ORNL/RRD/INT-174, Rev. 0

Test Plan for Normal Conditions of Transport and Hypothetical Accident Condition Tests, Oak Ridge National Laboratory Package Design USA/5797/B(U)F-96:

Bases for Selecting Tests, Orientations, and Test Conditions

Paul Blanton

September 2021

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

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Research Reactors Division

TEST PLAN FOR NORMAL CONDITIONS OF TRANSPORT AND HYPOTHETICAL ACCIDENT CONDITION TESTS, OAK RIDGE NATIONAL LABORATORY PACKAGE DESIGN USA/5797/B(U)F-96:

BASES FOR SELECTING TESTS, ORIENTATIONS, AND TEST CONDITIONS

Paul Blanton

September 2021

Prepared by
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Bases for Selecting Tests, Orientations, and Test Conditions

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Revision Log

Revision	Description
0	Initial Issue

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Acronyms

A	Ambient
AS	As Specified
CGB	Center of Gravity over Bottom Container Rim
CGT	Center of Gravity over Top Container Rim
CFR	Code of Federal Regulations
CV	Containment Vessel
DOE	Department of Energy
H	Horizontal
HAC	Hypothetical Accident Conditions
HFIR	High Flux Isotope Reactor
MNOP	Maximum Normal Operating Pressure
NA	Not applicable
NCT	Normal Conditions of Transport
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
RRD	Research Reactors Division
TD	Top Down
TSD	Top Slap Down
VTU	Vertical Top Up

1. INTRODUCTION

The Inner HFIR Unirradiated Fuel Element Shipping Container, and Outer HFIR Unirradiated Fuel Element Shipping Container, NRC package ID USA/5797/B(U)F, package design was developed and initially certified in the mid-1960s by Oak Ridge National Laboratory (ORNL) to transport unirradiated High Flux Isotope Reactor (HFIR) fuel elements. As permitted by 10CFR71, initial certification was granted based solely on analysis with no physical testing performed as documented in Safety Analysis for Packaging: The ORNL HFIR Unirradiated Fuel Element Shipping Container.[1] Certification authority was later assumed by the Department of Energy (DOE) and subsequently Nuclear Regulatory Commission (NRC), both of whom continued to certify 5797 for use. In 10CFR71 requirements (-96) were changed to include a crush test following the existing 30-foot drop test (10CFR71.73). Certifications have been granted since that time based on the historical analysis and limited scope review without consideration of the additional crush requirement. However, it is expected that any future certification of the 5797 will require the full 10CFR71-96 criteria be addressed. Test data sufficient to support analysis of a 10CFR71-96 specified post-drop crush is not available. Therefore, ORNL has decided to perform physical testing to support further 5797 certifications.

Table 1 identifies the regulatory conditions and tests that are planned for the Inner and Outer HFIR containers to support B(U)F-96 certification. Testing details are documented in ORNLs Test Plan for Normal Conditions of Transport and Hypothetical Accident Condition Tests.[2] Physical testing in support of new package development typically includes performance of from five to ten test sequences, each sequence being performed on one or more packages. Based on extensive experience in package testing and post-test damage inspection, including successful design and certification of eight packages, and on review of package test results for similar drum styles, a set of seven test sequences sufficient to demonstrate full compliance with current 10CFR71 requirements is recommended for 5797 testing. There are two models of the container, one to carry inner HFIR fuel elements and one to carry outer HFIR fuel elements, hereinafter referred to as the inner and outer models (Figures 1 and 2). Differences in the two models necessitate somewhat different test sequences resulting in seven inner and seven outer sequences which require a minimum of seven inner and outer packages for testing. Test conditions and potential failure criteria, as well as the basis for inclusion or omission of each test in the recommended set, are described in Table 2 for Inner package tests and Table 3 for Outer package tests. While the tables present only hypothetical accident conditions (HAC) drop and crush, it is assumed in all cases that those HACs are preceded by tests for normal conditions of transport (NCT) and followed by the HAC puncture, thermal and immersion testing identified in Table 1.

Simulated non-fissile content must be used for package testing. In a typical Type B package configuration, content to be transported is placed into a containment vessel that is then positioned inside the transportation package. Response to testing can then be obtained through containment vessel leak testing. Clad fuel, such as HFIR, is not transported in containment vessels. Rather, it is loaded directly into a transportation package and the fuel cladding fulfills the containment function. Only two HIFR inner/outer fuel element sets have been identified that are suitable for testing purposes, necessitating a reduction in the recommended set of seven test sequences to a set of two selected sequences listed in Table 1. The bases for selecting recommended tests 1 and 2 and for omitting

