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(A) Item No.	(B) Document/Drawing No.	(C) Sheet No.	(D) Rev. No.	(E) Title or Description of Data Transmitted	Approval Designator	Reason for Transmittal	Originator Disposition	Receiver Disposition
1	WHC-SD-WM-TI-782		0	LOAD DROP EVALUATION FOR TWRS FSAR	N/A KN	1	1	

16. KEY					
Approval Designator (F)		Reason for Transmittal (G)		Disposition (H) & (I)	
F, S, Q, D or N/A (see WHC-CM-3-5, Sec.12.7)		1. Approval 2. Release 3. Information		4. Review 5. Post-Review 6. Dist. (Receipt Acknow. Required)	
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(G)		(H)		17								(G)		(H)	
SIGNATURE/DISTRIBUTION															
(See Approval Designator for required signatures)															
Reason	Disp.	(I) Name (K) Signature (L) Date (M) MSIN				(I) Name (K) Signature (L) Date (M) MSIN				Reason	Disp.				
1		CogEng	LJ Julyk	9/27/96	R1-56	HH Ziada	Hisa H. Ziada	9-27-96	R1-56	1					
3		CogMgr	SH Rifaay		R1-56	GL Ralston	GL Ralston	9/27/96	H5-68	1					
		QA													
		Safety													
		Env.													

18. GL Ralston <i>[Signature]</i> 9/27/96 Signature of EDT Originator	19. GL Ralston <i>[Signature]</i> 9/27/96 Authorized Representative for Receiving Organization	20. SH Ziada <i>[Signature]</i> 9/27/96 Cognizant Manager	21. DOE APPROVAL (if required) Ctrl. No. ☐ Approved ☐ Approved w/comments ☐ Disapproved w/comments
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LOAD DROP EVALUATION FOR TWRS FSAR

5

L.J. Julyk/G.L. Ralston

Westinghouse Hanford Company, Richland, WA 99352
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 CONCRETE, PENETRATION

Abstract: Operational or remediation activities associated with existing underground high-level waste storage tank structures at the Hanford Site often require the installation/removal of various equipment items. To gain tank access for installation or removal of this equipment, large concrete cover blocks must be removed and reinstalled in existing concrete pits above the tanks. An accidental drop of the equipment or cover blocks while being moved over the tanks that results in the release of contaminants to the air poses a potential risk to onsite workers or to the offsite public. To minimize this potential risk, the use of critical lift hoisting and rigging procedures and restrictions on lift height are being considered during development of the new tank farm Basis for Interim Operation and Final Safety Analysis Report. The analysis contained herein provides information for selecting the appropriate lift height restrictions for these activities.

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Allen J. Roland 9/30/96
 Release Approval Date
 Release Stamp

Approved for Public Release

LOAD DROP EVALUATION FOR TWRS FSAR

September 25, 1996

Prepared
by

L. J. Julyk
ICF Kaiser Hanford Company

and

G. L. Ralston
Westinghouse Hanford Company

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LOAD DROP EVALUATION FOR TWRS FSAR

Prepared by: 9/27/96
L. J. Julyk, TWRS Design Authority Date

9/27/96
G. L. Ralston, Principal Engineer Date

Reviewed by: 9-27-96
H. H. Ziada, TWRS Design Authority Date

CHECKLIST FOR INDEPENDENT REVIEW

<u>Yes</u>	<u>No</u>	<u>N/A</u>	
☒	☐	☐	Problem completely defined.
☒	☐	☐	Necessary assumptions explicitly stated and supported.
☐	☐	☒	Computer codes and data files documented.
☒	☐	☐	Data used in calculations explicitly stated in document.
☒	☐	☐	Data checked for consistency with original source information as applicable.
☒	☐	☐	Mathematical derivations checked including dimensional consistency of results.
☒	☐	☐	Models appropriate and used within range of validity or use outside range of established validity justified.
☒	☐	☐	Hand calculations checked for errors.
☐	☐	☒	Code run streams correct and consistent with analysis documentation.
☐	☐	☒	Code output consistent with input and with results reported in analysis documentation.
☒	☐	☐	Acceptability limits on analytical results applicable and supported. Limits checked against sources.
☒	☐	☐	Safety margins consistent with good engineering practices.
☒	☐	☐	Conclusions consistent with analytical results and applicable limits.
☒	☐	☐	Results and conclusions address all points required in the problem statement.

Haider H. Ziada
 Reviewer: HH Ziada

9-27-96
 Date

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LOAD DROP EVALUATION FOR TWRS FSAR

INTRODUCTION

Operational or remediation activities associated with existing underground high-level waste storage tank structures at the Hanford Site often require the installation/removal of various equipment items. To gain tank access for installation or removal of this equipment, large concrete cover blocks must be removed and reinstalled in existing concrete pits above the tanks. An accidental drop of the equipment or cover blocks while being moved over the tanks that results in the release of contaminants to the air poses a potential risk to onsite workers or to the offsite public. To minimize this potential risk, the use of critical lift hoisting and rigging procedures and restrictions on lift height are being considered during development of the new tank farm Basis for Interim Operation and Final Safety Analysis Report. The analysis contained herein provides information for selecting the appropriate lift height restrictions for these activities.

OBJECTIVE

The objective of this analysis is to provide guidance in determining appropriate allowable lift heights for equipment or cover blocks used in the operation or remediation of existing underground high-level waste storage tank structures at the Hanford Site.

SCOPE

This analysis is applicable to equipment or cover block lifts over single-shell tanks (SSTs), double-shell tanks (DSTs), and double-contained receiver tanks (DCRTs), which could lead to impacts onto concrete riser pit floors or the soil cover in the event of an accidental load drop.

Only the local effects of the impacting projectile on the concrete target or soil are addressed. Impact loads onto concrete pits or the soil surface above the tank affect the global response of the tank dome. Potential failure modes associated with the global response of the target structure are not considered. For impact loads on the soil surface the main consideration is the global response of the structure.

RECOMMENDATIONS

In general, the lift height for any load should be minimized and kept as low as possible, consistent with the task at hand. The results presented here suggest that a general maximum lift height restriction of 6 m (20 ft) be imposed for all tank farm lift activities. This is to be measured from the lower boundary of the lifted item to either the pit floor surface or the soil surface, as applicable. This recommended lift height restriction includes an additional safety margin to account for as-built variations and other unknowns and envelopes all the equipment listed in Table 1.

This lift height restriction was developed on the basis of:

- ▶ Preventing local concrete perforation through the pit floor and dome for a drop within a pit, or
- ▶ Preventing full penetration of soil overburden for a drop onto the soil above the dome.

For the large SST and DST dome structures, the resulting short-duration impact loads considered here are not expected to cause a global-response induced dome failure. However, consideration should be given to verifying that a failure of this type is precluded with respect to the proposed lift height restriction.

More restrictive requirements on lift heights may be necessary for lifts over risers. By inspection, risers offer less resistance to impact loads and engineered safeguards may be required to protect risers from damage in the event of an accidental load drop.

ANALYSIS APPROACH

Empirically derived penetration correlations for compact cylindrical steel projectiles impacting soil or concrete targets are used in this analysis. The modified National Defense Research Council (NDRC) formula given in ASCE 1980 are used in this investigation for concrete targets, and Young's (1969) soil penetration correlation is used for drops onto the soil. The NDRC formula were modified to account for the difference in elastic modulus between steel and concrete in the case where a concrete cover block is dropped onto a concrete target (Adeli and Amin 1985). In addition, the NDRC formula can be extrapolated for lower velocities. A summary discussion of the analytical methods and equations used for this task can be found in Appendix A.

For situations involving a drop onto a concrete target, two different failure criteria were evaluated: scabbing and complete penetration (perforation). Scabbing, the generation of secondary missiles in the form of concrete fragments ejected from

the back face of an impacted concrete wall or roof structure, is usually the failure mode of interest in the design or evaluation of reinforced concrete structures. However, for this study failure due to perforation is of more interest since this provides a potential release path for airborne contamination.

It should be noted that the correlations used for concrete targets were developed for undeformable projectiles impacting massive concrete structures with a projectile velocity range of 30 to 915 m/s (100 to 3,000 ft/s). For large mixer pumps, drop height estimates associated with pit floor and tank dome perforation have corresponding velocities much less than 30 m/s (100 ft/s). However, the NDRC formula can predict reasonable results in this lower velocity domain.

It is also worth noting that the correlations used were developed for concrete targets exhibiting a high degree of stiffness relative to the large SST and DST dome or DCRT roof structures evaluated here. This is conservative because the tank roof structures can be expected to dissipate a significant amount of the impact energy.

In addition, estimates indicating the "missile crush load" has been exceeded for the various equipment items typically occur at lift heights well under those predicted for complete target penetration. The empirical equations used to predict the local effects of the projectile impacting a concrete target are based on tests using compact non-deformable projectiles. Hence, if the missile crush load is exceeded, then additional conservatism is added to the perforation and scabbing criteria.

Allowable lift heights over the soil are evaluated against full penetration of an assumed soil cover depth of 1.5 m (5 ft).

EQUIPMENT AND FACILITY CONFIGURATION

Table 1 lists supporting and reference information associated with the various equipment items and cover block/pit configurations. Items representative of existing and future tank farm equipment were selected for evaluation. Most of the equipment items reviewed range in weight from several hundred to several thousand pounds, with a limited number of large, special purpose mixer pumps approaching 13,610 kg (30,000 lbs). Cover blocks typically range between 4,535 to 9,070 kg (10,000 to 20,000 lbs), but can be as high as about 13,610 kg (30,000 lbs). Where drawings or other information did not explicitly call out weight information, estimates were made using engineering judgement and simple calculations of major components to arrive at approximate values.

Much of the equipment used in the underground tanks is designed to be inserted through a tank riser and reach down near or into the waste. Therefore, the equipment tends to be long relative to its cross section, often approaching or exceeding 15 m (50 ft) in length. Since the empirical correlations used in this

study assume a cylindrical solid projectile, an estimate of "equivalent diameter" must be made for the various equipment profiles. This was done considering the end geometry of the item in question, with estimates made of the net impact area. This process formed the basis for the assigned equivalent diameter.

Pit depth typically ranges from about 1.5 to 3 m (5 to 10 ft) over the large underground tanks, usually closer to 3 m (10 ft). DCRT pit structures reviewed had greater depths, ranging from about 3.5 to 5 m (11 to 16 ft).

Pit floor concrete thickness was found to be about 30 cm (1 ft) for DCRTs and typically in excess of 38 cm (15 in.) for pits over SSTs/DSTs. Several exceptions to this were discovered for TX Farm, and for a drain pit in SY Farm, neither of which are considered significant. This is because the TX drawing reviewed indicates several feet of soil are between the pit floor and dome. Drawing H-2-40397 for T, B, C, and BX Farms also shows a layer of soil between the pit floors and tank domes.

MATERIAL PROPERTIES

The material of the projectile (missile) is assumed to be mild steel for equipment drops and 20 MPa (3,000 lb/in²) concrete for cover block drops. In the evaluations for specific equipment or cover block drops the compressive strength of the concrete target is assumed to be 20 MPa (3,000 lb/in²). This is the minimum specified design strength for the concrete tank structures. Some tanks have design strengths of 28, 31, and 35 MPa (4,000, 4,500, and 5,000 lb/in²). The effect of this variation in strength is addressed in Appendix C.

RESULTS

Table 2 provides a summary listing of allowable drop heights for the typical tank farm equipment and cover blocks identified in Table 1. Note that the allowable drop heights in this table are associated with local perforation/scabbing criteria and do not address potential global-response induced failures. In particular, the large allowable drop heights listed here could potentially lead to dome failure. Global-response induced failure for the SST/DST dome is not expected if the drop height is restricted to 6 m (20 ft).

The allowable drop height for the original 101SY mixer pump is the most restrictive of the various equipment items considered and is estimated to be 7.6 m (25 ft) to prevent perforation of 76 cm (30 in.) of concrete. The concrete thickness of 76 cm (30 in.) is divided between the tank dome (38 cm [15 in.]) and the pit floor (38 cm [15 in.]). The actual floor thickness indicated by construction drawings for DST central pump pits is slightly more than 38 cm (15 in.). Past analyses performed for the 101SY mixer pump installation (LANL 1995) used 46 cm (18 in.)

for the central pump pit floor. If this is carried through in the present analysis, a maximum drop height of 9.8 m (32 ft) is predicted. However, to account for as-built uncertainties a pit floor thickness of 38 cm (15 in.) has been conservatively assumed in this report, and is applied to all drop scenarios within SST or DST pits.

For DCRTs, a height restriction of 12 m (40 ft) is predicted on the basis of a large cover block drop. This number is based on an assumed 10% end strike by the cover block, i.e., 10% of the end surface area is used as the equivalent diameter. This is a reasonable approach to account for an "off-square" impact, since a direct hit on the cover block edge would fail the edge, exposing a greater surface to the impact load.

Drops of equipment or cover blocks over the soil were not found to be controlling, but would affect the global response of the structure. In this case lift heights over the soil are restricted to drop heights that would not result in full penetration of an assumed soil cover depth of 1.5 m (5 ft). Although the minimum soil cover for shielding purposes is 1.5 m (5 ft), typical soil depths in the tank farms range from 2 to 3 m (7 to 10 ft) over the dome apex.

Drops of cover blocks over concrete pits were not found to be controlling for local perforation type failure, but could lead to global response type failure if drop heights based on perforation were adopted.

Appendix A provides the detailed analysis supporting the results presented in Table 2. Appendices B and C present results of drop height sensitivity to various parameters including projectile weight, equivalent frontal impact diameter of the projectile, and compressive strength of concrete.

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Table 1. Tank Farm Equipment Subject to Lifting for Installation/Maintenance

Application(Reference)	Item (Ref/other info)	Weight (lb)	Pit Depth (ft)	Notes
DOUBLE SHELL				
	Mixer Pmp (Original SY101)	25,000		► Weight/end geometry assumptions taken from LANL Calc Note (LANL 1995); weight includes lifting hardware/rigging.
	Mixer Pmp (VI 22515, SD-WM-TI-709)	27,000 ¹		► Weight includes about 500 gal water, motor(5000 lb), and upper turntable bearing and pump mount hardware (which will be on pump for installation); does not include allowance for lifting hardware/rigging. End Geometry: 36 in. OD SST Impeller/nozzle housing with about 20 in. ID inlet; filter screen extends below inlet about 6 in. (dwg D51356 and D51357).
	New Transfer Pump-submersible (No VI #: Vendor Rpt EM6673)	4,000 ²		► End Geometry: Suction Adapter is SST casting about 11 in. OD x 2 in. ID inlet; 4 fins extend slightly below the main body (dwg 4D97585). This pump is being considered for sluicing applications.
	"Turbine" Transfer Pump (shaft drive) (H2-91943, -79228)	<2,500		► End Geometry: Approx 6 in. suction bowl connected to approx 6 in. pipe, maximum length about 50 ft.
	Camera Sys (VI 22680 - typ. all Farms)	1,300		► End Geometry: Similar to a horizontal cylinder about 1 ft long x 6 in. diameter (O & M Manual, Dwg 59-1).
	MITs	<1,500		► Engineering judgement (no dwg review)
	Sluicing Equip ► Distributor Pipe (H2-818537)	2,000		► End Geometry: see dwg. Assumes Adapter Flange and Distributor Head would be installed/removed as a unit.
	► Booster Pump (H2-818503, 508; vendor dwg D55641)	3,250		► End Geometry: see dwg. Pump/motor are one unit; includes alignment fixtures for remote installation.
	► Transfer Pump-submersible (H2-818494; vendor dwg D55687)	5,500		► End Geometry: Pump/motor are one unit, 18 in. dia x approx 64 in. long (pump is held by winch cable and attached to rigid pipe via flex hose). Weight includes winch assembly with base plate, flex hose and fittings, and pump/motor unit.
AZ101, 102 ► Central Pump Pit (H2-68304, -67245)	Cover Blocks (2.5x4x8.8)ft Cover Blocks (2x5x7.3)ft	13,200 ³	~10	► Pit floor ⁴ : Includes 42-in. riser; min floor thickness ~ 1.3 ft poured on top of dome, 3000 psi (H2-68304) ⁵ ; area 8x12 ft.
► Sluice Pit (H2-68305)		11,000	~9.5	► Pit floor: Includes 42-in. riser; floor thickness ~ 1.3 to 3.3 ft wall to wall, poured on top of dome, 3000 psi (H2-68304); area 6.5x8 ft.

