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7. Abstract The purpose of this document is to remove pump without breaking through the dome.		

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ACRONYMS

BRL	Ballistic Research Laboratory
CEA/EDF	Commissariat a l'Energie Atomique - Electricité de France
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute

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REMOVAL OF MIXING PUMP IN TANK 102-AP

1.0 BACKGROUND

A recent study (Reference 1) showed that dropping of the mixing pump within the tank (102 AP-Tank) during its removal would not cause the tank to leak. However, once the pump clears the tank, roughly six feet more vertical traversal is required to clear the pump pit. The concern is for the damage, primarily to the tank integrity if the mixing pump is dropped during this final removal path (an additional 6-ft, 5-in). The situation is depicted schematically in Figure 1-1.

The specific concern is for damage to the top of the tank and pump pit floor and potential health and safety consequences resulting from this damage.

Figure 1-1. Perspective on Pump Drop in Pump Pit.

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2.0 METHODOLOGY

In lieu of a detailed finite element analysis of the effect, two assessments are made:

- Examination of local damage, that is, potential for perforation of the floor of the pump pit or for perforation of both the pump pit floor and the tank roof, by empirical formulas which characterize impact by missiles (in the same manner as was done in Reference 1 for the tank bottom)
- A bounding assessment on strain energy absorbed in the tank top to determine if the strain energy modeled is sufficient to cause unacceptable structural deformation in the tank (rather than local perforation).

2.1 LOCAL DAMAGE

The major concern for local damage is perforation (making a hole all the way through the barrier). The empirical formulas used for perforation are the Commissariat à l'Energie Atomique - Electricité de France (CEA/EDF) formula named for the abbreviations for French equivalent of our Nuclear Regulatory Commission and the major French Electrical Utility Company, who jointly developed this algorithm. It is recommended by the Electric Power Research Institute (EPRI) (Sliter, G. E.). The other is the Ballistic Research Laboratory (BRL) formula named for the Ballistic Research Laboratory who developed it, and it is recommended by U.S. Department of Energy (DOE) (J. R. McDonald and McDonald, Jr. R.).

Perforation formulas are respectively written as:

$$T = 0.765 \sigma_c^{-0.375} (W/D)^{0.5} V^{0.75}$$

and

$$T = 427 \sigma_c^{-0.05} W D^{-1.8} (V/1000)^{1.33}$$

where

T = barrier thickness in inches;

σ_c = concrete compressive strength in psi;

W = missile weight in pounds;

D = diameter in inches $(2(A/\pi))^{0.5}$ for non-circular missiles where A is cross sectional area of the missile in a direction perpendicular to the velocity vector);

V = incident velocity normal to barrier in fps.

Table 2-1 contains a summary application of these formulas to the concrete floor of the pump pit and a combination of the pump pit floor and the tank concrete roof.

Table 2-1. Perforation Parameters for Pump Pit Floor and for Combination of Floor and Tank Roof.

Prediction	By CEA-EDF Formula	By BRL Formula
Pit Floor Perforation Velocity at Full Missile Impact Area	78 fps	180 fps
Drop Height for Above Velocity	98 ft	450 ft
Missile Impact Area Which allows Perforation at 10-ft Drop Height	22 sq. inches	- - - -
Velocity to Perforate both Pit Bottom and Tank top	170 fps	280 fps
Drop Height for Above Velocity	448 ft	1200 ft
Missile Impact Area Which Allows Perforation of both Pit Bottom and Tank Top	2.3 sq. inches	- - -

* These heights do not account for air resistance, and are underestimated at high velocities.

The results of Table 2-1 are for a rigid missile, the plastic yielding of the pump pedestal is ignored.

Figure 2-1 shows the variation in concrete perforation thickness with impact velocity of the pump for each empirical formula and also indicates the drop height required to achieve such a velocity. A concrete compressive strength of 4200 psi (Reference 5) was used and the pit floor and tank roof thicknesses were obtained from Kaiser Engineering drawings H-2-90477 and H-2-90599.

