

SIGNIFICANT INSIGHTS FROM 15 YEARS OF IMPACT LIMITER DESIGN, TESTING AND ANALYSIS

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ABSTRACT

An overview of some of the more significant lessons learned from impact limiter design, testing and analyses performed by PacTec personnel over the past 15 years follows. Interesting observations from several packaging development programs are presented and discussed. Several examples are provided based on work during development of the 125-B Cask for transport of TMI-2 core debris, the TRUPACT-II and HalfPACT Packages for transport of Contact Handled Transuranic (CH-TRU) Waste, the MP-187 Cask for transport of commercial Spent Nuclear Fuel (SNF) and the Radioisotope Thermoelectric Generator (RTG) Package for transport of RTG power sources to Cape Canaveral. Specifically included are discussions of test surprises which occurred during some of these programs.

INTRODUCTION

Packaging Technology, Inc. (PacTec) personnel have been developing impact mitigating devices and delivering them to the nuclear industry since the early 1980s. The typical products provided are external, end impact limiters, or when appropriate, fully enclosing overpacks, which have been specifically designed to protect radioactive material transportation packages from the consequences of off-normal and accident conditions. Although protection from the consequences of accidental drop events is typically the primary focus, in many cases, the impact limiting devices serve the dual purpose of providing an insulating barrier, which protects critical packaging or payload features from the consequences of a hypothesized fire event.

A wide range of other devices, which provide similar energy absorbing functions, has also been developed. Included are impact absorbers used internal to packagings for the purpose of satisfying payload fragility limits and/or protecting critical packaging features from undesirable interactions with the payloads. Several types and sizes of energy absorbing pads have also been developed to protect facility structures from the consequences of hypothesized drops of casks or other equipment during handling operations.

Over the years, PacTec has utilized several different materials, geometries, and attachment methodologies to optimally address a wide variety of design constraints. A significant number of design development and certification test programs have been performed to respectively refine designs and conclusively demonstrate design adequacy. Not unexpectedly, over 15 years of experience has resulted in many lessons learned, and a significant refinement in the state-of-the-art in impact limiter design and analysis at PacTec. The remainder of this paper highlights some of the more interesting aspects, observations and conclusions from this work.

ADEQUACY OF ATTACHMENT DEVICES

Arriving at an effective means of attaching impact limiting devices to their respective packaging can often prove to be quite challenging. During the early stages of development of the 125-B packaging for transport of TMI-2 core debris, the cask and impact limiters possessed a set of immediately adjacent, mating lugs with an off-the-shelf bolt for attachment. An early engineering development test revealed that such a system was totally inadequate. With reference to Figure 1, in a flat bottom end drop of a 1/4-scale model, all attachment bolts failed. The use of a short bolt, which could not absorb any significant energy prior to failure, and a configuration which allowed direct shearing of the bolt at the cask-to-limiter lug interface was readily determined to be the problem. In the final design, specially designed fasteners which were over one meter (39 inches) long and necked down along the shaft were employed. This design precluded the possibility of any significant shear loads from developing, and allowed for a significant stretching of the attachment devices prior to their failure.

More recently, during what was anticipated to be final certification testing of the Radioisotope Thermoelectric Generator (RTG) Transportation Package, the combination of a worst case thirty foot drop followed by a worst case puncture event caused the loss of the end impact limiter. This was particularly surprising in that necked down fasteners had been utilized, and earlier testing of virtually the same configuration had been successful. The reason for the failure was attributed to the fact that prior to the final testing, impact limiter corner joints were strengthened somewhat to preclude tearing which had occurred at the corners in the earlier testing. That strengthening led to greater loads developing on impact, and as a consequence, the observed failure. The problem was readily resolved by switching to a higher strength fastener.

The lesson learned here is to always carefully revisit the potential impact on the entire packaging system whenever a change is made to any portion of the system. In the case of the RTG Package, a review of the earlier testing revealed that although successful, some of the impact limiter fasteners had approached their failure point. The change of the limiter corner joint configuration changed a small positive margin of safety into component failure.

