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THE PROCEDURES USED TO REVIEW SAFETY ANALYSIS REPORTS FOR PACKAGINGS SUBMITTED TO THE U.S. DEPARTMENT OF ENERGY FOR CERTIFICATION*

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ABSTRACT

This paper presents an overview of the procedures used at the Argonne National Laboratory (ANL) to review Safety Analysis Reports for Packagings (SARPs) submitted to the U.S. Department of Energy (DOE) for issuance of a Certificate of Compliance. Prior to certification and shipment of a packaging for the transport of radioactive materials, a SARP must be prepared describing the design, contents, analyses, testing, and safety features of the packaging. The SARP must be reviewed to ensure that the specific packaging meets all DOE orders and federal regulations for safe transport. The ANL SARP review group provides an independent review and evaluation function for the DOE to ensure that the packaging meets all the prescribed requirements. This review involves many disciplines and includes evaluating the general information, drawings, construction details, operating procedures, maintenance and test programs, and the quality assurance plan for compliance with requirements. In addition, detailed confirmatory analyses are performed on the structural, thermal, containment, radioactive shielding, and nuclear criticality aspects of the packaging to ensure adequate performance. Because the various elements of the SARP review must be synergetic for the safe operation and use of the packaging, the review must be a team effort, with all disciplines cooperating in all phases of the process. The paper emphasizes the structural and material aspects of the review process, but the general approach presented is generic to all the disciplines involved. Some of the specific issues and problems encountered during typical reviews are discussed.

INTRODUCTION

In the U.S., there are approximately 25,000 shipments anually that contain hazardous or radioactive materials. Many of these shipments fall within the regulatory jurisdiction of DOE, and require a DOE Certificate of Compliance showing the packaging is safe for transport. The certification procedure is intended to assure the public that a package is designed to comply with federal requirements. The Argonne National Laboratory (ANL) Safety Analysis Report for Packaging (SARP) review group provides DOE with an independent review and evaluation of the information contained in a SARP that describes the packaging used to transport radioactive materials. The review is conducted to apprise DOE of the suitability of the packaging to meet all DOE orders and federal regulations for safe transport. This process assures that a consistent and independent review is performed, while maintaining the authority granted to DOE by the DOT for the packaging evaluation and certification process.

The function of the ANL review group is to perform an interdisciplinary, in-depth assessment of the proposed packaging based on the SARP submitted by the application to DOE. The SARP contains detailed information on the design, construction, and contents of the packaging. The assessment of the packaging includes detailed confirmatory analyses of the structural, thermal, containment, radioactive shielding, and nuclear criticality aspects of the packaging design. In addition, the construction drawings and fabrication procedures, the operating procedures, the maintenance and test programs, and the quality assurance plan are evaluated.

The primary goal of this review is to establish that the packaging will perform as intended under both normal conditions expected to be encountered in transport and hypothetical accident conditions. These transport conditions are detailed in the regulations contained in Title 10 of the Code of Federal Regulations, Part 71[1] (10 CFR 71). The regulations contain specific environmental and mechanical loading conditions which the package must be able to accommodate during transport.

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Because of the hazardous nature of the package contents, the regulatory transport conditions are necessarily severe; and consequently, each element of the review is therefore essential. A successful review requires a team effort from the SARP review group. For example, the General Information and Drawings Section is reviewed to ensure there is sufficient information for each reviewer to understand the type and quantity and form of the radionuclides or fissile materials, the proposed use of the packaging, the operational and safety features, and the materials used in construction. The construction drawings and engineering sketches should provide sufficient details to evaluate the methods of fabrication and allow development of appropriate analytical models.

THE SARP REVIEW PROCESS

The objective of this paper is primarily a discussion of the structural design and related materials aspects of the package evaluation and review; and to illustrate how these and the other disciplines must interact to provide a comprehensive assessment of the SARP document. The principal purpose of the structural review is to verify that the package satisfies all requirements relating to the structural tests described in 10 CFR 71.71 (normal conditions of transport), and 10 CFR 71.73 (hypothetical accident conditions). This review includes analyses of the stresses and deformations during the postulated drop and penetration tests, thermal stresses and movements due to thermal gradients, stresses due to differential pressure and dynamic loadings, and leak tightness to water pressure. This verification analysis is based on the ASME Code[2], and utilizes handbook solutions where applicable and PC software or mainframe codes such as ANSYS[3] or SAP[4] where necessary. The following discussion presents some of the most common structural analysis and materials related problems that are encountered in the review of SARPs.