These results indicate no perforation at all unless the pump hits on the edge of the 42-inch riser, where concrete could be chipped off the edge. An edge hit could achieve a small enough impact area to perforate, according to the above table, for a drop from 10 ft (a drop from a higher elevation is not considered credible). However, the riser, itself, (presumably a steel liner welded to the 1/2-in tank steel liner) should prevent any such fragments from being dislodged. The results in the table and the figure do not consider resistance from the steel liners. Reference 1 showed that the dropping mixing pump was incapable of perforating the liner by itself. Obviously, the results based on these empiricisms indicate more than adequate resistance of the pit bottom and tank top to local damage.

It is necessary to consider the validity of these empirical relations for this type of missile. The BRL formula was originally developed for ordnance predictions then adapted to tornado and turbine missiles. The CEA-EDF formula was developed for predicting nuclear power plant protection against turbine and tornado missiles. Therefore, it is considered more applicable to this case, of a very heavy, slow moving missile. Many turbine and tornado missiles are similar

Figure 2-1. Perforation Vs. Impact Velocity.

Fig. 2 Perforation Vs. Impact Velocity

to the dropping pump. Some turbine missiles exceed 8000 lbs in weight and tornado missiles (automobiles, trucks, trees, I-beams) can be similar in size and weight. However, both turbine and tornado missiles have typically higher velocities than can be attained by the pump in dropping from any reasonably achievable height.

The results of Table 2-1 and Figure 2-1 indicate a significant margin of safety of the facility relative to local perforation, but since they require extrapolation of empirically derived algorithms to regions below the velocities associated with their derivation, a strain energy check is made to verify both that local damage is acceptable and that there is no significant structural displacement of the tank top. The margin predicted by these empirical relations is great enough that it is felt that these predictions in combination with a limit analysis demonstrating adequate strain energy capacity gives a very high confidence that the integrity of the storage tank will not be compromised by dropping the mixing pump in the pump pit.

It is noted that even if there were local damage and structural displacement of the tank top, it is not likely that these would produce a radiological hazard either to the facility workers or to the general public.

2.2 STRAIN ENERGY ANALYSIS

The purpose of the strain energy analysis is to corroborate the conclusions based on the empirical penetration relations that local perforation is impossible and also to check the upper limit of gross deflection of the tank top.

Since 10 ft is considered the maximum credible height above the pit floor that the pump would ever be raised before moving it away from the pit, this height forms the basis of the energy analysis. At this height, the velocity is calculated from the classical conversion of potential energy to kinetic energy:

$$mgh = Mv^2/2$$

which, for the 12000-pump, indicates 1.44E+06 in-lb of kinetic energy and an impact velocity of 25.4 fps. Therefore, it is necessary to allocate the 1.44 million in-lb of kinetic energy to strain energy in pit floor and tank top components.

In the previous case (Reference 1) the pump, itself, was conservatively treated as a rigid body. However, the bottom pedestal of the pump, as shown in the drawing of Reference 7, is actually capable of absorbing significant impact energy, and has a geometry which allows accurate calculation of this effect, so it is considered as part of this analysis.

The limit analysis for strain energy shows that the strain energy imparted locally to the pit floor and to general deflection of the tank roof is adequate to accommodate the kinetic energy of the impacting pump without imparting unacceptable deflection in the roof. The dome stays in the elastic domain during its deflection.

The approach is as follows:

1. The maximum force which can be developed as the impacting pump comes to rest is calculated for both the pump pedestal and the pump body. These are determined by the yield strength in the pump steel or in the pit floor concrete, depending on the cross section of each material which is actually resisting the impact.
2. The force in 1 is transmitted as a central load to the tank roof and the resulting deflection and energy calculated. The real load transmitted would be spread out over some area by being transmitted through the pit floor, but the centralized assumption is a worst-case effect.
3. Local impact energy deposited in the pump itself and in the concrete plus the flexural energy imparted to the roof are adjusted within the constraints of the models used to match the impact kinetic energy of the pump. Results of this allocation are shown in Table 2-2.

