EM Technical Review of the ARROW-PAK Container – 9439

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ABSTRACT

The Office of Environmental Management (EM), U.S. Department of Energy (DOE), conducted an external technical review of the ARROW-PAK container in 2007 for its potential use as a payload container for transportation and disposal of high-wattage, contact-handled transuranic (CH-TRU) waste at the Waste Isolation Pilot Plant (WIPP) facility, Carlsbad, NM. The CH-TRU waste transported to the WIPP must be shipped in a Nuclear Regulatory Commission (NRC)-approved Type B packaging, such as the Transuranic Package Transporter-II (TRUPACT-II) or HalfPACT. Safe and compliant shipping in approved packaging is governed by the Contact-Handled Transuranic Waste Authorized Methods for Payload Control (CH-TRAMPAC) document, which defines the requirements (e.g., nuclear and chemical properties) each container must meet prior to transportation. Some of the waste destined for WIPP cannot currently be shipped in TRUPACT-II (or HalfPACT), because the waste generates or has the potential to generate hydrogen gas that exceeds the limits set by the NRC. This waste, referred to as high-wattage waste, has the potential to exceed CH-TRAMPAC-defined gas generation levels.

The ARROW-PAK container was designed to provide a payload container for high-wattage CH-TRU waste. The ARROW-PAK is a cylindrical container constructed of high-density polyethylene, a thermoplastic material. The ARROW-PAK is designed to hold one high-wattage CH-TRU waste 55-gallon drum and to withstand any significant hydrogen deflagration event. Once loaded and sealed with a fused joint, three ARROW-PAK containers would be placed into one TRUPACT-II for shipment to WIPP. Upon arrival at the WIPP, the ARROW-PAK and its contents would be emplaced in the repository intact. NRC has issued two rounds of Requests for Additional Information (RAIs) on the Addendum for TRUPACT-II that included ARROW-PAK as a proposed new content. The EM technical review team has conducted an independent assessment that examined the key functional requirements of the ARROW-PAK container for overall compliance with federal regulations, material properties, deflagration testing, and the technical limitations of ARROW-PAK as a payload containers for high-wattage TRU waste. As the result of the EM external technical review and the significant reduction in the revised estimate of the inventory volume of the high-wattage TRU waste, the applicant submitted a request to the NRC in October 2007 to withdraw the ARROW-PAK exemption application to the TRUPACT-II Certificate of Compliance originally submitted on January 31, 2005.

