 ft on to the floor of the Waste Handling Building (WHB).

As noted earlier, no test data is available for the WIPP drum seven-pack configuration. Furthermore, none of the reported tests involved drums landing on their bottom surface (which is the most likely orientation for the crane drop scenario). As noted in Section 2.1.2 of this appendix, a four high by three across array of Type 17C drums was dropped from a height of 15 ft in a test performed by Rockwell International (Rockwell 1988). These drums were initially oriented and landed in a lateral configuration; i.e., on their side. The gross weight of the drums in the Rockwell International tests ranged from 116 lbs to 666 lbs with the lighter drums in the bottom two rows. Four of the twelve drums suffered a gap between the lid and drum wall; however, no loss of contents was reported. Each drum had a rigid polyethylene liner with lid and the simulated waste was placed in an inner plastic bag. Had it not been for the liner and bag, it is likely that some of the contents of the four drums that developed gaps as a result of the impact would have been released. All of the drums that experienced damage in the form of these gaps were located in the bottom two rows of the array. It is readily apparent that the bottom two layers of drums “cushioned” the impact that the upper two rows of drums experienced.

The six pallet tests performed at WHC involved a “four-pack” of drums. Two of the drums had gross weights of approximately 175 lbs and the other two weighed approximately 500 lbs. Three tests were performed with Type 17C drums and three tests were performed with Type 17H drums. Although the same test was performed, the drums sometimes landed on their edge, sometimes on their side, and sometimes on their lids. The tests were all performed from a height of 11 ft. No lid separation was observed in any of these tests; however, one drum lost a small amount of its contents (< 5 lbs or 4.3% of its contents).

Westinghouse Hanford Corporation also performed three single Type 17C drum drop tests and three single Type 17H drop tests from 11 ft. In each test, the gross weight of the drums was 1,000 lbs and material (sand and lead bricks were used to simulate the waste) was released upon impact. The tests were designed so that the drum would land on its edge with the locking ring bolt at the lowest position. For the Type 17C drums, the maximum loss was 250 lbs (27% of the contents) and the average for the three tests was 103 lbs (11% of the contents). For the Type 17H drums, the maximum loss was 500 lbs (53% of the contents) and the average loss was 170 lbs (18% of the contents). The three tests performed for each type of drum were conducted in a

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[33] The PLG-1121 recommendations were revised to address additional conservatism for the Contact Handled (CH) Waste DSA revision 9 (DOE/WIPP-95-2065).

similar manner; however, for the Type 17C drums, the losses of contents were 250, 30, and 30 lbs. For the Type 17H tests, the loss of contents were 500, < 5, and < 5 lbs. The variation in releases makes it apparent that there are random contributions to the extent of damage.

The indirect evidence indicates the following:

- The likelihood of failure is significant for drums (with a gross weight of 1,000 lbs) that are dropped on their edge from a height only slightly greater than 10 ft. Since 1,000-lb drums will be accepted by WIPP, it can be argued that heavy drums that directly impact the floor of the WHB will be breached.

- The additional loads induced by overlying drums or SWBs significantly increase the degree of damage to the bottom layer of waste containers that first contact the floor.

- The extent of damage to overlying drums is significantly mitigated by the energy absorbed by the underlying drums.

Therefore, in the absence of WIPP-specific seven-pack data for drops from 10 ft, it is conservatively assumed for scenario CH2 that seven drums are breached. This level of damage can be interpreted in two ways: (1) all seven of the drums on the bottom layer of the load are breached but none of the top layer are breached; or (2) one or two drums from the bottom layer are not breached but a like number from the upper layer are breached. The former interpretation is believed to be the more accurate representation.

It is judged that the loss of contents from the seven breached drums would be limited to an average release (per drum) of approximately 5% based on the following interpretation of test results. The WHC Type 17H tests (Westinghouse Hanford 1995a) indicated an average loss of 18% for three single drum tests from 11 ft. However, these tests were performed with drums having a gross weight of 1,000 lbs and the drums were dropped at an angle such that the lid locking ring would strike the test surface first, maximizing the extent of damage.

In the WHC pallet tests of Type 17H drums from a drop height of 11 ft, only one drum lost any of its contents (amounting to approximately 4.3%). In this particular test, the damaged drum landed on its edge.

The value of 5% is selected to represent the conditions at WIPP because it bounds the release measured in the WHC tests.

The above loss of contents percentage (5%) applies to drums containing a “sand like” material. Less material will be released if it is in larger pieces such as filters, pieces of wood and metal, etc.; i.e., “bulkier materials.” For these cases, it is estimated that the average loss can be reduced to approximately 2.5%. Note that the ARF will distinguish the amount of material actually released to the local atmosphere by various waste forms. It should be noted that this only addresses the contents of the container. Since the analysis addresses the drop and impact of a pallet of containers, the contents are subject to shock-vibration forces and, if the container fails, some fraction of the material that is airborne inside the drum can be expelled by the temporary compression of the contained volume. For this reason, the vibration stress is factored into the DR recommendations in this section that are more conservative than the PLG-1121 recommendations.

For the two 7-pack plastic-wrapped drum configuration with sand-like materials, a DR of 0.5 was recommended, i.e., either the lower 7 drums all breached (the more likely consequence), or half the 14 drums on either tier failed. Since 14 drums experience the shock and vibration from the fall, the DR should be based on the 14 drums per the traditional definition of a DR as defined in Section 4.4 of this Standard. Together with the 0.05 DR for sand-like materials, this results in a 0.025 DR when applied to the 14-drum MAR. For the bulkier contaminated material release, the PLG recommendation is half this value, i.e., 0.0125 DR affecting the 14 drums. These values may not be sufficiently conservative, but would at least represent the most likely consequences from a "best estimate" risk assessment perspective.

The PLG recommendation of 0.05 was based primarily on the 4.3% spillage from the WHC pallet test. The discussion considered the average loss of 18% per drum for the 7 drums from the 1,000-lb single drum drops, but the single drum drops were not chosen as the basis for the pallet fall recommendation. Although the dropped load is likely to impact on the bottom surfaces of the 7-pack as stated above for a crane drop, the possibility of the wrapped configuration rotating and impacting at an angle to the lid and locking ring cannot be precluded. Therefore, the results of the WHC single drum drops would provide a more conservative estimate for this scenario, and for the extrapolation to dropping palletized drums.

The average loss for the 7 drums is equivalent to 1.26 drum contents (7 x 0.18). If the maximum 53% were included for the first two drums to impact the floor at an angle, this would result in the equivalent of 1.96 drum contents (2 x 0.53 + 5 x 0.18). The DR for the 7 drums would be 1.96 / 7 = 0.28, and the overall DR for the 14 drums involved in the fall would be 1.96 / 14 or about 0.14. The effect of adding the maximum spill for two drums is to increase the average DR by about 56% (1.96 / 1.26). This approach is based on the concept similar to that for estimating a bounding MAR involving multiple containers as presented in Section 4.3, "Bounding the Material-at-Risk". Considering other uncertainties in drum performance, the 0.14 value is rounded to 0.2 for sand-like materials and 0.1 for bulkier contaminated items for this scenario of a crane drop of the two 7-pack wrapped drum configuration.

This seems to be a reasonable extrapolation for dropping banded pallets. By crediting container banding requirements, which requires drums that are going to be stacked above the second tier to be banded to each other, a pallet of drums falls in such a manner that one drum on the pallet is the first to impact a concrete floor and the other three drums impact the first drum causing it to breach (DR = 0.25). Assuming the 53% from the maximum drum spillage, the overall DR for the 4 drums is 0.13 for sand-like materials, which is one-fourth the unbanded recommendation, and about the same as the 0.14 DR for the 14-drum drop discussed above. Considering other uncertainties in drum performance, the 0.13 value is rounded to 0.15 for sand-like materials for this scenario of dropping banded, palletized drums from the third, fourth, or fifth tier. For bulkier, contaminated items, the 0.25 DR is applied to the unbanded recommendation of 0.1 DR, which results in 0.025 DR. However, considering uncertainties, and rounding, a 0.05 DR is recommended for banded, 4-drum palletized falls of contaminated items.

C.2.2.3 Waste Container Puncture by Forklift

A radioactive material spill may occur as a result of puncturing a TRU waste container by vehicle handling equipment such as from the tines of a forklift. For scenarios involving forklift tine impacts, the specific parameters to be used are based on container type and the container contents. Forklift operator error can result in a puncture, by the forklift tines, of either two adjacent TRU drums located on a pallet, one POC, one SWB, or one TDOP[34].

DOE-HDBK-3010-94 discusses this scenario for contaminated waste items in a container and recommends the DR/ARF/RF parameters to be 1.0/1E-3/0.1. The RF was set to 0.1 (from 1.0) to account for the degree of shielding provided by the waste drum. However, it is considered more appropriate for the DR to be set to 0.1 and the RF left at 1.0 since the energy of the accident is not anticipated to decrease the proportion of respirable particles. This RF value is appropriate for TRU and may be adjusted if there is site-specific characterization of the particle size distribution.

For breached drums, it is conservatively assumed that 10% of the material exits the waste container(s) following the removal of the forklift tines from the container(s). The involvement of 10% of a waste container inventory is judged to be conservative based on the following considerations: (1) a forklift tine puncture only creates a small breach of the container, (2) few, if any, non-liquid wastes would “flow” out of the container through the breach, (3) any packaging (plastic) in the container will tend to inhibit the “flow” of waste due to recovery from the breach rather than having permanent deformation as might be the case with the metal container wall. Sand-like waste material that is capable of “flowing” could clog at the exit before much material has passed through the container hole, however, is conservatively assumed to lose all of its contents, i.e., DR = 1.0..

A TDOP container or SWB 4-pack could also be punctured. At most, two of the 55-gallons drums packaged in the over-pack could be punctured. This is considered an unconfined material release since the internal packaging of the 55-gallon drum and the SWB will be breached and does not contain the material nor prevent it from being released to the atmosphere. It is conservatively assumed that 5% of the material exits the over-pack configuration following the removal of the forklift tines from the waste container. The involvement of 5% of a waste container inventory is judged to be conservative based on the following considerations:

- a forklift tine puncture only creates a small breach of the container,
- few, if any, non-liquid wastes would “flow” out of the container through the breach,
- any packaging (plastic) in the container will tend to inhibit the “flow” of waste due to recovery from the breach rather than having permanent deformation as might be the case with the metal container wall,
- waste material that is capable of “flowing” is most likely to clog at the exit before much material has passed through the container hole; and

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[34] or four 55-gallon drums overpacked in one SWB.

- waste material not only has to exit the punctured 55-gallon drums but also has to exit the void space in the over-pack secondary confinement.

A factor of two reduction for forklift puncture of a 55-gallon drum with contaminated items is conservative. Therefore the DR for puncturing an over-pack container is 0.05.

The forklift tine accident with the POC was evaluated in the Finite Element modeling, discussed above. A breach was shown possible for the POC holding the 6-inch pipe component (but probably not for the 12-inch, for a realistic tine shape). This type of accident is not only quite unlikely (the conditions have to be exactly right) but corresponds to an accident more severe than the puncture test for Type B containers, but was considered due the presence of the forklift tines during normal material handling. A tine that punctures the 6-inch pipe component would probably also puncture an interior package within it; only one interior package would be breached (2 pipes are stacked if a 12-inch pipe is not loaded). The tine puncture remains localized so that material can escape only through the small tear, once the tine is removed. As long as the POC remains vertical, the amount of material that would escape through this opening and into the air would be very small. The amount escaping would depend upon the nature of the material within the interior package; if it were chunky or bulky contaminated items, then virtually none of the material would escape but if it were a fine powder with little self-adhesion, some of it would be pulled out with the tine and may continue to flow out until the weight of the material above the hole can no longer overcome the flow resistance. The distance the powder would have to travel before reaching the air would be about one foot, which means that much of the powder escaping from the interior package would be trapped in the packaging before reaching the edge of the drum; the DR would be expected to be quite small. Should the POC topple over after the tine is removed and should the puncture hole become oriented downward, much of the material could pour out if it were a fine powder; on the other hand, should the hole become oriented upward, none would pour out. Because there are no experimental data for this type of accident, the DR can only be estimated. For fine powders, the maximum value would be 1.0, assuming the POC held only one interior package, but the fall distance is very short. The DOE-HDBK-3010 recommended ARF/RF values of 2E-03 and 0.3 for < 3 m powder spill height would certainly be bounding, but with a 1.0 DR is considered overly-conservative. Therefore, a 0.1 DR is recommended with the free-fall spill ARF and RF for puncture of a POC. For a forklift tine puncture of a POC with contaminated bulky items, the DR is reduced by a factor of 2 to 0.05.