Table 1. Tank Farm Equipment Subject to Lifting for Installation/Maintenance
(Cont'd)

Application(Reference)	Item (Ref/other info)	Weight (lb)	Pit Depth (ft)	Notes
AY101...102 ► Central Pump Pit (H2-64313, -64310) ► Suction Pit (H2-64314)	Cover Blocks (2.5x4.7x8.9)ft Cover Blocks (2x5.1x6.9)ft	15,600 10,600	~7.9 ~9	► Pit floor: Includes 42-in. riser; min floor thickness ~ 1.3 ft poured on top of dome, 3000 psi (H2-64322); area 8x12 ft. ► Pit floor: Includes 34-in. riser; floor thickness ~ 1.3 to 3.3 ft wall to wall, poured on top of dome, 3000 psi (H2-64322); area 6x8 ft.
AN101...107 Central Pump Pit (H2-71912)	Cover Blocks (1.7x5.8x9)ft	13,300	~6	► Pit floor: includes 42-, 12-, 4-in. risers; min floor thickness ~ 1.3 ft poured on top of dome, 3000 psi (H2-71916); area 8x14 ft.
AP101...108 ► Central Pump Pit (H2-90447) ► Mixer Pump Pit (H2-77445)	Cover Blocks (2x5.7)ft Cover Blocks (“future” per dwg) (1.5x5)ft	18,000 11,300		► Pit floor: includes 42-, 12-, 4-in. risers; min floor thickness ~ 1.3 ft poured on top of dome, 4000 psi (H2-90446); area 8x14 ft. ► Pit floor: Includes 42-in. riser; floor thickness not verified (dwg is not correct - realistically it would range from about 1 to 3 ft wall to wall), poured on top of dome, 4000 psi (H2-27445); area 8x8 ft.
AW101...106 Central Pump Pit (H2-70312)	Cover Blocks (1.7x5.7)ft	9,800 (per dwg)		► Pit floor: assume 3000 psi (cover block may not fit into pit if dropped on end).
	Cover Blocks (1.7x5.7)ft	12,900		► Pit floor: includes 42-, 12-, 4-in. risers; min floor thickness ~ 1.3 ft poured on top of dome, 3000 psi (H2-70317); area 8x14 ft.
SY101...103 ► Central Pump Pit (H2-37711) ► Drain Pit (H2-37713)	Cover Blocks (1.7x5.7)ft Cover Blocks	13,300 12,500	8.8	► Pit floor: includes 42-, 12-, 4-in. risers; min floor thickness ~ 1.3 ft poured on top of dome, 3000 psi (H2-37713); area 8x14 ft. ► Pit floor: includes 4-in. riser; min floor thickness ~ 1”, NOT clear if poured on top of dome, 3000 psi (H2-37713); area 6x6 ft (cover block may not fit into pit if dropped on end).

Table 1. Tank Farm Equipment Subject to Lifting for Installation/Maintenance
(Cont'd)

Application(Reference)	Item (Ref/other info)	Weight (lb)	Pit Depth (ft)	Notes
SINGLE SHELL				
	Camera Sys (VI 22680 - typ. all Farms)	1,300		► End Geometry: Similar to a horizontal cylinder about 1 ft long x 6 in. diameter (O & M Manual, Dwg 59-1).
	New Transfer Pump-submersible (No VI #; Vendor Rpt EM6673)	4,000		► End Geometry: Suction Adapter is SST casting about 11 in. OD x 2 in. ID inlet; 4 fms extend slightly below the main body (dwg 4D97685). This pump is being considered for sluicing applications.
	Sluicing Equip ► Booster Pump (H2-818503, 508; vendor dwg D55641)	3,250		► End Geometry: see dwg. Pump/motor are one unit; includes alignment fixtures for remote installation.
	► Transfer Pump-submersible (H2-818494; vendor dwg D55687)	5,500		► End Geometry: Pump/motor are one unit. 18in dia x approx 64in long pump is held by winch cable and attached to rigid pipe via flex hose). Weight includes winch assembly with base plate, flex hose and fittings, and pump/motor unit.
	► Sluicer (H2-818549, 551)	1,700		► End Geometry: Nozzle/pipeline components ranging from about 2 to 6 in. dia.
	Saltwell Equip ► Casing (solid & perforated) (H2-73990, -68553, -68555)	1,500 ^a		► End Geometry: Capped 10 in. pipe, max length about 50 ft (lower 20 ft is special perforated section)
	► Pump Assy	1,250 ^a		► End Geometry: Multiple pipes (1/2", 1", 1.25 in., some coupled together at bottom for suction inlet - see dwg)
A101...106 Central Pump Pit (H2-55919)	Cover Blocks (2.5x3.7ft)	16,600		► Pit floor: includes 42 in. riser; min floor thickness ~ 1.3 ft poured on top of dome, hi-density (3000 psi assumed - HWS-5614 not oked); area 11x12 ft (only 1 lift ball on cover block).
TY101, 102 ► Central Pump Pit (H2-2293, -2294) ► Sluice Pit (H2-2293, -2295)	Cover Blocks Cover Blocks	(dwg illegible) 10,350	<8 <10	► Pit floor: includes 42", 12", 4-in. risers; min floor thickness ~ 1.3 ft poured on top of dome, 3000 psi (assumed); area 8'x14'. ► Pit floor: Includes 42-in. riser; floor thickness ~ 1.3 to 4.5 ft wall to wall, poured on top of dome, assume 3000 psi; area 9x11 ft.

Table 1. Tank Farm Equipment Subject to Lifting for Installation/Maintenance
(Cont'd)

Application(Reference)	Item (Ref/other info)	Weight (lb)	Pit Depth (ft)	Notes
AX101...104 ► Central Pump Pit (H2-63826, -44561) ► Side Pump Pit (H2-63825) ► Sluice Pit	Cover Blocks (4 lifting balls)	15,900	<10	► Pit floor: includes two 12-in. risers; min floor thickness ~ 1.7 ft poured on top of dome, 3000 psi (H2-44561); area 6x7.5 ft.
	Cover Blocks	10,600	9.2	► Pit floor: Includes ~42-in. riser; floor thickness ~3 to 4 ft wall to wall, poured on top of dome, assumed 3000 psi (HWS-9089 not ckd); area 6x8 ft.
	Cover Blocks	9.2	9.2	► Pit floor: floor thickness ~3 to 4 ft wall to wall, poured on top of dome, assumed 3000 psi (HWS-9089 not ckd); area 6x8 ft.
	Cover Blocks	9.2	9.2	► Pit floor: floor thickness ~3 to 4 ft wall to wall, poured on top of dome, assumed 3000 psi (HWS-9089 not ckd); area 6x8 ft.
TX101...118 ► Central Pump Pit (H2-33452) ► Side "Slurry" Pump Pit (H2- 36636) ► Side "Heat Exchanger" Pit (H2-36637)	Cover Plates		<4.5	► Pit floor: Includes 12-, 4-in. risers; floor thickness ~0.7 ft assumed poured on soil (dwg unclear - believe to be 2.3 ft of soil under concrete floor), 3000 psi (assumed); area 4.5x7 ft.
	Cover Blocks	10,700	<9.5	► Pit floor: Includes 42-in. riser; floor thickness ~0.7 ft assumed poured on soil (dwg unclear); 3000 psi (H2-36638); area 8x14.8 ft.
	-Cover Plate -Heat Exchanger (H2-36616)	7,000 (w/H ₂ O)	<8.5	► Pit floor: Includes 42-in. riser; floor thickness ~0.7 ft assumed poured on soil (dwg unclear); 3000 psi (H2-36638); area ~7x12 ft.
	Cover Blocks	31,200 (per dwg)	~8	► Pit floor: Includes ~42-, 12-, 4-in. riser; floor thickness ~1.5 ft poured on soil (dwg unclear); 3000 psi (H2-41345); area 11x14.5 ft.
C106 ► O6A Pump Pit (H2-818448, 41343) ► O6C Sluice Pit (H2-818450)	Cover Blocks (2.5x5.7x12.7/ft (+ lip extension))			

Table 1. Tank Farm Equipment Subject to Lifting for Installation/Maintenance
(Cont'd)

Application(Reference)	Item (Ref/other info)	Weight (lb)	Pit Depth (ft)	Notes
DCRT				
	"Turbine" Transfer Pump (shaft drive) (H2-38232, 93156, 69898)	<1,000		► End Geometry: Approx 4-in. suction bowl connected to 4-in. sch 40 pipe column, max length about 25 ft.
	Submersible Transfer Pump (H2-38232, 93156, 69898)	<1,000		► End Geometry: Approx 6-in. dia closed end pump/motor unit connected to 2.5-in. sch 40 pipe column, max length about 25 ft.
	Cover Blocks (2x4.6x20ft)	26,900		► Floor thickness 12-in. concrete plus corrugated steel sheet and wide flange beams for support structure.

Exclusions: Heating coils (approx weight 9200 lb, reference H2-38620) are excluded because installed units are not typically removed.

ENDNOTES:

1. Weight is based on AZ101 design; for comparison, first SY101 pump was several thousand lbs less.
2. "Next Generation" submersible, available in FY97; for comparison, current turbine (shaft drive) transfer pumps for DST est at <2,500 lbs (H2-79228)
3. Weight based on largest cover block (per set) using 150 lbs/ft²; no credit taken for taper/step or penetrations (typical all cover block data unless noted otherwise).
4. Pit floor thickness estimate scaled from dwg (typical unless noted otherwise).
5. Reference Dwg for concrete strength (typical thru out).
6. Weight data from LANL Calc Note TSA10-CN-WF-SA-ST-088.

VI = Vendor information

lb = 0.454 kg, ft = 0.305 m, in. = 2.54 cm, psi = 6,895 Pa

Where drawings or other information did not provide weight values, simple calculations and engineering judgement were used to arrive at approximate values.

Table 2. Tank Farm Drop Analysis Summary - Equipment or Cover Block Drop within Tank Riser Pit of SST or DST or on Roof Slab of DCRTs.

Item	Missile Projectile		Maximum Drop Height (ft) ¹				Reference Analysis Page A
			15-in. Thick Concrete Target (Pit Floor)		30-in. Thick Concrete Target (Pit Floor + Dome)		
	Weight (lb)	Equiv. ² Dia. (in)	Perforation ³	Scabbing ⁴	Perforation ³	Scabbing ⁴	
DST and/or SST							
Water Lance	200	1.2	183	144	466	398	6
Camera System	1,300	9.6	73	10	502	80	10
Sluicing Equip - Distributor Pipe	2,000	4.5	37	6	309	186	15
Saltwell Equip - Saltwell Casing Screen	1,500	10.8	67	9	428	65	20
"New" Transfer Pump (minimum 12-in. riser)	4,000	10.8	23	3	144	22	25
Original 101SY Mixer Pump	25,000	6.8	3	<1	25	8	30
101AZ Mixer Pump	27,000	29.9	6	<1	30	4	35
Cover Block - AP Pump Pit ⁵	18,000	46	125	45	>300	>300	40
Cover Block - C106 Pump Pit ⁵	31,200	51	65	30	>300	200	45
DCRT			12-in. Thick Concrete Target (Roof Slab)				50
Turbine Transfer Pump	1,000	2	43	23			
Submersible Transfer Pump	1,000	6	43	6			
Cover Block ⁵	27,000	41	40	16			

Notes:

The results given in this table only address potential local failures (perforation, punching shear, and scabbing) of the concrete target; the global response of the target structure and associated potential failure modes are not addressed. Shaded cell indicates controlling acceptance criteria.

¹Drop heights less than 155 ft require an extrapolation of the modified National Defense Research Council (NDRC) empirical formulas for missile projectiles impacting concrete targets.

²Effective or equivalent diameter of missile projectile on contact with target.

³Maximum drop height to prevent perforation (full penetration) or punching shear failure of concrete target -- greater drop heights will result in perforation or punching shear failure of concrete target.

⁴Maximum drop height to prevent scabbing of concrete target -- greater drop heights will result in scabbing failure of concrete target. Results are conservative for double-shell tanks (DSTs) because inner primary steel tank is attached to concrete dome which would reduce or prevent scabbing of back face of concrete dome target.

⁵Allowable lift heights reported for cover blocks are based on an edge strike of 10% of the block end surface area.

lb = 0.454 kg, ft = 0.305 m, in. = 2.54 cm

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APPENDIX A

DETAILED DROP ANALYSIS FOR TANK FARM SPECIFIC EQUIPMENT AND COVER BLOCKS

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ICF Kaiser Hanford

EVALUATION ANALYSIS

Calc. No. _____

Revision: _____

Page No. A-1 of A-59Client: Westinghouse Hanford Company

WO/Job No. _____

Subject: Tank Farm Drop Load EvaluationDate: Sept 14, 1996By: L. J. JurekChecked: 9-24-96By: H. H. ZickLocation: 200 Area - Hanford Site

Revised: _____

By: _____

PROBLEM STATEMENT

Determine allowable drop height for equipment (i.e., pumps, cover blocks, etc.) that could potentially be dropped onto existing underground waste storage tank structures so as not to cause a potential air born radiological and toxicological release to the environment.

SCOPE

Consider all heavy equipment or cover blocks that could potentially be dropped onto soil above the tanks or within riser pits of all underground waste storage tanks (i.e., 100 and 200 series single-shell tanks, double-shell tanks, DCRTs, etc.) located in the 200 Area of the Hanford Site.

APPROACH

Apply empirically derived penetration correlations for steel projectiles impacting soil or concrete targets to determine allowable maximum drop height of equipment without causing local perforation (full penetration) of tank structures. The methods given in Kennedy 1976, ASCE 1980, and Kulianoff and Drake 1991 are applied.

Only local effects are considered herein.

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LOCAL MISSILE IMPACT EFFECTS ANALYSIS FORMULAS

Perforation or scabbing from missile impacts are considered unacceptable local effects for safety-related structures serving as containments for nuclear waste material. The prediction of perforation or scabbing of concrete structures is typically estimated from empirically derived formulas. According to Section C.7 of Commentary on Appendix C — Special Provisions for Impulsive and Impactive Effects of ACI 349 (ACI 1992):

"A large number of empirical formulas exist for predicting the required concrete thicknesses to prevent perforation or scabbing. None of these formulas have yet been sufficiently verified or accepted to enable the Code committee to specify a single formula and require its usage. ... The Modified National Defense Research Council formulas, the Bechtel formulas, and the Stone and Webster formulas appear to be in reasonable agreement with the available published pertinent test data for perforation and scabbing thicknesses. Any of these formulas are tentatively recommended for usage for relatively **nondeformable** missiles. Other previously used formulas such as the Modified Petry, and the Modified Ballistic Research Laboratory Formulas ... are not recommended for usage."

"For highly **deformable** missiles, usage of nondeformable missile impact formulas for calculating the required perforation or scabbing thicknesses may result in excessive conservatism..."

Kennedy (1976) strongly recommends that the modified National Defense Research Council (NDRC) formula be used to predict the required perforation and/or scabbing thicknesses in the case of nondeformable missiles and massive concrete barrier walls. The formula agree with test results generally within +/- 20% over the entire range of missile diameters (up to 16 in.), calibre densities (0.2-6.0 lb/in³), and missile velocities (100-3000 ft/sec). In addition, the formula has the added advantage of being based on an approximate theory of penetration rather than being a purely empirical relation, thus giving greater confidence in the extrapolation of its results.

For the prediction of depth of penetration of a projectile into soil the empirical relation developed by Young (1969) appears to provide reasonable results.

The distinction between nondeformable and deformable missiles is important. Missile penetration formulas are dependent on the relative hardness of the missile and target. A missile or projectile is considered hard relative to a concrete target (i.e., missile penetrates target) if the average crushing or buckling strength of the projectile, σ_p , is greater than the average contact stress, σ_t , required to cause local crushing and penetration of the target. For reinforced concrete targets, σ_t is set equal to the bearing stress given in ACI 349, Section 10.15 ($\phi = 1$) increased by the dynamic increase factor (DIF) given in Appendix C, Section C.2 of ACI 349 as a function of strain rate but not to exceed 1.25. This results in a σ_t slightly greater than $2 f'_c$ per Kulianoff and Drake (1991) where f'_c is the specified ultimate compressive strength of the concrete.