Structural Evaluation of the Hypothetical Accident 9 Meter Free Drop Test. The hypothetical accident condition tests specified in 10 CFR 71.73 represent the most severe loading conditions that a shipping package is designed to accommodate. Of these, the 9 meter (30 ft.) free drop onto an unyielding surface is usually the most severe and, unless the applicant has clearly demonstrated that the packaging can survive this accident scenario by testing, this loading condition is subject to confirmatory analysis by the SARP review team. The simulation of the free drop of a package with some impact limiting hardware, such as a foam cylinder or layers of wood on its end, is a typical example of a confirmatory structural review task. A schematic drawing of a hypothetical shipping package, illustrating the major structural components, is shown in Fig. 1. Although several sophisticated computer codes are available to do this type of dynamic analysis, they are not entirely satisfactory for this confirmatory analysis. General purpose dynamic analysis programs require much effort to define the geometry of the structure and the mechanical properties of the various materials. The running time of these programs is also a problem since the solution process is typically the same for all parts of the model, regardless of the need to treat any particular part with a finer time step. On the other hand, specialized programs have been found lacking, because they typically treat the impact limiting feature as a single element and analyze the relatively rigid part of the package as a detailed elastic model, considering its dynamics and stress recovery, but ignoring the inelastic large deformation behavior of the limiter. In addition, essential details of material behavior, such as the unloading during strain reversal, is not considered. Moreover, for these specialized codes, the behavior of the impact limiter as a component, rather than the behavior of the limiter material, must be specified. Yet determining this behavior is a major part of the problem to be solved.

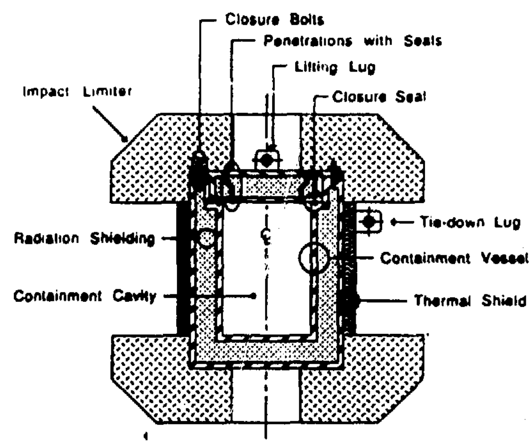

Fig. 1. Cross-section through a hypothetical cylindrical shipping package illustrating the major structural components.

The package drop simulation analyses performed by the ANL SARP review group have consisted of three types: first, single body dynamic, energy balance type calculations where the container is treated as a rigid body loaded by the force generated in the impact limiter, and the impact limiter is treated as a massless inelastic member. Second, one dimensional models with detailed simulation of the limiter geometry and nonlinear material properties. And third, some limited efforts using large finite element codes.

An approximation of the dynamic behavior of a cask such as shown in Fig. 1 can be obtained from a one dimensional model which concentrates all the mass of the cask at selected points, referred to as nodes, along its vertical axis.

The force deformation behavior of the segments of structural material between each pair of nodes, referred to as elements, is then estimated by some suitable relationship. An element may be treated as being rigid if it is extremely stiff as compared to other elements of the model. The solution for the displacements as a function of time is obtained by numerical integration using a simple fixed time step method.

For an analysis of the cask shown in Fig. 1 the foam material behavior was characterized by its stress strain curve which is highly nonlinear but can be approximated by a series of line segments. Additional considerations taken into account in this computation are the dynamic damping provided by the material, incorporated by including a stress that is dependent on strain rate; and, inelastic behavior, incorporated by assigning a zero force for any foam material in which the compressive strain is decreasing. The latter technique replaces the nonlinear elastic model in which the stress strain curve is the same for decreasing as for increasing strains.

