Puncture Evaluation of Shippingport Package*

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1.0 Introduction

The Shippingport Atomic Power Station in Shippingport, Pennsylvania, is being decommissioned and dismantled by the Department of Energy (DOE) to return the government-leased property in a radiologically safe condition to its owner, the Duquesne Light Company. Most of the radioactive material inside the reactor pressure vessel (RPV) was removed and transported to the DOE Hanford Reservation in Richland, Washington, for burial. The integral reactor pressure vessel and neutron shield tank (NST) was filled with a lightweight concrete to form a transport package.

The package weighs 850 tons and is 17.5 ft in diameter and 43 ft in length. A cross section of the package. Although this package can be classified as a category II package based on its aggregate radioactivity of 16,000 ± 3,000 Ci, it was evaluated to the requirements of title 10 Code of Federal Regulations Part 71 (10 CFR 71). A puncture evaluation is required under Section 71.73 of the Code.

The main concern about puncture of the Shippingport package is the integrity of the RPV. The NST and the concrete between the RPV and NST are considered to be sacrificial material for additional protection of the radioactive material inside the RPV. Hence a finite element analysis using the LLNL computer code DYNA2D (Hallquist 1987) was performed to evaluate the RPV.

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Engineering judgment indicates that it is unlikely that a puncture pin of 6 in. in diameter can puncture a steel shell with a minimum thickness of 6 in. This paper demonstrates that puncture of RPV indeed will not occur. The study used a puncture evaluation method for shipping casks described in a report for the U.S. Nuclear Regulatory Commission (Lo 1989).

2. Assumptions and Method of Analysis

To simplify the problem in analysis, the 6-in.-diameter mild steel puncture pin was assumed to have already punched through the NST and the concrete between the RPV and NST, and to have kept its original configuration intact. This simplification was made because the integrity of the RPV is of main interest and the NST is relatively thin compared to the diameter of the puncture pin and the amount of kinetic energy that is available in the package. Also, the strength of the concrete is much lower than that of the RPV steel vessel. The tangent surface of the RPV shell at the point of contact was also conservatively assumed to be perpendicular to the axis of the puncture pin to avoid any bending moment in the pin.

Because the curvature at any location of the RPV is much larger than the radius of the puncture pin, the effect of shell curvature is expected to be minimum. In this case, the most vulnerable location is where the RPV shell thickness is a minimum. The reactor closure head is extremely thick; there is little likelihood that it can be punched through by a 6-in.-diameter steel pin.

Figure 1 shows a 2-D axisymmetric finite-element analysis model at the start of RPV impact against the puncture pin. The axis of the RPV is vertical and is aligned with the puncture pin. The center of gravity of the package is direcly over the point of contact with the puncture pin. This orientation avoids any RPV rotation and provides maximum energy for puncture. The shell thickness at the point of contact is 6.0 in., the least thickness in the RPV. This is the RPV's most vulnerable orientation for puncture pin impact. Thus, other puncture locations, including puncture on the sidewall of the RPV, are not considered.

The interface friction between the puncture pin and the RPV was modeled in the analysis. The coefficient of friction used was 0.15 (Harris and Crede 1976). Higher coefficients of friction are possible and could have been used in the analysis. However, the use of 0.15 is conservative as will be explained in more detail in Section 3.

The puncture pin is assumed to be over 41 in. long, which is long enough to reach the RPV. However, to reduce the amount of computer running time, the pin was assumed to be rigid except for the top 8 in. This assumption is conservative because less energy is wasted in compressing the pin. The top 8 in. is sufficient to simulate the effects of plastic deformation of the puncture pin on the RPV.

The RPV is assumed to be dropped from a height of 40 in. above the tip of the puncture pin. Thus, the RPV has a velocity of 175.8 in./s at the start of the puncture analysis. With this drop height and package orientation, the lowest point of the RPV is at least 81 in. above the ground, an unusual height for such a large package.

In this puncture analysis, the puncture pin was assumed to have the mechanical properties of ASME SA212 Grade B (same material as the neutron shield tank). This material has yield and tensile strengths of 38 and 70 ksi, respectively, and can be considered a mild steel. The RPV material is ASTM A302 Grade B with yield and tensile strengths of 72 and 93 ksi, respectively. Isotropic elastic-plastic material models are used for the RPV and the puncture pin in the finite element analysis with DYNA2D. These materials were conservatively assumed to have unlimited strain-hardening capability with hardening moduli of 81 and 180 ksi, respectively, for RPV and the puncture pin.