Determination of the penetration of the projectile into the concrete using modified NDRC formula (see ASCE 1980, Section 6.4.1, Equation 6.33)

$$g = 32.174 \frac{\text{ft}}{\text{sec}^2} \quad \text{acceleration due to gravity} \quad E_m = 29 \cdot 10^6 \frac{\text{lb}}{\text{in}^2} \quad \text{reference modulus of elasticity for mild steel missile}$$

$$V(h) = \sqrt{2 \cdot g \cdot h} \quad \text{initial impact velocity (ft/sec) of projectile dropped from height, h, above target}$$

$$K_{cp}(f_c, E) = \frac{180}{\sqrt{f_c}} \cdot \sqrt[1.25]{\frac{1}{\text{lb}} \left(\frac{E}{E_m} \right)} \quad \text{modified concrete penetrability factor by Kar (Adeli and Amin 1985)}$$

$$x_1(f_c, W, d, h, N_p, E) = \sqrt[4]{4 \cdot K_{cp}(f_c, E) \cdot N_p \cdot W \cdot d \cdot \left(\frac{V(h)}{1000 \frac{\text{ft}}{\text{sec}} \cdot \frac{d}{\text{in}}} \right)^{1.80}} \quad \text{for } x/d < 2.0$$

$$x_2(f_c, W, d, h, N_p, E) = K_{cp}(f_c, E) \cdot N_p \cdot W \cdot \left(\frac{V(h)}{1000 \frac{\text{ft}}{\text{sec}} \cdot \frac{d}{\text{in}}} \right)^{1.80} + d \quad \text{for } x/d > 2.0$$

$$x(f_c, W, d, h, N_p, E) = \text{if} \left(\frac{x_1(f_c, W, d, h, N_p, E)}{d} \leq 2, x_1(f_c, W, d, h, N_p, E), x_2(f_c, W, d, h, N_p, E) \right)$$

where

x = Total penetration depth (in), i.e., the depth which a projectile will penetrate into an infinitely thick target. As defined herein, the penetration depth neglects all rear boundary effects and is applicable only when the target thickness is sufficiently great to prevent rear face scabbing.

h = Initial drop height (ft) of projectile above target

N_p = Nose-shape factor for projectile
 = 0.72 for flat nosed projectile
 = 0.84 for blunt nosed projectile
 = 1.0 for average bullet nosed (spherical end) projectile
 = 1.14 for very sharp nosed projectile

W = Weight of projectile (lbf)

A_p = Frontal (projected) area of projectile (in²)

$V(h)$ = Projectile initial impact velocity (ft/s)

f_c = Ultimate compressive strength (lbf/in²) of concrete target

$$d = d_c(A_p) = \sqrt{\frac{4 A_p}{p}} = \text{Effective missile diameter (in.)}$$

E = Modulus of elasticity of missile material

Perforation Thickness for Soft Missiles Impact

Soft missiles will not cause local penetration with the exception of possible punching shear. However, punching shear can be prevented by requiring that the concrete thickness is at least 1.2 times that required at perforation as obtained for hard missile impact. The minimum concrete target thickness for perforation is

$$e_1(f_c, W, d, h, N_p, E) = d \left(1.32 + 1.24 \frac{x(f_c, W, d, h, N_p, E)}{d} \right) \quad \text{for } 1.35 < x/d < 13.5$$

$$e_2(f_c, W, d, h, N_p, E) = d \left[3.19 \frac{x(f_c, W, d, h, N_p, E)}{d} - 0.718 \left(\frac{x(f_c, W, d, h, N_p, E)}{d} \right)^2 \right] \quad \text{for } x/d < 1.35$$

$$e(f_c, W, d, h, N_p, E) = \text{if} \left(\frac{x(f_c, W, d, h, N_p, E)}{d} \leq 1.35, e_2(f_c, W, d, h, N_p, E), e_1(f_c, W, d, h, N_p, E) \right)$$

The minimum concrete target thickness to prevent perforation or punching shear failure for soft missile impact is

$$t_e(f_c, W, d, h, N_p, E) = 1.2 \cdot e(f_c, W, d, h, N_p, E)$$

For Hard Missile Impact

$$t_d(f_c, W, d, h, N_p, E) = \frac{2 \cdot x(f_c, W, d, h, N_p, E)}{V(h)} \quad \text{duration of impact}$$

$$F_A(f_c, W, d, h, N_p, E) = \frac{W}{g \cdot t_d(f_c, W, d, h, N_p, E)} \quad \text{average constant impact force}$$

Scabbing Thickness for Hard Missile Impact

The concrete thickness required to resist hard missile impact should be at least 1.2 times the scabbing thickness. The minimum concrete target thickness for scabbing with Kar correction neglecting aggregate size effect (Adeli and Amin 1985) is

$$s_1(f_c, W, d, h, N_p, E) := d \left(2.12 + 1.36 \frac{x(f_c, W, d, h, N_p, E)}{d} \right) \left(\frac{E}{E_m} \right)^{0.2} \quad \text{for } 0.65 < x/d < 11.75$$

$$s_2(f_c, W, d, h, N_p, E) := d \left[7.91 \frac{x(f_c, W, d, h, N_p, E)}{d} - 5.06 \left(\frac{x(f_c, W, d, h, N_p, E)}{d} \right)^2 \right] \left(\frac{E}{E_m} \right)^{0.2} \quad \text{for } x/d < 0.65$$

$$s(f_c, W, d, h, N_p, E) := \text{if} \left(\frac{x(f_c, W, d, h, N_p, E)}{d} \leq 0.65, s_2(f_c, W, d, h, N_p, E), s_1(f_c, W, d, h, N_p, E) \right)$$

The minimum concrete target thickness to prevent scabbing failure for hard missile impact is

$$t_s(f_c, W, d, h, N_p, E) := 1.2 \cdot s(f_c, W, d, h, N_p, E)$$

See Appendix B and C for parametric behavior of NDRC equations.

Young's Equation for Depth of Soil Penetration by Impacting Projectile

The penetration of a missile into soil is estimated from empirical equation given by Young (1969) as

$$x_{s1}(W, A_p, h, S, N_p) := 0.53 \cdot S \cdot N_p \cdot \sqrt{\frac{W}{A_p} \frac{\text{in}^2}{\text{lb} \cdot \text{ft}}} \cdot \ln \left[1 + 2 \cdot 10^{-5} \cdot \left[\frac{V(h)}{\left(\frac{\text{ft}}{\text{sec}} \right)} \right]^2 \right] \cdot \text{ft} \quad \text{for } V < 200 \text{ ft/sec}$$

$$x_{s2}(W, A_p, h, S, N_p) := 0.0031 \cdot S \cdot N_p \cdot \sqrt{\frac{W}{A_p} \frac{\text{in}^2}{\text{lb} \cdot \text{ft}}} \cdot \left[\left[\frac{V(h)}{\left(\frac{\text{ft}}{\text{sec}} \right)} \right] - 100 \right] \cdot \text{ft} \quad \text{for } V > 200 \text{ ft/sec}$$

$$x_{\text{soil}}(W, A_p, h, S, N_p) := \text{if} \left(V(h) < 200 \frac{\text{ft}}{\text{sec}}, x_{s1}(W, A_p, h, S, N_p), x_{s2}(W, A_p, h, S, N_p) \right)$$

where

x_{soil} = Penetration depth (ft) into soil

h = Initial drop height (ft) of projectile above target

N_p = Nose-shape factor for projectile

= 0.72 for flat nosed projectile

= 0.84 for blunt nosed projectile

= 1.0 for average bullet nosed (spherical end) projectile

= 1.14 for very sharp nosed projectile

W = Weight of projectile (lb_f)

A_p = Frontal (projected) area of projectile (in²)

$V(h)$ = Projectile initial impact velocity (ft/s)

S = Soil coefficient, range for Hanford soil conditions is estimated at 4 to 6 on basis of data given in Young.

See page B-33 of Appendix B for parametric behavior of Young's equations.

Limiting Potential Energy for Dropped Missile

$$PE(W, h_{\max_allowable}) := W h_{\max_allowable}$$

where

W = Weight of projectile (lbf)

$h_{\max_allowable}$ = Maximum allowable drop height

Crushing Strength of Slender Missile

Yield load of impacting missile

$$P_y(S_y, A) := S_y \cdot A$$

where

S_y = Yield strength of projectile (lbf/in²)

A = Cross-sectional area (in²) of projectile.

Cross-sectional properties of pipe section

$$A_{\text{pipe}}(d, t) := \frac{\pi}{4} [d^2 - (d - 2t)^2]$$

$$I_{\text{pipe}}(d, t) := \frac{\pi}{64} [d^4 - (d - 2t)^4]$$

Elastic buckling load of impacting slender missile (Timoshenko and Gere 1961, Johnston 1976)

$$P_{\text{buckling}}(K_{bc}, E, I, L) := \frac{\pi^2 \cdot E \cdot I}{(K_{bc} \cdot L)^2}$$

where

E = Elastic modulus (lbf/in²) of projectile

I = Cross-sectional area moment of inertia (in⁴)

L = Length of projectile (in.)

K_{bc} = Boundary condition coefficient

	K_{bc}	
	Theoretical	Recommended
Fix-Fix	0.5	0.65
Fix-Pin	0.7	0.8
Fix-Guided	1.0	1.2
Pin-Pin	1.0	1.0
Fix-Free	2.0	2.1
Pin-Guided	2.0	2.0

Guided => fixed against rotation, free to translate

Crushing strength, P_c , is estimated by means of Rankine's equation (Bignon and Riera 1980)

$$P_c(P_{\text{buckling}}, P_y) := \frac{P_{\text{buckling}} \cdot P_y}{P_{\text{buckling}} + P_y}$$

$$\sigma_p(P_c, A) := \frac{P_c}{A}$$

Classification of impact type (Kuilanoff and Drake 1991)

$\sigma_p > \sigma_t = 2 f'_c$ => hard missile impact

$\sigma_p < \sigma_t = 2 f'_c$ => soft missile impact

Modulus and yield strength of steel projectile (neglect dynamic strength increase effect)

$$E_s := 29 \cdot 10^6 \frac{\text{lbf}}{\text{in}^2}$$

$$S_{y304L} := 36 \cdot 10^3 \frac{\text{lbf}}{\text{in}^2}$$

$$S_{y304L} := 25 \cdot 10^3 \frac{\text{lbf}}{\text{in}^2}$$

Modulus and ultimate compressive strength of concrete (neglect dynamic strength increase effect)

$$f'_c := 3000 \frac{\text{lbf}}{\text{in}^2}$$

$$E_c := 57000 \sqrt{f'_c} \frac{\text{lbf}}{\text{in}^2}$$

$$E_c := 3.122 \cdot 10^6 \frac{\text{lbf}}{\text{in}^2}$$

$$\sigma_t = 2 f'_c$$

$$\sigma_t = 6000 \frac{\text{lbf}}{\text{in}^2}$$

Velocity of propagation of stress wave in impacting missile

$$c_o(E, \rho) := \sqrt{\frac{E}{\rho}}$$

where E , ρ are the elastic modulus and mass density of the impacting missile, respectively.

ALLOWABLE DROP HEIGHT EVALUATION FOR SELECTED EQUIPMENT DROPS**Water Lance Drop - SST and DST**

$$W_{\text{water_lance}} := 200 \cdot \text{lbf} \quad L_{\text{water_lance}} := 50 \cdot \text{ft}$$

$$d_{\text{water_lance}} := 2.375 \cdot \text{in} \quad \text{2-in. Schedule-40 carbon-steel pipe}$$

$$t_{\text{water_lance}} := 0.154 \cdot \text{in}$$

$$A_{\text{water_lance}} := A_{\text{pipe}}(d_{\text{water_lance}}, t_{\text{water_lance}})$$

$$d_{e_water_lance} := d_e(A_{\text{water_lance}})$$

$$I_{\text{water_lance}} := I_{\text{pipe}}(d_{\text{water_lance}}, t_{\text{water_lance}})$$

$$\gamma_{\text{water_lance}} := \frac{W_{\text{water_lance}}}{A_{\text{water_lance}} \cdot L_{\text{water_lance}}}$$

Specific weight

$$\rho_{\text{water_lance}} := \frac{\gamma_{\text{water_lance}}}{g}$$

Density

$$c_{o_water_lance} := c_o(E_s, \rho_{\text{water_lance}})$$

Velocity of stress wave
in impacting missile

$$P_{y_water_lance} := P_y(S_y, A_{\text{water_lance}})$$

Frontal (projected) area of projectile

$$A_{\text{water_lance}} = 1.075 \cdot \text{in}^2$$

Effective missile diameter

$$d_{e_water_lance} = 1.17 \cdot \text{in}$$

$$I_{\text{water_lance}} = 0.666 \cdot \text{in}^4$$

$$\gamma_{\text{water_lance}} = 0.31 \cdot \frac{\text{lbf}}{\text{in}^3}$$

$$\rho_{\text{water_lance}} = 8.035 \cdot 10^{-4} \cdot \frac{\text{lbf} \cdot \text{sec}^2}{\text{in}^4}$$

$$c_{o_water_lance} = 1.583 \cdot 10^4 \cdot \frac{\text{ft}}{\text{sec}}$$

$$P_{y_water_lance} = 3.868 \cdot 10^4 \cdot \text{lbf}$$

$$K_{bc} = 1$$

Buckling/Crush Load Evaluation for Missile

$$P_{b_water_lance} := P_{\text{buckling}}(K_{bc}, E_s, I_{\text{water_lance}}, L_{\text{water_lance}})$$

$$P_{b_water_lance} = 529.303 \cdot \text{lbf}$$

$$P_{c_water_lance} := P_c(P_{b_water_lance}, P_{y_water_lance})$$

$$P_{c_water_lance} = 522.158 \cdot \text{lbf}$$

$$\sigma_{p_water_lance} := \sigma_p(P_{c_water_lance}, A_{\text{water_lance}})$$

$$\sigma_{p_water_lance} = 486 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$\sigma_t = 6000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

Type of impact (hard/soft) predicted

$$\sigma_{p_water_lance} < \sigma_t \Rightarrow \text{soft impact}$$

For drop in tank concrete pit

thickness of concrete target = thickness of pit floor + thickness of dome

$$t_{\text{pit_floor}} = 15 \cdot \text{in} \quad t_{\text{tank_dome}} = 15 \cdot \text{in} \quad t_c := t_{\text{pit_floor}} + t_{\text{tank_dome}} \quad t_c = 30 \cdot \text{in}$$

$$N_p = 0.84 \quad \text{assume blunt nose projectile}$$

Penetration of missile to missile effective diameter ratio (x/d)

$$x_d(h) := \frac{x(f_c, W_{\text{water_lance}}, d_{e_water_lance}, h, N_p, E_s)}{d_{e_water_lance}}$$

Water Lance Drop - SST and DST

$$W_{\text{water_lance}} = 200 \cdot \text{lb} \cdot \text{f}$$

Drop in Concrete Pit of Tank

$$d_{\text{e_water_lance}} = 1.17 \cdot \text{in}$$

$$N_p = 0.84$$

$$f_c = 3000 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2}$$

Maximum drop height to preclude perforation or punching shear failure of concrete target (for soft missile impact).

$$t_{\text{e_water_lance}}(h) = t_{\text{e}}(f_c, W_{\text{water_lance}}, d_{\text{e_water_lance}}, h, N_p, E_s)$$

For Pit + Dome concrete thickness $h_{\text{e_water_lance}} = \text{root}(t_c - t_{\text{e_water_lance}}(h), h)$ $h_{\text{e_water_lance}} = 466 \cdot \text{ft}$
 $t_c = 30 \cdot \text{in}$ $x/d = x_d(h_{\text{e_water_lance}}) = 16.2$

Corresponding initial impact velocity.

$$V(h_{\text{e_water_lance}}) = 173 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{water_lance}}, h_{\text{e_water_lance}}) = 9.315 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

For Pit only

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$h_{\text{e_water_lance}} = \text{root}(t_{\text{pit_floor}} - t_{\text{e_water_lance}}(h), h)$ $h_{\text{e_water_lance}} = 183 \cdot \text{ft}$
 $x/d = x_d(h_{\text{e_water_lance}}) = 7.5$

$$V(h_{\text{e_water_lance}}) = 109 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{water_lance}}, h_{\text{e_water_lance}}) = 3.662 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

Maximum drop height to preclude scabbing of concrete target (for hard missile impact).

$$t_{\text{s_water_lance}}(h) = t_{\text{s}}(f_c, W_{\text{water_lance}}, d_{\text{e_water_lance}}, h, N_p, E_s)$$