INTRODUCTION

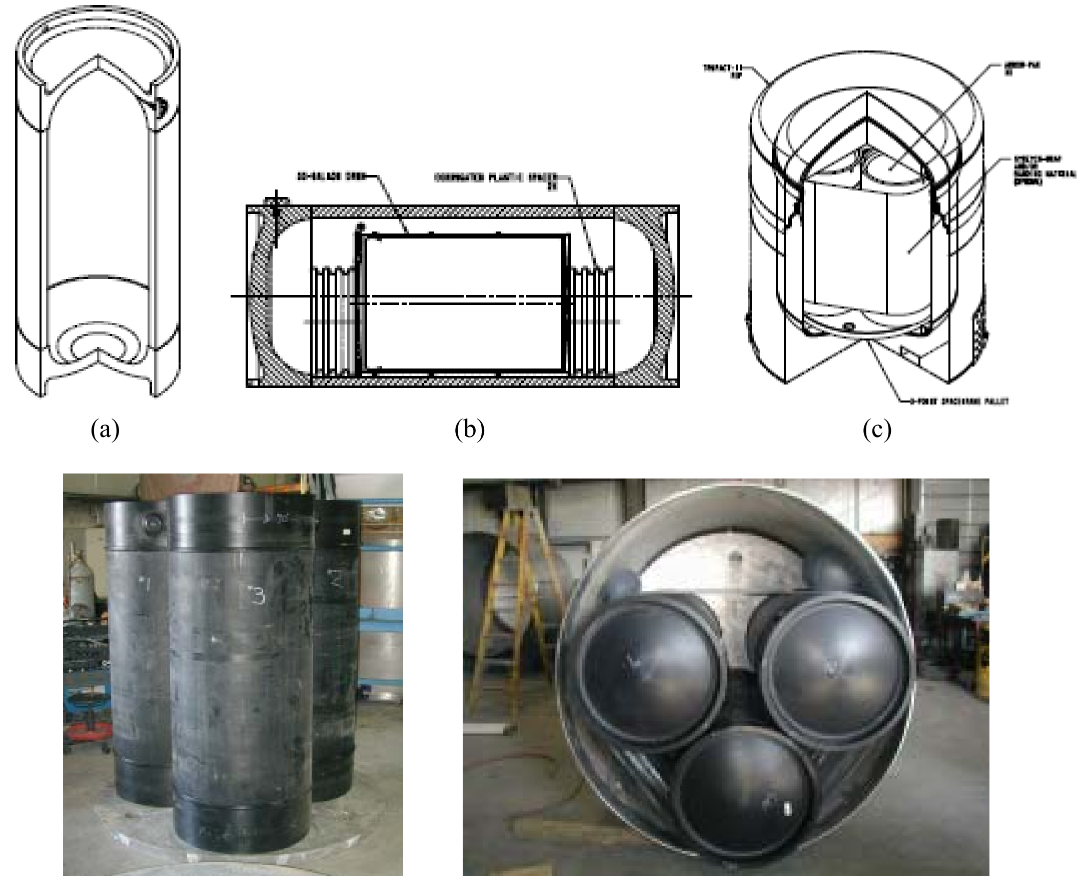
The ARROW-PAK payload container is intended for use in the shipment of high-wattage contact-handled transuranic (CH-THU) waste within the TRUPACT-II packaging. Three ARROW-PAK containers are designed to fit onto a standard pallet in a TRUPACT-II. The ARROW-PAK is a fused, welded container whose purpose is to isolate and protect the TRUPACT-II packaging from potential occurrence of a significant chemical reaction, i.e., hydrogen generation in the high-wattage TRU waste and potential deflagration inside the ARROW-PAK.

The ARROW-PAK is a cylindrical container constructed of extra-high molecular weight, high-density polyethylene (EHMW-HDPE) pipe-grade material with modified torispherical heads of the same material at each end. The approximate dimensions of the ARROW-PAK container and the inner and outer containment vessels (ICV and OCV) of TRUPACT-II are listed in Table I.

Table I. Approximate Dimensions of the ARROW-PAK Container and Inner and Outer Containment Vessels

Characteristic	ARROW-PAK	TRUPACT-II (ICV)	TRUPACT-II (OCV)
Inside diameter/height (cm)	67.3/161.3	184.5/248.9	187.0/256.5
Outside diameter/height (cm)	76.2/179.1	185.1/248.9	187.6/256.5
Wall/head thickness (cm)	4.5/6.4	0.64/-	0.64/-

Figure 1 shows cutaway schematics and photos of the ARROW-PAK containers revealing internals and arrangement within the Inner Containment Vessel (ICV) of TRUPACT-II.



(a) (b) (c)

(d) (e)

Fig. 1. Cutaway schematics and photos of ARROW-PAK containers showing internals, (a) empty, (b) with a 55-gallon drum and corrugated spacers, (c) arrangement within the Inner Containment Vessel (ICV) of TRUPACT-II, (d) before, and (e) after loading into ICV. [Note: the side orientation in (e) is a configuration for a horizontal drop test.]

The nominal weight of an empty ARROW-PAK container is 238.6 kg (525 lbs), and the maximum payload weight (i.e., one loaded 55-gallon drum) is 625 kg (1,375 lbs). The maximum weight of a loaded ARROW-PAK container is 863.6 kg (1,900 lbs).

The TRUPACT-II package weighs a maximum of 8,750 kg (19,250 lbs) when loaded with the allowable contents of 3,302.3 kg (7,265 lbs). Three fully loaded ARROW-PAKs of 2,591 kg (5,700 lbs) are within the maximum weight allowance for TRUPACT-II.

The design basis for the ARROW-PAK container can be found in the TRUPACT-II SAR Addendum for ARROW-PAK, Rev. 0, February 2006 [1]. This document supersedes an earlier version dated January 2005, which was the original SAR Addendum submitted to the NRC as part of the exemption application for an amendment to Certificate of Compliance No. 71-9218, Revision 17, for the TRUPACT-II transportation package. The application proposed an exemption from 10 CFR 71.43(d) for transporting ARROW-PAK waste containers in TRUPACT-II packages. There have been two rounds of NRC review of the exemption application since its submittal.

