CERTIFICATION TEST PROGRAMS – AFTER TWO DECADES, WE MUST HAVE LEARNED SOMETHING

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ABSTRACT

The authors have been involved with the design, testing, and certification of radioactive materials transportation packages since the early 1980s. This paper summarizes the specific insights gained from planning, implementing, documenting and defending numerous certification test programs over the last 20 years. Starting with the NuPac 125-B Package (developed in the mid 1980s for transport of TMI-II fuel debris) and ending with the TRUPACT-III Package [for transport of oversized boxes of contact-handled transuranic (CH-TRU) waste], lessons learned from participation in a wide variety of certification test programs are consolidated and summarized.

Within the paper, challenges associated with the selection of appropriate test article scale factors, initial conditions (i.e., pressures and temperatures), worst-case orientations, instrumentation and post-test data reduction approaches are identified and discussed. The potential significance of strength and thickness tolerances for packaging materials of construction is addressed. The perceived role of the regulator in the selection of test program details is also discussed. Many examples of test successes, test anomalies, and test surprises as well as a few test failures are provided in an effort to clarify points being made. Finally, the paper presents a top level summary of the authors' current views on the use of physical testing as an integral part of the certification process.

INTRODUCTION

Starting in 1984, while at Nuclear Packaging, the authors have worked together in various capacities and for various organizations for nearly 20 years, devoting the vast majority of their time to development and certification of Type B transportation packages for radioactive materials. During that time, numerous U.S. Nuclear Regulatory Commission (NRC) and U.S. Department of Energy (DOE) Certificates of Compliance were successfully obtained. In nearly all cases, some form of physical testing was utilized as an integral part of demonstrating package performance capabilities, ranging from material and sub-component bench tests to subscale testing of impact limiting devices to full scale testing of entire packages. The focus of most tests was on structural performance, however, thermal tests were performed on certain package components, and a few full scale packages were subjected to fully engulfing fire testing.

Table I provides a representative set of test programs that were performed during the last two decades. Although each package development and certification project presented unique issues and solution paths, a consolidated review of these particular test programs, as well as many others, allows several top level observations to be made which have general applicability to virtually any certification test program.

Table I. Summary of representative package certification test programs

Package Identification	NRC/DOE/DOT C of C Number	Scale Factor	Component(s) Tested	Test Type			
				Drop	Punch	Fire	Other
125-B	9200/B(M)F	1/4	Entire Package	✖	✖		
		5-gallon buckets	Polyurethane Foam			✖	Fire tests of various damaged conditions
TRUPACT-II	9218/B(U)F-85	1	Entire Package	✖	✖	✖	
		1	Closure Design				Gross deformation testing
		1	O-ring Material				Time, temp, compression testing
		3/4	Upper Torispherical Head	✖	✖		Used to guide design; not for certification
		1/2	Various Shell/Foam Combinations	✖	✖		Used to guide design; not for certification
		1/4	Closure Region				Compression verifying leaktight configuration
HalfPACT	9279/B(U)F-85	1	Entire Package	✖	✖	✖	
72-B	9212/B(M)F-85	1/2	Impact Limiters	✖	✖		Static crush for force deflection
RTG	9904/B(U)F-85	1	Entire Package	✖	✖		Normal operations thermal performance
		1/2	Entire Package	✖	✖		Used to guide design; not for certification
Sterigenics Eagle	9287/B(U)-85	1/4	Impact Limiters	✖	✖		Static crush
2000 MED	0575/H(U)-96	1	Entire Package	✖		✖	
TRUPACT-III	TBD	1/2	Entire Package	✖	✖		
		1	O-ring Seal				Reduced compression testing

KEY STEPS IN THE CERTIFICATION TESTING PROCESS

Not surprisingly, any successful certification test program requires significant up-front planning, engineering judgment, and coordination with the regulatory reviewers. A typical certification test program starts with identification and assessment of potential package vulnerabilities to determine whether they are best addressed by analysis, test, or a combination of both. Once those decisions are in place, a limited set of worst-case test orientations and initial conditions, which will be most demanding relative to package performance capabilities, must be selected. A decision on test article size (i.e., scale factor) generally follows. The level of detail desired for the test article (both packaging and payload) must then be established, followed by fabrication of a test article. Test facility requirements and capabilities must also be addressed (this activity is considered to be relatively straightforward and is therefore not addressed within this paper). With a test article and a global set of test conditions established (i.e., orientations, pressures, and temperatures), detailed acceptance criteria need to be selected along with a means to address those criteria via an appropriate combination of instrumentation, leakage rate testing, physical measurements, and/or data reduction processes. A decision must also be made regarding what role the regulator will play in pre-test plans and whether they will attend the testing. Since virtually all test programs exhibit a few unexpected results, ranging from minor anomalies to design failures requiring redesign, refurbishment, and retest, governing test plans must be sufficiently flexible to allow in-process changes to originally planned test activities. Independent of how much advanced planning takes place, surprises will occur. Each of the above steps making up the overall certification test process is further discussed in the remainder of this paper.