For Pit + Dome concrete thickness $h_{\text{s_water_lance}} = \text{root}(t_c - t_{\text{s_water_lance}}(h), h)$ $h_{\text{s_water_lance}} = 398 \cdot \text{ft}$
 $t_c = 30 \cdot \text{in}$ $x/d = x_d(h_{\text{s_water_lance}}) = 14.2$

Corresponding initial impact velocity.

$$V(h_{\text{s_water_lance}}) = 160 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{water_lance}}, h_{\text{s_water_lance}}) = 7.958 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

For Pit only

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$h_{\text{s_water_lance}} = \text{root}(t_{\text{pit_floor}} - t_{\text{s_water_lance}}(h), h)$ $h_{\text{s_water_lance}} = 144 \cdot \text{ft}$
 $x/d = x_d(h_{\text{s_water_lance}}) = 6.3$

$$V(h_{\text{s_water_lance}}) = 96 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{water_lance}}, h_{\text{s_water_lance}}) = 2.889 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

Water Lance Drop in Concrete Pit of Tank Perforation/Scabbing of Concrete Target

$$h = 0.1 \cdot \text{ft}, 2 \cdot \text{ft}, 500 \cdot \text{ft}$$

Water Lance Drop - SST and DST

Penetration into Concrete Pit of Tank for Hard Missile Impact

$$x_{\text{water_lance}}(h) := x(f_c, W_{\text{water_lance}}, d_{\text{e_water_lance}}, h, N_p, E_s)$$

Penetration

$$t_{d_water_lance}(h) := t_d(f_c, W_{\text{water_lance}}, d_{\text{e_water_lance}}, h, N_p, E_s)$$

Duration of impact

$$F_{A_water_lance}(h) := F_A(f_c, W_{\text{water_lance}}, d_{\text{e_water_lance}}, h, N_p, E_s)$$

Average constant impact force

$$h = .5 \cdot \text{ft} \quad h_{c_water_lance} := \text{root}(P_{c_water_lance} - F_{A_water_lance}(|h|), h)$$

Missile crush load drop height

$$h_{c_water_lance} = 0.273 \cdot \text{in}$$

$$h = 0.01 \cdot \text{ft}, 2 \cdot \text{ft}..20 \cdot \text{ft}$$

Penetration

Duration of impact

Average Constant Impact Force

Missile crush load
 $P_{c_water_lance} = 522 \cdot \text{lbf}$

Water Lance Drop - SST and DST

Drop on Soil above Tank

$t_{\text{soil}} := 5 \cdot \text{ft}$ minimum soil cover depth

$S := 5$ approximate soil factor for dry sandy soil conditions at Hanford

$W_{\text{water_lance}} = 200 \cdot \text{lb} \cdot \text{f}$

$A_{\text{water_lance}} = 1.075 \cdot \text{in}^2$

$N_p = 0.84$

Maximum drop height to just perforate minimum soil cover.

$$x_{\text{soil_water_lance}}(h, S) := x_{\text{soil}}(W_{\text{water_lance}}, A_{\text{water_lance}}, h, S, N_p)$$

$$h_{\text{soil_water_lance}} := \text{root}(t_{\text{soil}} - x_{\text{soil_water_lance}}(h, S), h) \quad h_{\text{soil_water_lance}} = 139 \cdot \text{ft}$$

Corresponding initial impact velocity.

Corresponding initial potential energy of missile.

$$V(h_{\text{soil_water_lance}}) = 94.595 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{water_lance}}, h_{\text{soil_water_lance}}) = 2.781 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

**Water Lance Drop on Soil above Tank
Penetration into Soil**

$h = 0.1 \cdot \text{ft}, 2 \cdot \text{ft} \dots 200 \cdot \text{ft}$

Camera System Drop - SST and DDT

$$W_{\text{camera}} := 1300 \cdot \text{lb} \cdot \text{f}$$

$$L_{\text{camera}} := 18 \cdot \text{ft}$$

$$d_{\text{camera}} := 1.660 \cdot \text{in}$$

**4 1-1/4-in. Schedule-40 304L
pipe with reinforcing cross braces**

$$t_{\text{camera}} := 0.140 \cdot \text{in}$$

$$A_{\text{camera}} = A_{\text{pipe}}(d_{\text{camera}}, t_{\text{camera}})$$

$$A_{\text{camera}} = 0.669 \cdot \text{in}^2$$

$$d_{\text{p_camera}} = 12 \cdot \text{in}$$

contacting impact end - 1 ft long horizontal 6-in. dia. cylinder

$$t_{\text{p_camera}} = 6 \cdot \text{in}$$

$$A_{\text{p_camera}} = d_{\text{p_camera}} \cdot t_{\text{p_camera}}$$

Frontal (projected) area of projectile

$$A_{\text{p_camera}} = 72 \cdot \text{in}^2$$

$$d_{\text{e_camera}} = d_{\text{e}}(A_{\text{p_camera}})$$

Effective missile diameter

$$d_{\text{e_camera}} = 9.575 \cdot \text{in}$$

$$I_{\text{camera}} = 2 \cdot \left[I_{\text{pipe}}(d_{\text{camera}}, t_{\text{camera}}) + A_{\text{camera}} \cdot (6 \cdot \text{in})^2 \right]$$

$$I_{\text{camera}} = 48.524 \cdot \text{in}^4$$

$$\gamma_{\text{camera}} = \frac{W_{\text{camera}}}{4 \cdot A_{\text{camera}} \cdot L_{\text{camera}}}$$

Specific weight

$$\gamma_{\text{camera}} = 2.251 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^3}$$

$$\rho_{\text{camera}} = \frac{\gamma_{\text{camera}}}{g}$$

Density

$$\rho_{\text{camera}} = 0.006 \cdot \frac{\text{lb} \cdot \text{f} \cdot \text{sec}^2}{\text{in}^4}$$

$$c_{\text{o_camera}} = c_{\text{o}}(E_{\text{s}}, \rho_{\text{camera}})$$

**Velocity of stress wave
in impacting missile**

$$c_{\text{o_camera}} = 5.878 \cdot 10^3 \cdot \frac{\text{ft}}{\text{sec}}$$

$$P_{\text{y_camera}} = P_{\text{y}}(S_{\text{y304L}}, 4 \cdot A_{\text{camera}})$$

$$P_{\text{y_camera}} = 6.685 \cdot 10^4 \cdot \text{lb} \cdot \text{f}$$

$$K_{\text{bc}} = 1$$

Buckling/Crush Load Evaluation for Missile

$$P_{\text{b_camera}} = P_{\text{buckling}}(K_{\text{bc}}, E_{\text{s}}, I_{\text{camera}}, L_{\text{camera}})$$

$$P_{\text{b_camera}} = 2.977 \cdot 10^5 \cdot \text{lb} \cdot \text{f}$$

$$P_{\text{c_camera}} = P_{\text{c}}(P_{\text{b_camera}}, P_{\text{y_camera}})$$

$$P_{\text{c_camera}} = 5.459 \cdot 10^4 \cdot \text{lb} \cdot \text{f}$$

$$\sigma_{\text{p_camera}} = \sigma_{\text{p}}(P_{\text{c_camera}}, A_{\text{camera}})$$

$$\sigma_{\text{p_camera}} = 81660 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2}$$

$$f_{\text{c}} = 3000 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2}$$

$$\sigma_{\text{t}} = 6000 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2}$$

Type of impact (hard/soft) predicted

$$\sigma_{\text{p_camera}} > \sigma_{\text{t}} \Rightarrow \text{hard impact}$$

For drop in tank concrete pit

thickness of concrete target = thickness of pit floor + thickness of dome

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$$t_{\text{tank_dome}} = 15 \cdot \text{in}$$

$$t_{\text{c}} := t_{\text{pit_floor}} + t_{\text{tank_dome}}$$

$$t_{\text{c}} = 30 \cdot \text{in}$$

$$N_{\text{p}} = 0.84 \quad \text{assume blunt nose projectile}$$

Petration of missile to missile effective diameter ratio (x/d)

$$x_{\text{d}}(h) = \frac{x(f_{\text{c}}, W_{\text{camera}}, d_{\text{e_camera}}, h, N_{\text{p}}, E_{\text{s}})}{d_{\text{e_camera}}}$$

Camera System Drop - SST and DDT Drop in Concrete Pit of Tank

$$W_{\text{camera}} = 1300 \cdot \text{lb} \quad d_{\text{e_camera}} = 9.575 \cdot \text{in} \quad N_p = 0.84$$

$$f_c = 3000 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

Maximum drop height to preclude perforation or punching shear failure of concrete target (for soft missile impact).

$$t_{\text{e_camera}}(h) := t_c(f_c, W_{\text{camera}}, d_{\text{e_camera}}, h, N_p, E_s)$$

For Pit + Dome concrete thickness $h_{\text{e_camera}} := \text{root}(t_c - t_{\text{e_camera}}(h), h)$

$$h_{\text{e_camera}} = 502 \cdot \text{ft}$$

$$t_c = 30 \cdot \text{in}$$

$$x/d = x_d(h_{\text{e_camera}}) = 1.08$$

Corresponding initial impact velocity.

Corresponding initial potential energy of missile.

$$V(h_{\text{e_camera}}) = 180 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{camera}}, h_{\text{e_camera}}) = 6.529 \cdot 10^5 \cdot \text{ft} \cdot \text{lb} \cdot \text{ft}$$

For Pit only

$$h_{\text{e_camera}} := \text{root}(t_{\text{pit_floor}} - t_{\text{e_camera}}(h), h)$$

$$h_{\text{e_camera}} = 73 \cdot \text{ft}$$

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$$x/d = x_d(h_{\text{e_camera}}) = 0.46$$

$$V(h_{\text{e_camera}}) = 69 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{camera}}, h_{\text{e_camera}}) = 9.533 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{ft}$$

Maximum drop height to preclude scabbing of concrete target (for hard missile impact).

$$t_{\text{s_camera}}(h) := t_s(f_c, W_{\text{camera}}, d_{\text{e_camera}}, h, N_p, E_s)$$

For Pit + Dome concrete thickness $h_{\text{s_camera}} := \text{root}(t_c - t_{\text{s_camera}}(h), h)$

$$h_{\text{s_camera}} = 80 \cdot \text{ft}$$

$$x/d = x_d(h_{\text{s_camera}}) = 0.47$$

Corresponding initial impact velocity.

Corresponding initial potential energy of missile.

$$V(h_{\text{s_camera}}) = 72 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{camera}}, h_{\text{s_camera}}) = 1.037 \cdot 10^5 \cdot \text{ft} \cdot \text{lb} \cdot \text{ft}$$

For Pit only

$$h_{\text{s_camera}} := \text{root}(t_{\text{pit_floor}} - t_{\text{s_camera}}(h), h)$$

$$h_{\text{s_camera}} = 10 \cdot \text{ft}$$

$$x/d = x_d(h_{\text{s_camera}}) = 0.19$$

$$V(h_{\text{s_camera}}) = 26 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{camera}}, h_{\text{s_camera}}) = 1.329 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{ft}$$

$$h := 0.1 \cdot \text{ft}, 2 \cdot \text{ft} \dots 500 \cdot \text{ft}$$

**Camera System Drop in Concrete Pit of Tank
Perforation/Scabbing of Concrete Target**

Camera System Drop - SST and DDT

Camera System Drop in Concrete Pit of Tank Perforation/Scabbing of Concrete Target

 $h = 0.02\text{ ft}, 1\text{ ft}.. 80\text{ ft}$

Camera System Drop - SST and DDT

Penetration into Concrete Pit of Tank for Hard Missile Impact

$$x_{\text{camera}}(h) := x(f_c, W_{\text{camera}}, d_{\text{e_camera}}, h, N_p, E_s)$$

$$t_{d_camera}(h) := t_d(f_c, W_{\text{camera}}, d_{\text{e_camera}}, h, N_p, E_s)$$

$$F_{A_camera}(h) := F_A(f_c, W_{\text{camera}}, d_{\text{e_camera}}, h, N_p, E_s)$$

$$h = 1 \cdot \text{ft} \quad h_{c_camera} = \text{root}(P_{c_camera} - F_{A_camera}(h), h)$$

$$h_{c_camera} = 4.22 \cdot \text{ft}$$

$$h = 0.01 \cdot \text{ft}, 2 \cdot \text{ft}..20 \cdot \text{ft}$$

Penetration

Duration of impact

Average constant impact force

Missile crush load drop height

Penetration

Duration of impact

Average Constant Impact Force

Missile crush load

$$P_{c_camera} = 5.459 \cdot 10^4 \cdot \text{lbf}$$

Camera System Drop - SST and DDT

Drop on Soil above Tank

$$t_{\text{soil}} = 5 \cdot \text{ft} \quad \text{minimum soil cover depth}$$

$$S = 5 \quad \text{approximate soil factor for dry sandy soil conditions at Hanford}$$

$$W_{\text{camera}} = 1300 \cdot \text{lb}$$

$$A_{p_camera} = 72 \cdot \text{in}^2$$

$$N_p = 0.84$$

Maximum drop height to just perforate minimum soil cover.

$$x_{\text{soil_camera}}(h, S) = x_{\text{soil}}(W_{\text{camera}}, A_{p_camera}, h, S, N_p)$$

$$h_{\text{soil_camera}} = \text{root}(t_{\text{soil}} - x_{\text{soil_camera}}(h, S), h) \quad h_{\text{soil_camera}} = 541 \cdot \text{ft}$$

Corresponding initial impact velocity.

$$V(h_{\text{soil_camera}}) = 187 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{camera}}, h_{\text{soil_camera}}) = 7.036 \cdot 10^5 \cdot \text{ft} \cdot \text{lb}$$

**Camera System Drop on Soil above Tank
Penetration into Soil**

$$h = 0.1 \cdot \text{ft}, 2 \cdot \text{ft}, 600 \cdot \text{ft}$$

Sluicing Equipment - Distributor Pipe Drop - SST and DST

$$W_{\text{dist_pipe}} := 2000 \cdot \text{lbf} \quad L_{\text{dist_pipe}} := 37 \cdot \text{ft}$$

$$d_{\text{dist_pipe}} := 4.5 \cdot \text{in} \quad \text{4-in. Schedule-80 304L pipe}$$

$$t_{\text{dist_pipe}} := 0.337 \cdot \text{in}$$

$$A_{\text{dist_pipe}} = A_{\text{pipe}}(d_{\text{dist_pipe}}, t_{\text{dist_pipe}})$$

$$A_{\text{dist_pipe}} = 4.407 \cdot \text{in}^2$$

$$d_{\text{p_dist_pipe}} := 4.5 \cdot \text{in}$$

closed pipe - contacting
impact end

$$t_{\text{p_dist_pipe}} := \frac{d_{\text{p_dist_pipe}}}{2}$$

$$A_{\text{p_dist_pipe}} = A_{\text{pipe}}(d_{\text{p_dist_pipe}}, t_{\text{p_dist_pipe}})$$

Frontal (projected) area of projectile

$$A_{\text{p_dist_pipe}} = 15.904 \cdot \text{in}^2$$

Effective missile diameter

$$d_{\text{e_dist_pipe}} = 4.5 \cdot \text{in}$$

$$d_{\text{e_dist_pipe}} = d_{\text{e}}(A_{\text{p_dist_pipe}})$$

$$I_{\text{dist_pipe}} := I_{\text{pipe}}(d_{\text{dist_pipe}}, t_{\text{dist_pipe}})$$

$$I_{\text{dist_pipe}} = 9.61 \cdot \text{in}^4$$

$$\gamma_{\text{dist_pipe}} := \frac{W_{\text{dist_pipe}}}{A_{\text{dist_pipe}} \cdot L_{\text{dist_pipe}}}$$

Specific weight

$$\gamma_{\text{dist_pipe}} = 1.022 \cdot \frac{\text{lbf}}{\text{in}^3}$$

$$\rho_{\text{dist_pipe}} = \frac{\gamma_{\text{dist_pipe}}}{g}$$

Density

$$\rho_{\text{dist_pipe}} = 0.003 \cdot \frac{\text{lbf} \cdot \text{sec}^2}{\text{in}^4}$$

$$c_{\text{o_dist_pipe}} := c_{\text{o}}(E_{\text{s}}, \rho_{\text{dist_pipe}})$$