For the SWB, the tines would create two holes as opposed to one for a drum. The DR is not doubled, however, because volume of the crate is larger than that of a drum and each hole in a box represents a smaller relative leak path compared to that of a drum.[35] Considering that the SWB has about 9 times the volume of a 55-gallon drum (i.e., 66.4 / 7.45 ft^3), and its load capacity is a factor of 4 higher (i.e., 4,000 / 1,000 lb), a factor of 2 reduction is conservative considering that the contamination may not be uniformly distributed. Therefore, the DR is 0.05 for SWBs. For sand-like materials, a DR of 0.5 is assumed due to the free-flowing potential of the contents, i.e., the material could flow out until the weight of the material above the hole can no longer overcome the flow resistance as mentioned earlier. This value is much larger than a

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[35] Alternatively, two boxes could be modeled with one hole each, but the effect would be the same.

forklift puncture of a POC due to the much larger volume of the SWB, however, it is a factor of 2 less than the 55-gal direct-loaded drum of sand-like materials (i.e., 1.0 DR).

C.2.2.4 Compressed Gas Cylinder Missile Impact

A radioactive material spill may occur as a result of puncturing a TRU waste container by compressed gas bottles that become airborne missiles. Compressed gas cylinders (*e.g.,* nitrogen, acetylene, propane, etc.) are routinely used during maintenance activities. If a cylinder valve were accidentally sheared off during cylinder handling (change-out), the cylinder would become an airborne missile that could potentially impact and puncture nearby waste container(s) resulting in a release of a portion of the container contents.

The amount of damage caused by the impact of a compressed-gas-cylinder-turned-missile depends upon many factors. These include the internal pressure of the gas in the cylinder, the mass of the cylinder, the molecular weight of the gas, the cross-sectional area of the cylinder, the robustness of the target, the forces opposing the cylinder motion, and the manner in which the missile strikes the target. The scenarios of concern are those in which the internal pressure of the cylinder is high enough that the compressed gas exits through the break (say, a broken valve stem) at sonic velocities. The internal pressure must be at least about twice atmospheric pressure for this to occur, and this is the case for the four typical compressed gases considered here (hydrogen, acetylene, oxygen, and propane). The theoretical maximum velocity that could be attained by such a missile is the sonic velocity of the gas in the cylinder. The cylinder would never reach this velocity because of opposing forces, air resistance in part but mostly because of the drag associated with friction on the floor and banging into other objects, and because the cylinder will expel all its gas before such a speed could be attained. Without knowing the precise layout of the objects in the facility that could impede the cylinder or the direction of motion of the cylinder, it is impossible to determine its ultimate speed.

An estimate can be made, however, of the speed it could attain at impact by assuming it starts with zero velocity and travels a certain distance before impact, the distance depending on the available space to travel. The Rocky Flats SARAH (Kaiser-Hill 2002) has shown that for a short travel distance available for small drum storage areas within nuclear processing facilities, the hydrogen and oxygen cylinder missiles could breach 55-gallon drums but acetylene and propane cylinder missiles would not according to the calculation. For short distances, due to the higher energy of the cylinder missile compared to the forklift tine puncture, a 0.5 DR is recommended for puncturing 55 gallon drums, and a factor of two credit for overpacked drums, i.e., DR = 0.25. This assumes impact and puncture of one drum.

For a large waste container storage area, the travel distance is likely sufficient for the cylinder to become airborne or impact containers at a much higher velocity. Due to the higher energy of this event, a DR of 1.0 is recommended for impacting drums and overpacked drums for the larger travel distances. A compressed gas cylinder missile may impact more than one drum considering industry experience where missiles have breached unreinforced masonry walls. Three drums are considered sufficiently conservative for this scenario.

The SWB and the POC, however, would not be breached by any of the compressed gas cylinder missiles for relatively short distances for small drum storage areas (Kaiser-Hill 2002). Although the recommended value of DR for SWBs and POCs is zero, there may be an exception. If the cylinder were to travel a great distance, such as down an empty aisle separating rows of waste packages, and the cylinder were airborne the entire time, it might be possible for a cylinder to attain sufficient speed to rupture a SWB. For the longer travel distance, the SWB is expected to experience the shock and vibration forces of the cylinder missile, therefore, no reduction in DR is recommended.

Due to the fiberboard material (Celotex®) fill in the POC, the robust design of the Schedule 20 or 40 inner pipe, and the POC drop test performance, no release is expected from a cylinder missile impact. The POC was determined to be vulnerable to the forklift tine puncture due to the chisel design assumption and very small impact area. This is not the case for a cylinder missile impacting the 55-gallon POC drum with the fiberboard fill.

Tornado-generated missiles or windborne missiles are assumed to cause damage similar to the gas cylinder missile, rather than the forklift tine punctures. Therefore, the same DRs apply.

The ARF/RFs associated with missile impacts to waste containers are considered "low-energy impacts" as described in Section 4.5 due to the drum absorbing some of the impact energy from the missile. Compared to a forklift puncture, the amount released is a factor of 10 higher due to the 1.0 DR.

C.2.2.5 Damage Ratio Summary for Accidents

Based on extrapolations and interpretation of the test data discussed in this appendix as well as DOE Complex precedence established for SB development, Damage Ratios for mechanical impacts or drops are summarized in Table A.4.4.4-1. These DR recommendations apply a gradation based on energy imparted and container robustness for the range of container breaches presented.

TABLE C.-1 Container Drop and Impact Damage Ratios

Accident Stress	Damage Ratio (DR)[d]			Reference
	Drum	SWB and RH canister	POC	
1. Stress within container qualifications	0	0	0	Containers of sound integrity per Section 4.4.1 dropped from 4 ft or less (e.g., 2nd tier[a] in stacked array).
2. Minor stress causes breach, e.g.: - Single container or unbanded palletized containers dropped from 3rd tier in stacked array - Multiple containers impacted by low-speed vehicle (e.g., less than ~10 mph in congested or tight areas) - Containers containing closed pipes or welded containers that are dropped from 4th or 5th tier in stacked array	0.01	0.01	0	Section C.2.2.1 and C.2.2.2
3. Container(s) punctured by forklift tines: - Contaminated solids - Sand-like materials	 0.1 1.0	 0.05 0.5	 0.05 0.1	Section C.2.2.3
4. Single container or unbanded[b] palletized containers dropped from 4th or 5th tier in stacked array: - Contaminated solids - Sand-like materials	 0.1 0.5	 0.1 0.25	 0 0	Section C.2.2.1 and C.2.2.2
5. Moderate to severe stress causes breach, e.g.: - Multiple containers impacted by a vehicle whose speed may be restricted by physical layout of the facility/site and associated obstacles, but whose speed can't reasonably be assumed to be < ~10 mph - Vehicle crash affecting multiple containers, but not in the first row directly crushed by the vehicle (low or high speeds)	0.1	0.1	0	Section C.2.2.1 and C.2.2.2

TABLE C.-1 Container Drop and Impact Damage Ratios--Continued

Accident Stress	Damage Ratio (DR)[d]			Reference
	Drum	SWB and RH canister	POC	
6.Catatrophic stress causes breach, e.g.: - Containers directly impacted by high-speed vehicle with crushing force - Container(s) impacted by compressed gas cylinder traveling long distance and/or airborne - Container(s) impacted by tornado- or wind-generated missile	1.0	1.0	0[c]	Section C.2.2.1, C.2.2.2, C.2.2.3, and C.2.2.4

[a] Stacking height applies to 55-gallon drums stacked three or more high (i.e., typical drum height of 3 feet plus a nominal 4 inch pallet per tier).

[b] Credit a factor of 2 reduction for banding 4 drums to a pallet as discussed in Section C.2.2.2.

[c] Use natural phenomena hazard DRs in Table 4.4.5-1 if severe crushing is possible.

[d] For vitrified/concreted wastes in metal containers, a 50% reduction in the DRs associated with the metal container is generally recommended for contaminated solids.

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Appendix D

Criteria for TRU Waste Drums Requiring Venting/Purging Due to Elevated Internal Hydrogen Concentrations

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Executive Summary

A criterion is needed for safe handling of a 55-gallon transuranic waste drum to prevent the catastrophic ejection of the drum lid due to the deflagration of an internally accumulated hydrogen gas-air mixture in the drum. This event can occur if the hydrogen-air mixture deflagrates and generates sufficient internal pressure (on the order of 100-psig or more) in a short time frame (less than a few seconds). If internal pressure is generated over a much longer time frame (such as a minute or more), the drum closure has time to respond and results in seal-failure (venting) at a pressure in the range of 10- to 20-psig. Although 4% by volume (vol%) of a hydrogen-air mixture can burn, the combustion is not complete and generates a pressure much less than the adiabatic isochoric complete combustion pressure that is approximately eight times the initial pre-combustion pressure. Complete burning does not occur until hydrogen reaches 8- to 12-vol% in air. Burning does not propagate in the downwards direction until the hydrogen concentration exceeds 9-vol%. Experimental data shows that "lid-loss" does not occur in new Department of Transportation Type 7A drums until the hydrogen concentration exceeds 15-vol% in air. To compensate for the uncertainty of the structural strength of "legacy" drums and the variation in wall thickness between 17-C and 17-H drums, a conservative value of 8-vol% hydrogen is chosen as the minimum hydrogen concentration that may generate sufficient internal pressure to result in catastrophic failure with lid loss and the concentration where special controls (e.g., aspiration wait time for adequate diffusion, segregation, etc.) must be instituted until the hydrogen concentration is below this level.

D.1 Introduction

Hydrogen (H_2) gas generation in transuranic (TRU) waste drums is due to the radiolysis of hydrogenous materials (i.e., surface contaminated cellulose and plastic materials) by the alpha-emitters (principally plutonium [Pu] isotopes) in contact with the waste, but may also be from other mechanisms such as metal/solution reactions or chemical interactions for unique waste forms. The presence of the H_2 gas raises concerns for the consequences of the ignition of the internal H_2-air mixture that may fail the drum containment and pose a direct threat to workers from the debris and the airborne release of the actinide surface-contamination (predominantly Pu isotopes) to the ambient environment that would pose a threat to workers and the public.

Three components are necessary to ignite a flammable gas-oxidant mixture: 1) a fuel concentration that will propagate the reaction; 2) sufficient oxidant to support the combustion; and 3) an ignition source. Typically, the latter two are assumed to be present. Experimental and field study data on TRU waste drums indicate that during the generation of hydrogen gas within a TRU waste drum, the oxygen (O_2) concentration in the air is reduced by some mechanism (potentially the reaction between the hydrogen ions generated and oxygen to form water vapor) and may be insufficient to support complete combustion of the H_2. However, see the discussion in Appendix B.1.2 regarding recent data from the Savannah River Site on TRU drums with elevated H_2 and O_2 concentrations. Furthermore, electrical ignition sources external to the drum are attenuated or prevented by the insulating properties of the liners (i.e., high density polyethylene [HDPE]).

For complete combustion of the gases, fuel vapors and oxidant (typically air) must be premixed and have a free path that does not interfere with the flame propagation. With the waste configuration in drums (formation of pockets due to the presence of rigid noncombustible material, compression of the loose combustible materials by settling, and folding of flexible hydrogenous material), this assumption is questionable. Thus, although the free volume is considered, the void volume (empty space above the contents and lid of the drum) may be the determinant volume.

The concern is the combustion of an internal accumulation of hydrogen that could result in a reaction that generates sufficient internal pressure to fail the container and release the actinide contaminant to the atmosphere. The internal pressure is a function of the fraction of the reactants (H_2 and O_2) that actually react and release their heat of combustion, i.e., how complete the combustion is. For "legacy" drums[36] there is no free passageway from the contents in a sealed "poly bag" or liner to the drum and ambient atmosphere. Gas generated in the contents is collected in the liner (6-mil "poly bags" or 90-mil HDPE rigid liner). Liners may degrade/harden (especially 6-mil "poly bags" that are sealed by twisting the material and securing with tape), lose their integrity with time, and release the gaseous contents to the sealed drum. TRU waste drums generated to meet the Waste Isolation Pilot Plant (WIPP) Waste Acceptance Criteria (WAC) are vented to attenuate the accumulation of internal hydrogen gas or other gases, and do not contain the prohibited items.

The drums of concern ("legacy" drums) are typically recovered from long-term storage that could allow the generation and accumulation of hydrogen gas and degradation of the drums. The integrity of such drums of concern can be due to loss of structural strength under storage conditions. Visual inspections would detect the drums that are grossly compromised and these degraded drums are more likely to have pathways to the ambient atmosphere at seams and badly degraded spots, thus venting the accumulated gases.

This appendix covers the following:

- TRU waste and the drums that contain the waste
- Properties of hydrogen relevant to its combustion
- A review of the literature of selected experimental studies on hydrogen combustion and deflagration
- The potential for deflagration-to-detonation transition (DDT) in TRU waste drums
- The minimum hydrogen concentration in TRU waste drums that may pose a threat for the catastrophic loss of containment

This appendix does not cover other mechanisms that may fail the containment such as the behavior of volatile organic compounds (VOCs) or other combustible vapors, or venting of pressurized cylinders such as spray paint cans, etc. The potential deflagration pressure of TRU waste drums due to the presence of VOCs alone or in the presence of hydrogen is addressed in "*Evaluation of Deflagration Pressure of Solid Waste Drums with VOCs and Hydrogen at*

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[36] Legacy drums are drums previously generated that may be degraded due to long storage under conditions that may result in some loss of the drum structural integrity, are un-vented, and may contain currently prohibited items (e.g., aerosol spray cans, items that are considered "pyrophoric", liquids, etc).

