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Certification Testing of the MOX Fresh Fuel Package (MFFP)

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Packaging Technology, Inc. (PacTec) is designing the MFFP as part of the Duke, COGEMA, Stone and Webster (DCS) consortium. DCS is tasked with providing the Department of Energy (DOE) with domestic MOX fuel fabrication and reactor irradiation services for the purpose of disposing of surplus weapons usable plutonium.

This paper will discuss the development of the MFFP certification test program. The MFFP was subjected to a total of eleven free and puncture drops of the course of the certification testing. Because of the plutonium content, the design must be a Type BF, which among other things requires a containment boundary with a tested leakage rate of 1×10^{-7} cm^3/s air at 1 atm absolute and 25°C, or less. Both economics (desire for maximized payload) and operational (conveyance mode restricts size and weight) constraints lead to a highly optimized design. The optimized package design led to a significant test program which needed to address the containment boundary stability, puncture resistance of the package and lid end impact limiter, structural performance of the light weight lid structure, and stability of the internal structures. The test program efficiently balanced the test objectives while minimizing the number of costly hardware items used during this destructive testing. This balance achieved by strategic replacement of mock & prototypic payloads, impact limiters, and by careful test order considerations. The paper will conclude with a selected summary of the testing and an assessment of the test programs thoroughness.

Introduction

This paper discusses the selected free drop and puncture drop test sequence for the MFFP certification test unit (CTU). Since the HAC thermal event of 10 CFR §71.73(c)(4) [1] is evaluated by analysis, fire testing of the CTU will not be included in the certification tests.

The MFFP design process resulted in a package that is highly optimized to meet both regulatory and customer requirements. The optimized package design led to a significant test program which needed to address the containment boundary stability, puncture resistance of the package and lid end impact limiter, structural performance of the light weight lid structure, and stability of the internal structures. The following sections summarize the significant amount of planning and discussion that preceded the performance of the certification tests

Certification Test Plan

The primary method of demonstration of compliance of the MFFP with the requirements of 10 CFR §71.73 in HAC free drop and puncture drop events is full-scale prototypic testing. The test program addressed the following objectives:

1. To demonstrate a leaktight condition (leakage rate no greater than 1×10^{-7} ref-cm^3/sec, air, per ANSI N14.5 [2]) after sequential 30-foot free drop and 40-inch puncture drop tests [10 CFR §71.73(c)(1) and 10 CFR §71.73(c)(3)].
2. To demonstrate that the payload remains subcritical after the free drop and puncture tests [10 CFR §71.55(e)].

Objective Number 1 was demonstrated directly by leakage rate testing of the certification test unit (CTU) prior to and following the tests. Using deformation and/or reconfiguration data collected from the certification testing, demonstration of Objective Number 2 is by Criticality Evaluation. In a similar manner, the effect of the HAC fire event on containment is evaluated by analysis, using deformation data collected from the certification tests. The evaluation of the MFFP for water immersion per the requirements of 10 CFR §71.73(c)(6) is demonstrated by analysis only.

Certification Test Unit (CTU)

Certification tests of the MFFP utilized a full-scale CTU that was prototypic in design, materials, and fabrication. Consequently, the weight and center of gravity of the CTU were prototypic. The CTU included a prototypic strongback assembly for most tests. For some certification tests, the behavior of the strongback was not important and hence, was conservatively simulated by the equivalent dead weight, as discussed in the Mock Payload description. Multiple impact limiters were used to prevent accumulation of damage for the selected test series, as appropriate.

The hypothetical accident condition tests specified by the 10CFR71 transport regulations for Type B(U) packages require that the tests be conducted at that ambient temperature condition which is most unfavorable for the package. Usually, and for good reasons, only the hot and cold temperature extremes are considered. Of greatest interest to the evaluation of containment integrity is the maximum impact acceleration. For the MFFP, this corresponds to the minimum temperature (-29ºC (-20ºF) ambient) condition, due to the increase in crush strength of the foam with decreasing temperature. The maximum temperature condition (38ºC (100ºF) ambient) is of interest only if deformations of the impact limiter are so great that higher impact occurs through “bottoming” of the impact limiter structure. Otherwise, the minimum temperature condition governs. Consequently, the impact limiters were tested at a material temperature of -29ºC (-20ºF) or less.