The EM external technical review of the ARROW-PAK focused on several areas to evaluate its potential for certification exemption as an additional payload container for TRUPACT-II packaging by NRC. These areas are:

- Regulatory requirements and NRC guidance for packaging certification;
- Design basis of the ARROW-PAK, as described in the TRUPACT-II SAR Addendum for ARROW-PAK [1];
- NRC review of the exemption application that includes the Requests for Additional Information (RAI) and the applicant's response plan; and
- An independent assessment that examines the key functional requirements of the ARROW-PAK container for overall compliance with federal regulations, material properties, deflagration testing, and technical limitations of the ARROW-PAK as a payload containers for high-wattage TRU waste in TRUPACT-II.

A full report entitled, "External Technical Review of ARROW-PAK Container" has been published [2]. The report contains detailed review results and other aspects, such as TRU waste inventory review and assessment, additional regulatory and management approvals, and potential other ARROW-PAK uses. Because of the page-length limitation, this paper will focus only on the independent assessment described above. The EM external technical review of the ARROW-PAK container was performed by a team with members from DOE/EM, three national laboratories (Argonne, Lawrence Livermore, and Los Alamos), and Bechtel BWXT Idaho. The independent assessment mentioned in this paper was conducted primarily by staff members at Argonne National Laboratory and Lawrence Livermore National Laboratory.

FUNCTIONAL REQUIREMENTS FOR OVERALL COMPLIANCE

The TRUPACT–II SAR Addendum for ARROW-PAK [1] describes TRUPACT-II as a Type B package carrying three ARROW-PAK containers loaded with high-wattage TRU waste. High-wattage TRU waste can generate a hydrogen gas concentration >5%, which could result in deflagration/detonation in an air environment. The function of the ARROW-PAK is to prevent any detonation from occurring, and to contain any deflagration that might occur from hydrogen gas >5% (by volume).

The ARROW-PAK payload container is fabricated of extra-high molecular weight, high-density polyethylene (EHMW-HDPE) material meeting ASTM D3350-04 [3]. Currently, there is no NRC guidance on fabrication or use of non-metal containments for Type B radioactive material packaging for transportation. Although the ARROW-PAK has been used to transport Type A quantities of low-level waste permitted under the Department of Transportation regulations, Type A packaging needs only to be a strong container with no observable leakage of contents.

In the SAR Addendum, the ARROW-PAK is identified as a payload container — i.e., contents — in TRUPACT-II, not as a containment system. As such, the applicant must demonstrate, per 10 CRF 71.31, that the failure of ARROW-PAK will not reduce the effectiveness of the TRUPACT-II containment system. However, the applicant has not evaluated the consequences of a failure of ARROW-PAK inside the TRUPACT-II. The applicant assumes that ARROW-PAK will not fail, and, therefore, there will be no consequence of failure. Although not explicitly stated, the key requirement of the ARROW-PAK is to function as a containment system to contain deflagration and to prevent failure of the TRUPACT-II containment system. The team has concluded that ARROW-PAK provides a system for containing the deflagration gases, and should be defined as a secondary containment system. A secondary containment system offers the advantage of defense in depth, which should increase the assurance of the containment boundary integrity of the primary containment system of TRUPACT-II, especially since ARROW-PAK appears to be relatively robust based on the testing data. Rather than claiming that ARROW-PAK will not fail under any circumstances during transportation, a different approach would be to demonstrate that ARROW-PAK has a very low probability of failure during transportation, and that even if does fail, the consequence will be minimal because the pressure (due to volume dilution) will be too low to challenge the primary containment boundary of TRUPACT-II.

The codes and standards listed in the SAR Addendum do not meet the intent of 10 CFR 71.31 for nuclear applications. The listed ASTM Standards for the ARROW-PAK are primarily for non-nuclear applications. As a containment system and according to the NRC Standard Review Plan for Transportation Packages of Radioactive Material, NUREG-1609 [4], the applicant needs to use the codes and standards similar to those listed in NUREG/CR-1815 [5], NUREG/CR-3019 [6] and NUREG/CR-3854 [7], but for EHMW-HDPE.