Concentrations Higher than the Lower Flammability Limit (U)" (WSRC 2007), which is summarized in Section D.7.9.

D.2 Purpose

This appendix provides a criterion for determining the level of hydrogen gas present in the free volume of a TRU waste drum that requires special treatment (venting/purging). This treatment removes the potential hazard of an internal deflagration that would fail stored/staged TRU waste drum containment and release the actinide surface-contaminant to the ambient atmosphere, by preventing concentrations of H_2.

D.3 Criteria

Although the experimental data strongly indicate that hydrogen concentrations must exceed 15-vol%, with a minimum of 7.5-vol% oxygen, to fail new TRU waste drums and experimental data supports the position that complete combustion (and, therefore higher internal pressures) are difficult even for higher H_2 concentrations, a conservative value of 8-vol% was selected to bound the uncertainties in the measurement of hydrogen, the location of the ignition, potential degradation of the drums structure, and physical configuration of contents in the drums.

D.4 Definitions

AICC	Adiabatic isochoric (constant volume) complete combustion
DDT	Deflagration-to-detonation transition
Deflagration	Combustion fronts traveling at subsonic speeds relative to the unburned gases; typically much less than sonic
Detonation	Combustion fronts traveling at or above sonic speeds relative to the unburned gases
DOT	Department of Transportation
FRP boxes	Fiberglass reinforced (wooden) box
HDPE	High-density polyethylene
Inventory	The quantity of the material-of-concern in terms of mass or activity that is found in the item or location
"Legacy" waste	Contained TRU waste that does not meet the WIPP WAC and may contain prohibited items
ℓ/d	Length/diameter ratio
LFL	Lower flammable limit
Lid-displacement	Any displacement of the drum lid/retaining ring

Lid Loss	The catastrophic, violent, physical ejection of the lid from an open-head 55-gal drum due to rapidly rising internal pressure >100-psig
MAR	Material-at-risk
PE	Polyethylene
psia	Pounds per square inch absolute
psig	Pounds per square inch above atmospheric pressure
Pyrophoric	Material that spontaneously ignite at ambient temperature and pressure. For the purposes of these analyses, materials that can ignite at elevated temperatures exposed to air
"Reasonably" bounding	The majority of parameters used to evaluate value are "conservative"
Release fraction (drum deflagration)	The fraction of the content ejected from the drum by the internal deflagration
Seal Failure	The venting of the internal overpressure in a sealed, 55-gal, open-head drum to a slow increase in pressure to a level >14-psig
Speed of Sound, Sonic Velocity	~346 m/s at 25^{o} C at 14.7 psia, 1135-ft/s
Stoichiometric	Composition in accordance with the Law of Definite Proportions
TRU Waste	Solid combustible and noncombustible material with an alpha-activity concentration of >100-nanocuries/gram; (e.g., 300 lb of TRU waste would have a minimum of (100) (10^{-9} Ci/g) (300-lb) (453.6 g/lb) = 0.014 Ci, ~0.2-g ^{239}Pu Equivalence [PE-Ci])
VOC	Volatile organic compounds
WIPP WAC waste	Contained TRU waste that does meets the WIPP Waste Acceptance Criteria (WAC)

D.5 TRU Waste

D.5.1 55-gal DOT, Metal Drums

TRU waste covered in these analyses is predominantly stored in 55-gal, metal, DOT, open-head drums. Two categories of drums have been used: DOT 17-C and 17-H. The drums have a nominal diameter of 24-in. and height of 35-in. DOT 17-C drums have a 16-gauge (0.060-in.) wall thickness and DOT 17-H have a 18-gauge (0.049-in.) wall thickness. The drums have a solid lid sealed with a flexible gasket and are retained by a clamping ring with a bolted closure. WIPP WAC drums have a filtered vent that allows light gas to escape. "Legacy" drums do not have a filtered vent.

Other containers such as standard waste boxes, FRP wooden boxes, other size waste drums, and remote-handled waste containers are not considered in these analyses.

D.5.2 Types of Waste

TRU wastes are a variety of physical and compositional forms. Some of the typical waste forms are the following:

- *Combustible*—cellulose material forms (tissue, paper, rags, wood), plastics (polyethylene, polyvinylchloride; polypropylene, polystyrene [depleted ion exchange resin])

- *Noncombustible*— glassware, plastic containers, metal pieces and containers.

- *Cemented wastes*— waste and powders containing trace quantities of actinides, spent ion exchange resin, and non-radioactive salts entombed in Portland-type cement.

Except for cemented waste, the contents of the drums are initially loosely packed (tossed) in drums, but will settle with time. The contents will always have "pockets" of atmosphere in mass that are most likely not connected. Therefore, flammable mixtures will not propagate through these pockets.

Drummed TRU waste are typically small-sized, actinide (principally the isotopes of plutonium, although some higher atomic number TRU elements are also found) surface-contaminated combustible and noncombustible materials. The waste is typically enclosed in a sealed 6-mil "poly bag" (the end of the bag is twisted and held shut with masking or duct tape) or a 90-mil, rigid, HDPE liner (the lid is sealed with adhesive and a flexible gasket) in the drums. The inner bag or liner in WIPP WAC wastes also have filtered vents to attenuate the accumulation of flammable/combustible gases and vapors that are lighter than air.

The combustible waste can be one or all of various forms of cellulose or various compositions of plastics. Noncombustible materials can be glassware, metal, or sheet metal (containers, scraps, and tools). The exact composition of the waste depends on the process from which the waste was collected. Waste with known contamination (e.g., waste from glove boxes, processes, etc.) is often compressed to remove air associated with the waste and multiply-encased in containers and one or more layers of plastic wrap/bags.

WIPP WAC drummed TRU waste is configured to minimize the accumulation of flammable/combustible gases and vapors and, for the purpose of these analyses, is not considered further.

"Legacy waste" is the item of concern. Wastes drummed prior to the promulgation of the WIPP WAC are older wastes that have been in storage under various environmental conditions such as entombment under soil or in outdoor storage. "Legacy waste" was generated and drummed under the conditions mandated at the time of generation. Bags of various plastics and thickness were used to hold the waste. Sometimes, multiple bags were placed into a single drum. Sometimes, bags were compressed to eliminate excess air. Any items from a potentially contaminated area were loosely tossed into the waste, and thus, "legacy waste" may contain many items that are currently forbidden in TRU waste to be disposed of at WIPP (e.g., aerosol spray cans, liquids, and items termed pyrophoric, such as reactive metals, reactive chemical compounds, etc.). The alpha-emitting material on hydrogenous materials may generate hydrogen gas. Hydrogen or combustible/flammable gases may be trapped in the bags and liner enclosing the waste accumulating H_2 or other combustible/flammable gases in vapor concentrations that will support combustion.

The activity for emplaced contact-handled drummed TRU waste shows an overall average activity of 6.85-PuEq/drum in the WIPP database for all sites. The average weight of the drum plus contents is 132.95-kg (293.2-lb). With an average weight for the drums of 27-kg (59.6-lb), the average weight of the contents would be 105.95-kg (233.7-lb).

The most favorable configuration for propagating a hydrogen deflagration in drummed TRU waste would be a bottom-initiated combustion (flame propagation in the upward direction) in the open space above the contents (void space). External electrical ignition is precluded by the electrical insulating characteristics of the bag/liner, but the presence of pyrophoric items or metal pieces that could generate a spark make the contents a possible ignition source. As will be shown later, there are many factors with experimental support to show that a DDT may be precluded for this configuration.

D.6 Hydrogen from TRU Wastes

D.6.1 Hydrogen Gas Properties

Some of the pertinent properties of hydrogen gas are shown in Table D-1.

TABLE D-1 Properties of Gaseous Hydrogen (H_2) (after LANL 2002)

Property	**Value**
Molecular weight	2.0159
Critical temperature	33.19 K (-239.81° C)
Critical pressure	12.98-atm (190.8-psia)
Specific volume (reference temp & 1-atm pressure)	191.4 ft^3/lb (0.0119-m^3/g)
Specific heat, C_p	3.425-Btu/lb-R (14.33-J/g-K)
Specific heat, C_v	2.419/Btu/lb-R (10.12-J/g-K)
Heat of combustion, low	51.596-Btu/lb (119.93-kJ/g)
Heat of combustion, high	61.031-Btu/lb (141.86-kJ/g)
Stoichiometric composition in air	29.53-vol%
Stoichiometric flame temperature	3712°n F (2045° C)
Auto ignition temperature in air	1084° F (585° C)
Flammability limits, air	4- and 75-vol% (3.6- to 67-g/m^3)[a]
Explosive limits, air	18.3- and 59-vol%
Minimum spark ignition, air (1-atm)	1.9 X 10^{-8} Btu (0.02-mJ), 1-mJ[a]
Burning velocity in air	Up to 2.6-m/s;1.968 m/s[b]
Minimum quenching distance	0.5-mm[a]
Reference temperature, 68° F (20° C) [a] Drysdale 1985 [b] Chapman-Jouguet (Baker et al. 1983)	

D.6.2 Hydrogen Gas Combustion Phenomenon

Hydrogen gas (H_2) in air is readily ignited (see Table D-1) and may burn (combust) with a wide range of concentrations. The limits are for H_2 pre-mixed with air under ideal conditions. These limits are not to be confused with the ignition and deflagration (fast burning—a combustion front traveling at subsonic speed relative to the unburned combustible gas) in typical accident conditions for TRU waste drums. Ordinary deflagrations travel at speeds much less than sonic (1135-ft/s, 346-m/s). For these deflagrations, the pressure will be nearly uniform throughout the containment, and the peak pressure will be bounded by the adiabatic isochoric (constant volume) complete combustion (AICC) (SNL 1989).

Although the H_2 concentration is the principal factor that affects the combustion, other factors may affect various aspects of the combustion such as initial temperature, igniter location, turbulence, compartment size and configuration, and possibly others (EPRI 1988). As an example, the limits for combustion in various directions vary significantly—upwards 4-vol% (the effect of heat induced turbulence results in the propagation of the flames in this direction, but the flame front is not continuous and the balls of flame rise through the mixture generating much less than the AICC pressure value), but ~5-vol% is necessary for a continuous flame front for burning in the upwards direction, 6.5-vol% in the horizontal direction, and 9.0-vol% in the downwards direction under ideal conditions.

D.6.3 Combustion of Hydrogen-Air Mixtures.

Some of the factors that have a substantial effect on the combustion of hydrogen-air mixtures are the following:

- Hydrogen concentration
- Oxygen concentration
- Strength and location of ignition source
- Direction of flame propagation
- Size of enclosed volume
- Presence of obstacles that allow flow through/around them (create turbulence)
- The presence of water vapor

The reader should bear in mind the significance of these factors when assessing the experimental studies cited below.

D.6.4 Hydrogen Gas Combustion Properties

Hydrogen gas combustion properties are shown in Table D-2.

TABLE D-2 Hydrogen Gas Combustion Properties

Property	**Value** (Reference)
Flame temperature, K	2400 (Baker et al. 1983,Table 1-1 2318 @31,6-vol% H_2 (Drysdale 1985, Table 4.1)
Flame speed, m/s	2.70 (Baker et al. Table 1983, 1-1) 1.968[a] (Baker et al.1983, Table 1-3)
Minimum ignition energy, milli-joules	0.018 (Baker et al. 1983, Table 1-1) 0.01 (Tewarson 1985, Table 13)
Minimum ignition temperature, °C	400 (Drysdale 1985, Table 6.3)
Auto-ignition temperature, K	673 (Baker et al. Table 1983, 1-1)
Lower flammable limit, vol%	4 (Baker et al.1983, Table 1-1)
Upper flammable limit, vol%	75 (Baker et al. 1983, Table 1-1)
Low heat value, kJ/kg	50.0 (Baker et al. 1983, Table 2-4)
TNT equivalency	11.95 (Baker et al. Table 1973, 2-4)
Energy content, Btu/lb	52,000 (Steciak, Tewarson, and Newman 1983, Table 2) 435 kJ/m^3 @ 0° C

[a] Chapmen Jouguet

D.6.5 Hydrogen Concentrations in TRU Waste Drums

Although, the H_2 concentration varies with time and activity level, the data are limited and no reasonable trend based on either parameter can be deduced. On the assumption that the initial atmosphere in the drums is air (~21-vol% O_2), the O_2 concentration decreases significantly and appears to be less than required to support the complete combustion of the H_2 present, except for the lowest concentration, 5-vol%. The fraction of TRU waste drums that can attain the range of H_2 concentrations that can burn (~5-vol%) is small. The analyses performed in previous safety documentation appear to ignore the need for an O_2 concentration that would support complete combustion (lesser O_2 may support incomplete combustion resulting in reduced pressure generation).

The O_2 concentrations in TRU waste drums appear to decrease significantly with increasing H_2 level and are not adequate to support the complete combustion of the H_2 present (>½ the vol% of H_2). It is postulated that the hydrogen atoms generated by radiolysis may be reactive with the O_2 molecules present and result in the formation of water. The greater the H_2 concentration, the greater the probability for the two ions to react.