SIGNIFICANCE OF STRAIN RATE EFFECTS

With an initial velocity at the time of impact equal to 1,340 cm/sec (527 in/sec) for a nine meter (thirty foot) free drop, strain rate effects can be significant for certain materials of construction. However, at the time of the 125-B Cask development effort (mid 1980s), consistent with state-of-the-art at the time, static crush strength was assumed for the polyurethane foam used within the impact limiters. In hindsight, it is somewhat surprising that such an assumption resulted in analytic results which compared favorably with 1/4-scale test results. Investigation into this reveals that the 125-B Safety Analysis Report (SAR), reference 1, considered two bounding cases when analytically addressing how the limiter materials would behave in regions which were not directly backed by the cask body. A fully effective assumption and a partially effective assumption were both evaluated in order to bound the problem. As it turns out, deformation and acceleration results using a fully effective assumption and static foam crush properties were found to agree well with testing. This agreement led to a claim in the 125-B SAR that "Test data ... indicates that the partially effective foam assumptions are not realistic..." The fallacy with this claim is that a

partially effective assumption, combined with use of dynamic foam crush properties, would also have led to a reasonably good comparison between analyses and tests.

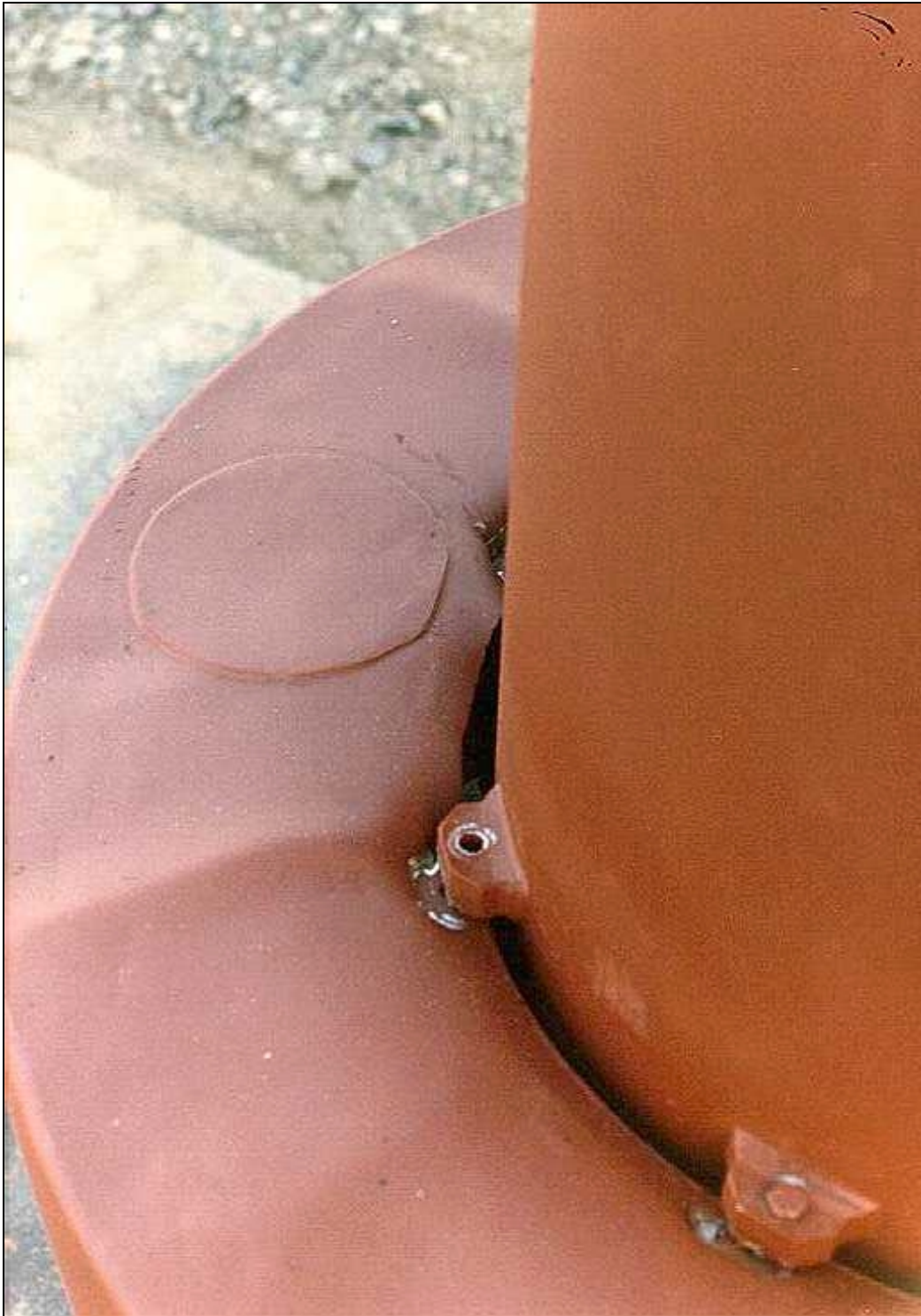


Figure 1
Impact Limiter Attachment Bolt Failure - Flat End Drop of a 1/4-Scale Model of the 125-B Cask

We now know that the dynamic effect is significant for foam, and needs to be properly accounted for in design. On Transnuclear West's (TNW's) MP-187 program, reference 2, careful studies of static versus dynamic strength of the energy absorbing polyurethane foam and aluminum honeycomb materials was performed. The results were factored into pre-test predictions and led to good agreement between analysis and test. However, the good agreement was also very dependent on the backed versus unbacked assumptions used for analyses of the various drop orientations. To obtain valid performance predictions for a given impact limiter configuration, a proper combination of material dynamic strength characteristics with realistic assumptions of behavior in unbacked regions must be utilized. Alternatively, conservative sets of strength and backing assumptions can be identified and bounding cases analytically evaluated. In the absence of meaningful test data, such a bounding set of conservative analytic evaluations will nearly always be required.

DESIGNING TO ACCOMMODATE GEOMETRIC CONSTRAINTS