Assess Package Vulnerabilities

Given a package design, the most vulnerable package features need to be identified so any demonstration approach, be it test or analysis or a combination of the two, can be properly focused and will completely cover all potential certification issues. Containment boundary closure is typically the place to start and often times testing directed specifically at package closure features will dominate a test program. Seals and closure bolts will always warrant careful attention and a test program that does not exercise the closure design is generally of little value. For example, extensive high and low temperature compression testing of various O-ring seal materials was performed prior to actual TRUPACT-II package certification testing to assure, with a very high degree of confidence, subsequent certification testing success (see Figure 1).

Easily overlooked are containment penetrations such as vent or drain ports. Such ports can be vulnerable from both a structural and thermal perspective. In more than one instance, considerations associated with performing a puncture test directly on a location of a containment penetration have led to design changes being implemented even before testing ever commenced. If the puncture bar can penetrate external structures and reach the location of a port, the port and its seals will generally need to be recessed below the outer surface of the containment boundary, or surrounded by additional structure and/or thermal insulating material or a significant thermal mass. Even if such mitigating design features exist, unless their performance is readily established via analysis, specific testing directed at containment penetrations is normally in order.

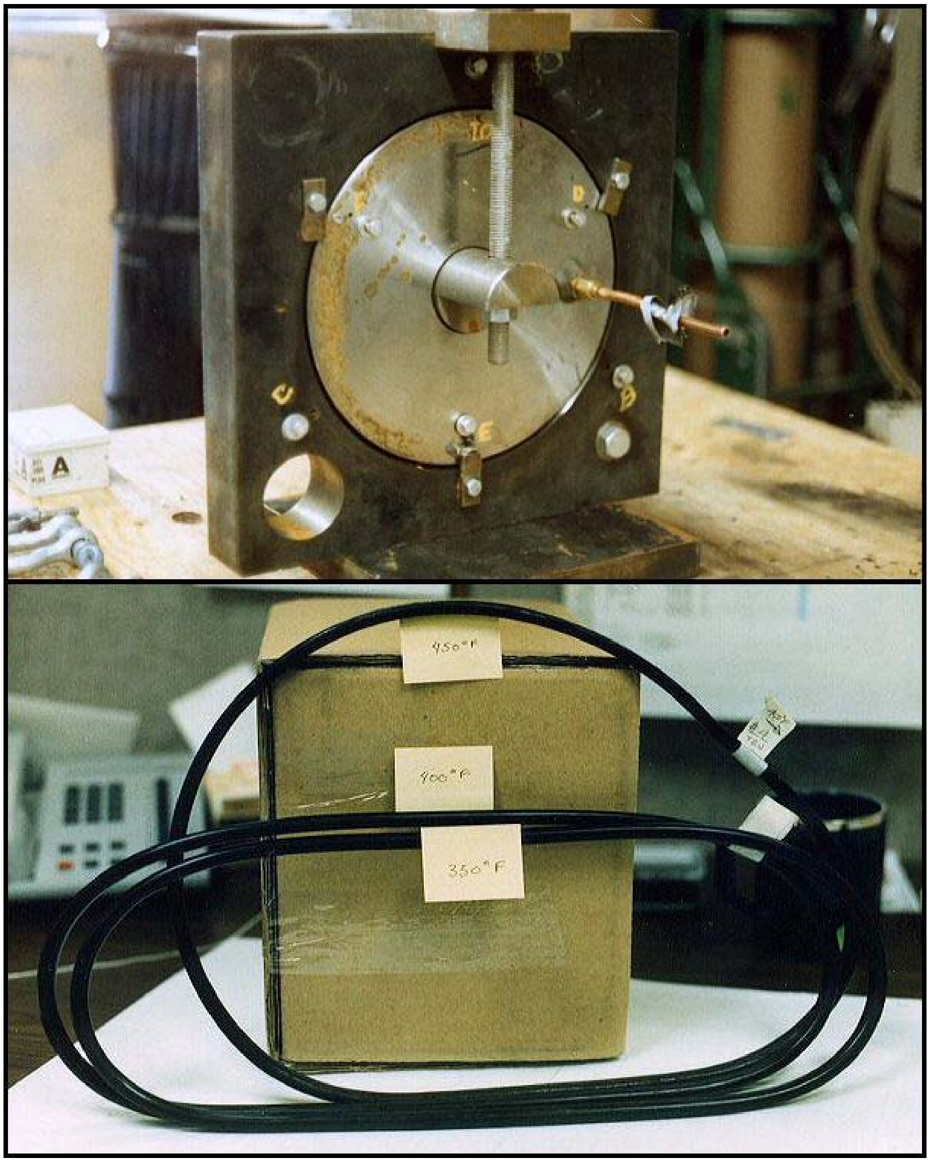

Fig. 1 High and low temperature O-ring seal compression testing

Although buckling failures have become a rare occurrence in licensed packages, potential vulnerability to buckling modes of failure also needs to be considered. The authors believe that buckling vulnerabilities generally should be addressed by analysis only or a combination of analysis and testing unless test articles purposely simulate worst-case imperfections and configurations possible in production. Immersion is a buckling sensitive load condition which can and normally should be evaluated analytically.