The data indicate that the presence of H_2-air mixture that can deflagrate and fail DOT 55-gal, metal TRU waste drum (>15-vol% H_2 + 7.5-vol% O_2) from the radiolysis of the contained hydrogenous material are improbable.

Hydrogen Generation & Accumulation in TRU Waste Drums. DP-1604 (from HNF-19492, Fluor Hanford 2004) –Three drums filled with typical waste from a ^{238}Pu facility were held and the hydrogen and oxygen concentrations monitored. The results were:

- Inventory 37-Ci (595.8-g PuEq[a])– peak H_2 concentration ~5-vol% at Day-900 (~2.5-yr), O_2 reduced to 2- to 7-vol%.
- Inventory 113-Ci (1819.6-g PuEq[a])– peak H_2 concentration 50-vol% at Day-1280 (~3.5-yr), O_2 concentration reduced to 1- to 5-vol%.

- Inventory 47.5-Ci (876.5-g PuEq[a]) – peak H_2 concentration 4-vol% at Day 1420 (3.9-yr), O_2 <4-vol%.

[a] PuEq is plutonium equivalent grams based on the specific activity of ^{239}Pu of 0.0621-Ci/g.

The PuEq activity of the of the drums tested are considerably greater than the inventories typically found in TRU waste drums and allowed by the WIPP WAC based on fissile mass (200-g PuEq).

Table D-3 shows the fraction of stored TRU waste drums containing flammable hydrogen concentrations (from HNF-19492).

TABLE D-3 Fraction of Stored TRU Waste Drums Containing Flammable Hydrogen Concentrations (from HNF-19492)

Site	Total Drums	Drums with >5-vol% H_2	Fraction	Drums with >5-vol% O_2	Fraction
Savannah River	10,169	797	0.078	N	---
INL	210	6	0.028	1	0.005
LANL	13,000	175	0.013	N	---
Rocky Flats	298	5	0.017	1	0.003
N=No Data					

The limited data appear to indicate that <8% of the drums contain hydrogen concentrations that could deflagrate complex-wide, but only the drums at the lowest hydrogen level appear to contain an O_2 concentration that could support the combustion of the H_2 present.

D.7 Literature Data on Burning of Hydrogen-Air Mixtures

The interest in the combustion behavior of H_2-air in large container has increased after the Three Mile Island accident. Summaries of selected experimental studies are given in the following subsections.

D.7.1 AI 1973

H_2-air mixtures were ignited in a 40-ft long X 16-in. diameter with a ℓ/D of 30.0, horizontal shock-tube. The test conditions were:

- H_2 gas concentration: 4- to 28-vol% (dry basis)
- Initial pressure levels: 1-, 1.5-, & 2-atm (abs)
- Initial temperature: ambient
- Water spray was 0 or 72-gpm
- Detonation source: spark-gap for stoichiometric of H_2-O_2 in driver-section
- Ignition sources for flame tests: continuous sparking across 0.050-in. spark gap

The report shows that:

- No detonation was initiated at H_2 concentration of <16-vol% in air. This finding is supported by the published literature.

- Flame propagation in a horizontal direction resulted in a partial detonation at 20- & 24-vol% H_2 in air; complete detonation require 28-vol% H_2 in air.

- Combustion wave propagation (burning) at ≥7-vol% (dry basis), the H_2 concentration that may deflagrate, continued with varying degrees of completion.

- Complete burning was not propagated for H_2 in air concentration <12-vol% (i.e., internal pressure in a drum would be less than the AICC value).

- The behavior was similar for the tests with water vapor present, an important factor due to the presence of some level of moisture (relative humidity and potential water formation during radiolysis in TRU waste drums filled with hydrogenous materials).

- Values reported for burning in a horizontal direction may be high for burning in upwards direction and low for downwards direction.

- Initial pressure (more fuel and oxidant available) affects burning and (deflagration) maximum pressures – 29.9-psi @ 12-vol% H_2 in air & 48.4-psi @ 16-vol% H_2 in air (both values less than the internal pressures typically assumed to result in catastrophic loss of the drum lid – “lid loss”).

- Ignition not sustained at 5-vol% H_2 in air; partial (erratic) burning was observed at 7- & 9-vol% H_2 in air.

The experimental study is a part of an effort to obtain information on Loss-of-Coolant Accident. Known water droplets dispersed in combustible mixtures of H_2-air may limit combustion/ detonation. This study used a shock-tube to determine flame and detonation-initiation and detonation-propagation characteristics.

The test apparatus was a 16-in. diameter X 40-ft long ($\ell/d = 30.0$) shock tube, oriented in a horizontal direction. H_2 concentrations ranged from 5- to 16-vol% (dry basis) in flame tests (plus 1 flame test at 28-vol% -air with initial pressure ½-atm). The flammable mixtures were initiated by spark, flame, and detonation.

No combustion was initiated at 5-vol%-air, even using a well-establish flame. With the same initiators, 7-vol% H_2 -air with a water spray did not ignite; partial burning was observed without water spray. More substantial combustion was obtained at 9-vol%-air, but combustion was incomplete. No combustion was initiated for 5-, 7-, and 9.3-vol% in air using a spark gap. Ignition and flame propagation occurred even with water spray at 11-, 12-, and 16-vol% in air.

No detonation propagation was observed at H_2 concentration of <16-vol% in air and 1-, 1.5-, and 2-atm pressure and combustion wave propagation. Partial detonation propagation was found at H_2 concentration of 20- and 24-vol% (dry basis) in air and combustion wave propagation. Short-duration, non-reflected pressure of 325-psig recorded with a well-established detonation propagation at H_2 28-vol% (dry basis) in air.

D.7.1.1 Detonation Tests

A detonation wave was established in the driver section to initiate subsequent detonations of H_2-air mixtures. Stoichiometric H_2-O_2 concentrations were used in the driver section. Twenty two experiments were performed with H_2 concentrations up to 28-vol% H_2 and pressures ranging from 0.5-atm (7.4-psi) to 2-atm (29.4-psi). The initial test performed at local ambient pressure (13.7-psi). The tests were conducted with and without water spray.

Table D-4 summarizes the detonation testing results.

TABLE D-4 Detonation Test Summary (after AI 1973)

#	P_i, psia	H_2, vol%[a]	Maximum Pressure[b]					Remarks
			1	2	3	4	5	
1	13.8[c]	0						System check-out
2		4						No detonation observed
3		8.7						No detonation observed
4		12						No detonation observed
5		16						No detonation observed
6		20	178	160	---	---	---	Partial detonation observed
7								Water spray
8		24	158	160	132	133	135	Partial detonation observed
9								Water spray
10		28	245	325	302	278	198	Detonation observed
11								Water spray
12								Water spray
13			130	---	---	---	150	Dry test
14	22	16	180	---	---	--	---	No detonation observed
15								Water spray
16		20	270	200	---	---	---	Partial detonation
17								Water spray
18	29.4	16	240	---	---	---	---	No detonation observed
19		20	250	---	---	---	---	No detonation observed
20								Water spray
21	13.8[a]	7	---	---	---	---	---	No detonation observed
22		9	---	---	---	---	--	No detonation observed

[a] Dry basis

[b] At photocon locations noted in FIGURE 2 of source document

[c] Local ambient pressure

Findings were the following:

- The flame speed and pressure increased with increasing H_2 concentration
- Flame acceleration is evident for H_2 mole fraction of 18-vol% and above, but not at 12-vol%
- DDT first occurred at H_2 mole fraction between 18.4-vol% and 24.7-vol% near the exit
- The initially convex flame shape became slightly-to-strongly concave
- Ignition was not sustained at 5-vol% H_2 in air (horizontal direction); partial burning was observed at 7- and 9-vol% H_2 in air
- If the shock tube was oriented in the vertical direction with the ignition source at the lower end, the burning fraction for concentration <9-vol% H_2-air would increase significantly

- If flame direction was downward, concentration <9-vol% H_2 in air probably would not sustain flame. The Reference shows that 9-vol% H_2 in air LFL is needed for downward propagation and for "coherent" upwards flame propagation

- For "*lean mixtures tests having a H_2 concentration <8-vol%, the quiescent flame speeds generated as the flame front propagated away from the ignition site were augmented by the buoyant rise of hot gases. This caused the flame front to only accelerate in the upward direction with little lateral growth during the initial period following ignition*"

- The pressure ratio began to depart significantly from AICC values at H_2 concentrations <8-vol%; maximum temperatures ranged from essentially ambient to 1102^{o} C for the tests

- Large vessels inherently provide more vigorous combustion conditions than small vessels, particularly for lean mixtures

- Complete combustion was found only for H_2 concentrations >7.7-vol% (bottom ignition)

No detonation was maintained at H_2 concentration <16-vol%. Combustion waves were propagated in concentration ≥7-vol% H_2 resulting in varying degrees of completeness. Published literature supports this finding. Partial detonations occurred in the range of 20- to 24-vol% H_2 and were well established at 28-vol% H_2.

Using a spark gap ignition, H_2-air mixtures did not ignite at H_2 concentrations in air of <9.3-vol%. Using a flame igniter (16-vol% H_2-air) that is much more energetic than the spark gap, above, combustion waves were propagated (burning) at ≥7-vol% (dry basis) and continued with varying degrees of completion.

D.7.1.2 Flame Tests

Twenty six experiments were performed with H_2 concentrations ranging from 5- to 16-vol% (dry basis) and initial pressures from 1- to 2-atm. One additional test was performed at 28-vol% H_2 in air at initial pressure 0.5-atm. In tests 1-18, both the driver and shock tube were filled with H_2-air and ignited by spark plug (no diaphragm separation). For tests 19-26, the driver section was filled with 16-vol% H_2-air, ignited by spark plug (effective flame ignition source), and separated from the mixture in the shock tube by a plastic membrane. The driver reaction produces a highly turbulent flame (temp 2100^{o}F/1379^{o}C) that ruptured the diaphragm and jetted out into the shock tube. Some H_2 recombination with O_2 is expected. An automotive spark plug (60/s sparks across 0.050-in. spark gap) and a high voltage cell were used as an ignition source. No ignition was detected for H_2 concentrations of 5-, 7-, and 9.3-vol% (dry basis) in air. Using the flame ignition source, 16-vol% H_2 in air ignited. Ignition was not sustained at 5-vol% H_2 in air; there was partial (erratic) burning at 7- & 9-vol% H_2 in air. If the shock tube is oriented in vertical direction with the ignition source at lower end, the burning fraction for concentrations <9-vol% H_2-air would increase significantly. If flame direction is downward, concentrations <9-vol% H_2 in air probably would not sustain flame. A reference is provided to show that 9-vol% H_2 in air is the LFL for downward propagation; also the concentration for “coherent upwards flame propagation” - combustion is anticipated as a cone shape flame above the ignition source.

Table D-5 summarizes the flame testing results.

TABLE D-5 Flame Test Data Summary

#	H_2 Conc., vol%[a]	Pressure, psia			Remarks
		Initial	Maximum	Final	
1	5.0	14.7	14.7	14.7	No ignition
2	7.0	14.7	14.7	14.7	No Ignition
3	9.3	14.7	14.7	14.7	No ignition
4	12.0	14.7	28.9	12.9	
5					Water spray
6					Water spray
7	16.0	14.7	48.8	12.2	
8					Water spray
9	9	22.0[b]	22.0	22.0	No ignition
10	12.0	22.0[b]	54	19.2	
11					Water spray
12	16.0	22.0	70	18.0	
13					Water spray
14	12.0	29.4[c]	64	25.3	
15					Water spray
16	16.0	29.4[c]	85	23.7	
17					Water spray
18	28.0	7.4[d]	28.5	5.0	
19	5.0[e]	13.7	15.0[f]	13.6	No ignition
20	7.0[e]	13.6	15.6	13.25	20% to 40% complete
21	9.0[e]	13.6	20.1	13.0	30% to 50& complete
22	7.0[e]	13.6	15.3	13.5	10% to 20% complete
23	5.0[e]	13.7	15.0[f]	13.7	No ignition
24	7.0[e]				Water spray
25	9.0[e]				Water spray
26	11.0[e]				Water spray

Footnotes Table D-5 Flame Test Data Summary

[a] Dry basis

[b] 22.0-psi ÷14.7-psi/atm = 1.497-atm = ~1.5-atm

[c] 29.4-psi ÷14.7-psi/atm = 2.0-atm

[d] 7.4-psi ÷14.7-psi/atm = 0.503-atm

[e] 16-vol% H_2 in air in driver section

[f] Short duration spike

D.7.2 EPRI 1988 (Note: complete document was not available for review, only Section 4)

A sphere, 2.3-m/8-ft diameter and a large vessel (sphere, 16.0-m/52-ft diameter, Surface-to-Volume Ratio 0.39) resembling a reactor containment vessel with some equipment were filled with H_2 concentrations from 5.3-vol% to 13.2-vol% with various concentrations of water vapor (4.2- to 38.7-vol%). Temperatures and pressure were measured at various locations and the completeness of combustion measured. Fans and obstructions (e.g., work platform, etc.) created turbulence in some experiments. Active igniter locations included the bottom, center, and top of the spherical vertical axis and along the equator walls. The AICC pressure was computed. At most, the AICC pressure for H_2-air mixtures is 8X the pre-combustion pressure.