In a typical analysis, the packaging shown in Fig. 1 was modeled by four elements through the height of the foam limiter with the mass representing a rigid cask body assigned to the top node. The results of such an analysis are shown in Fig. 2 where the displacement of each node in the foam region and the displacement of the cask body node are plotted against time. Time and displacements are zero at the instant of contact of the packaging with the rigid impact surface and downward displacements are positive. Another analysis considered the walls of the cask to be rigid, but allowed deformation of the lead. The model described above was used for the foam limiter and the steel components of the cask. The lead in the cask body was modeled by five elements, one for the bottom lead shielding region and four for the lead shielding in the walls. The lead was modeled as a nonlinear elastic material. Displacements for the six nodes defining the lead elements are shown in Fig. 3. The curves for the three uppermost node displacements appear as one curve at the scale of this plot. The lead slump is approximated by the largest difference between the top and bottom curves.

Other Confirmatory Stress Analyses. Some conventional linear elastic and elastic-plastic analyses are also used. Typical examples include consideration of the tie-down and support hardware under the unusual loadings postulated by 10 CFR 71.45 (lifting and tie-down standards for all packages). Both handbook solutions and conventional structural model solutions have been developed.

Another example is the solution of linear elastic models for stresses in cask vessels under pressure and thermal loadings. Handbook analyses and simple finite element solutions have been used here with particular attention to the interaction between a vessel and its lid. In general, the confirmatory analysis of the closure lid follows the ASME Code rules for bolted closures, augmented by analyses to determine the stresses and deformations in the vessel, its flange, and the cover. Indeed, the design of the mechanical closures is one of the common deficiencies found in the review of SARPs. The three critical constituents of closure design most often overlooked are: (1) the loads necessary to seat the gasket and maintain the seal under operating pressures and temperatures, (2) the correct bolt torque to provide this load, and (3) the local stresses in the vessel caused by the flange itself.

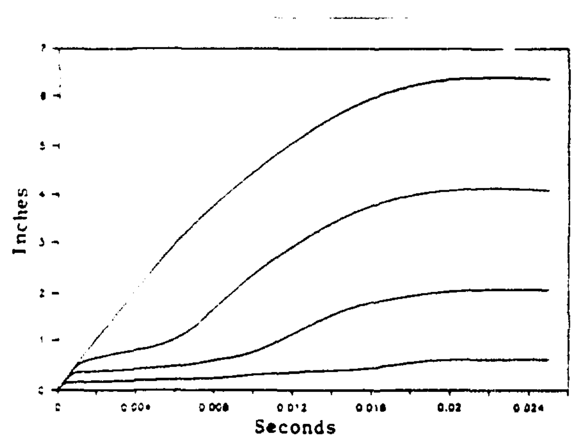

Fig. 2. Nodal point displacements for foam and cask nodes for 30 foot drop for rigid cask model.

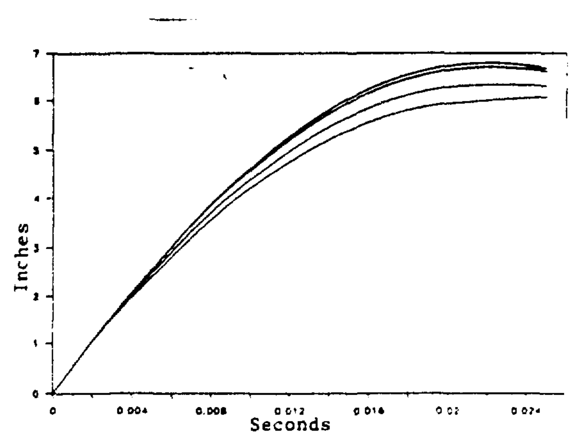

Fig. 3. Displacements for the six nodes of the five lead elements for 30 foot drop analysis.

As an example of an analysis of the closure of a cask subjected to a normal temperature loading consider Fig. 4 which shows the cask in cross section as deformed by its normal operating temperature gradient. The deformations are exaggerated by a factor of 200 in this display which was obtained by a conventional finite element method analysis of an axis symmetric structure using the SAP[4] program. A second loading condition in the same analysis considered a unit shear load parallel to the closure surface applied in opposite directions to the lid and to the cask. The ratio of the relative displacements in the direction along the closure plane measured at the bolting circle produced by these two loadings is an estimate of the shear force that the closure needs to be able to resist if it is to function without slipping.