Nearly all Type B packages include some type of impact limiter or impact mitigating structure. The method of attachment typically is one of the weaker links in the design, especially if the impact limiters are removable. Experience has shown that the ability to analyze impact limiter attachments is extremely difficult and usually requires they be specially designed (e.g., using long, necked down fasteners to ensure stretching rather than breaking). Often, even if specially designed, a test specifically directed at retention of impact limiting devices is in order.

In general, fire tests are directed at elastomeric seal performance, with little concern for structural steel components. However, since the regulations require a Hypothetical Accident Condition (HAC) sequence of events with the fire following a 9-meter free drop and 1-meter puncture, the package is generally more vulnerable to a fire after a worst-case set of drops and punctures. In addition, the worst case for fire generally results from preceding structural tests that maximize package deformations, whereas worst-case structural loadings on a package are usually associated with structural tests that result in small deformations and, hence, large accelerations. Therefore, structural and thermal responsibilities can indeed be very different and both must be considered.

Many packages include lead or other shielding material that can reconfigure under impact conditions (e.g., lead slump or neutron shielding cracking), or can be degraded under high temperatures (e.g., lead melt). If post-accident shielding criteria are compromised by such conditions, testing may be needed to confirm initial conditions used in post-accident shielding evaluations.

If the payload is fissile in nature, and criticality analyses assume that payload geometry is retained or partially retained in a worst-case accident scenario, testing may require that a carefully simulated payload or payload support structure be subjected to worst-case structural loadings. The authors acknowledge that if the payload support structure is not overly complex and impact accelerations are credibly bounded by conservative analysis or test, an analytical evaluation of the payload structure may be acceptable.

Decide on Analysis Versus Testing Demonstration Approaches

Once package vulnerabilities are well understood, a decision must be made whether these vulnerabilities should be addressed by analysis, test, or a combination of the two. In general, analysis with confirmatory testing or testing with confirmatory analysis is the best route for rapid certification. The problem with a "test–only" approach is that numerous test orientations and initial conditions may have to be tested to ensure the worst case is addressed. Performing at least some comparative analyses of candidate test conditions is a far better approach, thus allowing as small a subset of tests to be performed as possible. In some cases, unfortunately, the design is sufficiently complicated that heavy reliance on testing is virtually required. The TRUPACT-II package is one such example. The extensive testing identified in Table I for that package was a direct result of the perceived difficulty to credibly perform structural analyses for free drop and puncture events. Even if a package's geometry is well suited for analysis, unless inherently conservative bounding impact accelerations can be established by analysis, testing to establish impact magnitudes is often times warranted. Dynamic testing with accelerometers or static tests to establish force deflection characteristics of a package for a given impact orientation are often times employed to confirm, if not establish, appropriate impact forces which can then be used in a finite element analysis of the package containment boundary or other feature or structure important to safety. Sub-scale free drop testing in conjunction with static tests was used to calibrate the finite element analysis models for the Sterigenics Eagle cask (see Figure 2).