Payload simulation was accomplished by a combination of a prototypic FA and dummy FAs with the strongback, or a mock payload by itself. These simulated payloads are discussed in the following sections.

Mock Payload

The Mock payload was a bundle of approximately 800, 12.7 mm (1/2 inch) diameter steel bars, bringing the total weight of the mock payload to 3,402 kg (7,500 pounds). This payload was used to simulate the payload in the first test series where the free drop was primarily focused on buckling behavior of the shell.

The buckling behavior of the containment body shell depends in part, on the distribution of the payload weight and the payload bending stiffness. The bending moment of inertia of the Mock payload was significantly less than that of the strongback. The central structure of the strongback moment of inertia is approximately $114.5\text{x}10^6$ mm^4 (275 in^4). The moment of inertia of one steel bar is $\pi/64\times (12.7)^4 = 1.28\text{x}10^3$ mm^4 (0.00307 in^4). Since the bars lack shear continuity and will act independently, the mock payload has a total moment of inertia of $800 \times 1.28\text{x}10^3 = 1.02\text{x}10^6$ mm^4 (2.45 in^4), or less than one percent of the actual strongback. Therefore, use of the steel bars as a Mock payload for the horizontal side drop was conservative.

Dummy Fuel Assembly

The Dummy Fuel Assemblies (FA) used for certification testing were designed to econimically simulate the weight distribution and structural properties of an actual FA. To meet this requirement, each Dummy FA consisted of simulated end nozzles, guide sleeves, grids, and fuel rods. Each end of the Dummy FA included a simulated end nozzle. The end nozzles was connected to each other by nine (9) 12.7 mm (1/2 inch) OD × 9.53 mm (3/8 inch) ID tubes made of aluminum. The fuel rods were simulated by nominally 4.76 (3/16 inch) diameter solid steel rods, which were restrained by simulated grids (grid straps). The end nozzles and simulated grids interfaced with the strongback at the same locations and in the same manor as an actual FA. The Dummy FA had conservative weight properties compared to the real assembly. All of the Dummy FA weights were slightly more than the combined maximum weight of the upper bound FA weight of 717 kg (1,580 pounds).

The Dummy FAs were designed to have less bending stiffness than the actual FA. The steel rods were loosely contained by the grid assemblies and added very minimal stiffness to the Dummy FA. The elastic stiffness of the dummy FA resulted only from the moment of inertia of the array of nine simulated guide sleeves (aluminum tubes), which had a total moment of inertia of 845 mm^4 (2.03 in^4), or, conservatively, 17.5% less than the moment of inertia of the 24 guide sleeves in the real fuel assembly. The frictional attachment of the real fuel rods to the grids provides somewhat more stiffness in the actual FA, which were conservatively not included in the dummy assembly. The dummy fuel assembly is depicted in Figure 1.