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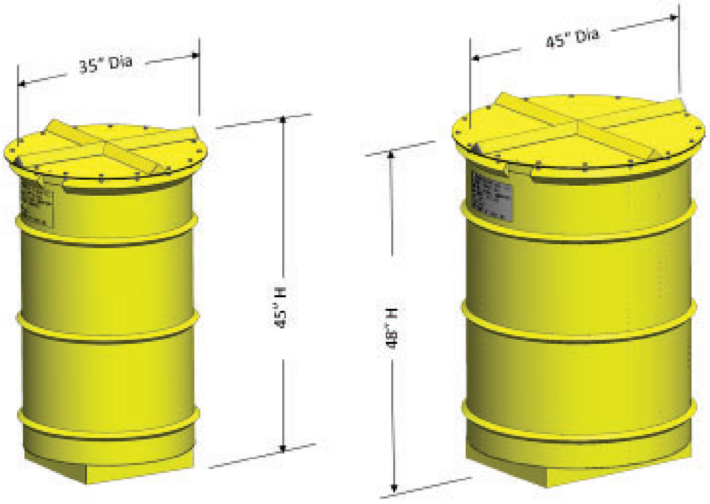
[1] Safety Analysis for Packaging: The ORNL HFIR Unirradiated Fuel Element Shipping Container, ORNL/TM-11656/Vol 1 and Vol 2, Oak Ridge National Laboratory.

[2] Test Plan for Normal Conditions of Transport and Hypothetical Accident Condition Tests, ORNL/RRD/INT-173, Revision 1, Oak Ridge National Laboratory, September 2021.

recommended tests 3 through 7 are included in Tables 2 and 3 for the inner and outer HFIR container models, respectively.

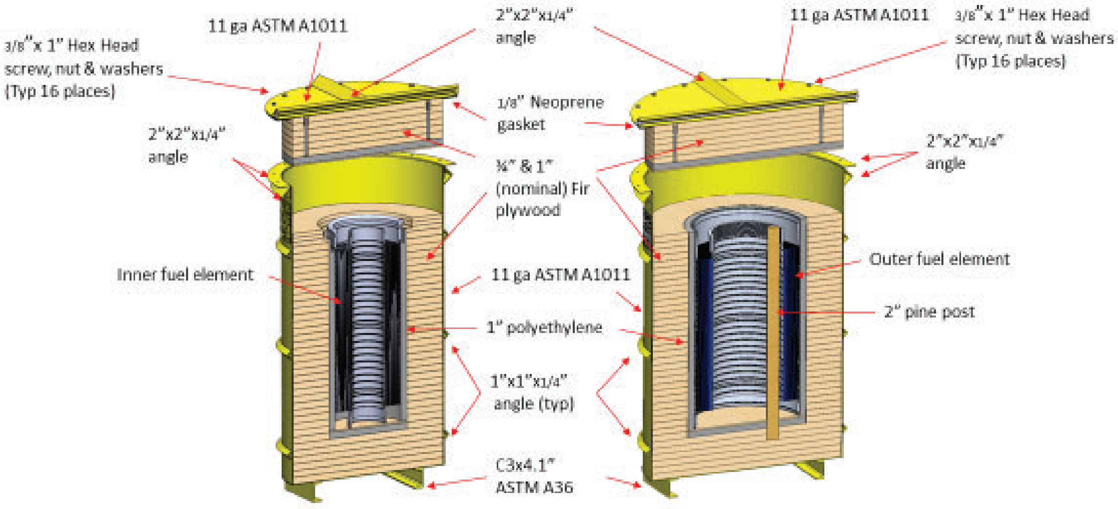
The selected test sequences, Table 1, are expected to bound potential damage conditions not currently addressed by SARP analyses and, combined with historical analysis, will demonstrate package release, dose rate limits and subcriticality determinations are not compromised.



Inner element container
(557 lb, tare)

Outer element container
(845 lb, tare)

Figure 1. 5797 Inner and Outer HFIR Unirradiated Fuel Element Shipping Containers



Inner element container **Outer element container**

Figure 2. 5797 Inner and Outer HFIR Unirradiated Fuel Element Shipping Container Cross Sections