The results are listed in Table 6 (EPRI 1988).

TABLE D-6 Test Conditions (EPRI 1988)

	Initial						Test Results			
#	H_2, vol%	H_2O, vol%	Ign Loc.[1]	Fan/Spray	T, °C	Pres, psia	Δ_P, psi	T_{Max}, °C[2]	T_{Max}, $_o$C[3]	% Burn
P-1	5.3	4.2	B	---	29.7	14.5	7.1	290	640	32
P-7	5.5	14.3	2E	F	52.2	14.0	9.4	325	630	37
P-2	5.8	14.3	C	S	51.1	13.2	15.3	470	658	61
P-3	5.8	14.4	C	F	52.7	14.2	11.2	365	659	44
P-6	6.0	13.7	T	---	50.0	13.1	0.0	50	677	0
P-6’	6.0	13.7	T	F	50.0	13.1	11.2	380	677	54
Sco	6.6	4.5	B	30.0	13.7	16.8	16.8	435	734	66
P-4	7.7	4.8	B	---	32.2	14.5	31.9	765	842	100
P-5	7.8	31.3	B	---	67.8	13.1	21.8	750	829	100
P-8	11.1[4]	27.2	B	F	75.0	19.5	53.2	1130	1128	100
P-22	5.2	14.5	1E	S	52.6	13.9	5.0	195	601	31
P-9	6.1	4.2	B	---	28.8	13.7	11.1	320	684	60
P-9’	6.0	4.6	B	---	29.7	13.3	8.8	305	674	53
P-11	5.8	4.9	T	S	31.6	13.9	7.8	368	655	58
P-12’	6.9	28.3	B	---	66.7	13.8	26	440	753	58
P-18	7.0	27.7	T	---	69.2	15.8	0.0	70	766	8
P-18’	6.6	27.3	T	S	69.2	15.7	17.2	480	730	69
P-13	7.8	4.4	[5]	---	30.6	NA	NA	NA	681	100
P-13’	7.8	4.4	B	---	30.9	14.4	31.0	740	851	100
P-14	8.1	38.7	B	---	74.1	13.9	16.0	600	847	92
P-15	9.9	4.2	B	---	30.4	14.9	40.6	950	1-5-	100
P-16	10.1	29.5	B	---	69.7	15.1	32.4	915	1033	100
P-20	12.9	27.8	B	---	69.0	15.6	43.7	1195	1274	100
P-21	13.2	27.4	B	F&S	68.3	15.3	43.6	1145	1297	100

[1] Igniter location: (B) bottom, (C) center, (T) top, or (E) ---on wall at the equator
[2] Maximum gas temp recorded using 0.0080dia. thermocouple
[3] Calculated AICC complete combustion value based on actual test conditions
[4] Volume average value based on integrated mass flow of hydrogen, actual concentration may have been higher
[5] Inadvertent ignition, prior to high-speed data recording

Twenty-four tests were performed in a large spherical vessel. The H_2 concentrations ranged from 5.3-vol% to 13.2-vol% with various concentrations of water vapor (4.2 to 38.7-vol%). Active igniter locations included the bottom, center, and top of the spherical vertical axis and along the equator walls. Three regimes were noted in the combustion of pre-mixed H_2-air or H_2-air-steam: ordinary deflagration, highly accelerated deflagration, and detonations. For very lean or very rich mixtures (far from stoichiometric) with flame speeds far from sonic, pressure in all accessible volumes was very uniform. Flammability limits are the concentrations of the fuel that will propagate a deflagration. The limit was assumed to be *independent of method of ignition provided it is sufficiently strong to ignite a flame* and independent of size of enclosure provided it is much larger than the quenching distance (0.5-mm, see Table D-1 above). Flammability limits depend on direction of flame propagation due to the buoyancy effect—lean and rich limits have a wider range for upward than downward propagation. A moderate degree of turbulence has no significant effect on flammability limits. For initially quiescent lean mixtures, this study shows combustion completeness varies with a low fraction in the upward direction and complete combustion in the downward direction (Note: *reader should bear in mind that the limits are different depending on direction of flame propagation*).

For H_2-air mixtures at room temperature, flame speed is ~3-m/s for a rich mixture (~40-vol%), 2-m/s for a stoichiometric mixture, and progressively less for leaner mixtures. For lean mixtures, the laminar flame front is not stable, but deforms and increases the flame surface area that could result in some small increase in flame speed.

Conclusions and observations from the document are:

- For "lean mixtures tests having a H_2 concentration <8-vol%, the *"quiescent flame speeds generated as the flame front propagated away from the ignition site were augmented by the buoyant rise of hot gases. This caused the flame front to only accelerate in the upward direction with little lateral growth during the initial period following ignition. During the upwards inverse of the vessel, the growing flame front displaced cooler gases from the upper region of the test vessel. When the flame reached the top of the vessel, the momentum of the plume was able to drive the flame front downwards along the vessel wall with final combustion occurring in the lower region of that vessel. In these cases, incomplete combustion occurred (i.e., burn fraction ranged from 30- to 70-%."*

- Two significant variations were noted:

    - For attempts to ignite a quiescent lean mixture at 0.5-m (1.5-ft) below top of vessel; only minimal combustion occurred in the local region above igniter … initial upward flame propagation impinged on dome surface and quenched. Insufficient vertical height above igniter precluded full development of rising plume and global propagation throughout vessel (an important observation for TRU waste drums that are half full of waste and the distance to the top is ~1.5-ft);
    - For H_2 concentrations of >8-vol%, flame propagation more spherical as H_2 increased from 8- to 13-vol% … test P-20, H_2 12.9-vol%, initial flame front essentially spherical.

- Hydrogen burn completion ranged from 0% to 100%. Complete combustion was found only for H_2 concentrations >7.7-vol% and up to 30-vol% steam, all upwards flame direction (bottom ignition). Top ignition under quiescent conditions resulted in very low burn completions due to quenching of flame at dome surface

- Large vessels inherently provide more vigorous combustion conditions than small vessel, particularly for lean mixtures.

D.7.2.1 Combustion in Premixed Hydrogen-Air-Steam Atmospheres

Twenty-four tests were performed with H_2 concentrations of 5- to 13-vol% and 4- to 40-vol% H_2O vapor concentrations (Note: *reader should bear in mind that water vapor concentrations at the lower fractions are well within the relative humidity anticipated at generator sites during packaging and storage*). Fans and water sprays were used in nine tests. Active igniter located at bottom, center, and top of the sphere's vertical axis and along equator wall. Saturated condition at beginning of each test with temperatures from 29^{o} C (84^{o} F) to 75^{o} C (167^{o} F). Test condition is listed in Table 7 "*Peak Pressure Rise Measurements Premixed Combustion Tests*" (see referenced document). AICC and pressure ratios were calculated. Suspect data were excluded—probably from water accumulation and boil-off in pressure sensing tubes.

D.7.2.2 Pre-mixed Combustion Phenomenon

Table 7, "*Peak Pressure Rise Measurements Premixed Combustion Tests*" (see referenced document) shows that for "*lean mixtures tests having a H_2 concentration <8-vol%, the quiescent flame speeds generated as the flame front propagated away from the ignition site were augmented by the buoyant rise of hot gases. This caused the flame front to only accelerate in the upward direction with little lateral growth during the initial period following ignition. During the upwards inverse of the vessel, the growing flame front displaced cooler gases from the upper region of the test vessel. When the flame reached the top of the vessel, the momentum of the plume was able to drive the flame front downwards along the vessel wall with final combustion occurring in the lower region of that vessel. In these cases, incomplete combustion occurred, i.e. burn fraction ranged from 30- to 70-%*".

Two significant variations were noted:

- For attempts to ignite quiescent lean mixture at 0.5-m (1.5-ft) below the top of vessel, only minimal combustion occurred in the local region above the igniter --initial upward flame propagation impinged on dome surface and quenched. Insufficient vertical height above igniter precluded full development of rising plume and global propagation throughout vessel
- For H_2 concentrations >8-vol%, flame propagation was more spherical as H_2 increased from 8- to 13-vol% … test P-20, H_2 12.9-vol%, initial flame front essentially spherical with negligible flame acceleration

The referenced document states that,

- "*Igniter location affects combustion primarily through its role in buoyancy-induced mixing and turbulence*".

- "*… spark-ignition in an 8-ft diameter sphere at an initial temperature of* $28^o \pm 2^o$ *C under quiescent conditions indicate that a top ignition will burn to completion at 8.5-vol%* H_2 *…*"
- "*…The data illustrates that even though 'global' flame propagation might not occur under lean quiescent conditions with top ignition …*"

Turbulence effects are more important for lean mixtures for flame speeds. Figure 4-39 on pg. 4-39 of the referenced document that plots "*Upwards Flame Speed, m/s versus the Hydrogen Concentration* shows no significant increase in flame speed at <10-vol% H_2.

Pressure ratio began to depart significantly from AICC values at H_2 concentrations <8-vol%; maximum temperatures ranged from essentially ambient to 1102^o C for the tests.

D.7.2.3 Effect of Scale

Prior to the EPRI tests, hydrogen combustion data were from bench-scale experiments. These tests show that scale affects primary combustion parameters: pressure ratios and time to peak pressure.

Large vessels inherently provide more vigorous combustion conditions than small vessels, particularly for lean mixtures. The fireball rises from point of ignition and accelerates through the first two-thirds of its upward travel. The rising buoyant plume draws air down the sides of the vessel to the bottom to replace the air rising up the center. This effectively promotes turbulence and mixing throughout the test volume. This self-induced turbulence is more effective in a large vessel that provides a longer vertical path for the rising plume to start the unburned gases in motion.

D.7.2.4 Effect of Hydrogen and Steam Concentrations

Variations in peak pressure ratios with H_2 concentrations were highly non-linear (see Fig 4-5 in document), particularly for lean mixtures. Factors that affect pressure transient, each with different sensitivity to H_2 concentration:

- Burn completeness
- Flame speed
- Buoyancy-induced turbulence

All increase with increasing H_2 concentration.

D.7.3 SNL 1989 (Note: complete document was not available for review.)

D.7.3.1 Abstract

This report describes research on flame acceleration and DDT for hydrogen-air mixtures in the FLAME facility. Flame acceleration and DDT can generate high peak pressures that may cause containment failure.

FLAME is a large, rectangular "U"-shaped, channel made of heavily reinforced concrete—30.5-m long X 2.44-m high X 1.83-m wide (calculated hydraulic diameter and ℓ/D [2.44-m X 1.83-m = 4.465-m^2, 4.465 ÷ 3.1416 = 1.4213-m^2, $\sqrt{1.4213} \approx 1.192$-m radius, $D \approx 2.38$-m $\therefore$ $\ell/D \approx 30.5$-m ÷ 2.38-m] ≈ 12.8]). Closed at ignition end (PE bag) and open at far-end. H_2 was inserted in FLAME via three penetrations (one at either end and one in middle) and mixed by two air-driven fans (one at ignition SE end and one near NW exit). Ignition system had three independent ignition methods: bridge-wire, spark plug, and glow plug. All tests were conducted using single point bridge-wire ignition (capacitive firing set used to provide high-amplitude current to vaporize the bridge-wire).

Test variables were:

- H_2 mole fraction tested ranged from 12% - 30%
- Degree of transverse venting (by moving steel, top plate) 0%, 13%, and 50%
- The absence or presence of certain obstacles in the channel, 0 to 33% blockage ratio.

The hydrogen mole fraction is the most important variable. Obstacles greatly increased flame speed, overpressure, and tendency for DDT. Different obstacle configurations could have greater or lesser effect on flame acceleration and DDT. A large degree of transverse venting reduces flame speed, overpressure, and possibility of DDT. For reactive mixtures >18% H_2, the effect of turbulence from venting is greater than from venting out of channel. DDT observed for H_2 beyond some threshold level. DDT observed at 15% H_2 with obstacles and no transverse venting.

Deflagrations are combustion fronts traveling at subsonic speeds relative to the unburned gases; typically much less than sonic. Pressures are nearly uniform throughout containment and peak pressure is bounded by the AICC pressure. The AICC can be computed with high accuracy by thermodynamic calculations. At most, the AICC pressure is eight times the pre-combustion pressure for H_2-air or H_2-air-steam. Deflagration flame speed accelerated to >100-m/s generate shock waves and peak instantaneous pressures are much higher. If accelerated to a fast enough speed, deflagration may transition into a detonation—combustion fronts traveling at supersonic speed relative to the unburned gases. Peak reflected pressure for detonation considerably greater than AICC, up to 35X pre-combustion pressure.

Obstacles in the path of expanding flame front promotes/accelerates by enlarging the burning surface and increasing local burning rate. A limited set of obstacle configurations were tested. Obstacles lower the minimum mole fraction necessary for DDT. Even if no detonation occurs, deflagrations accelerated to 500 -to 700-m/s (sonic velocity ~330-m/s) and generate high pressure pulses. DDT was observed at 15% H_2 with obstacles and no top venting. This is less than the old lean "detonation limit". Venting effects are complex.