Velocity of stress wave
in impacting missile

$$c_{\text{o_dist_pipe}} = 8.722 \cdot 10^3 \cdot \frac{\text{ft}}{\text{sec}}$$

$$P_{\text{y_dist_pipe}} := P_{\text{y}}(S_{\text{y304L}}, A_{\text{dist_pipe}})$$

$$P_{\text{y_dist_pipe}} = 1.102 \cdot 10^5 \cdot \text{lbf}$$

$$K_{\text{bc}} = 1$$

Buckling/Crush Load Evaluation for Missile

$$P_{\text{b_dist_pipe}} = P_{\text{buckling}}(K_{\text{bc}}, E_{\text{s}}, I_{\text{dist_pipe}}, L_{\text{dist_pipe}})$$

$$P_{\text{b_dist_pipe}} = 1.395 \cdot 10^4 \cdot \text{lbf}$$

$$P_{\text{c_dist_pipe}} = P_{\text{c}}(P_{\text{b_dist_pipe}}, P_{\text{y_dist_pipe}})$$

$$P_{\text{c_dist_pipe}} = 1.238 \cdot 10^4 \cdot \text{lbf}$$

$$\sigma_{\text{p_dist_pipe}} = \sigma_{\text{p}}(P_{\text{c_dist_pipe}}, A_{\text{dist_pipe}})$$

$$\sigma_{\text{p_dist_pipe}} = 2810 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$f_{\text{c}} = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$\sigma_{\text{t}} = 6000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

Type of impact (hard/soft) predicted

$$\sigma_{\text{p_dist_pipe}} < \sigma_{\text{t}} \Rightarrow \text{soft impact}$$

For drop in tank concrete pit

thickness of concrete target = thickness of pit floor + thickness of dome

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$$t_{\text{tank_dome}} = 15 \cdot \text{in}$$

$$t_{\text{c}} = t_{\text{pit_floor}} + t_{\text{tank_dome}}$$

$$t_{\text{c}} = 30 \cdot \text{in}$$

$$N_{\text{p}} = 0.84 \quad \text{assume blunt nose projectile}$$

Penetration of missile to missile effective diameter ratio (x/d)

$$x_{\text{d}}(h) := \frac{x(f_{\text{c}}, W_{\text{dist_pipe}}, d_{\text{e_dist_pipe}}, h, N_{\text{p}}, E_{\text{s}})}{d_{\text{e_dist_pipe}}}$$

Sluicing Equipment - Distributor Pipe Drop - SST and DST

Drop in Concrete Pit of Tank

$$W_{\text{dist_pipe}} = 2000 \cdot \text{lb} \cdot \text{f}$$

$$d_{\text{e_dist_pipe}} = 4.5 \cdot \text{in}$$

$$N_p = 0.84$$

$$f_c = 3000 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2}$$

Maximum drop height to preclude perforation or punching shear failure of concrete target (for soft missile impact).

$$t_{\text{e_dist_pipe}}(h) = t_c(f_c, W_{\text{dist_pipe}}, d_{\text{e_dist_pipe}}, h, N_p, E_s)$$

For Pit + Dome concrete thickness

$$h_{\text{e_dist_pipe}} = \text{root}(t_c - t_{\text{e_dist_pipe}}(h), h)$$

$$h_{\text{e_dist_pipe}} = 309 \cdot \text{ft}$$

$$t_c = 30 \cdot \text{in}$$

$$x/d = x_d(h_{\text{e_dist_pipe}}) = 3.4$$

Corresponding initial impact velocity.

Corresponding initial potential energy of missile.

$$V(h_{\text{e_dist_pipe}}) = 141.077 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{dist_pipe}}, h_{\text{e_dist_pipe}}) = 6.186 \cdot 10^5 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

For Pit only

$$h_{\text{e_dist_pipe}} = \text{root}(t_{\text{pit_floor}} - t_{\text{e_dist_pipe}}(h), h)$$

$$h_{\text{e_dist_pipe}} = 36.6 \cdot \text{ft}$$

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$$x/d = x_d(h_{\text{e_dist_pipe}}) = 1.2$$

$$V(h_{\text{e_dist_pipe}}) = 48.5 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{dist_pipe}}, h_{\text{e_dist_pipe}}) = 7.324 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

Maximum drop height to preclude scabbing of concrete target (for hard missile impact).

$$t_{\text{s_dist_pipe}}(h) = t_s(f_c, W_{\text{dist_pipe}}, d_{\text{e_dist_pipe}}, h, N_p, E_s)$$

For Pit + Dome concrete thickness

$$h_{\text{s_dist_pipe}} = \text{root}(t_c - t_{\text{s_dist_pipe}}(h), h)$$

$$h_{\text{s_dist_pipe}} = 186 \cdot \text{ft}$$

$$x/d = x_d(h_{\text{s_dist_pipe}}) = 2.5$$

Corresponding initial impact velocity.

Corresponding initial potential energy of missile.

$$V(h_{\text{s_dist_pipe}}) = 109 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{dist_pipe}}, h_{\text{s_dist_pipe}}) = 3.722 \cdot 10^5 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

For Pit only

$$h_{\text{s_dist_pipe}} = \text{root}(t_{\text{pit_floor}} - t_{\text{s_dist_pipe}}(h), h)$$

$$h_{\text{s_dist_pipe}} = 6.1 \cdot \text{ft}$$

$$x/d = x_d(h_{\text{s_dist_pipe}}) = 0.53$$

$$V(h_{\text{s_dist_pipe}}) = 19.8 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{dist_pipe}}, h_{\text{s_dist_pipe}}) = 1.221 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

$$h = 0.1 \cdot \text{ft}, 1 \cdot \text{ft} \dots 300 \cdot \text{ft}$$

Sluicing Equipment - Distributor Pipe Drop in Concrete Pit of Tank Perforation/Scabbing of Concrete Target

Sluicing Equipment - Distributor Pipe Drop - SST and DST

Sluicing Equipment - Distributor Pipe Drop in Concrete Pit of Tank
Perforation/Scabbing of Concrete Target $h = 0.02\text{ ft}, 0.05\text{ ft}.. 40\text{ ft}$

Sluicing Equipment - Distributor Pipe Drop - SST and DST

Penetration into Concrete Pit of Tank for Hard Missile Impact

$$x_{\text{dist_pipe}}(h) := x(f_c, W_{\text{dist_pipe}}, d_{\text{e_dist_pipe}}, h, N_p, E_s)$$

Penetration

$$t_{\text{d_dist_pipe}}(h) := t_d(f_c, W_{\text{dist_pipe}}, d_{\text{e_dist_pipe}}, h, N_p, E_s)$$

Duration of impact

$$F_{A_dist_pipe}(h) := F_A(f_c, W_{\text{dist_pipe}}, d_{\text{e_dist_pipe}}, h, N_p, E_s)$$

Average constant impact force

$$h = 1 \cdot \text{ft} \quad h_{\text{c_dist_pipe}} := \text{root}(P_{\text{c_dist_pipe}} - F_{A_dist_pipe}(h), h)$$

Missile crush load drop height

$$h_{\text{c_dist_pipe}} = 3.995 \cdot \text{in}$$

$$h = 0.01 \cdot \text{ft}, 2 \cdot \text{ft}..20 \cdot \text{ft}$$

Penetration

Duration of impact

Average Constant Impact Force

Missile crush load

$$P_{\text{c_dist_pipe}} = 1.238 \cdot 10^4 \cdot \text{lbf}$$

Sluicing Equipment - Distributor Pipe Drop - SST and DST

Drop on Soil above Tank

$$t_{\text{soil}} = 5 \cdot \text{ft} \quad \text{minimum soil cover depth}$$

$$W_{\text{dist_pipe}} = 2000 \cdot \text{lb}_f$$

$$S = 5 \quad \text{approximate soil factor for dry sandy soil conditions at Hanford}$$

$$A_{p_dist_pipe} = 15.904 \cdot \text{in}^2$$

$$N_p = 0.84$$

Maximum drop height to just perforate minimum soil cover.

$$x_{\text{soil_dist_pipe}}(h, S) = x_{\text{soil}}(W_{\text{dist_pipe}}, A_{p_dist_pipe}, h, S, N_p)$$

$$h_{\text{soil_dist_pipe}} = \text{root}(t_{\text{soil}} - x_{\text{soil_dist_pipe}}(h, S), h)$$

$$h_{\text{soil_dist_pipe}} = 172 \cdot \text{ft}$$

Corresponding initial impact velocity.

$$V(h_{\text{soil_dist_pipe}}) = 105 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{dist_pipe}}, h_{\text{soil_dist_pipe}}) = 3.446 \cdot 10^5 \cdot \text{ft} \cdot \text{lb}_f$$

Sluicing Equipment - Distributor Pipe Drop on Soil above Tank Penetration into Soil

$$h = 0.1 \cdot \text{ft}.. 180 \cdot \text{ft}$$

Saltwell Equipment - Saltwell Screen Drop - SST

$$W_{\text{screen}} := 1500 \cdot \text{lbf}$$

$$L_{\text{screen}} := 50 \cdot \text{ft}$$

$$d_{\text{screen}} := 10.75 \cdot \text{in}$$

10-in. Schedule-40

$$t_{\text{screen}} := 0.365 \cdot \text{in}$$

pipe

$$A_{\text{screen}} := A_{\text{pipe}}(d_{\text{screen}}, t_{\text{screen}})$$

$$A_{\text{screen}} = 11.908 \cdot \text{in}^2$$

$$d_{p_screen} := 10.75 \cdot \text{in}$$

contacting impact end - closed end pipe

$$t_{p_screen} := \frac{d_{p_screen}}{2}$$

$$A_{p_screen} := A_{\text{pipe}}(d_{p_screen}, t_{p_screen})$$

Frontal (projected) area of projectile

$$A_{p_screen} = 90.763 \cdot \text{in}^2$$

$$d_{e_screen} := d_e(A_{p_screen})$$

Effective missile diameter

$$d_{e_screen} = 10.75 \cdot \text{in}$$

$$I_{\text{screen}} := I_{\text{pipe}}(d_{\text{screen}}, t_{\text{screen}})$$

$$I_{\text{screen}} = 160.734 \cdot \text{in}^4$$

$$\gamma_{\text{screen}} := \frac{W_{\text{screen}}}{A_{\text{screen}} \cdot L_{\text{screen}}}$$

Specific weight

$$\gamma_{\text{screen}} = 0.21 \cdot \frac{\text{lbf}}{\text{in}^3}$$

$$\rho_{\text{screen}} := \frac{\gamma_{\text{screen}}}{g}$$

Density

$$\rho_{\text{screen}} = 5.438 \cdot 10^{-4} \cdot \frac{\text{lbf} \cdot \text{sec}^2}{\text{in}^4}$$

$$c_{o_screen} := c_o(E_s, \rho_{\text{screen}})$$

Velocity of stress wave
in impacting missile

$$c_{o_screen} = 1.924 \cdot 10^4 \cdot \frac{\text{ft}}{\text{sec}}$$

$$P_{y_screen} := P_y(S_{y304L}, A_{\text{screen}})$$

$$P_{y_screen} = 2.977 \cdot 10^5 \cdot \text{lbf}$$

$$K_{bc} := 1$$

Buckling/Crush Load Evaluation for Missile

$$P_{b_screen} := P_{\text{buckling}}(K_{bc}, E_s, I_{\text{screen}}, L_{\text{screen}})$$

$$P_{b_screen} = 1.278 \cdot 10^5 \cdot \text{lbf}$$

$$P_{c_screen} := P_c(P_{b_screen}, P_{y_screen})$$

$$P_{c_screen} = 8.941 \cdot 10^4 \cdot \text{lbf}$$

$$\sigma_{p_screen} := \sigma_p(P_{c_screen}, A_{\text{screen}})$$

$$\sigma_{p_screen} = 7508 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$\sigma_t = 6000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

Type of impact (hard/soft) predicted

$$\sigma_{p_screen} > \sigma_t \Rightarrow \text{hard impact}$$

For drop in tank concrete pit

thickness of concrete target = thickness of pit floor + thickness of dome

$$t_{\text{pit_floor}} := 15 \cdot \text{in}$$

$$t_{\text{tank_dome}} := 15 \cdot \text{in}$$

$$t_c := t_{\text{pit_floor}} + t_{\text{tank_dome}}$$

$$t_c = 30 \cdot \text{in}$$

$$N_p := 0.84 \quad \text{assume blunt nose projectile}$$

Petration of missile to missile effective diameter ratio (x/d)

$$x_d(h) := \frac{x(f_c, W_{\text{screen}}, d_{e_screen}, h, N_p, E_s)}{d_{e_screen}}$$

Saltwell Equipment - Saltwell Screen Drop - SST

Drop in Concrete Pit of Tank

$$W_{\text{screen}} = 1500 \cdot \text{lb} \cdot \text{ft} \quad d_{e_screen} = 10.75 \cdot \text{in}$$

$$N_p = 0.84$$

$$f_c = 3000 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

Maximum drop height to preclude perforation or punching shear failure of concrete target (for soft missile impact).

$$t_{e_screen}(h) = t_e(f_c, W_{\text{screen}}, d_{e_screen}, h, N_p, E_s)$$

For Pit + Dome concrete thickness $h_{e_screen} = \text{root}(t_c - t_{e_screen}(h), h)$

$$h_{e_screen} = 428 \cdot \text{ft}$$

$$t_c = 30 \cdot \text{in}$$

$$x/d = x_d(h_{e_screen}) = 0.92$$

Corresponding initial impact velocity.

Corresponding initial potential energy of missile.

$$V(h_{e_screen}) = 165.9 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{screen}}, h_{e_screen}) = 6.413 \cdot 10^5 \cdot \text{ft} \cdot \text{lb} \cdot \text{ft}$$

For Pit only

$$h_{e_screen} = \text{root}(t_{\text{pit_floor}} - t_{e_screen}(h), h)$$

$$h_{e_screen} = 67.3 \cdot \text{ft}$$

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$$x/d = x_d(h_{e_screen}) = 0.4$$

$$V(h_{e_screen}) = 65.8 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{screen}}, h_{e_screen}) = 1.009 \cdot 10^5 \cdot \text{ft} \cdot \text{lb} \cdot \text{ft}$$

Maximum drop height to preclude scabbing of concrete target (for hard missile impact).

$$t_{s_screen}(h) = t_s(f_c, W_{\text{screen}}, d_{e_screen}, h, N_p, E_s)$$

For Pit + Dome concrete thickness $h_{s_screen} = \text{root}(t_c - t_{s_screen}(h), h)$

$$h_{s_screen} = 64.5 \cdot \text{ft}$$

$$x/d = x_d(h_{s_screen}) = 0.39$$

Corresponding initial impact velocity.