In the case of the recently licensed MP-187 cask, NRC Certificate of Compliance number 71-9255, a significant geometric constraint was imposed on the design of the impact limiters. The strong desire to ship the greatest number of spent fuel assemblies in a single cask led to a relatively large outer diameter for the cask. In addition, a requirement to meet AAR unrestricted interchange dimensional envelopes limited the overall size of the impact limiter which could be developed. It was quickly concluded that a traditional, circular impact limiter was not feasible. The problem is that with a circular external geometry, the first several inches of crush absorb very little energy.

By using a flat sided impact limiter, much more energy can be absorbed during the initial stages of crush. This design approach results in a relatively constant force as the limiter is crushed, which allows for the minimum impact acceleration possible consistent with the available crush depth. This is desirable from an accident condition perspective; however, such an approach introduces a potential concern with package response to the normal free drop condition. This is because for a given drop orientation, the normal condition impact acceleration becomes nearly identical to that obtained for the corresponding accident condition (i.e., maximum impact force is nearly the same for any crush depth). With lower allowable limits for normal conditions, accident conditions may no longer govern the design. Using the MP-187 impact limiter design as an example, it became necessary to incorporate additional geometric features internal to the limiters in order to address this phenomenon, and to obtain acceptable margins of safety for normal conditions.

DESIGN FOR PUNCTURE RESISTANCE

Impact limiters are typically designed using analysis tools which rely on energy based principals to properly establish the crush characteristics needed for the energy absorbing material used within the limiter. For a constant crush strength energy absorbing material, such as aluminum honeycomb, energy absorbed during crushing simply equals volume crushed times material crush strength. For a material such as polyurethane foam, which exhibits varying crush strength versus strain, simple geometric relationships and integration schemes can still be used to select an appropriate internal energy absorbing material. However, these simplified approaches inherently contain an assumption that any external shell used around the energy absorbing materials will absorb very little energy during crush of the limiter. To achieve this in practice, thin, external steel shells are typically required. The use of thin shells is usually adequate when considering normal and accident condition free drop events onto flat, unyielding, horizontal surfaces, i.e., thin shells

can readily deform without failing when global crushing of the limiter occurs. However, such thin shells are very susceptible to rupture when exposed to the regulatory defined puncture event.