The roof of the tank affected by the impact is modelled as a flat roof. The true ellipsoidal top offers more resistance, so this, too, is a conservative element. In order to calculate the flexural energy of the roof, the equivalent solid steel roof which develops the same internal moment for a given rotation of its cross-sectional plane is determined. This is a 5.7-in thick steel roof (of the same properties as the re-bar). Details of the development are in Appendix A.

It should be noted that the worst case for dome deflection is assumed to be an impact of the pump at its full 31-in diameter base. If it were to strike the edge of the 42-in riser, the strain energy required to be absorbed would not change, the chances for additional strain energy being absorbed by the pump would actually increase due to the exposure of more of its frangible components, and the pump itself may deflect and fall into the riser. The energy absorption of the 1/2-in inner liner is ignored because it was shown in Reference 1 to be very small.

Table 2-2. Results of Strain Energy Analysis.

Component	Deflection	Strain Energy	Per Cent
Pump Pedestal	6 inches (plastic)	483,000 in-lb	33.5
Pit Floor	0.56 inches (plastic)	458,000 in-lb	31.8
Tank Dome	1.22 Inches* (elastic)	499,000 in-lb*	34.7

* Note discussion in section 3.

2.3 ADDENDUM, DROPPING PUMP IN PUMP PIT FROM FIFTEEN FEET

The analysis done for the effects on the pump pit of dropping the pump in the 102-AP Tank considered drop from ten feet above the pit floor. This addendum analyses the effects of dropping the pump from fifteen feet.

The preceding analysis was based on empirical missile impact algorithms and on elastic energy analysis. Table 2-1 indicated that the drop height required to achieve the required perforation velocity by empirical analyses was significantly in excess of either ten or fifteen feet, so that part of the analysis is essentially unaffected by the change from ten to fifteen feet drop height.

With respect to Table 2-2, the energy allocation between pump deformation energy, local concrete deformation energy and energy of gross structural deformation of the tank dome depends on assumptions regarding what part of the pump bottom can deform plastically, what the concrete yield strength is and what is the assumed radius of interaction in the dome. The concrete strength is fixed at 4200 psi, the deformation energy in the pump pedestal is fixed by its dimensions at 483,000 inch-lbs and the effective impact area of the pump following pedestal deformation was determined to be 195 square inches. This latter value is an assumed value, but it would require significant conjecture to determine any other value. Therefore, these three parameters are assumed to be fixed. In reality, there would be more deformation energy in the pump proper, but only the pedestal is sufficiently defined for accurate calculation. Ignoring the deformation energy in the remainder of the pump is conservative.

This means that the pump deformation energy will not change from 483,000 inch-lbs value calculated. With a fifteen foot drop, 2.16×10^6 inch-lbs of energy instead of 1.44×10^6 must be dissipated and 1.68×10^6 must be shared between local concrete deformation and gross tank deflection. The one parameter which will be allowed to vary is the range of effect in the tank dome. Table 2-2 was based on a range of 105 inches radius. This is compared in Table 2-3 to what would happen if 130 inches and 155 inches in radial interaction were assumed. The total energy from a fifteen foot drop can be accommodated without excessive deflection in the roof or unrealistic penetration in the concrete. In this case, "non-excessive" roof deflection is less than the equivalent thickness of a steel roof which has the same resistance to internal bending as the real reinforced concrete roof.

The roof deformation is calculated as a point load instead of being spread out in area, as is the real case as the load is transmitted through the pit floor. The roof deflection is uniquely determined by the load on the concrete and the assumed radius of interaction. This, then determines the energy absorption of the roof and the remaining energy can only be accommodated by further local yielding in the concrete. Table 2-3 shows that over a reasonable range of assumptions regarding the radial extent of the roof interaction the total energy from fifteen foot drop can be absorbed in the pump, the local concrete interaction and the roof deflection without unreasonable deflections either in the roof or locally in the concrete.