Corresponding initial potential energy of missile.

$$V(h_{s_screen}) = 64.4 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{screen}}, h_{s_screen}) = 9.676 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{ft}$$

For Pit only

$$h_{s_screen} = \text{root}(t_{\text{pit_floor}} - t_{s_screen}(h), h)$$

$$h_{s_screen} = 9.3 \cdot \text{ft}$$

$$x/d = x_d(h_{s_screen}) = 0.16$$

$$V(h_{s_screen}) = 24.5 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{screen}}, h_{s_screen}) = 1.397 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{ft}$$

Saltwell Equipment - Saltwell Screen Drop in Concrete Pit of Tank Perforation/Scabbing of Concrete Target

$$h = 0.1 \cdot \text{ft}, 1 \cdot \text{ft}, 450 \cdot \text{ft}$$

Saltwell Equipment - Saltwell Screen Drop - SST

Saltwell Equipment - Saltwell Screen Drop in Concrete Pit of Tank
Perforation/Scabbing of Concrete Target $h = 0.02\text{-ft}, 0.1\text{-ft}.. 40\text{-ft}$

Saltwell Equipment - Saltwell Screen Drop - SST

Penetration into Concrete Pit of Tank for Hard Missile Impact

$$x_{\text{screen}}(h) = x_c \left(f_c, W_{\text{screen}}, d_{e_screen}, h, N_p, E_s \right)$$

Penetration

$$t_{d_screen}(h) = t_d \left(f_c, W_{\text{screen}}, d_{e_screen}, h, N_p, E_s \right)$$

Duration of impact

$$F_{A_screen}(h) = F_A \left(f_c, W_{\text{screen}}, d_{e_screen}, h, N_p, E_s \right)$$

Average constant impact force

$$h = 1\text{-ft} \quad h_{c_screen} = \text{root} \left(P_{c_screen} - F_{A_screen}(h), h \right)$$

Missile crush load drop height

$$h_{c_screen} = 8.352 \cdot \text{ft}$$

$$h = 0.01\text{-ft}, 2\text{-ft}..20\text{-ft}$$

Penetration

Duration of impact

Missile crush load

$$P_{c_screen} = 8.941 \cdot 10^4 \cdot \text{lbf}$$

Average Constant Impact Force

Saltwell Equipment - Saltwell Screen Drop - SST**Drop on Soil above Tank**

$$t_{\text{soil}} = 5 \text{ ft} \quad \text{minimum soil cover depth}$$

$$S = 5 \quad \text{approximate soil factor for dry sandy soil conditions at Hanford}$$

$$W_{\text{screen}} = 1500 \cdot \text{lbf}$$

$$A_{p_{\text{screen}}} = 90.763 \cdot \text{in}^2$$

$$N_p = 0.84$$

Maximum drop height to just perforate minimum soil cover.

$$x_{\text{soil_screen}}(h, S) := x_{\text{soil}}(W_{\text{screen}}, A_{p_{\text{screen}}}, h, S, N_p)$$

$$h_{\text{soil_screen}} = \text{root}(t_{\text{soil}} - x_{\text{soil_screen}}(h, S), h)$$

$$h_{\text{soil_screen}} = 573 \cdot \text{ft}$$

Corresponding initial impact velocity.

$$V(h_{\text{soil_screen}}) = 192.043 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{screen}}, h_{\text{soil_screen}}) = 8.597 \cdot 10^5 \cdot \text{ft} \cdot \text{lbf}$$

Saltwell Equipment - Saltwell Screen Drop on Soil above Tank Penetration into Soil

$$h = 0.1 \text{ ft}, 2 \text{ ft}, 600 \text{ ft}$$

New Transfer Pump Drop - SST and DST

$$W_{\text{transfer_pump}} := 4000 \cdot \text{lb} \cdot \text{ft} \quad L_{\text{transfer_pump}} := 50 \cdot \text{ft}$$

$$d_{\text{transfer_pump}} := 8.625 \cdot \text{in} \quad \text{8-in. Schedule-40 304L}$$

$$t_{\text{transfer_pump}} := 0.322 \cdot \text{in} \quad \text{pipe (upper end)}$$

$$A_{\text{transfer_pump}} := A_{\text{pipe}}(d_{\text{transfer_pump}}, t_{\text{transfer_pump}}) \quad A_{\text{transfer_pump}} = 8.399 \cdot \text{in}^2$$

$$d_{\text{p_transfer_pump}} := 11 \cdot \text{in} \quad \text{contacting impact end}$$

$$t_{\text{p_transfer_pump}} := \frac{d_{\text{p_transfer_pump}} - 2 \cdot \text{in}}{2}$$

$$A_{\text{p_transfer_pump}} := A_{\text{pipe}}(d_{\text{p_transfer_pump}}, t_{\text{p_transfer_pump}})$$

Frontal (projected) area of projectile

$$A_{\text{p_transfer_pump}} = 91.892 \cdot \text{in}^2$$

Effective missile diameter

$$d_{\text{e_transfer_pump}} := 10.817 \cdot \text{in}$$

$$d_{\text{e_transfer_pump}} = d_{\text{e}}(A_{\text{p_transfer_pump}})$$

$$I_{\text{transfer_pump}} := I_{\text{pipe}}(d_{\text{transfer_pump}}, t_{\text{transfer_pump}})$$

$$I_{\text{transfer_pump}} = 72.489 \cdot \text{in}^4$$

$$\gamma_{\text{transfer_pump}} := \frac{W_{\text{transfer_pump}}}{A_{\text{transfer_pump}} \cdot L_{\text{transfer_pump}}} \quad \text{Specific weight}$$

$$\gamma_{\text{transfer_pump}} = 0.794 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^3}$$

$$\rho_{\text{transfer_pump}} := \frac{\gamma_{\text{transfer_pump}}}{g} \quad \text{Density}$$

$$\rho_{\text{transfer_pump}} = 0.002 \cdot \frac{\text{lb} \cdot \text{sec}^2}{\text{in}^4}$$

$$c_{\text{o_transfer_pump}} := c_{\text{o}}(E_{\text{s}}, \rho_{\text{transfer_pump}}) \quad \text{Velocity of stress wave in impacting missile}$$

$$c_{\text{o_transfer_pump}} = 9.898 \cdot 10^3 \cdot \frac{\text{ft}}{\text{sec}}$$

$$P_{\text{y_transfer_pump}} := P_{\text{y}}(S_{\text{y304L}}, A_{\text{transfer_pump}})$$

$$P_{\text{y_transfer_pump}} = 2.1 \cdot 10^5 \cdot \text{lb} \cdot \text{ft}$$

$$K_{\text{bc}} := 1$$

Buckling/Crush Load Evaluation for Missile

$$P_{\text{b_transfer_pump}} := P_{\text{buckling}}(K_{\text{bc}}, E_{\text{s}}, I_{\text{transfer_pump}}, L_{\text{transfer_pump}}) \quad P_{\text{b_transfer_pump}} = 5.763 \cdot 10^4 \cdot \text{lb} \cdot \text{ft}$$

$$P_{\text{c_transfer_pump}} := P_{\text{c}}(P_{\text{b_transfer_pump}}, P_{\text{y_transfer_pump}}) \quad P_{\text{c_transfer_pump}} = 4.522 \cdot 10^4 \cdot \text{lb} \cdot \text{ft}$$

$$\sigma_{\text{p_transfer_pump}} := \sigma_{\text{p}}(P_{\text{c_transfer_pump}}, A_{\text{transfer_pump}}) \quad \sigma_{\text{p_transfer_pump}} = 5384 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

$$f_{\text{c}} = 3000 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

$$\sigma_{\text{t}} = 6000 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

Type of impact (hard/soft) predicted

$$\sigma_{\text{p_transfer_pump}} < \sigma_{\text{t}} \Rightarrow \text{soft impact}$$

For drop in tank concrete pit

thickness of concrete target = thickness of pit floor + thickness of dome

$$t_{\text{pit_floor}} := 15 \cdot \text{in} \quad t_{\text{tank_dome}} := 15 \cdot \text{in} \quad t_{\text{c}} := t_{\text{pit_floor}} + t_{\text{tank_dome}} \quad t_{\text{c}} = 30 \cdot \text{in}$$

$$N_{\text{p}} := 0.84 \quad \text{assume blunt nose projectile}$$

Penetration of missile to missile effective diameter ratio (x/d)

$$x_{\text{d}}(h) = \frac{x(f_{\text{c}}, W_{\text{transfer_pump}}, d_{\text{e_transfer_pump}}, h, N_{\text{p}}, E_{\text{s}})}{d_{\text{e_transfer_pump}}}$$

New Transfer Pump Drop - SST and DST**Drop in Concrete Pit of Tank**

$$W_{\text{transfer_pump}} = 4000 \cdot \text{lb} \cdot \text{ft}$$

$$d_{e_transfer_pump} = 10.817 \cdot \text{in}$$

$$N_p = 0.84$$

$$f_c = 3000 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

Maximum drop height to preclude perforation or punching shear failure of concrete target (for soft missile impact).

$$t_{e_transfer_pump}(h) = t_e(f_c, W_{\text{transfer_pump}}, d_{e_transfer_pump}, h, N_p, E_s)$$

For Pit + Dome concrete thickness $h_{e_transfer_pump} := \text{root}(t_c - t_{e_transfer_pump}(h), h)$ $h_{e_transfer_pump} = 144 \cdot \text{ft}$
 $t_c = 30 \cdot \text{in}$

$$x/d = x_d(h_{e_transfer_pump}) = 0.91$$

Corresponding initial impact velocity.

Corresponding initial potential energy of missile.

$$V(h_{e_transfer_pump}) = 96.2 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{transfer_pump}}, h_{e_transfer_pump}) = 5.748 \cdot 10^5 \cdot \text{ft} \cdot \text{lb} \cdot \text{ft}$$

For Pit only

$$h_{e_transfer_pump} := \text{root}(t_{\text{pit_floor}} - t_{e_transfer_pump}(h), h) \quad h_{e_transfer_pump} = 22.8 \cdot \text{ft}$$

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$$x/d = x_d(h_{e_transfer_pump}) = 0.4$$

$$V(h_{e_transfer_pump}) = 38.3 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{transfer_pump}}, h_{e_transfer_pump}) = 9.116 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{ft}$$

Maximum drop height to preclude scabbing of concrete target (for hard missile impact).

$$t_{s_transfer_pump}(h) = t_s(f_c, W_{\text{transfer_pump}}, d_{e_transfer_pump}, h, N_p, E_s)$$

For Pit + Dome concrete thickness $h_{s_transfer_pump} := \text{root}(t_c - t_{s_transfer_pump}(h), h)$ $h_{s_transfer_pump} = 21.6 \cdot \text{ft}$
 $t_c = 30 \cdot \text{in}$

$$x/d = x_d(h_{s_transfer_pump}) = 0.39$$

Corresponding initial impact velocity.

Corresponding initial potential energy of missile.

$$V(h_{s_transfer_pump}) = 37.274 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{transfer_pump}}, h_{s_transfer_pump}) = 8.637 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{ft}$$

For Pit only

$$h_{s_transfer_pump} := \text{root}(t_{\text{pit_floor}} - t_{s_transfer_pump}(h), h) \quad h_{s_transfer_pump} = 3.1 \cdot \text{ft}$$

$$x/d = x_d(h_{s_transfer_pump}) = 0.16$$

$$V(h_{s_transfer_pump}) = 14.21 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{transfer_pump}}, h_{s_transfer_pump}) = 1.255 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{ft}$$

New Transfer Pump Drop in Concrete Pit of Tank Perforation/Scabbing of Concrete Target

$$h := 0.1 \cdot \text{ft}, 0.5 \cdot \text{ft} \dots 140 \cdot \text{ft}$$

New Transfer Pump Drop - SST and DST

 $h = 0.02\text{ ft}, 0.05\text{ ft}..25\text{ ft}$
**New Transfer Pump Drop in Concrete Pit of Tank
Perforation/Scabbing of Concrete Target**

New Transfer Pump Drop - SST and DST

Penetration into Concrete Pit of Tank for Hard Missile Impact

$$x_{\text{transfer_pump}}(h) := x(f_c, W_{\text{transfer_pump}}, d_{e_transfer_pump}, h, N_p, E_s)$$

Penetration

$$t_{d_transfer_pump}(h) := t_d(f_c, W_{\text{transfer_pump}}, d_{e_transfer_pump}, h, N_p, E_s)$$

Duration of impact

$$F_{A_transfer_pump}(h) := F_A(f_c, W_{\text{transfer_pump}}, d_{e_transfer_pump}, h, N_p, E_s)$$

Average constant impact force

$$h = 1 \cdot \text{ft} \quad h_{c_transfer_pump} := \text{root}(P_{c_transfer_pump} - F_{A_transfer_pump}(h), h)$$

Missile crush load drop height

$$h_{c_transfer_pump} = 0.987 \cdot \text{ft}$$

$$h = 0.01 \cdot \text{ft}, .2 \cdot \text{ft}..20 \cdot \text{ft}$$

Penetration

Duration of impact

Missile crush load

$$P_{c_transfer_pump} = 4.522 \cdot 10^4 \cdot \text{lbf}$$

Average Constant Impact Force

New Transfer Pump Drop - SST and DST**Drop on Soil above Tank** $t_{\text{soil}} := 5 \cdot \text{ft}$ minimum soil cover depth $S = 5$ approximate soil factor for dry sandy soil conditions at Hanford

$$W_{\text{transfer_pump}} = 4000 \cdot \text{lb} \cdot \text{f}$$

$$A_{\text{p_transfer_pump}} = 91.892 \cdot \text{in}^2$$

$$N_p = 0.84$$

Maximum drop height to just perforate minimum soil cover.

$$x_{\text{soil_transfer_pump}}(h, S) = x_{\text{soil}}(W_{\text{transfer_pump}}, A_{\text{p_transfer_pump}}, h, S, N_p)$$

$$h_{\text{soil_transfer_pump}} = \text{root}(t_{\text{soil}} - x_{\text{soil_transfer_pump}}(h, S), h)$$

$$h_{\text{soil_transfer_pump}} = 315 \cdot \text{ft}$$

Corresponding initial impact velocity.

$$V(h_{\text{soil_transfer_pump}}) = 142.364 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$\text{PE}(W_{\text{transfer_pump}}, h_{\text{soil_transfer_pump}}) = 1.26 \cdot 10^6 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

 $h = 0.1 \cdot \text{ft}..350 \cdot \text{ft}$ **New Transfer Pump Drop on Soil above Tank
Penetration into Soil**

Original 101SY Tank Mixer Pump Drop - DST

length between pump body and lower end outlet
 $W_{\text{mixer_pump}} = 25000 \cdot \text{lbf}$ $L_{\text{mixer_pump}} = 13 \cdot \text{ft}$ (full length of pump assembly is about 50 ft) Ref: LANL, 1995, Pump Drop Analysis, TSA6-CN-WT-SA-ST-073, Los Alamos National Laboratory, Los Alamos, New Mexico.

$d_{\text{mixer_pump}} = 6.625 \cdot \text{in}$ 2 6-in. Schedule-80 A-106 Gr. B pipe with 36-in. diameter 0.5-in. thick A-36 end plate

$t_{\text{mixer_pump}} = 0.432 \cdot \text{in}$

$A_{\text{mixer_pump}} = 2 \cdot A_{\text{pipe}}(d_{\text{mixer_pump}}, t_{\text{mixer_pump}})$ $A_{\text{mixer_pump}} = 16.81 \cdot \text{in}^2$

$t_{\text{plate}} = 0.5 \cdot \text{in}$ $R_m = \frac{d_{\text{mixer_pump}} - t_{\text{mixer_pump}}}{2}$ projected thickness of pipe sheared through end plate
 $R_m = 3.096 \cdot \text{in}$ $t'_p = t_{\text{mixer_pump}} + 2 \cdot t_{\text{plate}} \cdot \sin(30 \cdot \text{deg})$
 $t'_p = 0.932 \cdot \text{in}$

$A_{p_mixer_pump} = 2 \cdot (2 \cdot \pi \cdot R_m \cdot t'_p)$ contacting impact end Frontal (projected) area of projectile
 $A_{p_mixer_pump} = 36.266 \cdot \text{in}^2$

$d_{e_mixer_pump} = d_e(A_{p_mixer_pump})$ Effective missile diameter
 $d_{e_mixer_pump} = 6.795 \cdot \text{in}$

$I_{\text{mixer_pump}} = 2 \cdot I_{\text{pipe}}(d_{\text{mixer_pump}}, t_{\text{mixer_pump}})$ $I_{\text{mixer_pump}} = 80.981 \cdot \text{in}^4$

$\gamma_{\text{mixer_pump}} = \frac{W_{\text{mixer_pump}}}{A_{\text{mixer_pump}} \cdot L_{\text{mixer_pump}}}$ Specific weight $\gamma_{\text{mixer_pump}} = 9.533 \cdot \frac{\text{lbf}}{\text{in}^3}$

$\rho_{\text{mixer_pump}} = \frac{\gamma_{\text{mixer_pump}}}{g}$ Density $\rho_{\text{mixer_pump}} = 0.025 \cdot \frac{\text{lbf} \cdot \text{sec}^2}{\text{in}^4}$

$c_{o_mixer_pump} = c_o(E_s, \rho_{\text{mixer_pump}})$ Velocity of stress wave in impacting missile $c_{o_mixer_pump} = 2.856 \cdot 10^3 \cdot \frac{\text{ft}}{\text{sec}}$

$S_{yA106} = 35000 \cdot \frac{\text{lbf}}{\text{in}^2}$

$P_{y_mixer_pump} = P_y(S_{yA106}, A_{\text{mixer_pump}})$ $P_{y_mixer_pump} = 5.883 \cdot 10^5 \cdot \text{lbf}$

$K_{bc} = 1$ Buckling/Crush Load Evaluation for Missile

$P_{b_mixer_pump} = P_{\text{buckling}}(K_{bc}, E_s, I_{\text{mixer_pump}}, L_{\text{mixer_pump}})$ $P_{b_mixer_pump} = 9.524 \cdot 10^5 \cdot \text{lbf}$

$P_{c_mixer_pump} = P_c(P_{b_mixer_pump}, P_{y_mixer_pump})$ $P_{c_mixer_pump} = 3.637 \cdot 10^5 \cdot \text{lbf}$

$\sigma_{p_mixer_pump} = \sigma_p(P_{c_mixer_pump}, A_{\text{mixer_pump}})$ $\sigma_{p_mixer_pump} = 21635 \cdot \frac{\text{lbf}}{\text{in}^2}$

$f_c = 4500 \text{ lbf/in}^2$ for dome and 3500 lbf/in^2 for pit floor, use lower value for all for simplicity.