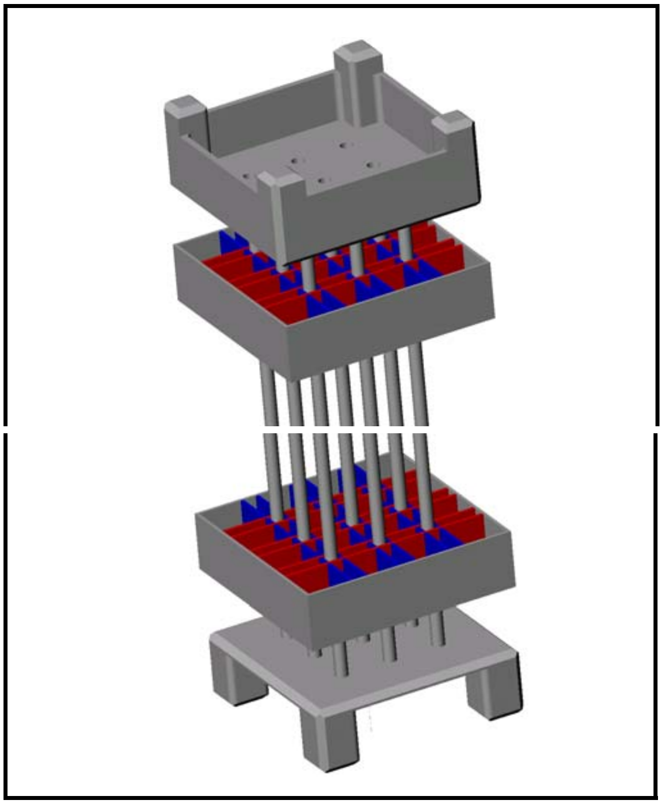

Figure 1 – Dummy Fuel Assembly (Fill Rods Removed for Clarity)

Prototypic Fuel Assembly

The prototypic fuel assembly was an nearly exact facsimile of the MK-BW/MOX1 FA without burnable poison rod assemblies (BPRAs), except that the fissile MOX fuel pellets are simulated using non-fissile tungsten carbide pellets. The prototypic FA will be utilized in those tests where the response of the FA is of primary interest.

Identification of Worst-Case Drop Tests

Two general categories of tests were considered, based on the potential vulnerabilities of the MFFP to free drop and puncture damage:

1. Tests that evaluate the containment of the package, including buckling of the shell, performance of the lid bolts, distortion of the sealing area, and all other leaktight concerns. These tests were governed by the maximum (cold) impact loads.

   In the same category are tests that evaluate the fire safety of the package. These tests are those which would cause thermally significant damage to, or loss of, the lid end impact limiter, since the only component of the package that is sensitive to HAC fire temperatures is the elastomer containment O-ring seal in the closure lid.
2. Tests which evaluate the criticality safety of the package, including the geometric stability of the strongback (i.e., maintaining an adequate spatial relationship between the FAs), the ability of the neutron poison plates to remain intact and in place, and the behavior of the fuel rods in key orientations. These tests are also governed by the maximum (cold) impact loads.

These categories were examined to identify specific areas of potential concern. According to 10 CFR §71.73, the package the orientation for which maximum damage is expectedis required. In the discussions below, candidate tests were identified by matching package features, characteristics, and design goals with relevant tests in worst-case orientations.

Tests of the Package Containment Performance

The following concepts related to containment performance were considered when selecting certification tests.

1. Buckling of the Package Shell: The MFFP is a relatively long and slender package and lateral buckling of the shell is of concern in both side and slapdown free drops.
   - The side drop case was determined to be governing over the slapdown based on bending moment in the shell.
   - Containment shell buckling in the vertical free drop was also of concern, however, based on analysis, much less so than the horizontal orientations.
2. Leakage Rate at Package Closure: The package closure must endure the governing drop impact forces and remain in a leaktight condition.
   - In the C.G.-over-corner drop (80° to the horizontal), the maximum axial forces are applied to the closure bolts and to the closure lid structure. This response is because the axial component of impact force at the C.G.-over-corner is essentially equal to the pure vertical case.
   - A slapdown free drop where the closure lid is at the secondary impact end of the package, the maximum lateral forces are applied to the closure lid and to the shell flange.
3. Perforation of the Containment Boundary. To fully demonstrate puncture resistance, experience has shown that the most likely orientation for perforation would be an oblique puncture through the package C.G.
   - The most damaging angles have been determined to be between 25° and 40° (measured between the puncture bar axis normal to the package).
   - The horizontal puncture through the package C.G. was considered, since, due to its greater stability, it could impart more deformation and material strain to the containment shell.
4. Puncture Perforation of the Lid End Impact Limiter Shell: The shell of the lid end impact limiter is designed to resist perforation by the puncture bar to prevent concentrated puncture loads and loss of thermal protection.
   - As stated above, an oblique angle of between 25° and 40° (measured between the puncture bar axis normal to the impact limiter shell) is the most likely orientation to experience perforation of the steel shell.
   - The most likely orientation of the package for perforation would therefore combine an oblique impact and a C.G. location as near as possible to the puncture bar axis.
   - Since the elastomer containment O-ring seals are located solely in the closure lid, perforation of the bottom end limiter shell was not of consequence.
5. Retention of the Lid End Impact Limiter: Because the presence of the lid end impact limiter is key to the thermal protection of the containment O-ring seals, loss of the impact limiter must not occur.
   - Due to the tapered design of the limiters, the separation moments during free drop impacts are negligible, since the center of impact force is directed through the package, and cannot generate a separation moment.
   - A direct attack by the puncture bar on the stiffer, outside edge of the limiter could have placed a separation load on the limiter.