Table 1 – USA/5797/B(U)F-96 Testing Matrix

Test Unit ID	CFR Ref.	Inner-1	Inner-1	Outer-1	Inner-2	Outer-2
Prototype Preparation						
Content measurements and weight		x	x	x	x	x
Package Measurements and weights		x	x	x	x	x
Package Marking		x	x	x	x	x
Instrumentation		x	x	x	x	x
Normal Conditions of Transport 10 CFR 71.71						
Initial Conditions (-20°F to 100°F)	(b)*	-	A	A	A	A
Maximum Normal Operating Pressure (MNOP)	(b)	Note 1	Note 1	Note 1	Note 1	Note 1
Conditions and Tests	(c)					
Heat (100°F/w solar)	(c)(1)	-	EBA	EBA	EBA	EBA
Cold (-40°F)	(c)(2)	-40°F	-	-	-	-
Increased external pressure	(c)(4)	-	Note 1	Note 1	Note 1	Note 1
Reduced external pressure	(c)(3)	-	Note 1	Note 1	Note 1	Note 1
Vibration (c)(5)	(c)(5)	-			VTU (Note 4&7)	VTU (Note 4&7)
Water Spray	(c)(6)	-	VTU	VTU	-	-
Free Drop (4-ft)	(c)(7)	-	CGT	CGT	TD	H
Corner Drop (1-ft)	(c)(8)	-	Note 1	Note 1	Note 1	Note 1
Compression	(c)(9)	-	VTU	VTU	-	-
Penetration	(c)(10)	-	AS	AS	AS	AS
Hypothetical Accident Conditions 10CFR71.73						
Test Conditions (-20°F to 100°F)	(b)	-	-20°F	-20°F	100°F	100°F
Tests	(c)	-				
Free Drop (30-ft)	(c)(1)	-	CGT	CGB	CGT	TSD Note 9
Crush Test (30-ft) 1,100 lb plate	(c)(2)	-	H Note 5	CGB	H Note 8	H Note 10
Puncture Test (40-in)	(c)(3)	-	AS	AS	AS	AS
Thermal	(c)(4)	-	-	-	AS	AS
Immersion- Fissile (3-ft)	(c)(5)	-	EBA	EBA	EBA	EBA
Immersion-all (50-ft)	(c)(6)	-	EBA	EBA	EBA	EBA
Special Requirements Type B (290psi)	10CFR71. 61	-	Note 11	Note 11	Note 11	Note 11
Post Test Evaluation						
Non-Destructive		Note 2	Note 3	Note 3	Note 3	Note 3
Destructive		-	Note 6	Note 6	Note 6	Note 6

*initial conditions are also applicable to HAC 10 CFR 71.73(b)
“x” designates required
“-” designates not applicable

Table Notes:

1. Evaluation is performed by analysis as discussed in Section 5.4 or 5.5 of the Test Plan.
2. Following -40°F test; inspect and reassemble for NCT/HAC testing.
3. External inspection; dimensional measurements, weight, verification of no broken bolts, cracked welds, drum breaches, etc.
4. Use ORNL designed tie-down to secure drum in as-shipped configuration.
5. 30-ft CGT damage facing crush plate
6. Internal inspection; open or section container for internal diameter measurements, remove dummy fuel whole and inspect for damage.
7. Internal inspection; open container; inspect fuel element and packaging; reassemble for continued NCT/HAC testing.
8. Horizontal crush; damaged side from CGT against pad.
9. 15-degree shallow angle drop; 2” diameter post positioned at 12 o’clock position, opposite secondary 30-ft drop impact point.
10. Horizontal crush; 2” diameter post at 12 o’clock position damaged side from TSD facing pad
11. The contents of the shipping containers are less than 10^5A_2. Therefore, this test is not applicable.

Table 2 – Recommended Inner Test Sequences

Test Sequence	Test Conditions			Potential Failure Criterion
	Temp	Drop Orientation	Crush Orientation	
Inner - 1	-20°F	CGT	Horizontal	Primary: Significant reduction in container confinement boundary effectiveness, sufficient to result in partial or full fuel exposure during thermal event. (containment and subcriticality) Secondary: Fuel deformation sufficient to compromise fuel integrity. (containment)

Bases for test recommendation:

The combination of this sequence is expected to produce the greatest bulk package deformation.

- Temperature: Minimizes energy absorption of the carbon steel overpack due to high strain rate and material nil-ductility properties.
- Drop orientation: Maximizes challenge to confinement boundary. Additionally, localized sheer loading may affect glue bond performance during subsequent crush.
- Crush orientation: Optimizes impact to approximate package center where laminated wood impact limiter cross section flexural rigidity is minimized. Addresses the performance of the wood impact limiter to resist buckling, splintering or slippage (delamination) from uniform plate impact and discrete impact from drum angle stiffeners that could breach the drum wall or damage fuel integrity.

Bases for inclusion in limited test:

This test sequence allows for baseline comparison of existing SARP 30-ft drop analysis. Minimal change in package performance at cold temperature will support validation of current SARP analysis of omitted tests at low temperature.

The horizontal crush challenges the package mid-section where there is less cross-sectional strength from the packaging materials of construction. In this orientation, the package ends are stiffer and cannot share a large portion of the crush load. This phenomenon is exaggerated for taller packages where the, typically less stiff, mid-section of the package is longer than the crush plate. The Inner HFIR package design is affected by this condition. The package is oriented such that the damaged corner of the package is facing the crush pad to compound damage. Damage to the package is typically greater where the crush plate impacts the package as opposed to the package side adjacent to the pad when the plate width is shorter than package height. [3,4]

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[3] Safety Analysis Report for Packaging Model 9981 Type AF Shipping Package, S-SARP-G-00020, Savannah River National Laboratory, March 2019.