3. Results of Finite Element Analysis

The analysis was carried out for the first 24 ms of impact. Table 1 shows the axial deformation of the puncture pin and the average velocity of the RPV at 12 and 24 ms after impact. There is no need to analyze the problem beyond 24 ms because, by this time, the length of the puncture pin is reduced to less than half of its original length in the nonrigid region of 8 in. even though the RPV still has most of its kinetic energy left.

As the puncture pin undergoes axial plastic deformation at an early stage of contact, the material flows in the radial direction and the diameter of the pin is increased except along the RPV/puncture-pin interface, where friction prevents relative motion between the RPV and the puncture pin. If no friction were modeled, the cross-sectional area would have expanded freely at the interface as in the rest of the pin. At later times, the frictional force is overcome. The contact area is actually reduced, rather than increased, below the original cross-sectional area of the puncture pin. Therefore the use of a small coefficient of friction is conservative because it results in a smaller contact area and higher stresses in both the puncture pin and the RPV shell. The side surface at the top of the puncture pin starts to touch the RPV at 19 ms. This, in effect, increases the interface area after it had initially decreased.

Based on our research work for the U.S. NRC (Lo 1989), a failure prediction method for shipping casks proposed by Larder and Arthur (1978) was used. This method, as applied to the Shippingport package, is as follows:

The RPV shell is considered to be punched through when the transverse shear stress on an imaginary cylindrical surface concentric to the axis of the puncture pin (Fig. 2) exceeds 60% of the material tensile strength throughout the thickness of the RPV except near the shell surfaces.

Transverse shear stress is zero at a free surface. It is a maximum close to the mid-surface of the steel vessel. The transverse shear stress drops sharply near the steel/concrete interface because concrete is a low strength material. The RPV has an engineering tensile strength of 93 ksi. Therefore, for a puncture to occur, the shear stress should exceed 56 ksi (60% of 93 ksi) throughout the thickness except near surfaces. In fact, the true material strength should be used instead of the engineering strength. However, it is conservative to use the engineering strength.

The most critical stress situation occurs at 19 ms after initial contact. Contours of y-z shear stress at this instantaneous time are shown in Fig. 2. Note that the orientation of the y-z shear stress is parallel to the imaginary surface and is perpendicular to the vessel surfaces.

As stated above, the shear stress is very small near the surface of the steel at an interface of concrete and steel. Unless very fine meshes are used close to the interfaces, it is difficult for a plot routine to capture the dramatic change in shear stress close to the surfaces. This difficulty explains why many contours shown in Fig. 2 intersect the surfaces of RPV at a rather high level of shear stress. However, the use of a very fine mesh is not warranted here because no significant improvement in results of the analysis would be realized.

The critical imaginary cylindrical surface is marked with a dashed line. The shear stress on this surface is far below the minimum of 56 ksi required for puncture. The stress in the RPV actually decreases right after 19 ms because of the increase in the interface contact area as a result of the side surface of the puncture pin coming into contact with the vessel.

4. Buckling of Puncture Pin

In the previous section, the puncture evaluation of the Shippingport package is based on stresses generated in the RPV by the puncture pin. Because the puncture pin material was assumed to have unlimited strain-hardening capability, the analysis was carried out far beyond the ultimate tensile strength of the puncture pin material. The average axial compressive stress in the puncture pin reaches the ultimate tensile stress (70 ksi) at around 5 ms. The average axial stress at 19 ms is about twice the ultimate tensile strength, as shown in Fig. 3.

In reality, it is impossible for the real nonrigid puncture pin to maintain its axisymmetric unbuckled position with that much plastic deformation. The puncture pin would have buckled long before reaching that state of deformation, due to possible initial imperfections, such as in the alignment of the contact surfaces, and to the material properties. It is also doubtful if the pin can maintain axisymmetric position even for 5 to 12 ms, which is the time at which the axial deformation of the pin reaches over 15 to 25% of its initial nonrigid length.

According to the tangent modulus theory of inelastic buckling (Johnson 1976), a column buckles close to a load predicted by Euler's elastic buckling formula with Young's modulus replaced by the tangent modulus. Another approach, the reduced modulus approach, predicts only a slightly higher buckling load than the tangent modulus approach.