As identified in the NRC RAIs the test and analysis performed in the SAR Addendum for normal conditions of transport (NCT) and hypothetical accident conditions (HAC) should include, as initial conditions, the extreme temperature conditions depicted in 10 CFR 71.71 and 71.73. Also, the NRC Regulatory Guide (RG) 7.6 [8] and 7.8 [9] should be used, to the extent possible, to demonstrate compliance to the 10 CFR 71 requirements.

The applicant has requested an exemption from 10 CFR 71.43(d). An exemption requires the applicant to demonstrate that (1) the health and safety of the worker and public will not be endangered, or (2) equivalent safety is provided. The apparent exemption request was to allow the hydrogen concentration to exceed 5%, which is prohibited by the NRC in NUREG-1609 based on NRC Information Notice No. 84-72 [10]. The SAR Addendum has not demonstrated equivalent safety where the ARROW-PAK was identified as a payload container. The applicant's request to use administrative controls to address extreme temperature conditions for unlimited, non-emergency shipments is not reasonable. This request has been denied by NRC.

MATERIAL PROPERTIES

It is apparent from the NRC review that the applicant has not provided sufficient data on the material properties of the EHMW-HDPE in the SAR Addendum [1] to allow a full assessment of the ARROW-PAK container. Material properties data include yield stress, tensile strength, stress-strain curves, Charpy V-notch energy, fracture toughness, resistance to crack growth as a function of strain rate and temperature (in the range of −40 to 60ºC [−40 to 140ºF] for both the parent material, i.e., EHMW-HDPE (PE 3408), and the fused joint. Since the shipping time for the "high-wattage" contents in ARROW-PAK/TRUPACT-II could be up to 70 days, creep/relaxation behavior of EHMW-HDPE may be relevant.

The team has learned during a site visit in July 2007 that Grade PE 4710, instead of Grade PE 3408, will be used for the ARROW-PAK container. The applicant claimed that PE 4710 has higher pressure capacity and better high- and low-temperature performance than PE 3408. The team has reviewed the information on PE 4710 provided by the applicant. The results of the Charpy impact test on PE 4710 showed a ductile-to-brittle transition temperature (DBTT) below −34.4ºC ºF), whereas the DBTT in the presence of machined or razor notches for PE 3408 is approximately 0ºC (32ºF). The fracture surfaces of the specimen tested at −45.6ºC (−50ºF) showed some level of ductility at that temperature [11]. Thus, the results show that PE 4710 has significantly improved performance over PE 3408 at low temperature. The applicant needs to perform similar Charpy impact tests on the fused joints of PE 4710 at comparable low temperatures.

The applicant also provided data on the tensile yield strength of PE 4710 (or DGDA-2490) at temperatures ranging from −40 to 60ºC (−40 to 140ºF) [12]. However, the applicant has not provided data on the ultimate tensile strength. The applicant should provide similar data for the fused joints. These data are needed to determine the margin of safety for the ARROW-PAK container when subjected to primary membrane and bending loads. The applicant should also provide (1) stress-strain data for PE 4710 at various temperatures of interest, and (2) material properties data for PE 4710 and its fused joint, as a function of strain rates and temperatures.

The team has concluded that the same set of material properties data mentioned above for PE 3408, and requested by the NRC, must be provided for PE 4710 (parent and fused joint) in order to allow for full assessment of the ARROW-PAK container.

The team has made the following additional observations related to the material properties of ARROW-PAK that depend on quality assurance, fabrication and inspection:

Relatively speaking, the weakest point in the ARROW-PAK container has to be located at or near the butt and/or saddle-fused joints. These joints may contain flaws and voids, and the applicant needs to describe the quality assurance program used to ensure adequate inspection of the fused joints. The applicant should discuss the inspection techniques for detecting flaws and voids in the fused joints. The discussion should include limitations of these techniques, and the smallest flaw size that can be detected by the techniques. This flaw size should be smaller than the critical flaw size determined using fracture toughness tests. The allowable flaw size should be larger than the smallest detectable flaw, but smaller than the critical flaw size by an adequate safety margin.