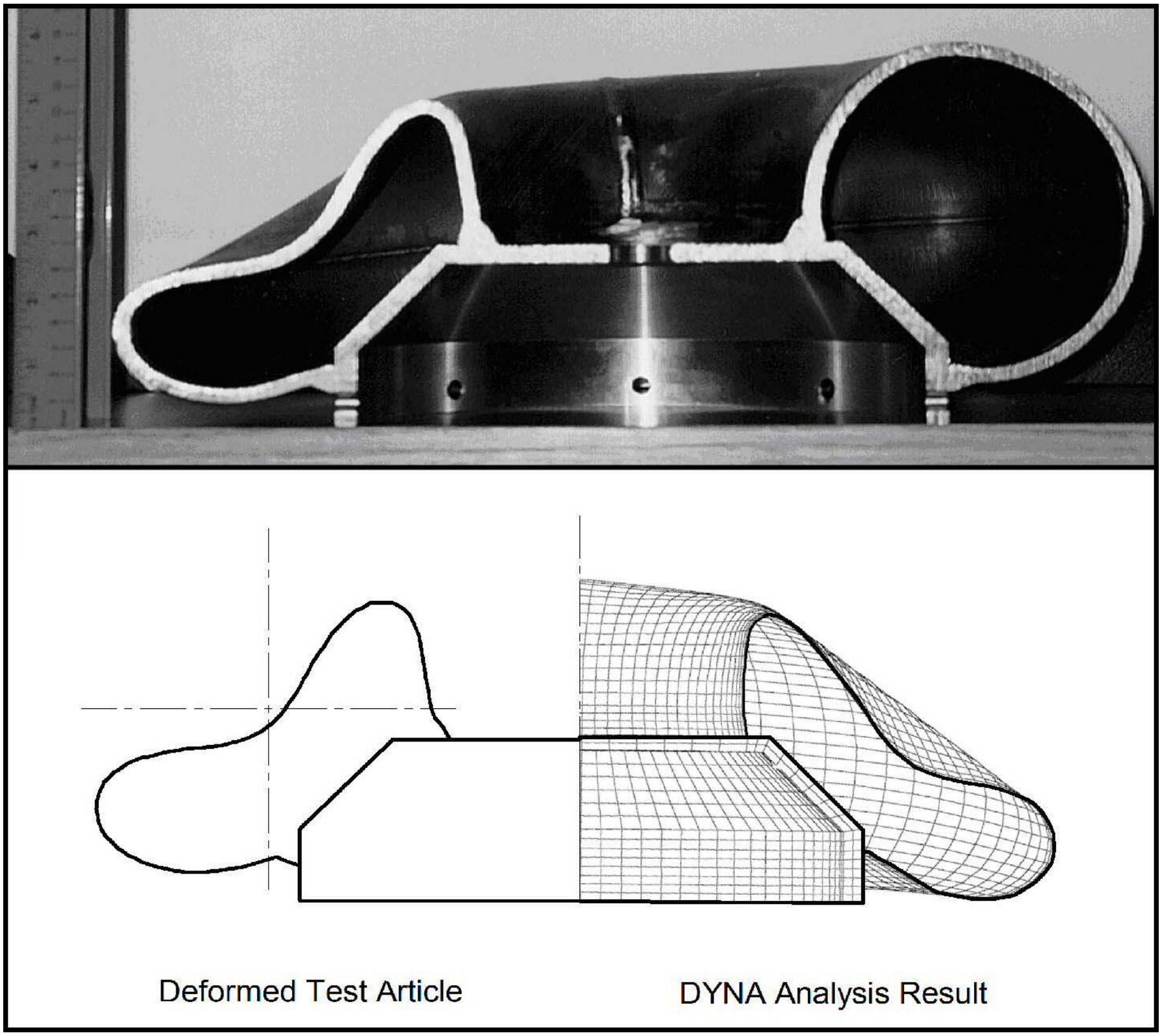

Fig. 2 Comparison of the Sterigenics Eagle corner drop test to DYNA-3D finite element results

HAC puncture is not readily addressed analytically unless package shells are sufficiently thick to allow standard puncture equations to demonstrate adequacy. This beneficial situation often exists for the case of heavy walled spent fuel packages such as the 125-B, but certainly is not the case for TRUPACT-II, HalfPACT or TRUPACT-III packages. Any package design which is focused on minimizing packaging weight and maximizing payload weight will likely require some level of puncture testing.

Evaluations for the HAC thermal (i.e., fire) event are generally by analysis. This is the preferred approach due to a number of factors, including the limited availability and significant costs of test sites set-up to perform such tests and the inherent need for a full-size test article (i.e., thermal response does not scale). If a credible analysis for the HAC thermal event can be performed using inherently conservative assumptions, such an approach has generally been acceptable to the regulators. Avoidance of a fire test can sometimes be achieved by careful selection of design features during the design development phase of a package development effort. For example, the RTG package closure design combined a very thermally massive set of seal flanges with many surrounding air gaps to insulate and isolate the elastomer seal from the effects of a fire. By doing so, in spite of a 4,500 watt internal heat load, an inherently conservative thermal analysis could be performed while still keeping seal temperatures within the defined limit.

The bottom line is that if a credible and inherently conservative analysis can be performed, be it structural or thermal, it usually should be. However, if a precedent setting analysis approach is employed or analysis assumptions and modeling details are likely subject to debate, testing should also be performed to validate the analysis. If credible analysis is out of the question, a demonstration by test only is possible, but will likely require multiple test articles and numerous tests. Testing with supplemental analysis is usually reserved for packages where reasonable design margins are not evident, and testing of worst-case extremes is not possible or for some reason is not achieved during testing. In such cases, analytic models can be adjusted to reflect as-tested conditions and correlated to give results in reasonable agreement with those observed from testing. The as-correlated models can then be adjusted to reflect worst-case scenarios (e.g., greater impact accelerations due to potentially colder temperatures or higher strength impact absorbing materials).

Select Detailed Test Orientations

With an understanding of package vulnerabilities and a decision regarding the specific features of the package to be exercised via testing, detailed orientations must be selected that will reflect or closely approach those leading to a worst-case response. Although a single free drop followed by a single puncture test and a subsequent fire is theoretically possible, in practice multiple tests are needed to address all worst cases. The real challenge is to select enough test orientations to support and expedite certification while limiting the number of test articles required to the greatest extent possible, preferably performing all tests using a single test article.