[4] Safety Analysis Report for Packaging, Bulk Tritium Shipping Package, S-SARP-G-00004, Savannah River National Laboratory, July 2018.

Table 2 – Recommended Inner Test Sequences (continued)

Test Sequence	**Test Conditions**			**Potential Failure Criterion**
	Temp	**Drop Orientation**	**Crush Orientation**	
Inner - 2	100 °F	CGT	Horizontal	Primary: Significant reduction in container confinement boundary effectiveness, sufficient to result in partial or full fuel exposure during thermal event. (containment and subcriticality) Secondary: Fuel deformation sufficient to compromise fuel integrity. (containment)

Bases for test recommendation:

Minimizes differences between existing SARP analysis and test conditions to support validation purposes.

- Drop orientation: Supports comparison of initial condition on package materials of construction (drum and wood impact limiter) to existing ambient analysis.
- Crush orientation: Maximizes potential for drum bottom breach (material split, weld failure) under a low temperature condition and overpack deformation-initiated fuel damage.

Bases for inclusion in limited test:

This test sequence allows for baseline comparison of existing SARP 30-ft drop analysis performed under ambient conditions to test results performed at 100°F. Minimal change in package performance at elevated temperature will support validation of current SARP analysis of omitted tests at elevated temperature.

The horizontal crush challenges the package mid-section where there is less cross-sectional strength from the packaging materials of construction. In this orientation, the package ends are stiffer and cannot share a large portion of the crush load. This phenomenon is exaggerated for taller packages where the, typically less stiff, mid-section of the package is longer than the crush plate. The Inner HFIR package design is affected by this condition. The package is oriented such that the damaged corner of the package is facing the crush pad to compound damage. Damage to the package is typically greater where the crush plate impacts the package as opposed to the package side adjacent to the pad when the plate width is shorter than package height.

Table 2 – Recommended Inner Test Sequences (continued)

<table>
<tr><th rowspan="2">Test Sequence</th><th colspan="3">Test Conditions</th><th rowspan="2">Failure Criterion</th></tr>
<tr><th>Temp</th><th>Drop Orientation</th><th>Crush Orientation</th></tr>
<tr><td>Inner - 3</td><td>-20°F</td><td>Horizontal</td><td>Horizontal</td><td>Primary: Weakening of the impact limiter laminate structure and possible shear of lid closure bolting. (containment)
Secondary: Impact limiter laminate structure failure (fuel damage from plywood failure buckling, joint failure, splintering, slippage). (containment).</td></tr>
<tr><td colspan="5">**Bases for test recommendation:**
• Temperature: Supports direct comparison to existing 30-ft horizontal drop analysis results under ambient conditions to low temperature testing results.
• Crush orientation: Optimizes impact to approximate package center where laminated wood impact limiter cross section flexural rigidity is smallest, maximizing potential for fuel buckling from limiter splintering or slippage (delamination).</td></tr>
<tr><td colspan="5">**Bases for omission from limited test:**
Historically, package damage from a 30-ft horizontal drop does not significantly challenge the package, the closure or the content. Packages of similar mass and size, BTSP (50-inch tall by 24.5 diameter, 650 lbs) and DT-23 (41-inch tall by 33-inch diameter, 860 lbs) as compared to the HFIR Inner (45-inch tall by 25-inch diameter, 650 lbs) support this conclusion. Further, differences in package performance under low versus elevated temperature conditions have not been structurally significant. Therefore, existing HFIR SARP analysis is considered to be sufficient to support conclusions regarding 30-ft drop package performance.
Horizontal crush damage observation from Inner-1 testing can be referenced to draw a conclusion on package performance for this combined sequence in lieu of testing.</td></tr>
</table>

Table 2 – Recommended Inner Test Sequences (continued)

Test Sequence	Test Conditions			Failure Criterion
	Temp	Drop Orientation	Crush Orientation	
Inner - 4	Ambient	Horizontal	Horizontal	Primary: Weakening of the impact limiter laminate structure and possible shear of lid closure bolting. (containment) Secondary: Deformation, buckling of the fuel element. (containment).

Bases for test recommendation:

- Temperature: Supports direct comparison to existing 30-ft horizontal drop analysis results under ambient conditions to test results.
- Crush orientation: Optimizes impact to approximate package center where laminated wood impact limiter cross section flexural rigidity is smallest, maximizing potential for buckling, splintering or slippage (delamination).

Bases for omission from limited test:

Historically, package damage from a 30-ft horizontal drop does not significantly challenge the package, the closure or the content. Packages of similar mass and size, BTSP and DT-23 as compared to the HFIR Inner Package support this conclusion. Therefore, existing HFIR SARP analysis is considered to be sufficient to support conclusions regarding 30-ft drop packaging and content performance.