Tests of the Package Criticality Performance

The following concepts related to criticality performance were considered when selecting certification tests.

1. Geometric Stability of the Strongback: To maintain the fuel in a subcritical condition, the relative geometry of the FAs and the neutron poison plates must be kept within certain bounds.
    - The greatest forces on the strongback result from the maximum lateral impact, which occurs at the secondary impact end of the package in the slapdown drop.
    - The worst-case secondary slapdown impact occurs for the shallow primary impact angle of 15° to the horizontal.
2. Geometric Stability of the Fuel: To maintain a subcritical state, the fuel rod pitch must remain within bounds.
    - In the side orientation, the fuel rods experience lateral loads, which have the tendency to push the fuel rods together and decrease the pitch, a condition for which k_{eff} decreases.
    - Under free drop impacts, the fuel rods could bend or buckle.
    - In the C.G.-over-corner (near-vertical) orientation, the relatively small lateral forces on the fuel are dominated by the axial forces, and fuel rod behavior is therefore less determinate, i.e., the pitch could increase or decrease.

Strongback Azimuth Orientation

As discussed above, the strongback should be tested to demonstrate its resistance to lateral impact in the slapdown free drop. The fuel assemblies are supported on the strongback by means of clamp arms at each FA grid strap position. The three clamp arms at each grid strap location connect to each other and to the strongback longitudinal structure to form what are effectively support disks. Since the structure of the support disks is not uniform, the response to impact loading may vary depending on the rotational, or azimuth, orientation of the strongback relative to the axis of impact. Therefore, to fully characterize the structural performance of the strongback and support disks, a slapdown test in two azimuth orientations were included in the certification test program, as shown in Figure 2.

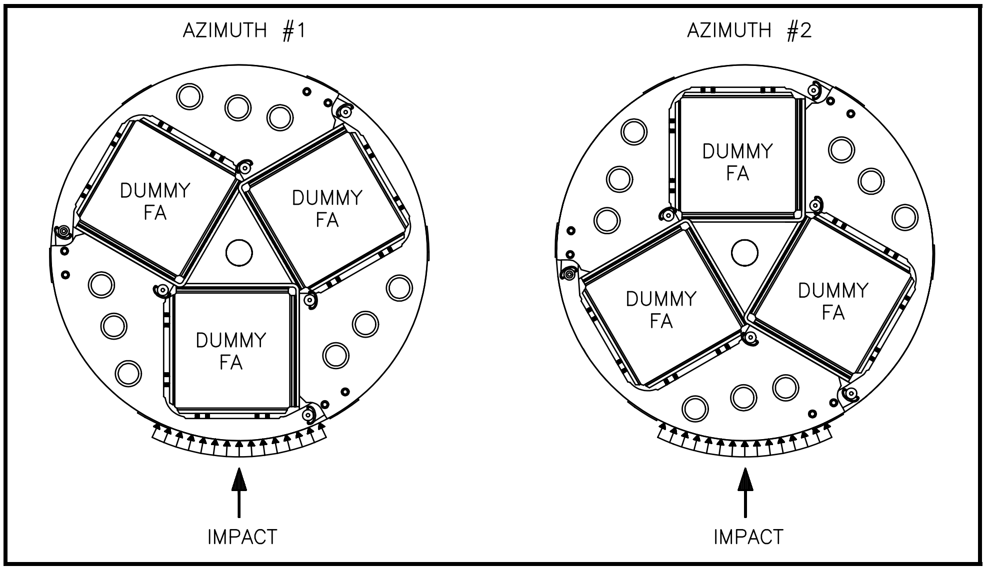

Figure 2 – Strongback Azimuth Orientations

Summary of Selected Certification Drop Tests

Based on the above discussions, four HAC, 30-ft free drop tests and six 40-inch puncture tests were identified for inclusion in the certification test program. Although only a single worst-case free drop followed by a single worst-case puncture drop are required by 10 CFR §71.73, all of the tests listed below were performed to ensure that each area of potential concern is subjected to worst-case conditions.