The tangent modulus of the mild steel and, therefore, the buckling load of the puncture pin become very small when the material is stressed far beyond the yield point. The puncture pin will buckle inelastically. However, it will buckle at a stress significantly lower than the tensile strength. The possibility of reaching the stress state obtained by the finite element analysis at 19 ms without buckling is practically nil.

5. Summary and Discussion

The assessments based on stresses described in Section 3 indicate that the RPV will not be punched through by the 6-in.-diameter puncture pin. The assessments were made for the most critical stress state, which occurs at 19 ms after initial contact, when the length of the puncture pin has already been significantly reduced.

The assessment based on the worst stress state at 19 ms is extremely conservative from the standpoint of inelastic buckling of the puncture pin. The pin will buckle long before the ultimate strength of the puncture pin material can be reached. It certainly will not reach the stress state twice the ultimate strength of material.

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Table 1. Axial deformation of puncture pin and the average velocity of the RPV.

Time (ms)	0	12	24
Axial deformation (in.) (original length = 8 in.)	0.0	2.1	4.1
Average velocity of RPV (in./s)	176	172	157

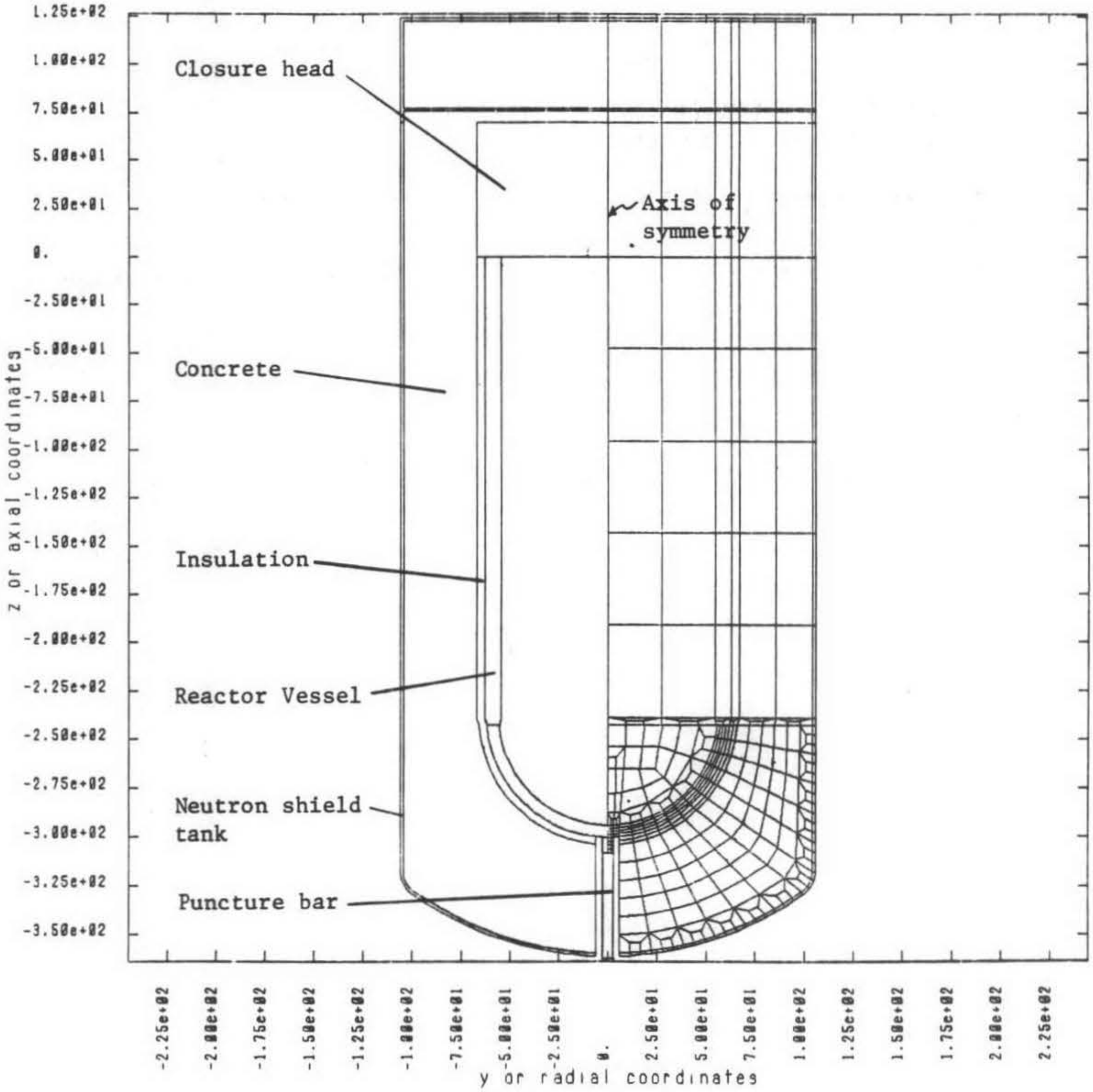

Fig. 1. Axisymmetric finite-element model of Shippingport RPV/NST package for puncture analysis.

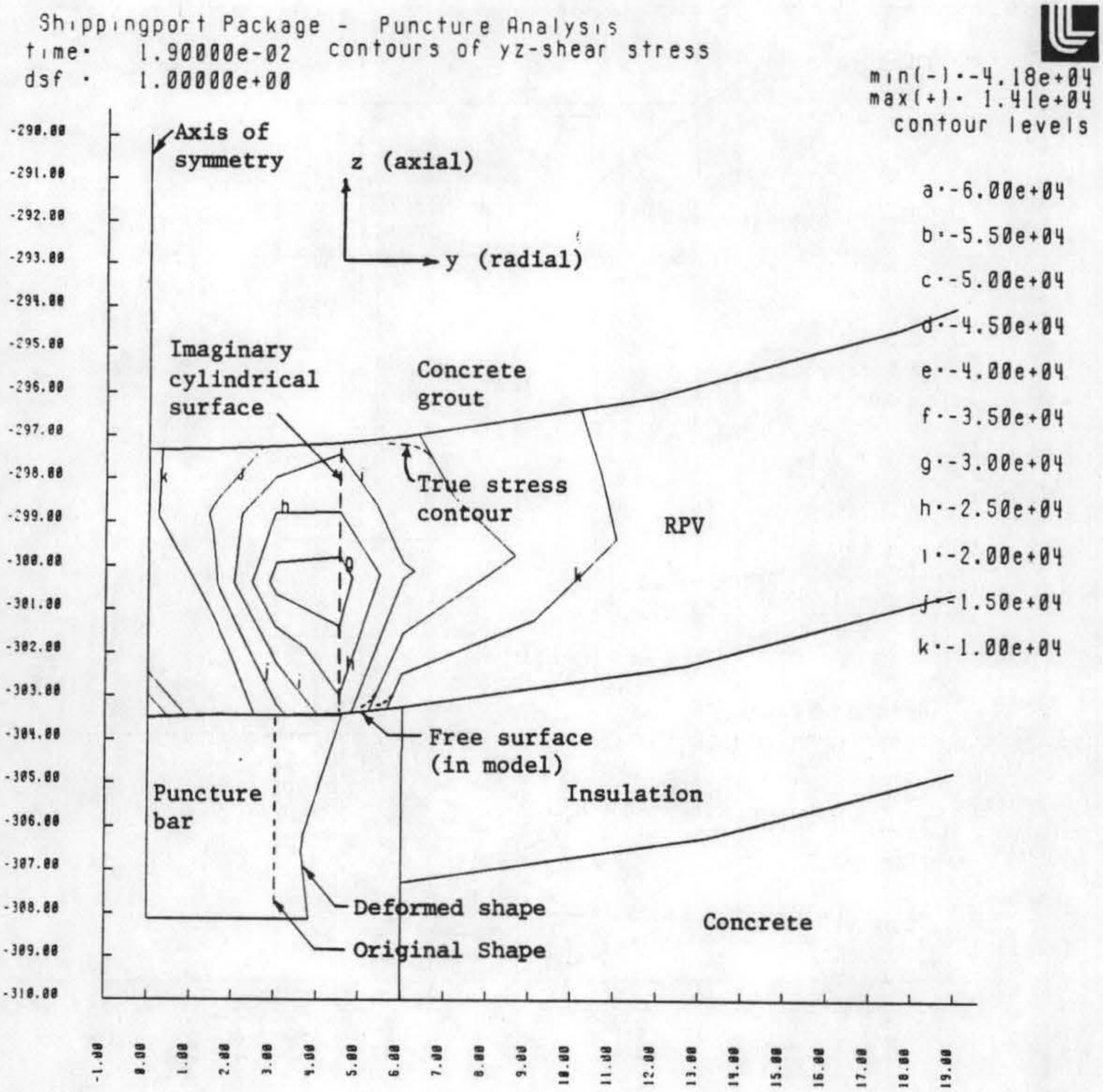

Fig. 2. Contours of y-z shear stress at time of 19 ms. (units are in in., lb, and s).