DEFLAGRATION TESTING

The team has reviewed the literature on deflagration, i.e., subsonic combustion and deflagration to detonation transition (DDT), with a focus on the physics principles and experimental data, and their implications on a confined system such as ARROW-PAK with a 55-gallon drum and corrugated spacers inside. The shock wave associated with a detonation has a cellular, fish scale-like structure, with a cell width λ that decreases with the reactivity of the fuel/air mixture [13, 14]. Thus, at a given initial system temperature and pressure, the minimum cell width, λ_{min}, is found at the stoichiometric composition of the mixture. For H_2/air mixtures, the stoichiometric composition is 29 vol % H_2 in air, and at 25ºC and 1 atmosphere, λ_{min} is $\approx$ 15 mm [14]. One may associate decreasing λ with increasing reactivity, and thereby, qualitatively, with increasing flame acceleration and the likelihood for DDT.

Since λ is determined by reactivity and chemical reaction kinetics, it is not surprising that the detonation cell width is sensitive to fuel/air composition, initial system temperature, and pressure. The minimum value of λ ($\approx$ 15 mm at 1 atm and 25ºC) may be further reduced by increasing the initial pressure above 1 atm [15–17], and the initial temperature above 25ºC [18]. The applicant has conducted only one deflagration test has been conducted using an empty ARROW-PAK at ambient temperature, and near stoichiometric composition with an initial pressure of 128.3 kPa (18.6 psia), which is well below the maximum normal operating pressure (MNOP) of 689.5 kPa (100 psig [114.7 psia]). Deflagration testing at 689.5 kPa and the maximum normal operating temperature (60ºC [140ºF] for EHMW-HDPE) at the stoichiometric composition of H_2/air would provide a substantially smaller λ, and, therefore, significantly increase the likelihood of flame acceleration and DDT. This is the technical basis for deflagration testing at the MNOP and the maximum normal operating temperature for the ARROW-PAK container, as indicated in one of the Requests for Additional Information of the NRC review.

For the occurrence of deflagration and DDT in a confined volume, two geometrical parameters, the axial length (L) and the diameter, or width (d) of the cross-sectional flow area are related to λ as

$$d > \beta \lambda \tag{Eq. 1}$$

where β depends on the cross-sectional flow geometry, e.g., $\beta = 1/3$ for a circular tube geometry; and $\beta = 1$ for a square channel geometry [19]. Since the detonation cell width (λ) may be only a few mm at the MONP of 689.5 kPa (100 psig [114.7 psia]), there are many possible configurations inside the ARROW-PAK with a 55-gallon drum and corrugated spacers that would satisfy $d > \beta \lambda$. In fact, since the 55-gallon drum has protruded circumferential ledges and the spacers have corrugated recesses, all kinds of flow areas with characteristic widths $>\lambda$ can be created when the drum and spacers move off center in the radial direction during handling, transport, or hypothetical accidents. Furthermore, these internal configurations have open, interconnected pathways with different aspect ratios (L/d), abrupt changes, turning corners, etc.

The effect of changing flow geometry is to increase the turbulence in the gas flow, and it is well known that turbulence enhances flame acceleration and DDT. The L/d ratio is often mentioned in the literatures on DDT. Experimental data are cited that below a certain threshold value of L/d, DDT will not occur because a run-up distance is required for flame acceleration into a supersonic regime [20]. The threshold value of L/d necessary for DDT is said to depend on the initial system pressure, L/d $\approx$10 for a pressure of 455.1 kPa (66 psig [80.7 psia]), versus L/d $\approx$ 60 if the system is not pressurized [21]. This threshold value of L/d can be even smaller, e.g., 3, for highly reactive and unstable fuels such as acetylene and ethylene. It is widely recognized that such L/d ratios and thresholds are highly system-dependent, and one should be very careful in applying them to other situations. For example, the applicant has indicated that the L/d for an empty ARROW-PAK is 2.4, which is well below the L/d threshold value of 10, hence rendering DDT impossible. One can also argue that since the MNOP is 689.5 kPa (100 psig), the critical L/d ratio for the ARROW-PAK should be <10, and some of the many pathways inside the ARROW-PAK with a 55-gallon drum and corrugated spacers could have L/d values greatly above the threshold value.