In most cases, the orientation selection process is relatively straightforward from an application of general engineering principles and logic. This is particularly true for free drop conditions. Stable, drops on the closure end of the package with the center of gravity over the impact point are the ones normally considered first. Here, dependent on design details, a decision is usually needed regarding whether a pure vertical or a slightly off-vertical drop orientation (i.e., 5º to 10º from vertical) is the worst case. Although a straight vertical orientation may result in greater impact accelerations for many designs, that orientation also provides a direct support path from the ground to the closure lid of the impacting package. A slightly off-vertical orientation may therefore impose greater stresses on the closure retention devices. Similarly, impact limiter attachments are generally most vulnerable to a slightly off-vertical drop orientation. Since vertical and near-vertical orientations will normally result in similar damage to the end of a package, unless several test articles are utilized, the best course is to select one or the other and defend that the tested orientation is the worst case. The more difficult to analyze orientation, off-vertical, is usually better tested and the pure vertical case analyzed.

A similar tradeoff between side drop and slapdown orientations is also usually in order, with a reasonable goal being to test one and dismiss the other by analysis. This usually leads to performing the difficult to analyze slapdown test and analyzing the pure side drop case. A reasonable alternative is to test both side and slapdown orientations with impacts occurring on opposite sides of the package.

A center of gravity over corner case is usually of interest relative to its being one of the "softer" drop orientations, thus leading to a maximum deformation of the package as an initial condition for a subsequent fire, especially at the closure end of the package. In addition, the potential to "bottom out" an impact limiting feature in the corner drop orientation, thus creating a "spike" in the impact acceleration response, can be of concern.

Puncture tests are also generally worst when the puncture bar is directed through the package's center of gravity. As discussed above, punctures directed at containment boundary penetrations are normally included. The puncture test is often used to open up potential thermal paths that can be problematic in a subsequent fire. Experience has shown that punctures occurring immediately adjacent to stiffened areas of a package and those where the axis of the puncture bar is off-normal to the surface of the package (typically 20º to 30º provides the worst case) are the ones most likely to penetrate deeply into the package surface. Such orientations are therefore normally included.

If fire testing is performed, elevation and orientation of the package in the fire is an issue to be addressed, but is considered to be beyond the scope of this current paper.

Identify Initial Conditions

In addition to orientation, initial temperature and pressure conditions must be selected for testing. If justifiable, a preference normally exists to test with the test article in thermal equilibrium with the prevailing ambient temperature, whatever it may be. However, if a package contains energy absorbing materials whose strength varies with temperature more significantly than does the strength of the containment boundary structural materials, testing at cold conditions will generally provide a worst case. Conversely, if testing with impact limiting materials at their maximum normal operating condition temperature, maximum deflections will be expected to occur. If tests are not performed at extreme cold or hot conditions, some type of analytical based extrapolation of observed responses to temperature extremes is usually required.

Due to potential safety concerns, dropping pressurized vessels should be avoided. If containment boundary stresses are relatively small for maximum normal operating pressures compared to Normal Conditions of Transport (NCT) allowable stress limits, such stresses can often times be dismissed as of little significance and tests can be performed without internal pressure. Although this situation often exists for thick walled containment vessels, such was not the case for the relatively thin-walled TRUPACT-II, HalfPACT and TRUPACT-III packages. Certification testing of these three packages therefore included an internally pressurized containment vessel. Although testing with pressure is generally considered to be the worst case when considering response of the closure system, such may not be the case if buckling modes are being assessed, since internal pressure stiffens the shell structure. Because of the highly localized external deformations and relatively low impact accelerations, pressurizing the containment boundary for puncture tests is typically not considered necessary.

If a fire test is to be performed, a decision on initial temperatures and pressures again needs to be made. For the TRUPACT-II package, the test article was preheated to normal operating temperatures and was internally pressurized prior to the fire. In general, if margins of safety for a given packaging design are relatively high, performance of a fire test without preheat and without internal pressure may be readily justifiable.

Select Test Article Scale Factors

With all intended test conditions having been identified, a physical test article must be developed. One of the first decisions to be made is whether to test at full or sub-scale. Factors affecting this decision include fabrication cost and schedule, and the ability of test facilities to handle the size and weight of a full-scale test article. If fire testing is to be performed, full scale is virtually a requirement. Recently, there has been an increase in technical and political scrutiny relative to the merits of full- versus sub-scale testing. In response to the growing interest in full- versus sub-scale testing, NRC's pending Package Performance Study (PPS) anticipates full-scale testing of truck and rail sized spent fuel casks. Most recently, on the TRUPACT-III project, the NRC regulatory review staff indicated that leakage rate testing of a subscale model alone would not be sufficient to demonstrate leaktightness since leakage rate tests do not scale, as documented in ANSI N14.5.