$f_c = 3500 \cdot \frac{\text{lbf}}{\text{in}^2}$ $\sigma_t = 2 \cdot f_c$ $\sigma_t = 7000 \cdot \frac{\text{lbf}}{\text{in}^2}$ Type of impact (hard/soft) predicted
 $\sigma_{p_mixer_pump} > \sigma_t \Rightarrow \text{hard impact}$

For drop in tank concrete pit

thickness of concrete target = thickness of pit floor + thickness of dome

$$t_{\text{pit_floor}} = 17.5 \cdot \text{in} \quad t_{\text{tank_dome}} = 15 \cdot \text{in} \quad t_c := t_{\text{pit_floor}} + t_{\text{tank_dome}} \quad t_c = 32.5 \cdot \text{in}$$

$$N_p = 0.84 \quad \text{assume blunt nose projectile}$$

Penetration of missile to missile effective diameter ratio (x/d)

$$x_d(h) = \frac{x(f_c, W_{\text{mixer_pump}}, d_{e_mixer_pump}, h, N_p, E_s)}{d_{e_mixer_pump}}$$

Original 101SY Tank Mixer Pump Drop - DST**Drop in Concrete Pit of Tank**

$$W_{\text{mixer_pump}} = 25000 \cdot \text{lb} \cdot \text{f}$$

$$d_{\text{e_mixer_pump}} = 6.795 \cdot \text{in}$$

$$N_p = 0.84$$

$$f_c = 3500 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2}$$

Maximum drop height to preclude perforation or punching shear failure of concrete target (for soft missile impact).

$$t_{\text{e_mixer_pump}}(h) = t_c(f_c, W_{\text{mixer_pump}}, d_{\text{e_mixer_pump}}, h, N_p, E_s)$$

For Pit + Dome concrete thickness $h_{\text{e_mixer_pump}} = \text{root}(t_c - t_{\text{e_mixer_pump}}(h), h)$

$$h_{\text{e_mixer_pump}} = 32.2 \cdot \text{ft}$$

$$t_c = 32.5 \cdot \text{in}$$

$$x/d = x_d(h_{\text{e_mixer_pump}}) = 2.15$$

Corresponding initial impact velocity.

$$V(h_{\text{e_mixer_pump}}) = 45.5 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{mixer_pump}}, h_{\text{e_mixer_pump}}) = 8.043 \cdot 10^5 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

For Pit only

$$t_{\text{pit_floor}} = 17.5 \cdot \text{in}$$

$$h_{\text{e_mixer_pump}} = \text{root}(t_{\text{pit_floor}} - t_{\text{e_mixer_pump}}(h), h)$$

$$h_{\text{e_mixer_pump}} = 3.9 \cdot \text{ft}$$

$$x/d = x_d(h_{\text{e_mixer_pump}}) = 0.83$$

$$V(h_{\text{e_mixer_pump}}) = 15.8 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{mixer_pump}}, h_{\text{e_mixer_pump}}) = 9.681 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

Maximum drop height to preclude scabbing of concrete target (for hard missile impact).

$$t_{\text{s_mixer_pump}}(h) = t_s(f_c, W_{\text{mixer_pump}}, d_{\text{e_mixer_pump}}, h, N_p, E_s)$$

For Pit + Dome concrete thickness $h_{\text{s_mixer_pump}} = \text{root}(t_c - t_{\text{s_mixer_pump}}(h), h)$

$$h_{\text{s_mixer_pump}} = 11.9 \cdot \text{ft}$$

$$t_c = 32.5 \cdot \text{in}$$

$$x/d = x_d(h_{\text{s_mixer_pump}}) = 1.37$$

Corresponding initial impact velocity.

$$V(h_{\text{s_mixer_pump}}) = 27.7 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{mixer_pump}}, h_{\text{s_mixer_pump}}) = 2.986 \cdot 10^5 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

For Pit only

$$t_{\text{pit_floor}} = 17.5 \cdot \text{in}$$

$$h_{\text{s_mixer_pump}} = \text{root}(t_{\text{pit_floor}} - t_{\text{s_mixer_pump}}(h), h)$$

$$h_{\text{s_mixer_pump}} = 0.57 \cdot \text{ft}$$

$$x/d = x_d(h_{\text{s_mixer_pump}}) = 0.35$$

$$V(h_{\text{s_mixer_pump}}) = 6 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{mixer_pump}}, h_{\text{s_mixer_pump}}) = 1.421 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

$$h = 0.1 \cdot \text{ft}, 5 \cdot \text{ft}, 30 \cdot \text{ft}$$

Original 101SY Tank Mixer Pump Drop in Concrete Pit of Tank Perforation/Scabbing of Concrete Target

Original 101SY Tank Mixer Pump Drop - DST

$$h = 0.01\text{-ft}, 0.05\text{-ft}.. 16\text{-ft}$$

Original 101SY Tank Mixer Pump Drop in Concrete Pit of Tank
Perforation/Scabbing of Concrete Target

Original 101SY Tank Mixer Pump Drop - DST

Penetration into Concrete Pit of Tank for Hard Missile Impact

$$x_{\text{mixer_pump}}(h) := x(f_c, W_{\text{mixer_pump}}, d_{\text{e_mixer_pump}}, h, N_p, E_s)$$

Penetration

$$t_{d_{\text{mixer_pump}}}(h) := t_d(f_c, W_{\text{mixer_pump}}, d_{\text{e_mixer_pump}}, h, N_p, E_s)$$

Duration of impact

$$F_{A_{\text{mixer_pump}}}(h) := F_A(f_c, W_{\text{mixer_pump}}, d_{\text{e_mixer_pump}}, h, N_p, E_s)$$

Average constant impact force

$$h := 1\text{-ft} \quad h_{c_{\text{mixer_pump}}} := \text{root}(P_{c_{\text{mixer_pump}}} - F_{A_{\text{mixer_pump}}}(h), h)$$

Missile crush load drop height

$$h_{c_{\text{mixer_pump}}} = 10.797\text{-ft}$$

$$h := 0.01\text{-ft}..15\text{-ft}$$

Penetration

Duration of impact

Missile crush load

Average Constant Impact Force

$$P_{c_{\text{mixer_pump}}} = 3.637 \cdot 10^5 \text{ lbf}$$

Original 101SY Tank Mixer Pump Drop - DST**Drop on Soil above Tank**

$$t_{\text{soil}} := 6.5 \cdot \text{ft} \quad \text{minimum soil cover depth}$$

$$S := 5 \quad \text{approximate soil factor for dry sandy soil conditions at Hanford}$$

$$W_{\text{mixer_pump}} = 25000 \cdot \text{lbf}$$

$$A_{\text{p_mixer_pump}} = 36.266 \cdot \text{in}^2$$

Maximum drop height to just perforate minimum soil cover.

$$N_p = 0.84$$

$$x_{\text{soil_mixer_pump}}(h, S) := x_{\text{soil}}(W_{\text{mixer_pump}}, A_{\text{p_mixer_pump}}, h, S, N_p)$$

$$h_{\text{soil_mixer_pump}} := \text{root}(t_{\text{soil}} - x_{\text{soil_mixer_pump}}(h, S), h) \quad h_{\text{soil_mixer_pump}} = 91.4 \cdot \text{ft}$$

Corresponding initial impact velocity.**Corresponding initial potential energy of missile.**

$$V(h_{\text{soil_mixer_pump}}) = 76.693 \cdot \frac{\text{ft}}{\text{sec}}$$

$$\text{PE}(W_{\text{mixer_pump}}, h_{\text{soil_mixer_pump}}) = 2.285 \cdot 10^6 \cdot \text{ft} \cdot \text{lbf}$$

Original 101SY Tank Mixer Pump Drop on Soil above Tank Penetration into Soil

$$h := 0.1 \cdot \text{ft}, 1 \cdot \text{ft} \dots 100 \cdot \text{ft}$$

AZ Tank Mixer Pump Drop - DST

$$W_{\text{mixer_pump}} := 27000 \cdot \text{lb} \quad L_{\text{mixer_pump}} := 50 \cdot \text{ft}$$

$$d_{\text{mixer_pump}} := 16 \cdot \text{in} \quad \text{16-in. Schedule-Std 304L pipe}$$

$$t_{\text{mixer_pump}} := 0.375 \cdot \text{in} \quad \text{upper end support}$$

$$A_{\text{mixer_pump}} = A_{\text{pipe}}(d_{\text{mixer_pump}}, t_{\text{mixer_pump}}) \quad A_{\text{mixer_pump}} = 18.408 \cdot \text{in}^2$$

$$d_{\text{p_mixer_pump}} := 3 \cdot \text{ft} \quad \text{contacting impact end - inlet casting}$$

$$t_{\text{p_mixer_pump}} := \frac{d_{\text{p_mixer_pump}} - 20 \cdot \text{in}}{2}$$

$$A_{\text{p_mixer_pump}} = A_{\text{pipe}}(d_{\text{p_mixer_pump}}, t_{\text{p_mixer_pump}})$$

Frontal (projected) area of projectile

$$A_{\text{p_mixer_pump}} = 703.717 \cdot \text{in}^2$$

Effective missile diameter

$$d_{\text{e_mixer_pump}} = 29.933 \cdot \text{in}$$

$$d_{\text{e_mixer_pump}} = d_{\text{c}}(A_{\text{p_mixer_pump}})$$

$$I_{\text{mixer_pump}} = I_{\text{pipe}}(d_{\text{mixer_pump}}, t_{\text{mixer_pump}})$$

$$I_{\text{mixer_pump}} = 562.084 \cdot \text{in}^4$$

$$\gamma_{\text{mixer_pump}} := \frac{W_{\text{mixer_pump}}}{A_{\text{mixer_pump}} \cdot L_{\text{mixer_pump}}}$$

Specific weight

$$\gamma_{\text{mixer_pump}} = 2.445 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^3}$$

$$\rho_{\text{mixer_pump}} := \frac{\gamma_{\text{mixer_pump}}}{g}$$

Density

$$\rho_{\text{mixer_pump}} = 0.006 \cdot \frac{\text{lb} \cdot \text{sec}^2}{\text{in}^4}$$

$$c_{\text{o_mixer_pump}} = c_{\text{o}}(E_{\text{s}}, \rho_{\text{mixer_pump}}) \quad \text{Velocity of stress wave in impacting missile}$$

$$c_{\text{o_mixer_pump}} = 5.64 \cdot 10^3 \cdot \frac{\text{ft}}{\text{sec}}$$

$$P_{\text{y_mixer_pump}} = P_{\text{y}}(S_{\text{y304L}}, A_{\text{mixer_pump}})$$

$$P_{\text{y_mixer_pump}} = 4.602 \cdot 10^5 \cdot \text{lb} \cdot \text{ft}$$

$$K_{\text{bc}} := 1$$

Buckling/Crush Load Evaluation for Missile

$$P_{\text{b_mixer_pump}} = P_{\text{buckling}}(K_{\text{bc}}, E_{\text{s}}, I_{\text{mixer_pump}}, L_{\text{mixer_pump}}) \quad P_{\text{b_mixer_pump}} = 4.469 \cdot 10^5 \cdot \text{lb} \cdot \text{ft}$$

$$P_{\text{c_mixer_pump}} = P_{\text{c}}(P_{\text{b_mixer_pump}}, P_{\text{y_mixer_pump}}) \quad P_{\text{c_mixer_pump}} = 2.267 \cdot 10^5 \cdot \text{lb} \cdot \text{ft}$$

$$\sigma_{\text{p_mixer_pump}} = \sigma_{\text{p}}(P_{\text{c_mixer_pump}}, A_{\text{mixer_pump}}) \quad \sigma_{\text{p_mixer_pump}} = 12317 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

$$f_{\text{c}} := 3000 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

$$\sigma_{\text{t}} := 2 \cdot f_{\text{c}}$$

Type of impact (hard/soft) predicted

$$\sigma_{\text{t}} = 6000 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

$$\sigma_{\text{p_mixer_pump}} > \sigma_{\text{t}} \Rightarrow \text{hard impact}$$

For drop in tank concrete pit

thickness of concrete target = thickness of pit floor + thickness of dome

$$t_{\text{pit_floor}} := 15 \cdot \text{in} \quad t_{\text{tank_dome}} := 15 \cdot \text{in} \quad t_{\text{c}} := t_{\text{pit_floor}} + t_{\text{tank_dome}} \quad t_{\text{c}} = 30 \cdot \text{in}$$

$$N_{\text{p}} := 0.84 \quad \text{assume blunt nose projectile}$$

Petration of missile to missile effective diameter ratio (x/d)

$$x_{\text{d}}(h) := \frac{x(f_{\text{c}}, W_{\text{mixer_pump}}, d_{\text{e_mixer_pump}}, h, N_{\text{p}}, E_{\text{s}})}{d_{\text{e_mixer_pump}}}$$

AZ Tank Mixer Pump Drop - DST

$$W_{\text{mixer_pump}} = 27000 \cdot \text{lbf}$$

Drop in Concrete Pit of Tank

$$d_{\text{e_mixer_pump}} = 29.933 \cdot \text{in} \quad N_p = 0.84$$

$$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

Maximum drop height to preclude perforation or punching shear failure of concrete target (for soft missile impact).

$$t_{\text{e_mixer_pump}}(h) = t_e(f_c, W_{\text{mixer_pump}}, d_{\text{e_mixer_pump}}, h, N_p, E_s)$$

For Pit + Dome concrete thickness $h_{\text{e_mixer_pump}} = \text{root}(t_c - t_{\text{e_mixer_pump}}(h), h) \quad h_{\text{e_mixer_pump}} = 29.5 \cdot \text{ft}$
 $t_c = 30 \cdot \text{in}$
 $x/d = x_d(h_{\text{e_mixer_pump}}) = 0.28$

Corresponding initial impact velocity.

$$V(h_{\text{e_mixer_pump}}) = 43.6 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{mixer_pump}}, h_{\text{e_mixer_pump}}) = 7.973 \cdot 10^5 \cdot \text{ft} \cdot \text{lbf}$$

For Pit only

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$$h_{\text{e_mixer_pump}} = \text{root}(t_{\text{pit_floor}} - t_{\text{e_mixer_pump}}(h), h) \quad h_{\text{e_mixer_pump}} = 5.9 \cdot \text{ft}$$

$$x/d = x_d(h_{\text{e_mixer_pump}}) = 0.13$$

$$V(h_{\text{e_mixer_pump}}) = 19.4 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{mixer_pump}}, h_{\text{e_mixer_pump}}) = 1.584 \cdot 10^5 \cdot \text{ft} \cdot \text{lbf}$$

Maximum drop height to preclude scabbing of concrete target (for hard missile impact).

$$t_{\text{s_mixer_pump}}(h) = t_s(f_c, W_{\text{mixer_pump}}, d_{\text{e_mixer_pump}}, h, N_p, E_s)$$

For Pit + Dome concrete thickness $h_{\text{s_mixer_pump}} = \text{root}(t_c - t_{\text{s_mixer_pump}}(h), h) \quad h_{\text{s_mixer_pump}} = 4 \cdot \text{ft}$
 $t_c = 30 \cdot \text{in}$
 $x/d = x_d(h_{\text{s_mixer_pump}}) = 0.11$

Corresponding initial impact velocity.

$$V(h_{\text{s_mixer_pump}}) = 16.1 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{mixer_pump}}, h_{\text{s_mixer_pump}}) = 1.084 \cdot 10^5 \cdot \text{ft} \cdot \text{lbf}$$

For Pit only

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$$h_{\text{s_mixer_pump}} = \text{root}(t_{\text{pit_floor}} - t_{\text{s_mixer_pump}}(h), h) \quad h_{\text{s_mixer_pump}} = 0.79 \cdot \text{ft}$$

$$x/d = x_d(h_{\text{s_mixer_pump}}) = 0.05$$

$$V(h_{\text{s_mixer_pump}}) = 7.1 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{mixer_pump}}, h_{\text{s_mixer_pump}}) = 2.124 \cdot 10^4 \cdot \text{ft} \cdot \text{lbf}$$

**AZ Tank Mixer Pump Drop in Pit of Tank
Perforation/Scabbing of Concrete Target**

$$h = 0.1 \cdot \text{ft}, 5 \cdot \text{ft}, 30 \cdot \text{ft}$$

AZ Tank Mixer Pump Drop - DST

 $h = 0.01\text{ ft}, 0.05\text{ ft} \dots 10\text{ ft}$
**AZ Tank Mixer Pump Drop in Pit of Tank
Perforation/Scabbing of Concrete Target**