Horizontal crush damage observation from Inner-2 testing can be referenced to draw conclusion on package performance for this combined sequence in lieu of testing.

Table 2 – Recommended Inner Test Sequences (continued)

Test Sequence	Test Conditions			Failure Criterion
	Temp	Drop Orientation	Crush Orientation	
Inner - 5	Ambient	Top Down	Horizontal	Primary: Fuel shear and buckling (containment) Secondary: Impact limiter laminate structure failure (fuel damage from plywood failure buckling, joint failure, splintering, slippage). (containment).

Bases for test recommendation:

- Temperature: Supports direct comparison to existing 30-ft top-down drop analysis results under ambient conditions to low temperature testing results.
- Crush orientation: Optimizes impact to approximate package center where laminated wood impact limiter cross section flexural rigidity is smallest, maximizing potential for fuel buckling from limiter splintering or slippage (delamination).

Bases for omission from limited test:

Historically, package damage from a 30-ft end drop does not significantly challenge the package with typical damage being a slight reduction in the overall height of the packaging from drum side wall crumpling in the immediate vicinity of impact and stresses in the containment vessel due to content impact on the containment vessel (CV). Since the HFIR packaging does not incorporate a containment vessel only those stresses in the fuel element are of importance. Existing HFIR package analysis of the fuel cladding due to inertia loads indicates a significant margin of safety against buckling and no stress exceeding allowable limits in the fuel cladding.

Therefore, the existing HFIR SARP analysis with results from similar mass and size package testing, BTSP and DT-23 is considered to be sufficient to support the conclusion that the 30-ft top drop will not adversely affect the packaging and or its content.

Horizontal crush damage observation from Inner-2 testing can be referenced to draw conclusion on package performance for the combined sequence in lieu of testing.

Table 2 – Recommended Inner Test Sequences (continued)

Test Sequence	Test Conditions			Failure Criterion
	Temp	Drop Orientation	Crush Orientation	
Inner - 6	Ambient	Oblique	Horizontal	Primary: Weakening of the impact limiter laminate structure and possible shear of lid closure bolting. (containment, confinement) Secondary: Impact limiter laminate structure failure (fuel damage from plywood failure buckling, joint failure, splintering, slippage). (containment).

Bases for test recommendation:

- Drop orientation: Maximizes challenge to container boundary closure. Additionally, localized sheer loading may affect glue bond performance during subsequent crush.
- Crush orientation: Optimizes impact to approximate package center where laminated wood impact limiter cross section flexural rigidity is minimized. Addresses the performance of the wood impact limiter to resist buckling, splintering or slippage (delamination) from uniform plate impact and discrete impact from drum angle stiffeners that could breach the drum wall or damage fuel integrity.

Bases for omission from limited test:

Two types of oblique drops, the slap-down (~15 degrees) and shallow-angle (~ 30 degrees), are typical of the 30-ft oblique drop. The slap-down typically challenges the drum and containment vessel closures of slender designs, since the added angular momentum to the non-impacting end due to rebound of the impacting end can be significant, whereas the shallow-angle drop targets the package overpack closure. [5]

The Inner HFIR package aspect ratio 45 inches / 25 inches, or ~1.9 indicates that secondary impact as result of a slap-down on its bolted closure would not introduce a significant amount of load into the drum closure because of its low mass. The Inner HFIR package does not incorporate a containment vessel but just the fuel element with an approximate aspect ratio of ~3. The fuel element positioning about the drums center of gravity and its mass (~100 lbs) would not introduce a significant amount of load into the fuel element as compared to horizontal drop, therefore existing horizontal drop analysis with its conservatism (fuel elements not welded to the inner and outer element shells) is sufficient to evaluate the performance of the fuel in a slap-down drop.

The shallow-angle drop was found to be challenging to industry standard bolt/ring closures. The Inner HFIR package incorporates a bolted lid closure protected by welded angle stiffeners and is not sensitive to shallow angle drops. [6,7,8]

Horizontal crush damage observation from Inner-2 testing can be referenced to draw conclusion on package performance for this combined sequence in lieu of testing.

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[5] P.S. Blanton and A.C. Smith, Response of Conventional Ring Closures Of Drum Type Packages To Regulatory Drop Tests With Application to The 9974/9975 Package, WSRC-MS-2001-00306, Westinghouse Savannah River Company, PVP (August 2002).

[6] David M. Speaks, Test Report of the DT-23 Shipping Package, YMA-92-2, Y -12 Plant Program Management Packaging Group, September 1992.

[7] Safety Analysis Report for Packaging, Bulk Tritium Shipping Package, S-SARP-G-00004, Savannah River National Laboratory, July 2018

[8] NUREG CR-6818, Drop Test Results for the Combustion Engineering Model No. ABB-2901, Lawrence Livermore National Laboratory, October 2003.