Because of the large number of tests performed, over-testing of some CTU features was of some concern. Of particular importance was the criticality performance tests, where FA or strongback deformations were of primary interest. If subject to over-testing, the deformations from one test could be invalidated by the deformations of the test which follows. Therefore, the selected tests were conducted in three separate test series.

As stated in 10 CFR §71.73(a), the puncture test follow the free drop test. Accordingly, each series of tests consisted of one to two free drop tests followed by one or more puncture drop tests. Prior to each series, the package was leakage rate tested to establish a leaktight configuration before testing. At the end of each series, the package was opened and the strongback and FA deformations were evaluated, as appropriate, prior to proceeding to the next test series. Before opening the package, however, a leakage rate test was performed to measure the leakage rate of all containment seals (closure lid and vent port penetrations). At the end of all tests, a leakage rate test of the entire containment boundary was performed. The containment acceptance criterion is a leakage rate not exceeding 1×10^{-7} ref-cm^3/sec, air (leaktight).

It was expected that a single containment boundary would suffice for all of the tests planned. The strongback, however, was likely to need and was replaced between test series. Due to the accumulation of free drop and puncture damage on the impact limiters, two sets bottom end limiters and three top end limiters were used.

The selected certification test series are summarized in Table 1, and depicted in Figure 3, Figure 4, and Figure 5. Series No. 1, Test 4, shown in italic font in Table 1, was performed out of the originally planned order. Because of the impact limiter damage which resulted from the horizontal 30 ft free side drop, the puncture axial to the limiter was

Table 1– Certification Test Series Summary

No.	Test Description	Addresses
Series No. 1		
1	Horizontal 30-ft free side drop	Containment shell buckling
2	Oblique puncture on tapered skin	Perforation of lid end impact limiter skin
3	Oblique puncture on bottom disk	Perforation of lid end impact limiter skin
4	*Puncture axial to limiter*	*Impact limiter retention*
Series No. 2		
1	C.G.-over-corner (near-vertical) 30-ft free drop	Closure lid integrity; prototypic fuel integrity
2	C.G.-over-corner puncture on free drop damage	Effect of puncture on prior damage; puncture load on closure region
Series No. 3		
1	15° Slapdown 30-ft free drop, lid primary	Strongback deformations
2	15° Slapdown 30-ft free drop, lid secondary	Strongback deformations, closure lid integrity
3	Horizontal puncture on containment shell	Containment shell leaktight integrity
4	Oblique puncture on containment shell	Containment shell leaktight integrity