The authors have significant experience with both full- and sub-scale test programs on a wide range of packages and believe that either can be effectively employed to demonstrate package design and performance capabilities when coupled with appropriate analytic evaluations and bench tests. Relative to assessing leaktight capabilities of a package design when employing sub-scale test articles, by scaling up observed/measured deformations in and around the location of the closure seals and comparing those deformations against seal material capabilities, as established via bench testing of full size seals over a wide range of time, temperature, and compression states, valid conclusions can be reached for how a full size article would perform. However, leakage rate testing is recommended for the sub-scale model as added evidence of leaktight design capabilities.

If sub-scale testing is to be utilized, there must be a demonstration or reasonable expectation that potential modes of failure are indeed scalable. If deformations of key packaging components of interest are scalable, use of subscale modeling remains an effective means of demonstrating package performance capabilities.

Establish Test Article Level of Detail and Fabrication Constraints

Once a commitment to testing has been made, an appropriate test article must be manufactured. Independent of scale, it is normal practice to use prototypic materials and adopt fabrication processes that are identical to those planned for the production packages. Any exceptions should be acknowledged and justified in the package safety analysis report (SAR). In limited cases, creativity has been employed when selecting materials. For instance, when certifying the RTG package with the DOE, higher density, higher strength polyurethane foam was employed to simulate its strength and performance at cold conditions, while allowing testing at ambient conditions. Interestingly, the NRC discouraged this approach on another project. As with any engineered solution, final decisions can be dependent on who reviews and ultimately approves them.

Decisions need to be made as to the importance of tightly controlling test article dimensions and tolerances to obtain worst-case conditions that could occur in production. Thicknesses of critical members such as seal flanges and seals themselves normally warrant careful consideration. On the TRUPACT-II package project, test article seal flanges were purposely machined to obtain the thinnest and, hence, weakest flanges possible in production. In addition, minimum cross-sectional diameter O-rings were purposely procured and utilized, again to reflect worst-case conditions possible for a production run of O-rings. From a practicality and cost standpoint, adopting production unit nominal dimensions and tolerances is usually preferable when producing a test article. However, doing so requires some consideration of how test article response would differ if dimensional extremes did exist. If such differences are not reasonably dismissed, consideration should be given to tighter dimensional controls for the test article than planned in production. Machined component tolerances are usually small compared to member nominal thickness and therefore are not normally expected to affect structural or thermal performance.

When it comes to welded construction, great care is usually warranted when producing the test article. Since welds can be the weak link in a structure, care is needed to ensure that welds are not oversized in tests compared to what would be minimally acceptable in production. This is especially true when test articles are fabricated at less than full scale. Subscale test article fabrication instructions should typically flag the need to ensure that welds do not exceed their nominal size callout.

Similarly, component scaling must also be considered during fabrication. For example, precise scaling for a 1-8UNC fastener in quarter scale, based on the tensile stress area, is a 1/4-32UN fastener. However, acquiring an "off-the-shelf" scaled fastener is usually difficult. Thus, a standard, coarser thread form such as a 1/4-28UNF fastener is readily available and results in a slightly conservative reduction in tensile stress area (~4%). If a scaling factor is too odd, finding readily available scaled components will be difficult, requiring custom fabrication of normally standard components and causing a substantial increase in test article fabrication costs.

Steel strength tolerance is an interesting issue not normally rigorously addressed in a test article, mostly because of the difficulty of obtaining material that is at the corresponding material standard's minimum allowed value. Instead, accepting off-the-shelf material strengths and leaving analytic evaluations to deal with potential minimum strengths is generally considered an acceptable process. In some cases, in particular if a design has been optimized for puncture resistance, sheet material thickness tolerances need to be considered. If sufficient margin is not evident from some type of analytic based assessment, or if post test observations indicate that failure may have been imminent, consideration should be given to performing at least one puncture test with the sheet stock thickness at the minimum toleranced production value.

Somewhat easier to control, or "dial in", are strengths of energy absorbing materials. If judged to be important to performance, such materials can be purposed manufactured at high strengths to achieve maximum impact loadings or at low strengths to maximize deformations. In cases where both impact loadings and deformation are of interest, two paths forward have been taken in the past. Tests at one extreme (usually that maximizing impact load) are performed and inherently conservative analytic extrapolations are then made for the other extreme. If the design includes removable impact limiters, and there is a concern with possible bottoming-out of the limiter, another option is to build and test two limiters, one at each extreme strength condition.