Table 2 – Recommended Inner Test Sequences (continued)

Test Sequence	Test Conditions			Failure Criterion
	Temp	Drop Orientation	Crush Orientation	
Inner - 7	Ambient	Bottom Down	Top Down	Primary: Fuel shear and buckling. Secondary: Weakening of the impact limiter laminate structure.

Bases for test recommendation:

- Temperature: Supports direct comparison to existing 30-ft drop analysis results under ambient conditions.
- Crush orientation: Optimizes impact to package ends challenging impact limiter performance and maximizing potential for fuel buckling in the event of limiter failure.

Bases for omission from limited test:

Historically, package damage from a 30-ft end drop does not significantly challenge the package with typical damage being a slight reduction in the overall height of the packaging from drum side wall crumpling in the immediate vicinity of impact and stresses in the containment vessel due to content impact on the CV. Since the HFIR packaging does not incorporate a containment vessel only those stresses in the fuel element are of importance. Existing HFIR package analysis of the fuel cladding due to inertia loads indicates a significant margin of safety against buckling and no stress in the fuel cladding exceeding allowable limits.

End drop crush damage is expected to produce a slightly greater reduction in package height occurring due to the continued crush of the package forklift pockets and lid reinforcing angles. Significant bulk deformation of the wood impact limiter is not expected. Therefore, no additional load is expected for the fuel element and conclusion on package performance can be drawn from the 30-ft drop impact analysis existing in the HFIR SARP.

Table 3 – Recommended Outer Test Sequences

Test Sequence	Test Conditions			Failure Criterion
	Temp	Drop Orientation	Crush Orientation	
Outer - 1	-20 °F	CG on Bottom edge	CG on Bottom edge	Primary: Significant reduction in container bottom effectiveness, sufficient to result in a breach that could affect fuel exposure during thermal event chimney effect-initiated wood impact limiter smoldering. (containment and subcriticality) Secondary: Weakening of the impact limiter laminate structure and fuel deformation sufficient to compromise fuel integrity in vicinity of the wood safety post. (containment)

Bases for test recommendation:

- Temperature: Reduces energy absorption of the carbon steel overpack due to high strain rate and material nil-ductility properties.
- Drop orientation: Maximizes challenge to the container bottom boundary. Additionally, localized sheer loading may affect glue bond performance during subsequent crush.
- Crush orientation: Maximizes challenge to package closure. Additionally, container buckling could challenge local fuel integrity against package safety post or produce limiter buckling or slippage affecting fuel integrity.

Bases for inclusion in limited test:

This test sequence allows for baseline comparison of existing SARP 30-ft center of gravity drop analysis performed under ambient conditions to test results performed at -20°F. Observation of minimal change in package performance at low temperature will support validation of current SARP analysis for omitted tests at low temperature.

No evaluation is available for package performance under a CG edge crush. The center of gravity top edge crush challenges the packages closure and mid-section where there is less cross-sectional strength from the packaging materials of construction. The package is oriented with the 30-ft damaged corner of the package facing the crush pad to maximize crush damage, as damage to the package is typically greater where the crush plate impacts the package as opposed to the package side adjacent to the pad where similar drop damage is expected to have occurred due to outer package weight.

The center of gravity on bottom edge crush orientation opposing the 30-ft impact damage maximizes the potential for package buckling and the possible breach of the drum due to weld failure and or carbon steel base material failure under low temperature condition.[9] Significant package buckling could impact fuel integrity.

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[9] M-TRT-A-00018, 9979 Type AF Package – Pre Prototype Testing, Savannah River National Laboratory, February, 2009.

Table 3 – Recommended Outer Test Sequences (continued)

Test Sequence	Test Conditions			Failure Criterion
	Temp	Drop Orientation	Crush Orientation	
Outer - 2	100 °F	Oblique Slap-down	Horizontal	Primary: Significant reduction in container confinement boundary effectiveness, sufficient to result in partial or full fuel exposure during thermal event. (containment and subcriticality) Secondary: Breach in the package bottom sufficient to affect fuel integrity due thermal event chimney effect initiated wood impact limiter smoldering (containment).

Bases for test recommendation:

Minimizes differences between existing SARP analysis and test conditions to support validation purposes.

- Drop orientation: No oblique drop orientation is currently evaluated in the SARP.
- Crush orientation: The horizontal crush challenges the packages mid-section where there is less cross-sectional strength from the packaging materials of construction and where the package stiffer ends cannot share a large portion of the crush load. This phenomenon is exaggerated for taller packages where the typically less stiff mid-section of the package is longer than the crush plate. The Outer HFIR package design is affected by this condition. The package is oriented with the damaged side of the package facing the crush pad to compound damage, as damage to the package is typically greater where the crush plate impacts the package as opposed to the package side adjacent to the pad.