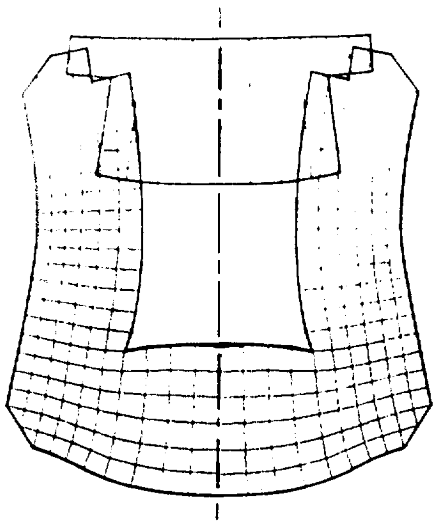

Fig. 4. Cask and lid deformations due to a normal conditions of transport temperture gradient.

Another area of structural design often questioned by the review team is the use of poor or inappropriate models and assumptions for the stress analysis of packaging components. For example, stiffening rings are sometimes treated as cantilevered beams, when in fact they should be treated as rings which include the appropriate portion of the attached shell. Handbook solutions are available for these structures, and the ASME Code provides guidance for including part of the shell. This approach not only results in more realistic stresses, but enhances the credibility of the overall packaging design.

ASME Code Design. The NRC Regulatory Guide 7.6[5] recommends the use of Section III of the ASME Code for the design of shipping cask containment vessels. Further guidance for Code use is provided in DOE's Packaging Review Guide[6], which recommends the use of Section VIII or III, depending on the packaging component and the contents to be transported. Section III of the ASME Code is intended for components in nuclear service and components that require superior reliability. The design by analysis approach adopted by Section III provides a greater safety margin, accounts for high local stresses, and considers thermal stresses which are not addressed by Section VIII. These additional requirements are deemed appropriate and necessary for the design of containment vessels for the transportation of radioactive materials.

The areas of packaging design and analysis covered by Code rules and most often overlooked are; (1) closure design, (2) penetrations, (3) inspection requirements for welded construction, and (4) the proper use and specification of materials. The typical deficiencies in closure design were discussed above, inspection requirements for welded construction are beyond the scope of the present paper, and the specification of materials will be discussed in a later section. The Code rules for penetrations in pressure vessels consider the stress concentrations due to the opening itself as well as those due to the reinforcement provided to strengthen the open area. These rules were developed to eliminate the potential "weak spots" and "hard spots" in a pressure vessel that can lead to high local stresses and the possibility of premature failure. The Code rules for penetrations provide adequate safety margins and, in most cases, eliminate the need for more sophisticated analysis as described above. Nevertheless, very few packaging designs reviewed by ANL satisfy Code penetration design requirements.

Mechanical Properties of Materials. The NRC Regulatory Guide 7.9[7] requires the applicant for packaging approval to provide a list of all mechanical properties used in the structural evaluation. This should include a tabulation of mechanical properties over a range of temperatures from -40°C (-40°F) to as high as applicable. Aside from the obvious reason that this avoids using material that is unsuitable for the service environment, this flags those materials that may undergo a change in mechanical properties under the environmental conditiona encountered in transport. For example, a precipitation-hardening thermal treatment below the normal transport temperature can lead to catastrophic failure of the containment structure. Or, radiation-induced embrittlement of the containment vessel steel due to the package contents. An example of how the mechanical properties of a structural material can be degraded by radiation is given in Fig. 5[8].

Brittle Fracture. The example cited in Fig. 5 demonstrates how radiation exposure can cause an otherwise ductile metal to become susceptible to brittle fracture. Of all the common structural alloys used in packaging components, only the austenitic stainless steels are relatively immune to low-temperature (-40°F) brittle fracture. For other structural metals, the possibility of brittle fracture occurring in a shipping package must be considered. Brittle fracture is caused by the inability of the metal to resist crack propagation by local crack tip plastic action; and therefore, the primary causes of brittle fracture are: (1) the presence of notches or crack-like defects, (2) the local stress state and intensity, (3) loading rate, and (4) temperature. All of these factors are abundantly present in the structural components comprising a shipping package.