The physics basis of the run-up distance, L_c, may be defined as the distance between the point of ignition and the point at which the flame front has reached a speed slightly below ≈ 95% of the isobaric sonic velocity in the combustion product [22]. In many cases $L_c \approx L_{DDT}$, which is the run-up distance to detonation [22]. It has been shown that when the flame front reaches L_c (the fast deflagration regime), substantial overpressure in the confined system may have already been generated [23]. Compared to the geometrical length L of the pathways in the system, the shorter the L_c, the easier it is for fast deflagration and DDT. L_c is determined by the acceleration of the flame front, which is greatly affected by obstructions in the flow path, and enhanced burning due to localized turbulence [24].

Literature data indicate that abrupt changes in flow pathways caused by turning corners, or changing cross-sectional areas may significantly reduce the run-up distances, thereby increasing the likelihood of fast deflagration and DDT. In many cases, detonation occurs immediately past the corners with ignition points located (≈ 66 cm) upstream from the 90-degree corner [25]. For pathways that traverse from a narrow to a larger cross-sectional area, the run-up distance is reduced by a factor ≈ 8 to 20, compared to that of a straight tube with a constant flow area [25]. Pathways with corners and changing flow geometries are abundant inside the ARROW-PAK with a 55-gallon drum and corrugated spacers.

The team has reviewed more literatures on deflagration and DDT beyond those included in the report [2]. Suffice it to say that based on the physics principles involved, and as demonstrated in many experiments, the effects of geometry and obstacles on flame acceleration and DDT must be considered in the deflagration testing of the ARROW-PAK. Specifically, the deflagration testing should be conducted using a full-size ARROW-PAK made of the new polyethylene material (PE 4710) with a 55-gallon drum and corrugated spacers inside. The test should be conducted at the MNOP of 689.5 kPa (100 psig) and 76.7ºC (170ºF) wall temperature at the stoichiometric composition of H_2 in air. (Note: the NRC would like to see the ARROW-PAK deflagration test conducted at a wall temperature of 76.7ºC [170ºF], rather than 60ºC (140ºF), according to the summaries of the February 7, 2007 meeting.)

The team notes that two of the NRC RAIs requested information on the function and capacity of the corrugated spacers to “roughly” center the 55-gallon drum within the ARROW-PAK during handling, transport, and hypothetical accidents. The underlying issues of these RAIs related to deflagration testing are the internal configuration, which affects deflagration and DDT inside an ARROW-PAK during NCT and HAC. It is highly likely that the ARROW-PAK will require more than one deflagration test to establish the bounding configuration for deflagration and DDT.

TECHNICAL LIMITATIONS

Low-Temperature Limit for EHMW-HDPE

The brittleness temperature for the EHMW-HDPE material is listed as −75ºC (−103ºF) in the TRUPACT-II SAR Addendum [1] (Materials Data Sheet, MSDS #240370, Marlex HHM TR-480X high density polyethylene, Chevron Phillips Chemical Company, Dec. 2005, www.cpchem.com/tds). In the absence of machined or razor notches, the brittleness temperature for EHMW-HDPE corresponding to no specimen failure is below −40ºC (−40ºF) and in the presence of machined or razor notches, the transition from ductile to brittle behavior occurs at less than 0ºC (32ºF), according to Ref. 20, p. 2-10 in the SAR Addendum [1]. The applicant requested an administrative control that allows ARROW-PAK shipment only at temperatures above 0ºC at any locations along the transportation route. This request was denied by the NRC.

High-Temperature Limit for EHMW-HDPE

The temperature has a significant effect on the mechanical properties of EHMW-HDPE. The hydrostatic design basis for EHMW-HDPE, according to the above Materials Data Sheet is 11,032 kPa (1,600 psi) at 23ºC (73ºF) and 800 psi at 60ºC (140ºF). The stress life of EHMW-HDPE, shown in Figure 2.5 on p.2-9 of the SAR Addendum [1] (Driscopipe Engineering Characteristics, Bulletin 1159-88-A17, Phillips Driscopipe Inc., now Chevron Phillips Chemical Company), contains three sets of limits on the hoop stress versus time at 23º, 48.9º, and 60ºC (73.4º, 120º, and 140ºF). For the maximum shipping period of 70 days for ARROW-PAK, the hoop stress limits at 23º, 48.9º, and 60ºC (73.4, 120, and 140ºF) are 12,411, 8,274, and 6,895 kPa (1,800, 1,200, and 1,000 psi), respectively, and the corresponding design stress limits, shown also on Fig. 2.5 of the SAR Addendum [1], are 5,516, 3,447.5, and 2,758 kPa (800, 500, and 400 psi), respectively.