Bases for inclusion in limited test:

No evaluation is available for package performance under oblique drop conditions.

Two types of oblique drops, the slap-down (~15 degrees) and shallow-angle (~ 30 degrees), are typical of the 30-ft oblique drop. The slap-down typically challenges the drum and containment vessel closures of slender designs, since the added angular momentum to the non-impacting end due to rebound of the impacting end can be significant, whereas the shallow-angle drop challenges industry standard bolt/ring closures. The Inner HFIR package incorporates a bolted lid closure protected by welded angle stiffeners and is not sensitive to shallow angle drops.

The Outer HFIR package aspect ratio 46 inches / 31 inches, or ~1.5 indicates that secondary impact as result of a slap-down on its bolted closure would not introduce a significant amount of load into the drum closure because of its low mass. The Outer HFIR package does not incorporate a containment vessel but just the fuel element with an approximate aspect ratio of ~1.8. The fuel element positioning about the drums center of gravity and its mass (~205 lbs) would not tend to introduce a significant amount of load into the fuel element as compared to horizontal drop except for the rigid attached safety post design that obstructs loading of an inner and outer fuel assembly together. Under conditions where the safety post is not at top dead center, 90 -degrees to the drop surface, the existing horizontal drop analysis with its conservatism (fuel elements not welded to the inner and outer element shells) is sufficient to evaluate the performance of the fuel in a slap-down drop. However, in the drop orientation where the safety post is near or at top dead center opposite package impact the oblique slap-down drop concentrates inertia loads of the fuel element from added angular momentum.

For the crush, 30-ft package drop damage faces the pad and crush plate impacts the package with the safety post at 90-degrees top dead center of the package. As crush damage is typically greater where the plate impacts the package and with the fuel sandwiched between the crush plate and safety post the combination of the drop and crush is expected to evaluate fuel integrity under worst case conditions.

Table 3 – Recommended Outer Test Sequences (continued)

<table>
<tr><th rowspan="2">Test Sequence</th><th colspan="3">Test Conditions</th><th rowspan="2">Failure Criterion</th></tr>
<tr><th>Temp</th><th>Drop Orientation</th><th>Crush Orientation</th></tr>
<tr><td>Outer - 3</td><td>Ambient</td><td>Center of Gravity over Top edge</td><td>Horizontal</td><td><u>Primary</u>: Significant reduction in container confinement boundary effectiveness, sufficient to result in partial or full fuel exposure during thermal event. (containment and subcriticality)
<u>Secondary</u>: Impact limiter laminate structure failure (fuel damage from plywood failure buckling, joint failure, splintering, slippage). (containment).</td></tr>
<tr><td colspan="5">Bases for test recommendation:
• <u>Temperature</u>: Supports direct comparison to existing 30-ft center of gravity over top edge drop analysis results under ambient conditions to testing results.
• <u>Crush orientation</u>: Optimizes impact to approximate package center where laminated wood impact limiter cross section flexural rigidity is smallest, maximizing potential for buckling, splintering or slippage (delamination).</td></tr>
<tr><td colspan="5">Bases for omission from limited test:
Center of gravity over bottom edge for Outer-1 test could be compared by analysis to a center of gravity over top edge impact.
Horizontal crush damage observation from Outer-2 testing can be referenced to draw conclusion on package performance for this combined sequence in lieu of testing.</td></tr>
</table>

Table 3 – Recommended Outer Test Sequences (continued)

<table>
<tr><th rowspan="2">Test Sequence</th><th colspan="3">Test Conditions</th><th rowspan="2">Failure Criterion</th></tr>
<tr><th>Temp</th><th>Drop Orientation</th><th>Crush Orientation</th></tr>
<tr><td>Outer - 4</td><td>-20°F</td><td>Horizontal</td><td>Horizontal</td><td><u>Primary</u>: Weakening of the impact limiter laminate structure and possible shear of lid closure bolting. (containment)
<u>Secondary</u>: Impact limiter laminate structure failure (fuel damage from plywood failure buckling, joint failure, splintering, slippage). (containment).</td></tr>
<tr><td colspan="5">Bases for test recommendation:
• <u>Temperature</u>: Supports direct comparison to existing 30-ft horizontal drop analysis results under ambient conditions to low temperature testing results.
• <u>Crush orientation</u>: Optimizes impact to approximate package center where laminated wood impact limiter cross section flexural rigidity is smallest, maximizing potential for buckling, splintering or slippage (delamination).</td></tr>
<tr><td colspan="5">Bases for omission from limited test:
Historically, package damage from a 30-ft horizontal drop does not significantly challenge the package, its closure or content. Similar mass and sized package DT-20 [10] (53-inches tall by 33 inches in diameter, 1,048 lbs. gross weight) versus the HFIR Outer Package (48 inches tall by 31.5 inches in diameter, 1,050 lbs. gross weight) support this conclusion. Therefore, existing HFIR SARP analysis is sufficient to support conclusion of 30-ft drop packaging and its content performance.
Horizontal crush damage observation from Outer-2 testing can be referenced to draw conclusion on package performance for this combined sequence in lieu of testing.</td></tr>
</table>