Table 2-3 Energies and Deflections in Pump Pit and Tank Roof from Pump Drop

Assumptions	Pump		Local Concrete		Tank Roof	
	Defl. (inches)	Energy (inch-lb)	Defl. (inches)	Energy (inch-lb)	Defl. (inches)	Energy (inch-lb)
10-ft Drop, 105-inch roof interaction	6	4.83E05 (34%)	0.56	4.58E05 (32%)	1.22	4.99E05 (34%)
15-ft Drop 105-inch roof intraction	6	4.83E05 (22%)	1.44	1.18E06 (55%)	1.22	4.99E05 (23%)
15-ft Drop, 130-inch roof interaction	6	4.83E05 (22%)	1.12	9.14E05 (42%)	1.87	7.66E05 (35%)
15-ft Drop, 155-inch roof interaction	6	4.83E)% (22%)	0.72	5.9E-05 (27%)	2.66	1.09E06 (50%)

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3.0 SUMMARY OF RESULTS AND CONCLUSIONS

The mixing pump, if dropped in the pump pit following its removal from the tank, is incapable of compromising the tank structure either locally or in a structural displacement mode to an extent which might allow dispersion of the contents. A drop from 10 ft above the pit floor (considered the maximum credible height) of a pump which is considered perfectly rigid does not approach the required perforation velocity. The velocity required to perforate requires a drop height which is physically impossible to attain with existing cranes. An analysis of the location of the deposition of the strain energy required to match the pump's impact kinetic energy, the results of which are shown in Table 2, verifies that there is no credible chance for compromise of the tank roof by such a drop.

In Table 2-2, the pump-pedestal energy calculation is reasonably accurate. The other two represent a balance of the remaining energy required to match the impact kinetic energy. The tank dome flexural energy can be made rather large if desired by assuming a large effective radius of interaction. However, if it were made large enough to make up the difference between the pump pedestal energy and the impact kinetic energy, the total center deflection would still be only 2.34 inches, which, for such a large dome is not considered structurally unacceptable and allows it to remain in the elastic response mode. There are other energy absorption mechanisms not calculated for both the pump and the pit floor, hence the values listed in Table 2-2 are reasonable.

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Appendix A
STRAIN ENERGY CALCULATIONS

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STRAIN ENERGY CALCULATIONS

A1.0 STEEL EQUIVALENT DOME

In order to calculate energy deposited in the dome (roof) of the 102 AP-Tank roof, the equivalent thickness in steel was determined so that plate theory, as based on homogeneous materials, could be applied. This approximation avoids the complexity of a strain energy analysis of the reinforced concrete. The appropriate equivalence is that thickness which develops the same moment for the same ϕ rotation of the cross sectional plane (see Figure A-1). The neutral axis of the reinforced concrete shifts from the vertical geometric center because the contribution to bending moment on the compression side of the centroid is caused both by concrete and by steel compression, while that on the tension side is caused only by steel. For the moment couple each side contributes equally.

The moment contributions from the steel (tension, only) side is:

$$E_s A_s (C-c)^2 \phi$$

where

E_s is the modulus of elasticity of steel;
 C is the distance between rebars;
 c is the distance from the opposite rebar to the neutral axis;
 ϕ is the angle of rotation of the plane of the plate
 A_s is the cross sectional area of steel in the rebar.

The compression side (concrete and steel) is:

$$\phi E_s A_s c^2 + \phi E_c W 2/3 [c+(D-C)/2]^2 / 2$$

where

E_c is the concrete modulus of elasticity;
 c is the distance of the rebar to the neutral axis;
 D is the total depth of the reinforced concrete roof;
 W is horizontal distance between rebars.

The two expressions are equated to permit solution for c . The value for the radial direction is 5.05 in. That for the circumferential direction is 4.5 inches. Use is made of the 5.05-in thickness in this strain energy demonstration.

The steel plate which develops the same moment per unit angle of bend (in the elastic regime), ϕ , is determined by equating the tensile side contribution to the moment couple in each case as follows:

$$\phi E_s 2/3 L^2 W/2 = \phi E_s (C-c)^2 \pi r^2$$

where L is the half thickness of the steel plate, r is the radius of the rebar and W is the horizontal distance between the rebars (10.75 inches). With $C = 12$, $c = 5.05$, $r = 0.4375$, and $W = 10.75$, L is solved for as 2.85 inches, so that the effective plate thickness is 5.7 inches.

Figure A-1. Properties of Dome Roof Section.