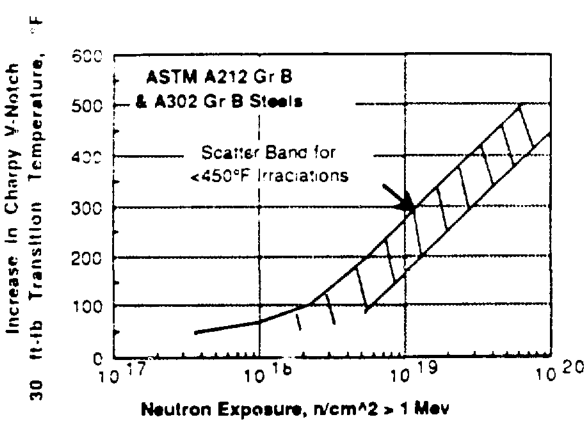

Fig. 5. Effect of irradiation exposure on the Charpy impact energy ductile-brittle transition temperature of ASTM A212 Gr B and A302 Gr B steels (Ref. 8).

The susceptibility of brittle fracture in carbon and low-allow structural steels is dependent on the factors listed above, as well as the following: (1) microstructure, (2) metallurgical condition, (3) tensile strength, (4) strain rate, and (5) section thickness. These steels generally exhibit an abrupt transition from ductile to brittle behavior, and this transition can occur anywhere from -7°C (+20°F) for ASTM A36 steel to -59°C (-75°F) for heat-treated high-strength low-alloy steels[9]. Furthermore, if the steel is used in the wrong metallurgical condition, the transition temperature can exceed 38°C (100°F).

Section size is another criteria factor in the brittle fracture of ferritic steels. It is well known that thin sections are less prone to brittle fracture than thick sections, and this is the basis for the recommendations given in NUREG/CR-1815[10], that for a thickness less than 4.8 mm (0.19-in.), the criteria for meeting toughness requirements are relaxed. Section thickness and minimum design temperature are also the basis for the new toughness rules in Section VIII, Division 1, of the ASME Code[11]. These new rules provide exemptions to impact test requirements for certain steels if the thickness is less than 25 mm (1-in.), and the design loadings and minimum temperture satisfies other requirements.

Impact Properties of Materials. Most materials exhibit loading-rate-dependent strength and deformation properties. For example, the ultimate tensile strength of structural steel can increase by 40% for low strength alloys, and by 10% for high strength alloys when subject to impact loadings[12]. The effect of strain rate on tensile yield strength for structural steels is even greater, and is shown in Fig. 6[13]. To illustrate this effect, a 25 mm thick block of carbon steel dropped from a height of 9 m onto an unyielding surface would experience a strain rate of ~$10s^{-1}$ at impact, and would increase its yield strength by a factor of ~1.5 over the static value.

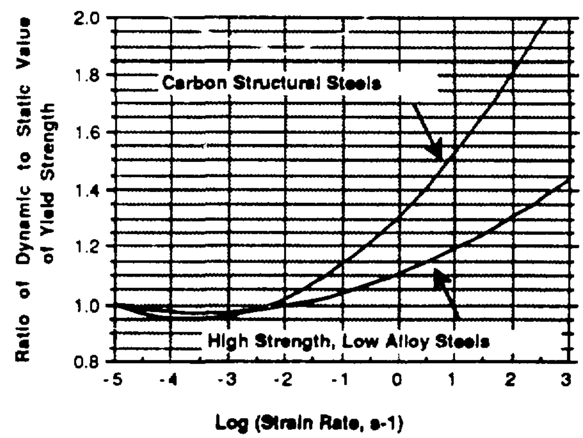

Fig. 6. Effect of strain-rate on the yield strength of typical carbon and low-alloy structural steels (Ref. 13).

Similarly, urethane foam which is often used as cushioning material has a nonlinear, thickness dependent stress-acceleration response that can impose significantly higher loads than anticipated on a component under impact loadings[14]. Impact cushioning aluminum honeycombs can also impose high loads to a component due to increased crush strength and/or a change from a crushing to a dynamic buckling behavior. These examples emphasize the need for the designer to consider the dynamic behavior of the materials used in the packaging construction.