D.7.3.2 Conclusions from Tests

- Reactivity of mixture was determined by hydrogen concentration. For very lean mixtures, there was no significant flame acceleration and no DDT.

- Presence of obstacles in the path of flames greatly increases flame speeds and overpressures, reduces lean limit for DDT.

- Large degrees of transverse venting reduce flame speed and overpressure.

- Small degrees of transverse venting reduce flame speed and overpressure for less reactive mixtures but increase them for more reactive mixtures.

D.7.3.3 Adiabatic Isochoric (Constant Volume) Complete Combustion (AICC) Pressure

Three regimes in combustion of H_2-air or H_2-air-steam:

- Ordinary deflagration
- Highly accelerated deflagration
- Detonation

Far from a stoichiometric mixture (~30% H_2), in very lean or very rich mixtures, speeds are small compared to sonic. Pressures in all accessible volume are uniform, rise for a few seconds and decay as gas cools. The peak is bounded by AICC pressure and can be less due to incomplete burning.

D.7.3.4 Flammability Limits

Flammability limits of combustible mixture, at a given pressure and temperature, are the concentration of fuel which will propagate a deflagration indefinitely. Lean and rich limits are independent of ignition method and size of enclosure, provided it is larger than the quenching distance. Flammability limit depends on the direction of flame propagation—lean and rich limits are wider for upwards than downwards direction. H_2-air-steam flammability limit measured at temperatures to 200^o C and pressures atmospheric to 7-atm are reported by several authors (lists 10 references). Steam acts as a diluent reducing the combustion temperature. Increasing the steam concentration narrows the combustible range. Sufficient steam may inert the reaction (~55%, but has varied from 52% to 63%).

A moderate degree of turbulence has no significant effect on flammability limits. Limits widen with increasing temperature.

There is no systematic study of completeness of combustion between the flammability limits. Studies for large-scale (5 references) and intermediate-scale (5 references) are referenced. For an initial quiescent lean mixture, combustion completeness varies from low fractions burned in the upwards direction at the flammability limit (~5-vol% H_2) to complete burning at the downwards flammability at the limit (9-vol% H_2).

"Burning velocity" is defined as *"normal component of velocity of a deflagration relative to the unburned gas ahead of the front."* Unless the unburned gases are stationary, the speed of propagation of a flame relative to a stationary observer will <u>not</u> be the burning velocity.

Hydrogen burn completion ranged from 0% to 100%. Complete combustion was observed for H_2 concentrations >7.7-vol% and up to 30-vol% steam; all bottom ignition (see Fig 4-12, "*Burn Completeness is a Function of Hydrogen Concentration*" in the reference document). Top ignition under quiescent conditions resulted in very low burn completions due to quenching of flame at dome surface. Burn fractions reported by other experimenters were lower for H_2 concentrations <8.5-vol%. Furthermore, one might expect this scale effect to be most significant with bottom ignition. "*In lean quiescent mixtures with top ignition, combustion stopped before depleting all the hydrogen. Apparently, the buoyant plume did not have a long enough run to generate the turbulence required to start moving much of the test volume's atmosphere*." For lean mixtures with H_2 about 12-vol%, the flame speeds are low and do not increase significantly with distance. At a H_2 concentration of 24.7-vol%, the pressure transitioned into a detonation near the exit of the 30.5-m long tunnel.

Laminar burning velocity is the minimum burning velocity. For H_2-air at room temperature, burning velocities are:

- Rich mixture (~40-vol% H_2) 3-m/s
- Stoichiometric mixture (30-vol% H_2) 2-m/s
- Progressively less for lean mixtures

At 250^{o} C, a burning velocity of ~9-m/s was observed. The presence of steam reduces the velocity. Laminar flame speed is 6X laminar burning velocity. For H_2-air mixtures at ambient conditions, burning velocity was <20-m/s (negligible compared to sonic velocity [~300-m/s]).

D.7.3.5 Ordinary Turbulent Deflagration

In ordinary accidents, flames will be turbulent (uncertain if conditions for drum deflagrations are included … document for PWR ice condenser system). With increasing turbulent intensity, turbulent flame speeds reaches a maximum and decreases, then quenched. Ratio between maximum turbulent flame speed to laminar flame speed is largest for near stoichiometric mixtures. For H_2-air mixtures at room temperature and pressure, maximum ratio is >16. The turbulent burning velocity may be as high as 35-m/s and turbulent flame speed as high as 200-m/s for high degree of turbulence. Flame speeds may be up to 15-m/s for 15-vol% H_2.

D.7.3.6 Flame Acceleration — Highly Accelerated Deflagration

It is possible to have deflagrations moving at 100-m/s, with considerable flame acceleration, and strong shock waves resulting in non-uniform pressures. Local pressures exceed AICC. DDT may occur between deflagrations and leading shock wave. For flames passing through an obstacle, the effective deflagration speed is greatly increased. In large volumes, effect of hydrodynamic-combustion instabilities can greatly increase flame speed.

D.7.3.7 Deflagration-to-Detonation Transition.

There is considerable uncertainty whether transition can occur in practical accident situations. "Gas Dynamic" explanation is one-dimensional: "*The volume expansion of the hot burned gases generate shock waves moving into the unburned gases. The shock waves preheat the unburned gases increasing the burning rate, which leads to generation of further shock waves. Some of the* *shock waves merge into strong enough waves so that a local explosion that transforms into a steady detonation*" (The transition and the effect on the upward flame propagation show the importance of temperature on the combustion of H_2-air mixtures).

D.7.3.8 Experimental Results

Table D-7 summarizes the test parameters and some test results.

TABLE D-7 Summary of the Test Parameters and Some Test Results (SNL 1989)

#	Top Vent, %	H_2 Mol Fraction, %	Peak Overpressure, kPa	Peak Equivalent Planar Flame Speed m/s	Comment
Tests with no obstacles					
1	50	12.4	*	7	---
2		19.7	2.8	54	---
3		20.8	*	65	---
4		28.0	20	125	---
5		12.6	0.9	4(12)[1]	Top sheet restraint.
6		15.5	3.4	19	---
7	0	12	1.2	15	---
8		18.4	25	170	---
9		6.9	*	1.2[2]	Limited burn.
10		12.3	2.5	17	---
11		12.9	4.5	30	---
12		24.7	95/1100[3][4]	374	DDT near exit.
13		12.0	---	---	All data lost.
14		30.0	250/2100[3][4]	932	DDT near exit.
15	15	15.4	3.1	50	---
16		17.6	10	75	---
17		14.9	---	---	Some data lost.
18		18.1	36	136	---
19		24.8	65/850	160	DDT at ⅓ length.
20		20.7	78	483	---
Tests with obstacles[5]					
21	0	10-15	650	580	No mixing fans.
22		15.0	3100	700	DDT near exit.
23		14.5	1200	540	---
24	50	15.5	*	45	---
25		19.7	1500	890	DDT near exit.
26		28.5	2000	1860	Box obstacle, DDT.
27		13.1	9	15	---
28		14.9	9	33.4	---
29		18.5	23	1430	---

- Indicates pressure signal within noise level.
- [1] Plastic top sheet restraint gave faster values early in test.
- [2] Indicates horizontal propagation velocity of thin layer below roof.
- [3] 1st pressure refers to deflagration, the 2nd to detonation.
- [4] Based on dynamic pressure transducer, somewhat uncertain.
- [5] Obstructions that allow flow around them.

Note that no significant overpressure was recorded for <24.7-vol% H_2.

DDT occurred under the following conditions:

- No obstacles and venting: at 24.7- and 30.0-vol% H_2 in air (none noted at 18.4-vol% H_2 in air)
- No obstacles and 15% venting: at 24.8-vol% H_2 in air
- No obstacles and 50% venting: did not occur
- Obstacle and no venting: at 15.0-vol% H_2 in air
- Obstacle and 50% venting: at 19.7- & 28.5-vol% H_2 in air

Tests F-7 to F-14 were evaluated with no obstacles and no top venting (note: test F-9 is different than all others and was considered separately). Some tests (F-10, -8, -12 & -14) considered increasing H_2 mole fractions (12.3-, 18.4-, 21.7- & 39.0-%).

- Test F-10, 12.4-mole fraction H_2: Combustion-front trajectory showed slight concave downwards, curvature indicate some flame acceleration, but not dramatic. Peak propagation velocity was 19.3-m/s. Deflagration front was initially convex, but gradually transitioned into un-symmetrical concave shape. Pressures are all relative to the ambient and typically 84-kPa (12.2 psig).

- Test F-8, 18.4-mole fraction H_2: Deflagration speed was much higher than for F-10. All pressure histories show rise to ~130-ms, second rise and fall, then a pressure spike. Exact location and condition of DDT is not known due to instrumentation set-up.

- Test F-14, 30% H_2 mole fraction: More pronounced flame acceleration, speed just prior to detonation was very large.

Summary of tests with no venting or obstacles:

- The flame speed and pressure increased with increasing H_2 concentration
- Flame-acceleration is evident for H_2 mole fraction of 18% and above, but not at 12%
- DDT 1st occurred at H_2 mole fraction between 18.4% and 24.7% near the exit
- The initially convex flame shape became slightly-to-strongly concave

D.7.4 LANL July 2002

This document reviewed the published literature on H_2 concentrations in air to burn in various directions. One document reviewed (McKinley 1980) states that "*4-vol% H_2 (LFL) for upwards propagation produces an average flame temperature of <350^o C, whereas the ignition temperature of H_2 in air is 585^o C ...can be understood from observation that the flame in the mixture rises as luminous balls that consuming only part of the hydrogen ... fresh hydrogen diffuses into the burning ball and yields higher effective concentrations of hydrogen than initially present. It has been observed that not all the hydrogen is consumed in upward propagation in a 2-in. diameter tube until a concentration of 19-vol% H_2 was present. Similar experiments with horizontal tube resulted in a LFL of 6.5-vol% in air; downward propagation requires ~9-vol% H_2 in air.*"

D.7.5 EG&G 1983 (Experimental Studies of H_2 Explosions in TRU Waste Drum)

The document shows that:

- The drums tested contained the burning of H_2-air mixtures up to 14-vol% H_2 with both hard- and soft spark ignition. At H_2 concentration of 14-vol% in air with a hard spark ignition, a reaction was noted by the smoldering HDPE liner.

- All 5 tests with drums filled a stoichiometric H_2 concentration in air deflagrated.

- For the drums that deflagrated (>20-vol% H_2), a fraction of the contents were ejected ranging from 7- to 41-% (this drum was horizontally oriented). The material ejected was thrown a maximum (wind-aided) 260-ft in Test #4C.

- One test was performed using a drum containing a stoichiometric H_2 concentration in air surrounded by 3 drums in an up-right array. Only the donor drum and the drum above the donor drum were filled with a stoichiometric H_2 concentration in air. The lid from the donor drum was not displaced. The top drum lid was blown 182-ft and its content blown 63-ft. Fire was observed in the drum residue material with a release fraction (material ejected) ~16%. This indicates that sympathetic deflagration occurs.

- Fraction of contents ejected were: 27% (Test 3B), 14% (Test 4B), 7% (Test 4C), 41% (Test 4D), and 16% (Test 7). Maximum fraction of contents ejected was 41%, and the average was 16%.

- Drum with a stoichiometric H_2 concentration in air punctured by a sharpened drill did not ignite.

The experimental program was initiated to address problem with generation of H_2 gas in stored TRU waste. The potential for gas generation has been recognized since TRU waste storage begun. It was generally believed that the amount of α-emitters were insufficient to generate sufficient H_2 to pose a problem. A first-stage sludge drum found in 1980 had a bulged lid. A program was initiated to estimate number of drums capable of accumulating flammable concentrations and to postulate a maximum credible hydrogen explosion in TRU waste drum(s) retrieval at the Idaho site. Also, tests to determine whether FRP boxes and M-III bins were capable of accumulating gas were performed. Work in FY ’83 was divided into two major tasks both requiring field testing.

Characterized H_2 explosions in new DOT 17C (55-gal metal) drums tests by:

- Overpressure
- Ignition
- Impact
- Puncture
- Sympathetic explosions (explosion induced in adjacent drums)

Test 1 (over pressurization tests) — Compressed air was injected into drum. Also established maximum internal pressure that could be used for explosion tests (see Table D-8).

Test 2—Seven ignition tests were performed using the two types of wastes most likely to generate flammable gas: sludge and combustibles. Two H_2-air mixtures, the maximum observed in drums and the calculated "worst case", were tested. Two ignition sources were used near the top of drums:

1. Soft sparks (spark-gap 20 mJ)
2. Hard spark chemical squib (5 J)

This is a less favorable configuration for combustion propagation than ignition at the bottom of the void space-burning in the upwards direction.

In addition, a drum was dropped 12-ft onto a hard, unyielding surface, simulating the effect of driving a puncturing device into drum, and sympathetic explosion was tested.

New DOT 17C drums with 90-mil high-density polyethylene liners were used.