Allowable Stress

The SAR Addendum [1] (p. 2-3) states that the allowable stress is conservatively assumed to be 2/3 of the yield strength, or 6,895 kPa (1,000 psi) at 60ºC (140ºF), which is consistent with the ASME Section III requirement for primary membrane stress (P_m). However, the ASME Section III also requires that the allowable stress should be less than 1/3 of the tensile strength. If the yield strength is greater than half of the tensile strength, 1/3 of the tensile strength would be a limiting criterion for the allowable stress. It is not clear whether the allowable stress discussed in Section 2.3.1 of the SAR Addendum [1] satisfies the 1/3 tensile strength criterion.

All engineering materials have inherent limitations in technical applications, which could be temperature, pressure, radiation, corrosive environment, etc. Certain limitations, however, may be imposed by system constraints, for example, the “high-wattage” TRU waste for the ARROW-PAK container. The SAR Addendum [1] (p. 10-14) lists the payload limits of 6.2 and 6.6 watts for each ARROW-PAK, which has been used to determine the inventory of TRU waste suitable for shipment. The thermal analysis of the SAR Addendum [1] (p. 3-9) showed that the allowable decay heat loading for ARROW-PAK is determined based on an average ARROW-PAK sidewall temperature of 60ºC (140ºF). Increasing the allowable temperature limit (from 60ºC [140ºF]) by using the new bi-modal resin polyethylene (PE 4710) will thus extend the allowable decay heat loading, i.e., high-wattage limit, for ARROW-PAK, and, therefore, the TRU waste inventory that could be shipped in the ARROW-PAK. For example, the team notes that Table 3-1 of the SAR Addendum [1] (p. 3-9) shows 68.3ºC (155ºF) as the maximum ARROW-PAK sidewall temperature for a decay heat load of 40 watts, which is also the decay heat limit of TRUPACT-II. A high-wattage limit of 40 watts could be set for a single ARROW-PAK (made of PE 4710), or 13.3 watts for each of the three ARROW-PAK containers, and shipped in the TRUPACT-II packaging.

The earlier independent assessment of deflagration testing focused on the conditions, i.e., gas composition, pressure, temperature, flow geometry, and obstacles that are most conducive to deflagration and DDT in an H_2/air mixture. The structural response of the ARROW-PAK to a deflagration, and/or a DDT inside the container, must be evaluated in order to determine if ARROW-PAK can satisfy its key functional requirement as a secondary containment system with a very low probability of failure during transportation.

It is important to recognize that the structural response of a containment vessel to a dynamic pressure loading is vastly different from that of a static pressure load. The Special Working Group, High Pressure Vessels (SWG/HPV) of the ASME Section VIII, Division 3 has been charged to develop a Code Case for impulsively loaded pressure vessels since December 2002. The impulsive load considered in the current Code Case is based on detonation by high explosives inside a pressure vessel containment structure. The SWG/HPV has included H_2/air deflagration and DDT in its charter in 2008. In a background document on pressure vessels subject to impulsive loads, the SWG/HPV made several key observations:

- Containment vessel peak response to dynamic loading is dependent upon the specific impulse of the pressure pulse (i.e., the area under the pressure-time history) rather than upon the peak pressure magnitude.

- Details of the pressure-time history, other than specific impulse, are of little importance to peak vessel responses.

- The peak containment vessel response typically occurs well beyond the time of application of the dominant portion of the dynamic pressure pulse, i.e., the pressure loading is over well before peak response is achieved.

- Because of the presence of higher modes of response of the vessel, the highest vessel response peak often occurs well beyond the first peak of response.