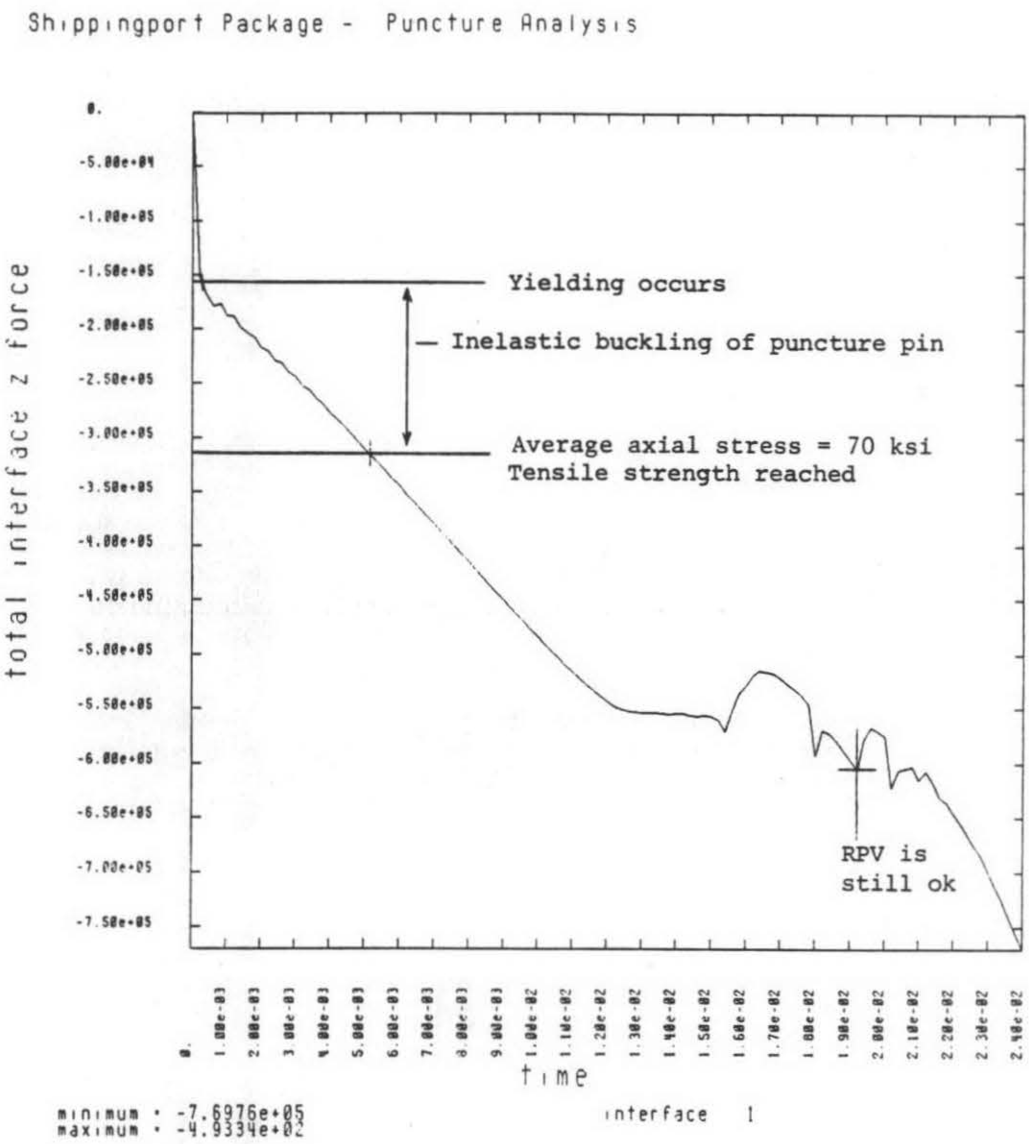

Fig. 3. Interface force between RPV and puncture pin (units are in in., lb, and s).