The drums for the tests were penetrated through drum and liners in three places:

1. Bottom of drum
2. Gas inlet
3. Exhaust lines

Results are presented in Table D-8

TABLE D-8 Purpose and Initial Conditions for Each Test (EG&G 1983)

Test	A	B[1]	C	D	E[7]	F	G	H
1	Determine hazards from over-pressurization without flammable gas.	None	22 psig	none	7.6 ft^3 @10 psig	Air	NA	NA
	Lid attached per specifications (determine reasonable maximum pressure to use in other tests.							
2	Determine the effects of the “worst observed” H_2-O_2-N_2 mixture in INEL TRU waste ignited by :soft spark” ignition.							
2A	Sludge	Soft spark[2]	10 psig[3]	Simulated sludge	4.8 ft^3	11% H_2, 50% O_2, 31% N_2[4]	Yes	NA
2B	Combustibles			Simulated combustibles plus metal	7.3 ft^3	6% H_2, 8% O_2, 86% N_2[4]	Yes	NA
3	Determine the effects of the “worst projected” H_2-O_2-N_2 mixture ignited by “soft spark” ignition.							
3A	Sludge	Soft spark[2]	10 psig[3]	Simulated sludge	4.9 ft^3	14% H_2, 62% O_2, 24% N_2 [5]	No	868 (1st stage sludge)
3B	Combustibles			Simulated combustibles plus metal	6.0 ft^3	30% H_2, 15% O_2, 55% N_2 [5]		271 (plastics)
4	Determine the effects of the “worst projected” H_2-O_2-N_2 mixture ignited by “hard spark” ignition.							
4A	Sludge	Hard spark[2]	10 psig[3]	Simulated sludge	4.3 ft^3	14% H_2, 62% O_2, 4% N_2 [5]	No	868 (1st stage sludge)

TABLE D-8 Purpose and Initial Conditions for Each Test (EG&G 1983)--Continued

Test	**A**	**B**[1]	**C**	**D**	**E**[7]	**F**	**G**	**H**
4B	Combustibles			Simulated combustibles plus metal	6.5 ft^3	30% H_2, 15% O_2, 55% N_2 [5]		271 (plastics)
4C	Combustibles (effects of less dense waste)			Kimwipes	7.7 ft^3 [4]			
4D	Combustibles (effects of exploding a drum on its' side)			Simulated combustibles plus metal	6.5 ft^3			
5	Determine if dropping a drum would ignite gas mixture	Impact	10 psig	Simulated combustibles plus metal	---	30% H_2, 15% O_2, 55% N_2 [5]	No	271 (plastics)
6	Determine if puncturing a drum would ignite gas mixture	Puncture						
7	Determine sympathetic explosion effect (if any)	Hard spark[2]						

Legend

A Purpose of Test
B **Ignition Source**
C **Internal Pressure**
D Waste Matrix
E Void Volume (Measured by comparing the pressure change of the drum with the pressure change of the mixing chamber, a known volume)
F Gas mixture
G Has this gas concentration been actually observed in waste drums?
H If not observed, the number of drums that could have this concentration in the year 2000

Notes

[1] A spark plug was used for the soft spark ignition source (~20 mJ); a squib (chemical spark) was used for the hard spark ignition source (~5 J).
[2] This is the maximum level to which drums could consistently be pressurized during the tests without significant leakage.
[3] This gas mixture was the "worst" gas mixture observed in the sampled drums containing this type of contents.
[4] These gas mixtures were the worst gas mixtures observed in sampled drums containing the listed type of contents.
[5] These gas mixtures were the worst gas mixtures calculated to be reasonably expected in drums containing the listed contents without excessively over-pressurizing the drums.
[6] The value of 7.7 ft^3 for the void volume is not a typographical error, and is 0.1 ft^3 higher than the volume measured for an empty drum plus liner (attributed to experimental error).
[7] Void volume was measured by comparing the pressure change of the drum (plus 90-mm polyethylene liner) with the pressure change of the mixing chamber (a known volume).

TABLE D.9 Gas Generation Tests Performed at the INEL Building FY-82 (EG&G 1983)

Test #	Container Type	Container Contents	Void Volume[a]	Gas Mixture	Pressure	Initiation Method	Results[b]
1	17C 55-gal drum with 90-mil liner (upright)	Empty	7.6 ft^3 @ 10 psig	Air	22 psig (max)	None	Pressure relieved by leakage around gasket. Drum lid did not blow off.
2A		Simulated sludge[c]	4.8 ft^3	11% H_2, 58% O_2, 31% N_2 [d]	10 psig[e]	Soft spark[f]	Drum lid remained on the drum and there was no release of the contents. [Did the gas mixture ignite?]
2B		Combustible plus metal[g]	7.3 ft^3	6% H_2, 8% O_2, 85% N_2 [d]			
3A		Simulated sludge[c]	4.9 ft^3	14% H_2, 62% O_2, 24% N_2 [h]			
3B		Combustible plus metal[g]	6.0 ft^3	30% H_2, 15% O_2, 55% N_2 [h]			Drum lid was blown ~130 ft into the air, some of the contents were blown by the wind more than 950 ft away, and a smoldering fire developed in the contents that burned 30 min. before being extinguished by water. Release fraction was 27%.
4A		Simulated sludge[c]	4.3 ft^3	14% H_2, 62% O_2, 24% N_2 [h]		Hard spark[f]	Drum lid remained on the drum and there was no release of the contents. Smoke was observed from the smoldering liner when the lid was removed.
4B		Combustible plus metal[g]	6.5 ft^3	30% H_2, 15% O_2, 55% N_2 [h][l]			Drum lid was blown about 175 ft into the air, some of the3 contents were blown away by the wind ~35 ft away, and a flaming fire developed in the contents following a second explosion that occurred after the lid has blown off [burning of residual H_2 when contacted oxygen in air?]. Release fraction 14%

Table D9 Gas Generation Tests Performed at the INEL Building FY-82 (EG&G 1983)-Continued

Test #	Container Type	Container Contents	Void Volume[a]	Gas Mixture	Pressure	Initiation Method	Results[b]
4C		Kimwipes	7.7 ft^3	30% H_2, 15% O_2, 55% n_2 [h]			Drum lid was blown ~50 ft into the air, some of the contents were blown by the wind ~260 ft away. No fire developed. Release fraction 7%.
4D	17C 55-gal drum with 90-mil liner (on its side)	Combustible plus metal[g]	6.5 ft^3				Drum lid was blown horizontally traveling ~ 200 ft away, some of the contents traveled ~35 ft away, and a flaming fire developed in the contents which burned for ~15 min. before self-extinguishing. Release fraction was 41%. The bottom weld failed in several places but the drum bottom was not blown off.
5	17C 55-gal drum with 90-mil liner (upright)		---			Drop 12 ft	Drum made 180° turn, landing on its' lid when dropped/ No ignition took place, and there was no release of contents. The drums held pressure following impact.
6						Puncture	Drum was punctured by a sharpened drill bit near the middle of the drum. Gas escaped through the hole, and no ignition took place.
7	A					Hard spark in bottom drum	Bottom drum gases were ignited. Lid of bottom drum was not blown off. Gases in the top drum ignited, the top drum lid was blown 182 ft into the air; some of the contents traveled 63 ft away in a slight wind, and a small fire resulted in the top drum. Release fraction was 16%.

Footnotes for Table D-9

[a] Void volume was measured by comparing the pressure change of the drum with the pressure of the mixing chamber (a known volume).
[b] Explosion over-pressures were not measured.
[c] Sludge was simulated by diatomaceous earth moistened with ~5-gal water.
[d] The gas mixtures were the worst observed in sampled drums containing those types of contents.
[e] This is the maximum reasonable pressure that drums could be expected to maintain without significant leakage.
[f] A spark plug was used for the soft spark ignition source (~20 mJ); a squib (chemical spark) was used for the hard spark ignition source (~5 J).
[g] The combustible material (e.g. cellulose of various forms, type of plastic such as PVC, PE, polypropylene, etc.) nor the size/weight of the individual pieces is not specified.
[h] These gas mixtures were the worst gas mixtures calculated to be reasonably expected in drums containing those contents (without over-pressurizing the drum).
[l] Handwritten notation, 3.5 mol H_2?

Additional Notes for Table D-9

- A 17C 55-gal drum with 90-mil liner (upright) with 3 adjacent drums. The top drum also contained a flammable gas mixture.
- Calculated volume of gases at STP
- Drum lid not blown off by 22 psig of internal pressure.
- Uncertain if all gas mixture ignited by soft spark. If the test that state “drum lid not blown off” are assumed to have ignited but generated insufficient internal pressure to blow lid off, 100% of the drums deflagrated but >14% H_2 necessary to generate sufficient internal pressure to dislodge lid.
- All the gas mixtures were ignited by a hard spark (5 J that is 1000X more energetic than the soft spark, 5 mJ). All the drums with 30% H_2 + 15% O_2 (a stoichiometric mixture) generated sufficient internal pressure to blow-off lid.
- Of the drums that blew off their lids and contained “combustibles and metal”, the Release Fraction (assumed to be the materials ejected from the drum) were: Release fractions were 27%, 14%, 7%, 41%, & 16%. Bounding value 41%, mean value 21%
- The single drum containing “kimwipes” (tissue), the release fraction 7%.

The tests provided the following:

- Important scooping data that helped establish a maximum credible accident
- No significant shrapnel danger was apparent other than from drum lids
- Pressure tests at maximum observed pressure did not cause lid to come off
- The worst explosive effect came from igniting drums containing a stoichiometric H_2-air mixture and simulated combustibles and metal
- Fires were observed in the combustibles, but *released contents did not sustain a fire.* Only one drum had to be extinguished
- More than one drum can explode in a given scenario. Based on the one sympathetic explosion test, only one drum is expected to eject its lid and contents in the scenario

D.7.6 WSRC-TR-90-165

The document findings are the following:

- The maximum pressure measured was 263.6-psig for a 47-vol% H_2 concentration at an initial pressure of 13.04-psig (near 2-atmospheres). The greatest pressure measured for a 30-vol% H_2 concentration (slightly less than stoichiometric for the experimental conditions) was 240.1-psig.

- TRU drum explosion tests—"Lid-loss" was observed for drums with >17-vol%. At <17-vol% (5 tests) drum bulged at top and bottom. Ignition of mixtures up to 15-vol% H_2 was contained in the drum without loss of containment.

Tests to determine minimum concentration for "lid-loss" plus the maximum pressure and rate pressure rise vs. H_2 concentration were performed. Preliminary small-scale pressure vessel tests were conducted to determine:

- The relationship between H_2 concentration vs. maximum pressure and pressure rise, over a H_2 range of 5- to 50-vol%, but variability of drum lid sealing and retaining ring closure prevented establishing relationship for drum

- Drum mixing tests (equilibration time for two H_2-air mixtures in drum, injection of 5- to 25-vol% in middle initial stratification but well-mixed in 50 min.)

Nine tests were performed over the range of 13- to 36-vol% H_2; suggests a concentration >15-vol% H_2 is necessary for "lid-loss". The drums were staged on a concrete pad. Both drum and liner have carbon composite filtered vents, but H_2 formation could occur in individual plastic bags.

D.7.6.1 Pressure Vessel Tests

- 1.7-liter vessel filled to slightly [not specified] above ambient pressure with H_2 5- to 50-vol% air concentration and ignited
- Selected H_2 concentrations for drum tests to determine any steep rise in maximum pressure and pressure rise rate over the range of concentrations

D.7.6.2 Drum Mixing Tests

- Concentration range: 5- and 25-vol% H_2 in modified drum
- Equilibrated by natural convection
- Concentration verified by gas chromatography

D.7.6.3 Drum Explosion Test

- Concentration range: 12- to 36-vol% H_2 equilibrated by natural diffusion
- Concentration verified prior to ignition by hot wire
- Not stated if drum filled with waste, or its composition, if filled. Presumed that drums were empty
- Filtered vent modified to allow plugging
- Sealed and closed according to established procedure

D.7.6.4 Results

- Maximum pressure and pressure rise rate highly dependent on H_2 concentration. (see Figure 7 and 8 in reference)
- Table D-10 shows the pressure vessel test data.

TABLE D-10 Pressure Vessel Test Data (WSRC-TR-90-165)

H_2 Conc, vol%	Initial Pressure, psig	Maximum Pressure, psig	Δp/Δt, psi/s
5	0.77	1.6	0.1
	0.77	20.5	229.2
	0.77	1.5	0.1
10	1.63	45.3	368.6
	1.63	45.3	329.8
15	2.59	78.9	4012
	2.59	76.8	3755
20	3.68	121.5	13039
	3.68	119.8	13645
25	4.9	186.4	30591.7
	4.9	189.1	34051.1
30	6.3	240	44132.3
	6.3	236	46444
	6.3	240.1	42188
35	7.92	253.5	51153.4
	7.92	250.8	51192
40	9.8	260.5	51780
	9.8	251.5	47344
	9.8	251.5	48346
45	12.03	268	49774
	12.03	258.3	47344
47	13.04	263.6	46444
50	14.7	252	39994.9
	14.7	185	22784

Note that the maximum pressure did not increase significantly for H2 concentration greater than the approximate stoichiometric mixture. This reflects the limited amount of fuel and oxidant present in closed system

- A third-order polynomial was found to be a good fit to data
- Under non-ideal condition (closed system), an excess of H_2 is required for complete combustion
- Complete mixing in drums for both concentrations was achieved in 60-min.
- TRU drum explosion tests showed that:
    - "Lid-loss" occurred in drums with >17-vol% H_2-air and for drums with <17-vol% (5 tests) bulged at top and bottom
    - Concluded ignition of mixtures up to 15-vol% H_2 are contained in drum without loss of containment
    - An empirical relationship could not be determined due to limited number of tests

Bulging indicates drum has been under internal pressure but does not show the drum is currently under pressure. The design makes drums capable of violent rupture. There is a significant difference in behavior between drums types.