FIGURE A-1. PROPERTIES OF DOME ROOF SECTION

A2.0 STRAIN ENERGY AT IMPACT

Reference 7 shows a pedestal on which the mixing pump rests, which is a ring supporting six uprights which extend vertically for approximately 5 inches and attach to the pump body. Figure A-2 is a reproduction of a portion of this drawing. These uprights are slanted inward from the bottom on a ring base at an angle of approximately 30 degrees. Their cross sectional area scales to 1.5 x 1.5 inches. At such an angle, the primary failure of these uprights is by buckling. The maximum buckling moment sustainable in these sections at full yield across the section is (see Figure A-3):

$$2(1.5 \cdot .75^2)(47700)/2 = 40,247 \text{ in-lb}$$

The moment arm for the vertical force sustaining this moment scales to 3 inches, so that each vertical force is 13416 lbs. And the total for the six is 80,494 lbs. A check is made on the compressive force developed in the uprights (at the start of yield) and this is $13,416 \cos(30^\circ)/2.25 = 5163 \text{ psi}$. This is significantly less than yield and, as the uprights buckle, will diminish even further. Since plastic strain energy is generally much greater than elastic strain energy, ignoring this component is justified. The full extent of potential travel for the force producing this buckling is 6 inches, so the strain energy available in the pump pedestal is 482,963 in-lbs, or 33.5 percent of the total $1.44\text{E}+06$ in-lbs available in the impact kinetic energy.

These uprights interact with a ring base which is the contact with the concrete of the pit floor with a contact area of 127 square inches (as scaled and calculated from Reference 7). Compressive stress on the concrete at this point is:

$$482,963/127 = 3798 \text{ psi}$$

which is still in the elastic range and, therefore, not likely to account for a significant amount of strain energy.

Assuming, conservatively, that the 80,494 lb load on the pit floor is transmitted to the tank roof at the rim of the 42-in riser, the predetermined solution for such a loaded flat plate with outer and inner diameters not fixed (an approximation) is from Reference 8 (case 17 of Section 19):

$$w = 0.7 PR^2/(Et^3)$$

when R is 5r, with R the outer radius and r the radius of the central hole in the plate. Using $R = 5r = 105$ inches as the effective radius of the roof plate, the deflection is 0.12 inches and the energy in the tank roof is:

$$Pw/2 = 4829 \text{ inch-lbs,}$$

truly negligible compared to that absorbed by the pump.

Following the collapse of the pump pedestal, the impact area, scaled from Reference 7 is a ring area below the pump impeller at approximately 195 sq inches, which extends for approximately 2.25 inches vertically. This is solid metal, so the concrete yields at this point to give a maximum transmittable force of $195 \times 4200 = 819000 \text{ lbs}$.

Figure A-3. Maximum Moment in Rectangular Beam.

$s = \text{yield stress}$

$$F = s WD/2$$

$$M_{\max} = FD/2$$

Figure A-3. Maximum Moment in Rectangular Beam.

$s = \text{yield stress}$

$$F = s WD/2$$

$$M_{\max} = FD/2$$

Checking for roof deflection with the above relation loaded with 819,000 at the rim of the central hole, it is found to be 1.22 inches (with the above relation from Reference 8), and the associated energy is:

$$Pw/2 = 499,000 \text{ inch-lbs}$$

Total strain energy in the tank roof and the pump pedestal is then 982,000 in-lb. Therefore, an additional 1,440,000 - 982,000 lbs = 458,000 in-lb must be accommodated and this can be achieved with 0.56 inches of local yielding in the concrete. Such a yield is not unreasonable.

As a check on the roof response, a continuous plate, fixed at the ends loaded in the center is modeled (Reference 8, Equation 81) with the central load of 819,000 lbs. In this case the deflection is $PR^2/(16\pi D) = 0.78$ inches and the energy is 318,150 in-lb. The remainder of the strain energy required can still be easily accommodated with local concrete deformation in the pump pit. Neither of these models exactly match the true behavior of the dome, but they do bracket the expected behavior and it is felt that the former case (both ends free) is a better match to the true behavior.

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ENGINEERING DATA TRANSMITTAL

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