Selection of a representative payload simulation is commonly a challenging aspect of the test article configuration. In many cases, multiple payloads of varying weights, strengths, and configurations are intended for a given package. If this is the case, assessing those payload features that are potentially most damaging to the packaging's containment boundary becomes necessary. If the payload includes protrusions or localized features that could adversely affect containment in an accident scenario, those features may need to be included in testing. Normally, testing with the heaviest possible payload is conservative. However, simulating worst-case payload strength can prove to be challenging. For example, structural strength and behavior of the payload can affect how the containment boundary is loaded; when driving onto the lid of a package, a payload may load the lid uniformly, at its center, or near its outer edges, depending on the payload's size and rigidity. The payload simulation used for testing should result in the worst-case loading on the containment boundary whenever possible. However, if the payload structure includes a strongback or other structure that is relied on for criticality control, testing may need to focus more on how loads transfer into the payload support structure than on how the payload loads the containment boundary.

Establish Acceptance Criteria, Instrumentation, and Data Reduction Processes

Once test conditions are specified and test unit configurations are known, a crucial part of any successful test program is a clear identification of acceptance criteria and the means to assess if the criteria are met. If the test article is a full-size package system, and testing includes free drop, puncture, and fire tests, acceptance criteria can approach a final "go/no-go" leakage rate test. However, if any correlation with analysis or verification of analysis assumptions is planned, additional geometric measurements and strain gage, accelerometer, and/or thermocouple readings must be taken. It is strongly recommended that the most important measurements be redundantly taken, preferably by multiple means such as the use of redundant instrumentation channels. In addition, even if a NCT free drop test appears to be of little importance, if strain gauges or accelerometers are employed during testing, such a test can serve as an excellent way to check out and ensure instrumentation systems are properly functioning while giving reasonable and credible results and doing little, if any, damage to the test article.

As discussed above, if subscale testing is used, leakage rate testing alone is normally not considered sufficient to demonstrate a leaktight condition for the full-size system. Instead, properly scaled up, detailed pre- and post-test geometry measurements of seal flanges and closure bolts coupled with material bench testing of seal materials at extreme time, temperature, and compression states will be needed. Measurements of residual, or back-off, bolt torques is also desirable since bolt torque frequently has a direct relationship with maintenance of a closure seal. To be the most meaningful, pre-testing of prototypical bolted joints to determine the relationship between applied torques and back-off torques is recommended. In many cases, a back-off torque on the order of two-thirds the originally applied torque indicates that full bolt preload was retained.

Obtaining maximum, instantaneous deformations at the time of peak impact loadings is often desirable. Frequently, post-test geometry measurements will not be sufficient to achieve this data due to a tendency of structures to spring back when unloaded. This situation is particularly true for impact absorbing plastic foam materials where experience has shown "springback" to be very significant. This phenomenon, if not properly considered and quantified, can lead to displacement and acceleration measurements that appear inconsistent with one another. High speed film or video has been used effectively to capture peak displacement responses. However, simple engineered "crush" gauges made of material that does not spring back when unloaded (e.g., most aluminum honeycombs) can prove to be a cost effective alternative.

If package shielding or criticality control materials are subject to reconfiguration as a result of testing, a means of measuring such movements or deformations will be needed. Destructive disassembly and inspection of the more critical package features for the test article is best performed once all tests are completed.

One major negative occurs for testing compared to analysis. Whereas an analytic evaluation readily leads to a quantification of margin of safety, design margin is not normally something that is readily measured during or after physical testing. Instead, testing tends to be much better suited to a "go/no-go" set of acceptance criteria; e.g., is the package leaktight, yes or no? Regardless, unless it can be clearly demonstrated that absolute worst-case conditions were tested (worst temperatures, worst orientations, worst-case material properties, worst-case component geometries, etc.), some measure of the design margin, that did exist for the as-tested condition, is highly desirable. Although a quantification of design margin is best, a qualitative discussion can also be of value and, unfortunately for a test program, often times is the only viable approach. For the TRUPACT-II package program, gross deformation testing of a full-scale mock-up of the closure seal configuration provided graphic evidence that the seal area could undergo significantly more distortion than it was actually subjected to during free drop and puncture testing before its leaktight capability would have been compromised (see Figure 3). Although margin was not quantified, the ability of the seal flanges to grossly deform while remaining leaktight left little doubt that relatively significant margin existed at the completion of physical testing.

An estimate of design margin can typically be obtained from a consideration of instrumentation measurements. Accelerations measured from testing can be appropriately filtered and employed in a finite element analysis to obtain traditional stress and/or displacement responses of a structure and quantitatively compared to allowable limits. If stain gauges are employed, peak structural response can be obtained at selected locations. However, the limited experience of the authors with strain gauge results (i.e., for the 125-B cask program) indicates direct comparison of strains measured in a test article with corresponding strains obtained from a finite element model is of limited value when establishing design margin. Conversely, thermocouple or temperature indicating label data lends itself well to quantification of a design margin since most temperature readings can be compared directly to a corresponding material capability in the form of a limiting temperature at which material performance begins to degrade. In general, when it comes to design margin, the smaller the margin of safety (real or perceived), the more extensive the testing and the more demanding the acceptance processes.