The maximum pressure measured was 268-psig for a 45-vol% H_2 concentration at an initial pressure of 12.03-psig (near 2-atmospheres). The greatest pressure measured for a 30-vol% H_2 concentration (slightly less than stoichiometric for the experimental conditions) was 240.1-psig.

D.7.7 WSMS 2006 (DDT)

The article concluded that a DDT is not credible for a DOT 55-gal, metal TRU waste-filled drum. For a detonation to occur, the reaction must transition requiring specific specialized conditions:

- ℓ/D, the ratio of length to diameter, of container is one of the key parameters that controls DDT in container. Literature values required ℓ/D 60
- If the pressure is at 4.5-atm (~66-psig), the ℓ/D reduces to ~ 10
- TRU waste drums are leaky and data indicates that these drums cannot hold pressure >11- to 14-psig (DOE 7A drum are only required to withstand 11-psig and the EG&G-1983 study reported that 17-C drum would not hold reliably >10-psig)
- The ℓ/D of a 55-gal drum is ~1.4 (ID 22½-in, 32-in. inner height)

Another factor is the run-up distance (distance from ignition point to transition) and the contents of a drum:

- Run-up distances in the literature is in the range of 10-m, the distance in the void space of a DOT, 55-gal, metal drum is insufficient (inner height 32-in., ~0.8-m). The distance available in a drum is an order-of-magnitude less than necessary for a DDT
- Solid contents that do not compress (e.g., metal, glass, etc.) would not undergo radiolysis and contribute to H_2 generation in drums
- Contents reduce the free-volume of a drum reducing the opportunity for DDT

Internal pressure could be a significant factor but pressure build-up in drums would be detected by bulging lids (>6-psig) and would reach a point where the seal fails allowing the drum to vent (>14-psig) … DOT-7A Type A packaging is designed for Δ_p ~11-psig. A large increase in pressure is required to reduce ℓ/D to 10.

Slow pressure build-up would result in failure ("seal-failure) of drum at weakest point, the lid, not the sidewall. Significant deflagration in drum may result in "fish-mouth" opening in sidewall.

For DDT to occur without transition, a strong energy source is required: ~4,000 J. Energies have been reported as low as 1-10 J under ideal conditions for stoichiometric conditions of pure H_2 and O_2 that do not exist for waste drums. A value closer to 4,000 J would be required for TRU waste drums. The energy associated with movement, venting, and storage (e.g., static electric discharge ~0.019-mJ with a 100-mJ energy required for deflagration) do not approach a value sufficient for DDT. The article did not consider the effect of drums engulfed in a trash or liquid hydrocarbon fire.

D.7.7.1 Introduction

WSMS 2006 contained a literature review that evaluated the potential for hydrogen detonation versus hydrogen deflagration in TRU waste drums and evaluated the potential explosions in unvented TRU waste drums based on experimental data, field tests, and various published references of hydrogen and other VOC explosions. The type of explosion effects (lid-loss + ejection of waste versus splitting the side wall seam) is the main concern.

D.7.7.2 Technical Position

Conclusion of WSMS's analysis indicates that the appropriate level of explosion event for the safety basis for TRU waste drums is a deflagration, not detonation, that produces catastrophic failure of drum with shrapnel and collateral damage

Slow pressure build-up would result in failure of drum at weakest point (lid not sidewall). Significant deflagration in the drum may result in a "fish-mouth" opening in the sidewall. The top tier of stacked drums is expected to fail by "lid-loss" or "fish mouth" failures.

Waste Management Programs require periodic inspections that would detect bulging, degraded, or breached drums.

D.7.7.3 Literature Review

- WSRC-TR-90-165 (WSRC 1990)
    - Empty drum used; waste drums that contain material would reduce the "free-volume" available for gas accumulation
    - Tested H_2 explosions in TRU drums with 13- to 36-vol% H_2, ignition by "hot-wire"
    - Drum failure by "lid-loss" at >15-vol% H_2
    - Maximum pressure was 320 psig @22.72-vol%
    - 2nd highest pressure measured was @17.97-vol% H_2, 211-psig
    - Observed response ranged from bulging to "lid-loss" but no catastrophic failure of the side walls or welded bottom
    - Ignition of VOC mixed with air did not generate sufficient internal pressure for "lid-loss"
    - Ignition VOC + 4-vol% H_2 mixed with air did not generate sufficient internal pressure for "lid-loss"
    - Compression of contents prevents "lid-loss"
    - Minimum internal pressure for "lid-loss" estimated at 105-psig

  - In explosion, significant amounts of heat absorbed by contents and drum (in duration of deflagration, ~0.2-s; also contrary to conservative assumption made to estimate the burn fraction of ejected wastes in the Fluor Hanford 2004 report, (HNF-19492) limiting consequences
  - Bulging of top and bottom of drum increases the volume

- LLNL 2005 (see the WSMS 2006 paper)

  - Rate of reaction determines the potential damage
  - Spatial requirements, initiating energy, and narrower concentration range requirement (matching the previous discussion) make potential for large, high energy, failure of drum incredible

- HNF-19492 (Fluor Hanford 2004)

  - Explosions of H_2 may result in some ejection of contents
  - High H_2 required for "lid-loss", 'worst-case" H_2 explosion 20-vol% H_2 + >10-vol% O_2; 182-psig calculated
  - 2nd explosion may occur due to compression and trapping of gas
  - Estimates 5% ejection and 18% burning as "base-case"
  - Worst-case ejection 33% evaluated in sensitivity study

The paper concluded that a DDT is not credible for TRU waste drums.

D.7.8 EMRTC 2004 (DDT)

ARROW-PAK™ , a proposed "no-consequence" container, has drum-like internal dimensions. A stoichiometric H_2-air mixture was ignited in the equipment and no DDT was observed. Document findings confirm that H_2-air mixtures do not transition into a detonation due to small ℓ/D and insufficient "run-up" distances in the item.

Relevant combustion characteristic of combustible materials that may be found in TRU waste are shown.

The New Mexico School of Mining Technology, Energetic Materials Research and Testing Center (EMRTC) performed tests to evaluate performance of ARROW-PAK™ to contain a stoichiometric hydrogen/air mixture deflagrated. ARROW-PAK™ is designed to fit into TRUPACT-II.

DOT CFR Part 49 para 173.465 Type A Packaging Test were performed on the package:

- *Water Spray Test:* Subjected to water spray for 1-hr

- *Free Drop Test:* Dropped from 4-ft 4½-in. onto steel plate on concrete slab (drum weight 1,248-lb), bounced and landed flat on end with no significant damage

- *Stacking Test:* Compressive load 5 X weight of the package (1804-lb) was applied for >24-hr; applied uniformly to 2 opposite sides … on steel plate with 2 plate weighing 9,100-lb, observed no significant changes to package

- *Penetration Test:* 1¼-in. diameter bar (weight 13.2-lb) with hemispherical end dropped, 4-ft to impact weakest point horizontally, 1/32-in dimple

D.7.9 WSRC 2007

The objective of a Savannah River calculation, *Evaluation of Deflagration Pressure of Solid Waste Drums with VOCs and Hydrogen at Concentrations Higher than Lower Flammability Limit (U)*, was to evaluate the deflagration pressure of unvented TRU drums that contain mixtures of Volatile Organic Compounds (VOCs) and hydrogen with concentration ranging from 4 volume percent to 8 volume percent (WSRC 2007). The VOCs that were selected inside the TRU waste drums for analysis were consistently identified in headspace gas analyses and have concentrations greater than 10 percent of the LFL value (WSRC 2005). Two series of drum explosion testing were conducted to determine the effects of igniting hydrogen-air mixtures inside TRU waste drums. Based on these experimental tests, it was determined that the minimum pressure that causes a lid to blow off the drum was measured to be 105 psig. This pressure is used as a Figure of Merit (FOM) for the results being reported here.

The calculated pressures from the combustion of the mixture of VOC and hydrogen at less than or equal to 8 volume percent are not expected to exceed the FOM, i.e., 105 psig, as a result of deflagration (WSRC 2007). This conclusion is dependent on the following key conditions:

- The waste drums are standard DOT 55-gallon TRU vented drums
- Drums are closed using standard lid bolts and closure rings. No special effort is used to “seal” the drums.
- Hydrogen concentration is not to exceed 8 volume percent

D.8 Summary and Conclusions

The literature on hydrogen combustion/deflagrations and experimental studies on the effects of hydrogen explosion in TRU waste drums were reviewed for this appendix. The results reported support the position that:

- The flammability limits are a function of the direction the combustion is propagated:
  - *Upward* - 4-vol% H_2 for upwards propagation produces an average flame temperature of <350° C, whereas the ignition temperature of H_2 in air is 585° C. This can be understood from observation that the flame in the mixture rises as luminous balls that consume only part of the hydrogen and fresh hydrogen diffuses into the burning ball and yields higher effective concentrations of hydrogen than initially present. (note: this is the traditional definition for the LFL).
  - *Horizontal* - 6.5-vol% H_2.
  - *Downward* - ~9-vol% H_2.

- The values from the large vessel experiments cited overstate the effect anticipated for 55-gal drums due to the limited volume available

- No combustion was initiated at 5-vol%-air in the Atomics International shock-tube tests (AI 1973), even using a well-establish flame. With the same flame initiator, a 7-vol% H_2 -air partial burning was observed without water spray, and more substantial combustion was obtained at 9-vol%-air, but combustion was incomplete. No initiation for 5-, 7-, 9.3-vol% in air using a spark gap initiator.

- Complete burning was not propagated for H_2 in air concentration <12-vol% (the internal pressure in a drum would be less than the AICC value). The behavior was similar for the tests with water vapor present—an important factor due to the presence of some level of moisture (relative humidity and potential water formation during radiolysis in TRU waste drums filled with hydrogenous materials). (AI 1973)

- Pressure ratio began to depart significantly from AICC values at H_2 concentrations <8-vol%; maximum temperatures ranged from essentially ambient to 1102° C for the tests (EPRI 1988)

- Two types of DOT 7A containers were used for packaging TRU waste – 17-C and 17-H open-head, metal, 55-gal drums. When new, the drums have a nominal capacity of 208-liter (l) (55-gal) and are constructed of 16-gauge steel (wall thickness of 1.52-mm/ 0.0598-in) for 17-C and 18-gauge (wall thickness of 1.214-mm/0.0478-in.) for 17-H. The drums have a nominal diameter of 61-cm/24-in. and are 86-cm/35-in. tall; lid held in place by a clamping ring secured with a nut and bolt. "Legacy" waste drums may exhibit some loss of structural strength due to prolonged storage under unfavorable conditions but significant degradation would be plainly visible when inspected prior to handling and movement. Experimental studies have shown that:

  - DOT 7A containers are designed for an overpressure (Δp) of 11-psig. The drums bulge at ~6-psig[37]. For slow increases in internal pressure, TRU waste drums vent ("seal-failure") at <14-psig. EG&G-ID found that new 17-C drums with a sealed 90-mil HDPE liner could only reliably maintain an internal pressure of 10-psig (EG&G 1983).
  - "Lid loss" (physical, forceful ejection of the lid) required a rapid increase of pressure to >100-psig (EG&G 1983, WSRC 1990, WSRS 2005, WSMS 2006)

- DDT is not a credible event for H_2-air combustion in TRU waste drums.

- The calculated pressures from the combustion of the mixture of VOC and hydrogen at less than or equal to 8-vol%t are not expected to cause lid loss as a result of deflagration.

Due to the potential degradation of the TRU waste drums (due to prolonged storage and storage conditions), some level of loss of sidewall strength may occur. To compensate for this uncertainty, the H_2-air concentration of 8-vol% (as opposed to 15-vol% determined in both experimental studies) is selected as the H_2 level that requires immediate venting/purging to eliminate the potential for the catastrophic ejection of the drum lid (and possibly a fraction of the contained waste).

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[37] based on the assumptions that the free-volume of the drum is 100-l (about 50% void space), the sole source of the increase pressure is the H_2 generation, and the drum does not leak, the H_2 concentration is 21-vol% and the O_2 concentration is 19.4-vol%.

D.9 References

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CONCLUDING MATERIAL

Review Activity:		**Preparing Activity:**
DOE	Field and Operations Offices	DOE-EM-3
DP-NNSA	AL	
EH	ID	Project Number:
		SAFT-0113
EM	OAK	
	OR	
	RL	
	SR	
	Carlsbad Field Office (CBFO)	
	Los Alamos Site Office	
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