The background document also described the fundamental principles involved in the dynamic response of a spherical shell subjected to a spatially uniform internal pressure pulse (I), which for simplicity, was taken to be a rectangular pressure pulse (p_o) in time (Δt), i.e.,

$$I = p_o \Delta t \qquad \text{(Eq. 2)}$$

Solving the equation of motion for the fundamental mode of a thin spherical shell of a density (ρ) and thickness (h) gives the radial displacement (w) of shell as a function of time (t) as

$$w = I / (\rho h \beta) \sin \beta t, \qquad \text{(Eq. 3)}$$

where β is related to the period of response of the shell (τ) as

$$\tau = 2\pi / \beta, \qquad \text{(Eq. 4)}$$

and

$$\beta^2 = 2E / [\rho a^2 (1 - \nu)], \qquad \text{(Eq. 5)}$$

where E, a, and ν are, respectively, the Young's modulus, radius, and Poisson's ratio of the spherical shell.

The in-plane biaxial strain in the shell (ε) is

$$\varepsilon = w / a, \qquad \text{(Eq. 6)}$$

and the in-plane biaxial membrane stress (σ) is

$$\sigma = E\varepsilon / (1 - \nu). \qquad \text{(Eq. 7)}$$

Eq. (3) is a sinusoidal function that reaches a maximum at $\sin \beta t = 1$, and

$$w_{max} = I / (\rho h \beta), \qquad \text{(Eq. 8)}$$

which is proportional to I, and inversely proportional to ρ, h, and β. Eq. (2) shows I to be proportional to the peak pressure (p_o) and the duration of the impulse (Δt) that are characteristic of the detonation and depend on the nature of the explosives. The density ρ of the HDPE (0.95–0.97 g/cc) is small compared to that of steels (7.6–8.1 g/cc); the value of β for the HDPE is ≈ 20% of that of steels, whereas the wall thickness of the HDPE used for the ARROW-PAK, 4.4 cm (1.765 in), may be thicker than that of steels, if steels were used for ARROW-PAK (Note: This discussion ignores the fact that the ARROW-PAK is a cylinder, not a sphere.)

Eq. (4) shows that the period of response (τ) of the shell to the pressure pulse is inversely proportional to β, hence,

$$\tau_{HDPE} = 5\, \tau_{steels} \qquad \text{(Eq. 9)}$$

other things being equal, which is an interesting observation that a structure made of HDPE is fundamentally a lower frequency structure than a structure made of steels. One implication could be damping of the dynamic response of a HDPE structure, and reduced likelihood of strain growth, reverberations, etc.

It should be noted that the strain capacity of HDPE is ≈ 800% and the deformation and fracture behavior of long-chained polymeric material is fundamentally different from that of steels. The structural response of the ARROW-PAK (made of HDPE) to deflagration and detonation in the elastic and plastic regimes is a topic worthy of further study.

SUMMARY AND CONCLUSION

An EM external technical review of the ARROW-PAK container has been conducted in 2007 to evaluate its potential for an NRC certification exemption as an additional payload container within the TRUPACT-II packaging. The technical review team reviewed the design basis of the ARROW-PAK container against the regulatory requirements, the NRC review of the exemption application, and the applicant's response plan to the NRC's RAIs. The team also conducted an independent assessment of the functional requirements of the ARROW-PAK container for overall compliance with federal regulations, material properties, deflagration testing, and technical limitations of the ARROW-PAK as a payload container for high-wattage TRU waste in TRUPACT-II.

One of the major conclusions of the EM external technical review of the ARROW-PAK container was that the applicant's plan to address the NRC's RAIs in the exemption application for ARROW-PAK did not offer sufficient assurance for NRC approval. The performance of the new, bi-modal polyethylene ARROW-PAK must be demonstrated, by tests or analysis, to meet all regulatory requirements. The applicant may consider a risk-informed and performance-based alternate approach for the exemption application. This alternate approach would treat the ARROW-PAK as a secondary containment system and demonstrate that it has a very low probability of failure during transportation, and that even if it does fail, the consequences would be minimal because the pressure (due to volume dilution) would be too low to challenge the primary containment boundary of TRUPACT-II.

As the result of the EM external technical review and the significant reduction in the revised estimate of the inventory volume of the high-wattage TRU waste, the applicant submitted a request to the NRC in October 2007 to withdraw the ARROW-PAK exemption application to the TRUPACT-II Certificate of Compliance originally submitted on January 31, 2005.

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