Chemical and Galvanic Reactions. This is an area that is apparently not well understood by the designers of shipping packages because our experience has shown that this topic is rarely considered and usually poorly addressed in SARPs. A typical misuse of incompatible materials occurs when high-strength steel bolts are used in a closure made from austenitic stainless steel, and any moisture can lead to corrosion of the screws. This is amplified by the fact that the cross-sectional area of the screws is generally small compared to the flange and cover, so serious corrosion problems can arise in short order.

Stress-corrosion cracking that results from chloride or other deleterious compounds released from insulating or sealing materials at elevated temperatures is yet another problem that should be (but seldom is) addressed by package designers. This can even affect the behavior of austeni ic stainless steels, particularly if the materia_ has been sensitized by welding prior to exposure.

Interdisciplinary Cooperation. The cooperation and interaction needed between the materials and structures and the thermal, shielding, and criticality evaluations of a SARP are illustrated by the following examples. The first example involved the review of a SARP for a package to transport spent fuel elements whose subcriticality was assured and maintained by a cadmium poison material contained within a thin walled stainless steel magazine. The preliminary analyses demonstrated that the structural, shielding, and criticality aspects of the design were adequate, but the thermal evaluation indicated that temperatures within the magazine are above the melting point of cadmium even during normal conditions of transport. This suggests not only serious implications for criticality; but structurally, the alternate melting and freezing of the cadmium could distort and possibly rupture the supporting magazine structure. Consequently, DOE acted to prevent the further use of the packaging until a resolution could be reached on the uncovered deficiency.

Another example of the interdisciplinary cooperation required for a SARP review is when a package contains lead for the radiation shielding. Since the lead thickness is dictated by the activity of the package contents and it is typically cast within the containment vessel boundary, designers have very little leeway in the physical configuration of the package. Nevertheless, the structural implications of using large quantities of this dense, low modulus material are significant. This is particularly evident for the hypothetical accident condition 9 m drop test which can transmit a considerable amount of impact energy to the lead shielding material. Thus, the structural aspects of this problem are associated with slumping of the lead which can cause high dynamic pressures and large deformations within the container. Similarly, lead slump can result in gaps in the shielding blanket which can in turn cause thermal and shielding deficiencies.

Interaction with DOE. The previous examples are typical problems encountered in a SARP review which can only be resolved by close cooperation among the review team members. Moreover, the ANL team must work closely with DOE, who in turn coordinates the review with the applicant's engineering staff. This process is both formal and informal. The formal communications between ANL and the applicant are in the form of questions submitted to DOE which address the various specific technical issues or omissions in the SARP that arise during the review. These are evaluated by DOE and transmitted to the applicant as questions which must be resolved before the Certificate of Compliance can be issued. The informal discourse between the applicant, ANL, and DOE usually relates to points of clarification or relatively minor technical questions of analysis. At times, the questions and findings of the review team lead to design changes or modifications to specific parts of the packaging. But, since each component is integrally related to the overall function of the shipping package, all changes must be examined for their impact on the total package performance. This further illustrates the need for a coordianted, interdisciplinary, review effort.

After the review and evaluation is complete, the ANL SARP review group provides DOE with a technical review report (TRR) which summarizes their analyses and conclusions as to the integrity of the packaging. Since the ANL SARP review group, DOE, and the applicant have been communicating during the entire review process, the TRR should not contain any surprises as to the applicability or limitations of the shipping packaging. The contents of the TRR are then used by DOE as input to judge the merits of the applicants packaging and either issue a Safety Evaluation Report (SER) and Certificate of Compliance (with or without restrictions), or request the applicant to reevaluate and/or modify his packaging design.

SUMMARY AND CONCLUSIONS

This paper presented an overview and described some of the typical problems that arise in the materials and structures review and evaluation of SARPs submitted to the DOE for issuance of a Certificate of Compliance. It also illustrated the need for interaction and teamwork with the other disciplines that are involves in the review process.

At present, ANL's experience in reviewing SARPs suggests there is a need for an authoritative and recognized document which provides guidance for the applicant's structural design and analysis of these packagings. This document could be authorized by the ASME Code, and should include the topics discussed in the present paper.

ACKNOWLEDGEMENT

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