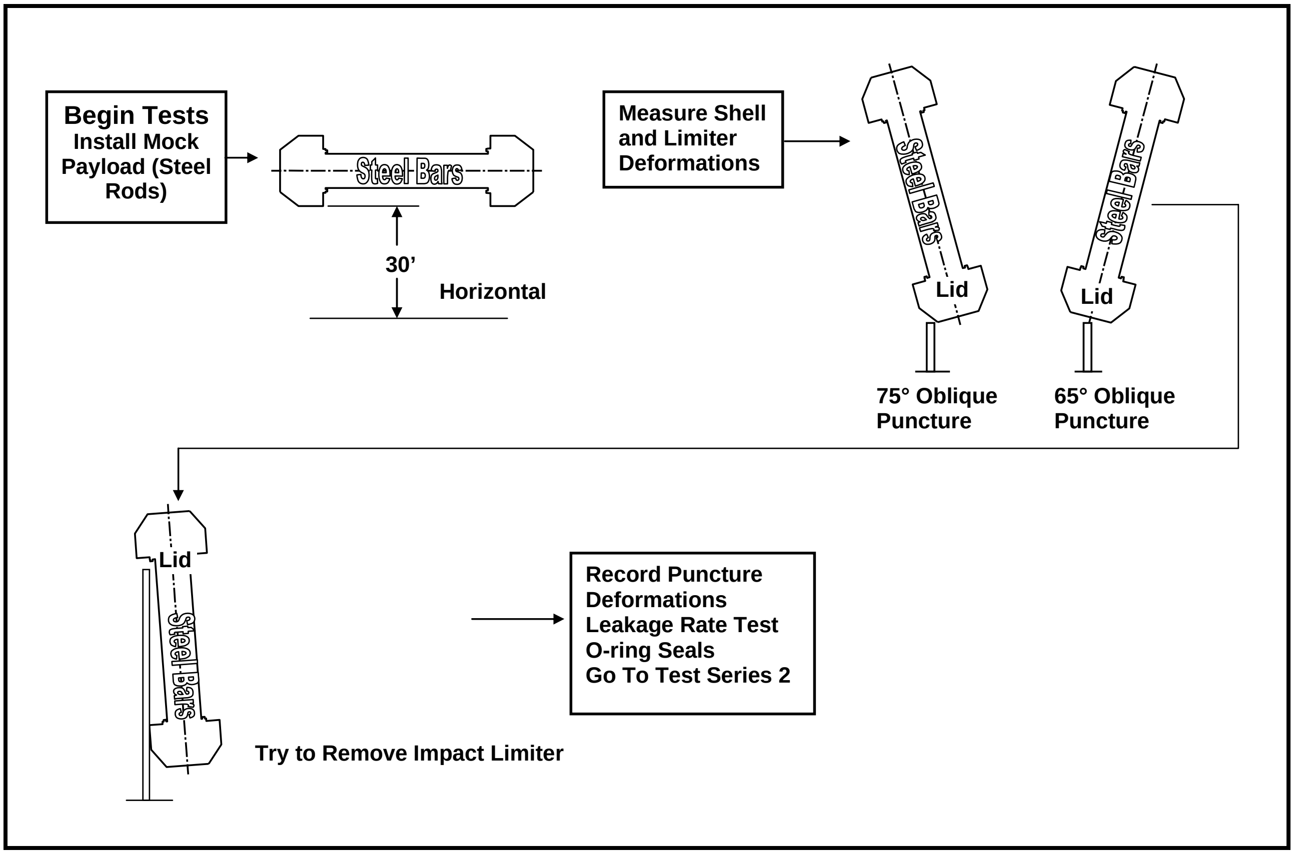

Figure 3 – Plan for Certification Test Series 1

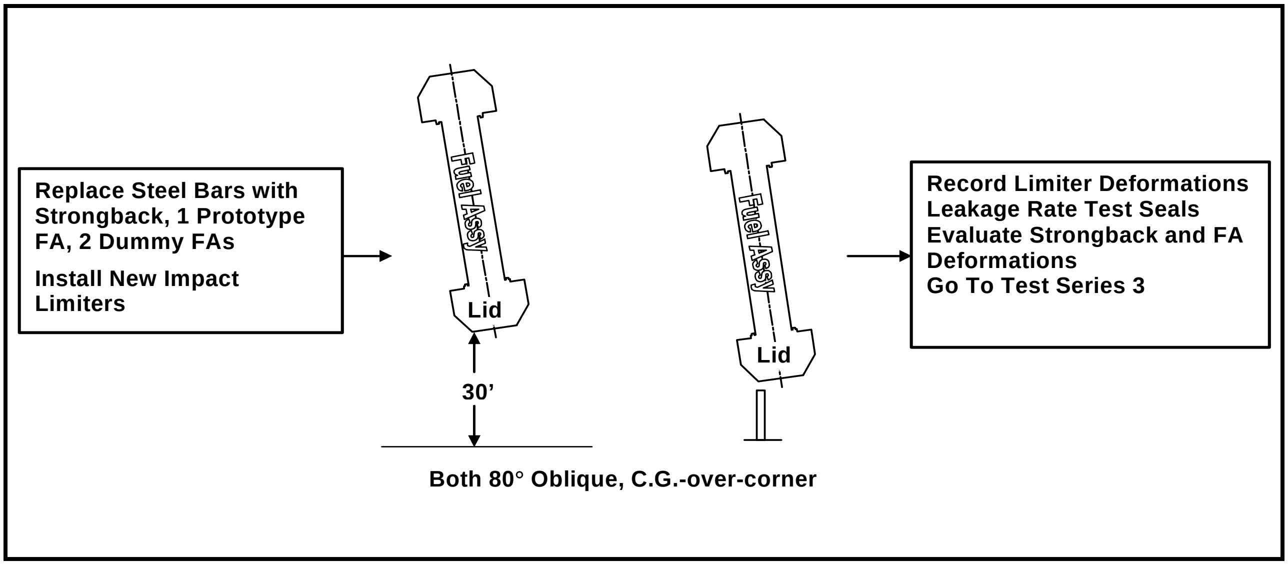

Figure 4 – Certification Test Series 2

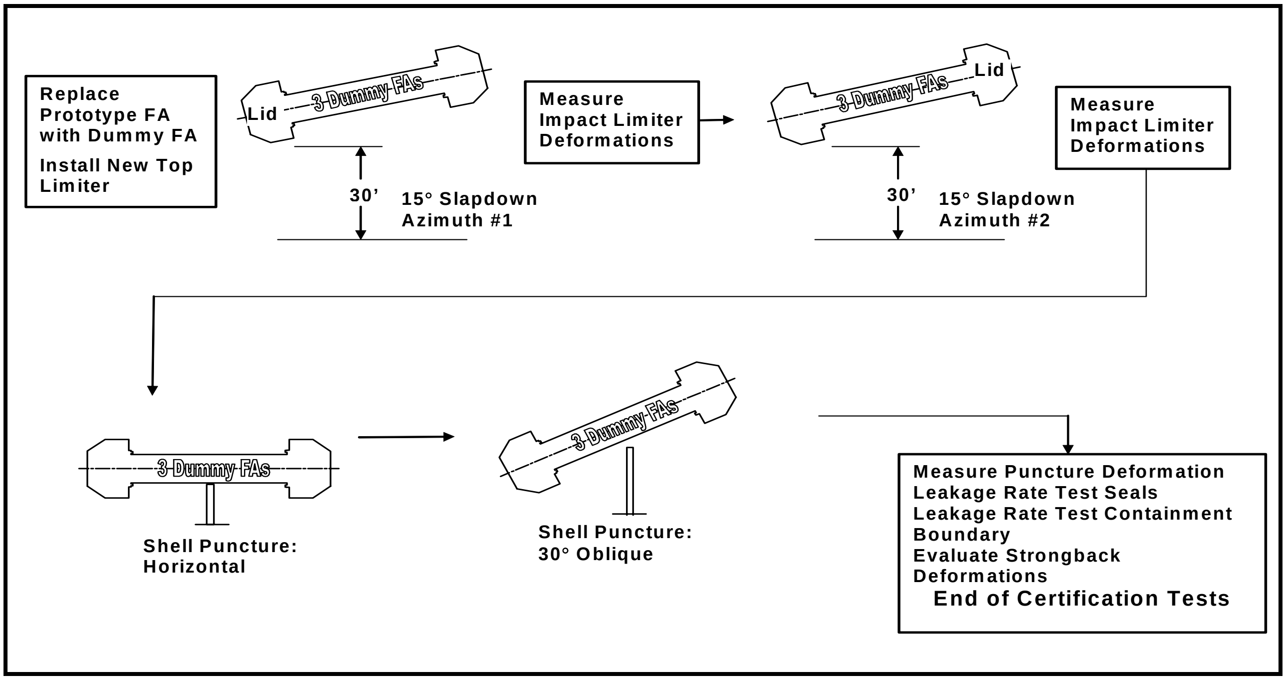

Figure 5 – Certification Test Series 3

References

[1] Title 10, Code of Federal Regulations, Part 71 (10 CFR 71), *Packaging and Transportation of Radioactive Materials*, Final Rule, 01-26-04.

[2] ANSI N14.5-1997, *American National Standard for Radioactive Materials - Leakage Test on Packages for Shipment*, American National Standard Institute, Inc. (ANSI).