One or more design approaches is typically required to address this puncture concern. First, thicker shells on the outside of the limiter can be employed, with thickness set so that rupture of the limiter will not occur. The problem with this approach is that the external shell thickness typically becomes such that it contributes rather significantly during the free drop events and its presence can no longer be ignored when making evaluations for those events. A second choice is to allow rupture of the external limiter shell to occur, but this typically requires the cask structure beneath the limiter to be of sufficient strength so that containment boundary deformations are minimized consistent with their ability to meet leakage rate criteria during and after an accident.

For large, rail transported packages, thick lids and substantial surrounding structures typically exist, thus the consequence of rupturing the limiter shell is minimal. However, for smaller, lighter weight packages, rupture of the limiters can lead to unacceptable deformations of the package closure hardware. Additionally, a significant thermal mass in the vicinity of thermally sensitive components such as containment seals may become required if the puncture bar is allowed to rupture the limiter and penetrate all the way to the packaging structure itself. In some instances, proper selection of internal energy absorbing and insulating materials can be used to effectively address this thermal concern. Dependent on their performance when exposed to high temperatures or flame, the inherent behavior of these materials can be sufficient to allow rupture of the impact limiter and deep penetration of the puncture bar, yet still provide significant insulation for the package in a subsequent fire. The intumescent character of certain foams is one such example.

It is worth noting that on the TRUPACT-II program, puncture resistance was one of the greatest design challenges. Because of the large number of shipments of TRU-Waste anticipated, a minimum packaging to payload weight ratio was inherently required. To achieve this, the thinnest shell possible on the outside of the packaging was desired. However, it was quickly established via testing that although external shell thickness requirements for the free drop condition were minimal (0.32 cm [1/8 inch], or less), in order to preclude rupture by the puncture bar, a thickness of at least 0.95 cm (3/8 inch) was required. Weight constraints also did not allow for significant structural or thermal mass in the vicinity of the critical containment seals, hence it became unacceptable for the puncture bar to penetrate into the vicinity of the closure devices and seals. From these considerations, the final design of the TRUPACT-II utilized 0.95 cm (3/8 inch) thick exterior shells in the immediate vicinity of the closure region, and 0.64 cm (1/4 inch) shells elsewhere. This approach resulted in temperatures and deformations at the elastomeric seals being kept within their leaktight capabilities, while much greater deformations and temperatures were allowed to occur for other portions of the containment vessels. Figure 2 presents a photo of puncture damage outboard of the TRUPACT-II closure region, which was shown to be acceptable. Of final note, the use of relatively thick shells on the outside of the TRUPACT-II packaging made analytic evaluations difficult at best and forced a nearly exclusive reliance on prototype testing to demonstrate design adequacy.



Figure 2
Puncture Damage to the TRUPACT-II Packaging Outboard of the Closure Regions

CONCLUSIONS

Over 15 years of experience in the design, testing, and analysis of impact limiters has lead to significant insights into their behavior and an identification of approaches which are successful and approaches which should be avoided. By thoroughly studying structural and thermal characteristics of materials of construction, and by paying careful attention to all other parameters, which can influence performance, effective impact limiter designs can be developed. If design constraints are not overly restrictive, conservative analytic assumptions and techniques can be utilized to arrive at effective impact limiter designs. If optimized performance is desired or required, prototype testing will almost always be required to ensure that limiters will satisfy their intended functions.

REFERENCES

1. "Safety Analysis Report for the NuPac 125-B Shipping Cask", NRC Certificate of Compliance No. 71-9200
2. "Safety Analysis Report for the NuHoms MP-187 Multi-Purpose Cask", NRC Certificate of Compliance No. 71-9255