Fig. 3 Compression testing of a full-scale TRUPACT-II package closure design

One caution when it comes to data gathering and subsequent reduction is to keep focused on the data actually needed to establish or confirm package performance. Resist the temptation to gather lots of data for the sake of its academic interest. Too much data can be as bad as not enough data in that it can raise false concerns or bring into question the primary sources of data being used to judge package performance.

Get the Regulator Involved – the Sooner the Better

Pre-application meetings with the Regulatory review staff are strongly encouraged. After initially considering all aspects associated with testing, as discussed above, a meeting is recommended that is devoted to discussing test versus analysis plans and anticipated test details. During the meeting, the logic leading to selection of the test conditions should be summarized and justifiably defended. If the employed number of test articles is to be reasonably limited, the previously discussed topics should be thoroughly considered prior to presenting plans to the Regulators; i.e., the better the rationale and defense for the selected test conditions, the fewer the number of tests that will ultimately need to be performed. If overall test logic is clear, much of the detail can be left for disclosure in the SAR.

A further recommendation is to invite the Regulator to attend testing. Although test surprises can be somewhat awkward, first-hand observation of what normally proves to be performance that meets or beats expectations is invaluable.

When the SAR is ultimately submitted, including a high level of detail relative to the test programs is important. At a minimum, identify and discuss all differences between tested units and planned production units. Not discussed in this paper, but important for inclusion in the SAR, is how QA was imposed on both test article fabrication and the testing itself. A thorough, clear and complete discussion of the basis of testing, photographs of the more significant damage (or hopefully, lack of damage) to the test article, and a complete discussion of results and their relationship to other analyses within the SAR will significantly support the certification process.

Plan for and Accommodate Test Surprises – They Will Occur!

All test programs will provide some unanticipated results. With careful planning and a bit of good luck, they will be limited to a few minor anomalies that are readily dismissed as being of little or no significance to package performance. To be in a position to better accommodate potential problems, as discussed previously, instrumentation systems should be redundant or key measurements should be taken using redundant approaches. A malfunction of the instrumentation system or the loss of one or more instrumentation channels is not an unusual occurrence. During TRUPACT-II package certification testing, for example, remote pressurization lines were cut in more than one instance.

Test plans should remain sufficiently flexible to allow alteration of test details dependent on observed results. Although free drop orientations are usually easy to establish in advance of testing, puncture test detailed orientations and alignments can be influenced by damage occurring during the free drop(s), where unexpected tearing of shells or opening of joints can identify package vulnerabilities not initially anticipated. Puncture tests do not typically lead to a concern with overtesting or cumulative damage, and the addition of a potential worst-case puncture test during testing should always remain an option.

Examples of more dramatic test surprises include failure of a TRUPACT-II package leakage rate test due to payload debris working its way into the seal area. Although it was not considered likely that a single free drop and subsequent puncture test could have caused the observed leakage, and that the failure was much more likely attributable to the fact that numerous free drop and puncture tests were performed on the same test article, a third (debris) seal was added to the design and the entire test series repeated. A more careful design for the test payload may have avoided the problem altogether and the original design may have been determined to be perfectly acceptable.

As another example, during testing of the RTG design, the impact limiter was separated from the package as a result of a free drop followed by a puncture. Although the specific set of tests was intended to address limiter retention, the design was expected to perform adequately based in part on earlier, successful engineering testing. Failure was eventually attributed to one of the joints in the impact limiter that was vulnerable to tearing having been redesigned and significantly stiffened subsequent to successful engineering testing. The consequence was that during subsequent certification testing, more energy went into the limiter attachments and less into the limiter itself; hence, the attachment failed. A closer look at the entire packaging system at the time the impact limiter was stiffened may have flagged the fact that limiter attachments should have also been strengthened, which is how the problem was finally addressed. The lesson learned here is that if a portion of a package is modified due to the occurrence of an undesirable test result, the potential impact of that local design change on the rest of the package design must be carefully considered; i.e., a system-wide look is needed.

CONCLUSION

From the authors' perspective, some form of physical testing is prudent, if not necessary, for certification of virtually any new Type B package design. However, no two test programs will be the same and test details for a given program will strongly depend on the complexity of the design and the inherent design margins that can be shown to exist. If design margins cannot be quantified or reasonably qualified in some fashion via measurement, correlated analytic study, or demonstration of performance under conservatively extreme conditions (e.g., beyond regulatory, gross deformation testing), test program requirements will likely become very demanding.

Even though each test program will be unique in its details, a reasonably generic, systematic approach to identifying and planning any test program is possible, with key steps as summarized below:

- Assess package vulnerabilities
- Decide on analysis versus testing demonstration approaches
- Select detailed test orientations
- Identify initial conditions
- Select test article scale factors
- Establish test article level of detail and fabrication constraints
- Establish acceptance criteria, instrumentation and data reduction processes
- Get the Regulator involved – the sooner the better
- Plan for and accommodate test surprises – they will occur!

If careful attention is paid to each of these steps, successful certification testing should be possible.

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