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[10] Ronald Poor, Physical and Thermal Test Report for the DT-20 Shipping Package, Y-12 Plant Program Management Packaging Group, YMD-91-34, Rev 2, October 1998

Table 3 – Recommended Outer Test Sequences (continued)

Test Sequence	Test Conditions			Failure Criterion
	Temp	**Drop Orientation**	**Crush Orientation**	
Outer - 5	Ambient	CG over Bottom edge	CG over Top edge	Primary: Significant reduction in container bottom effectiveness, sufficient to result in a breach that could affect fuel exposure during thermal event. (containment and subcriticality) Secondary: Weakening of the impact limiter laminate structure and fuel deformation sufficient to compromise fuel integrity in vicinity of the wood safety post. (containment)

Bases for test recommendation:

- Temperature: Supports indirect comparison to existing 30-ft center of gravity top drop analysis results under ambient conditions to testing results.
- Crush orientation: Maximizes challenge to package closure. Additionally, container buckling could challenge local fuel integrity against package safety post or produce limiter buckling or slippage affecting fuel integrity.

Bases for omission from limited test:

Center of gravity over bottom edge for Outer-1 test at -20°F could be compared to center of gravity over bottom edge under ambient temperature.

Center of gravity over top edge crush damage observation from Outer-1 testing can be referenced to draw conclusion on package performance for this combined sequence in lieu of testing.

Table 3 – Recommended Outer Test Sequences (continued)

Test Sequence	Test Conditions			Failure Criterion
	Temp	Drop Orientation	Crush Orientation	
Outer - 6	Ambient	Horizontal	Horizontal	Primary: Weakening of the impact limiter laminate structure and possible shear of lid closure bolting. (containment) Secondary: Impact limiter laminate structure failure (fuel damage from plywood failure buckling, joint failure, splintering, slippage). (containment).

Bases for test recommendation:

- Temperature: Supports direct comparison to existing 30-ft horizontal drop analysis results under ambient conditions testing results.
- Crush orientation: Optimizes impact to approximate package center where laminated wood impact limiter cross section flexural rigidity is smallest, maximizing potential for buckling, splintering or slippage (delamination).

Bases for omission from limited test:

Historically, package damage from a 30-ft horizontal drop does not significantly challenge the package, its closure or content. The DT-20 is of similar mass and size to the HFIR Outer package and package performance under low temperature vs elevated temperatures has been shown not to be structurally significant. Test data from the oblique drop for Outer-2 can be used to conclude package performance to a horizontal drop.

Horizontal crush damage observation from Outer-2 testing can be referenced to draw conclusion on package performance for this combined sequence in lieu of testing.

Table 3 – Recommended Outer Test Sequences (continued)

Test Sequence	Test Conditions			Failure Criterion
	Temp	Drop Orientation	Crush Orientation	
Outer - 7	-20 °F	Bottom Down	Top Down	Primary: Fuel shear and buckling. Secondary: Weakening of the impact limiter laminate structure.

Bases for test recommendation:

- Temperature: Supports indirect comparison to existing 30-ft drop analysis results under ambient conditions.
- Crush orientation: Optimizes impact to package ends challenging impact limiter performance and maximizing potential for fuel buckling in the event of limiter failure.

Bases for omission from limited test:

Historically, package damage from a 30-ft end drop does not significantly challenge the package with typical damage being a slight reduction in the overall height of the packaging from drum side wall crumpling in the immediate vicinity of impact and stresses in the containment vessel due to content impact on the CV as evidenced by DT-20 package testing.[11] Since the HFIR packaging does not incorporate a containment vessel only those stresses in the fuel element are of importance. Existing HFIR package analysis of the fuel cladding due to inertia loads indicates a significant margin of safety against buckling and no stress in the fuel cladding exceeding allowable limits.

End drop crush damage is expected to produce a slightly greater reduction in HFIR package height due to the continued crush of the package forklift pockets and lid reinforcing angles. Significant bulk deformation of the wood impact limiter under compression is not expected, like that observed in BTSP bottom crush testing.[12] Therefore, no additional load is expected for the fuel element and package performance can be drawn from the existing HFIR 30-ft drop impact analysis and DT-20 and BTSP testing.

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[11] Ronald Poor, Physical and Thermal Test Report for the DT-20 Shipping Package, Y-12 Plant Program Management Packaging Group, YMD-91-34, Rev 2, October 1998.

[12] Safety Analysis Report for Packaging, Bulk Tritium Shipping Package, S-SARP-G-00004, Savannah River National Laboratory, July 2018.