AZ Tank Mixer Pump Drop - DST

Penetration into Concrete Pit of Tank for Hard Missile Impact

$$x_{\text{mixer_pump}}(h) := x(f_c, W_{\text{mixer_pump}}, d_{e_mixer_pump}, h, N_p, E_s)$$

Penetration

$$t_{d_mixer_pump}(h) := t_d(f_c, W_{\text{mixer_pump}}, d_{e_mixer_pump}, h, N_p, E_s)$$

Duration of impact

$$F_{A_mixer_pump}(h) := F_A(f_c, W_{\text{mixer_pump}}, d_{e_mixer_pump}, h, N_p, E_s)$$

Average constant impact force

$$h = 1 \cdot \text{ft} \quad h_{c_mixer_pump} := \text{root}(P_{c_mixer_pump} - F_{A_mixer_pump}(h), h)$$

Missile crush load drop height

$$h_{c_mixer_pump} = 1.556 \cdot \text{ft}$$

$$h = 0.01 \cdot \text{ft}.. 10 \cdot \text{ft}$$

Penetration

Duration of impact

Missile crush load

Average Constant Impact Force

$$P_{c_mixer_pump} = 2.267 \cdot 10^5 \cdot \text{lb}_f$$

AZ Tank Mixer Pump Drop - DST**Drop on Soil above Tank** $t_{\text{soil}} := 5 \cdot \text{ft}$ minimum soil cover depth $S := 5$ approximate soil factor for dry sandy soil conditions at Hanford

$$W_{\text{mixer_pump}} = 27000 \cdot \text{lb} \cdot \text{f}$$

$$A_{\text{p_mixer_pump}} = 703.717 \cdot \text{in}^2$$

$$N_p = 0.84$$

Maximum drop height to just perforate minimum soil cover.

$$x_{\text{soil_mixer_pump}}(h, S) = x_{\text{soil}}(W_{\text{mixer_pump}}, A_{\text{p_mixer_pump}}, h, S, N_p)$$

$$h_{\text{soil_mixer_pump}} := \text{root}(t_{\text{soil}} - x_{\text{soil_mixer_pump}}(h, S), h) \quad h_{\text{soil_mixer_pump}} = 339 \cdot \text{ft}$$

Corresponding initial impact velocity.

$$V(h_{\text{soil_mixer_pump}}) = 147.782 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$\text{PE}(W_{\text{mixer_pump}}, h_{\text{soil_mixer_pump}}) = 9.164 \cdot 10^6 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

 $h := 0.1 \cdot \text{ft}..350 \cdot \text{ft}$ **AZ Tank Mixer Pump Drop on Soil above Tank
Penetration into Soil**

Cover Block Drop - AP Tank Central Pump Pit Cover Block - DST

$$W_{\text{cover_block}} := 18000 \cdot \text{lb} \quad L_{\text{cover_block}} := 10.5 \cdot \text{ft} \quad f_c = 3000 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2} \quad E_c = 3.122 \cdot 10^6 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

$$d_{\text{cover_block}} := 5.7 \cdot \text{ft}$$

end dimensions

$$t_{\text{cover_block}} := 2 \cdot \text{ft}$$

$$A_{\text{cover_block}} := d_{\text{cover_block}} \cdot t_{\text{cover_block}}$$

$$d_{e_cover_block} := d_e(A_{\text{cover_block}})$$

$$I_{\text{cover_block}} := \frac{1}{12} \cdot d_{\text{cover_block}} \cdot t_{\text{cover_block}}^3$$

$$\gamma_{\text{cover_block}} := \frac{W_{\text{cover_block}}}{A_{\text{cover_block}} \cdot L_{\text{cover_block}}}$$

Specific weight

$$\rho_{\text{cover_block}} := \frac{\gamma_{\text{cover_block}}}{g}$$

Density

$$c_{o_cover_block} := c_o(E_c, \rho_{\text{cover_block}})$$

Velocity of stress wave
in impacting missile

$$P_{y_cover_block} := P_y(f_c, A_{\text{cover_block}})$$

Frontal (projected) area of projectile

$$A_{\text{cover_block}} = 1.642 \cdot 10^3 \cdot \text{in}^2$$

Effective missile diameter

$$d_{e_cover_block} = 45.718 \cdot \text{in}$$

$$I_{\text{cover_block}} = 7.88 \cdot 10^4 \cdot \text{in}^4$$

$$\gamma_{\text{cover_block}} = 0.087 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^3}$$

$$\rho_{\text{cover_block}} = 2.254 \cdot 10^{-4} \cdot \frac{\text{lb} \cdot \text{ft} \cdot \text{sec}^2}{\text{in}^4}$$

$$c_{o_cover_block} = 9.808 \cdot 10^3 \cdot \frac{\text{ft}}{\text{sec}}$$

$$P_{y_cover_block} = 4.925 \cdot 10^6 \cdot \text{lb} \cdot \text{ft}$$

$$K_{bc} := 1$$

Buckling/Crush Load Evaluation for Missile

$$P_{b_cover_block} := P_{\text{buckling}}(K_{bc}, E_c, I_{\text{cover_block}}, L_{\text{cover_block}})$$

$$P_{b_cover_block} = 1.529 \cdot 10^8 \cdot \text{lb} \cdot \text{ft}$$

$$P_{c_cover_block} := P_c(P_{b_cover_block}, P_{y_cover_block})$$

$$P_{c_cover_block} = 4.771 \cdot 10^6 \cdot \text{lb} \cdot \text{ft}$$

$$\sigma_{p_cover_block} := \sigma_p(P_{c_cover_block}, A_{\text{cover_block}})$$

$$\sigma_{p_cover_block} = 2906 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

$$\sigma_t = 6000 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

Type of impact (hard/soft) predicted

$$\sigma_{p_cover_block} < \sigma_t \Rightarrow \text{soft impact}$$

For drop in tank concrete pit

thickness of concrete target = thickness of pit floor + thickness of dome

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$$t_{\text{tank_dome}} := 15 \cdot \text{in}$$

$$t_c := t_{\text{pit_floor}} + t_{\text{tank_dome}}$$

$$t_c = 30 \cdot \text{in}$$

$$N_p = 0.84 \quad \text{assume blunt nose projectile}$$

Penetration of missile to missile effective diameter ratio (x/d)

$$x_d(h) := \frac{x(f_c, W_{\text{cover_block}}, d_{e_cover_block}, h, N_p, E_c)}{d_{e_cover_block}}$$

Cover Block Drop - AP Tank Central Pump Pit Cover Block - DST**Drop in Concrete Pit of Tank**

$$W_{\text{cover_block}} = 18000 \cdot \text{lbf}$$

$$d_{\text{e_cover_block}} = 45.718 \cdot \text{in}$$

$$N_p = 0.84$$

$$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

Maximum drop height to preclude perforation or punching shear failure of concrete target (for soft missile impact).

$$t_{\text{e_cover_block}}(h) = t_e(f_c, W_{\text{cover_block}}, d_{\text{e_cover_block}}, h, N_p, E_c)$$

Perpendicular flat end drop

$$\text{For Pit + Dome concrete thickness } h_{\text{e_cover_block}} = \text{root}(t_c - t_{\text{e_cover_block}}(h), h) \quad h_{\text{e_cover_block}} = 1413 \cdot \text{ft}$$

$$t_c = 30 \cdot \text{in}$$

$$x/d = x_d(h_{\text{e_cover_block}}) = 0.18$$

Corresponding initial impact velocity.**Corresponding initial potential energy of missile.**

$$V(h_{\text{e_cover_block}}) = 302 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{cover_block}}, h_{\text{e_cover_block}}) = 2.544 \cdot 10^7 \cdot \text{ft} \cdot \text{lbf}$$

For Pit only

$$h_{\text{e_cover_block}} = \text{root}(t_{\text{pit_floor}} - t_{\text{e_cover_block}}(h), h) \quad h_{\text{e_cover_block}} = 289 \cdot \text{ft}$$

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$$x/d = x_d(h_{\text{e_cover_block}}) = 0.09$$

$$V(h_{\text{e_cover_block}}) = 136 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{cover_block}}, h_{\text{e_cover_block}}) = 5.21 \cdot 10^6 \cdot \text{ft} \cdot \text{lbf}$$

Maximum drop height to preclude scabbing of concrete target (for hard missile impact).

$$t_{\text{s_cover_block}}(h) = t_s(f_c, W_{\text{cover_block}}, d_{\text{e_cover_block}}, h, N_p, E_c)$$

$$\text{For Pit + Dome concrete thickness } h_{\text{s_cover_block}} = \text{root}(t_c - t_{\text{s_cover_block}}(h), h) \quad h_{\text{s_cover_block}} = 549 \cdot \text{ft}$$

$$t_c = 30 \cdot \text{in}$$

$$x/d = x_d(h_{\text{s_cover_block}}) = 0.12$$

Corresponding initial impact velocity.**Corresponding initial potential energy of missile.**

$$V(h_{\text{s_cover_block}}) = 188 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{cover_block}}, h_{\text{s_cover_block}}) = 9.883 \cdot 10^6 \cdot \text{ft} \cdot \text{lbf}$$

For Pit only

$$h_{\text{s_cover_block}} = \text{root}(t_{\text{pit_floor}} - t_{\text{s_cover_block}}(h), h) \quad h_{\text{s_cover_block}} = 107 \cdot \text{ft}$$

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$$x/d = x_d(h_{\text{s_cover_block}}) = 0.06$$

$$V(h_{\text{s_cover_block}}) = 83.1 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{cover_block}}, h_{\text{s_cover_block}}) = 1.932 \cdot 10^6 \cdot \text{ft} \cdot \text{lbf}$$

Cover Block - AP Tank Central Pump Pit Cover Block Drop**in Concrete Pit of Tank - Perforation/Scabbing of Concrete Target**

$$h = 0.1 \cdot \text{ft}, 2 \cdot \text{ft} \dots 1400 \cdot \text{ft}$$

Cover Block Drop - AP Tank Central Pump Pit Cover Block - DST

$$t_{e_cover_block}(h, d_e) = t_e(f_c, W_{cover_block}, d_e, h, N_p, E_c)$$

$$h = 0.1\text{-ft, } 1\text{-ft}.. 300\text{-ft}$$

$$t_{s_cover_block}(h, d_e) = t_s(f_c, W_{cover_block}, d_e, h, N_p, E_c)$$

Cover Block - AP Tank Central Pump Pit Cover Block Drop
in Concrete Pit of Tank - Perforation/Scabbing of Concrete Target

Cover Block Drop - AP Tank Central Pump Pit Cover Block - DST

Perpendicular flat end drop

Penetration into Concrete Pit of Tank for Hard Missile Impact

$$x_{\text{cover_block}}(h) := x(f_c, W_{\text{cover_block}}, d_{\text{e_cover_block}}, h, N_p, E_c)$$

Penetration

$$t_{\text{d_cover_block}}(h) := t_d(f_c, W_{\text{cover_block}}, d_{\text{e_cover_block}}, h, N_p, E_c)$$

Duration of impact

$$F_{A_cover_block}(h) := F_A(f_c, W_{\text{cover_block}}, d_{\text{e_cover_block}}, h, N_p, E_c)$$

Average constant impact force

$$h := 1\text{-ft} \quad h_{\text{c_cover_block}} := \text{root}(P_{\text{c_cover_block}} - F_{A_cover_block}(h), h)$$

Missile crush load drop height

$$h_{\text{c_cover_block}} = 33.414 \cdot \text{ft}$$

$$h := 0.01\text{-ft}, 2\text{-ft}, 20\text{-ft}$$

Penetration

Duration of impact

Missile crush load

$$P_{\text{c_cover_block}} = 4.771 \cdot 10^6 \cdot \text{lbf}$$

Average Constant Impact Force

Cover Block Drop - AP Tank Central Pump Pit Cover Block - DST

Drop on Soil above Tank

$t_{\text{soil}} = 5 \cdot \text{ft}$ minimum soil cover depth

$S = 5$ approximate soil factor for dry sandy soil conditions at Hanford

$W_{\text{cover_block}} = 18000 \cdot \text{lb}$

$A_{\text{cover_block}} = 1.642 \cdot 10^3 \cdot \text{in}^2$

$N_p = 0.84$

Maximum drop height to just perforate minimum soil cover.

$x_{\text{soil_cover_block}}(h, S, A) := x_{\text{soil}}(W_{\text{cover_block}}, A, h, S, N_p)$

$h_{\text{soil_cover_block}} := \text{root}(t_{\text{soil}} - x_{\text{soil_cover_block}}(h, S, A_{\text{cover_block}}), h)$ $h_{\text{soil_cover_block}} = 725 \cdot \text{ft}$

Corresponding initial impact velocity,

Corresponding initial potential energy of missile.

$V(h_{\text{soil_cover_block}}) = 215.979 \cdot \frac{\text{ft}}{\text{sec}}$

$PE(W_{\text{cover_block}}, h_{\text{soil_cover_block}}) = 1.305 \cdot 10^7 \cdot \text{ft} \cdot \text{lb}$

Cover Block - AP Tank Central Pump Pit Cover Block Drop on Soil above Tank Penetration into Soil

$h = 0.1 \cdot \text{ft}, 2 \cdot \text{ft} \dots 800 \cdot \text{ft}$

Cover Block Drop - Tank C106 Pump Pit Cover Block - SST

$$W_{\text{cover_block}} := 31200 \cdot \text{lbf} \quad L_{\text{cover_block}} := 12.7 \cdot \text{ft} \quad f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2} \quad E_c = 3.122 \cdot 10^6 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$d_{\text{cover_block}} := 5.7 \cdot \text{ft}$$

$$t_{\text{cover_block}} := 2.5 \cdot \text{ft} \quad \text{end dimensions}$$

$$A_{\text{cover_block}} := d_{\text{cover_block}} \cdot t_{\text{cover_block}}$$

$$d_{e_cover_block} := d_e(A_{\text{cover_block}})$$

$$I_{\text{cover_block}} := \frac{1}{12} \cdot d_{\text{cover_block}} \cdot t_{\text{cover_block}}^3$$

$$\gamma_{\text{cover_block}} := \frac{W_{\text{cover_block}}}{A_{\text{cover_block}} \cdot L_{\text{cover_block}}}$$

$$\rho_{\text{cover_block}} := \frac{\gamma_{\text{cover_block}}}{g}$$

$$c_{o_cover_block} := c_o(E_c, \rho_{\text{cover_block}}) \quad \text{Velocity of stress wave in impacting missile}$$

$$P_{y_cover_block} := P_y(f_c, A_{\text{cover_block}})$$

$$K_{bc} := 1$$

Buckling/Crush Load Evaluation for Missile

$$P_{b_cover_block} := P_{\text{buckling}}(K_{bc}, E_c, I_{\text{cover_block}}, L_{\text{cover_block}}) \quad P_{b_cover_block} = 2.042 \cdot 10^8 \cdot \text{lbf}$$

$$P_{c_cover_block} := P_c(P_{b_cover_block}, P_{y_cover_block}) \quad P_{c_cover_block} = 5.976 \cdot 10^6 \cdot \text{lbf}$$

$$\sigma_{p_cover_block} := \sigma_p(P_{c_cover_block}, A_{\text{cover_block}}) \quad \sigma_{p_cover_block} = 2912 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2} \quad \sigma_t = 6000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

Type of impact (hard/soft) predicted

$$\sigma_{p_cover_block} < \sigma_t \Rightarrow \text{soft impact}$$

For drop in tank concrete pit

thickness of concrete target = thickness of pit floor + thickness of dome

$$t_{\text{pit_floor}} := 15 \cdot \text{in} \quad t_{\text{tank_dome}} := 15 \cdot \text{in} \quad t_c := t_{\text{pit_floor}} + t_{\text{tank_dome}} \quad t_c = 30 \cdot \text{in}$$

$$N_p = 0.84 \quad \text{assume blunt nose projectile}$$

Penetration of missile to missile effective diameter ratio (x/d)

$$x_d(h) := \frac{x(f_c, W_{\text{cover_block}}, d_{e_cover_block}, h, N_p, E_c)}{d_{e_cover_block}}$$

Cover Block Drop - Tank C106 Pump Pit Cover Block - SST Drop in Concrete Pit of Tank

$$W_{\text{cover_block}} = 31200 \cdot \text{lbf}$$

$$d_{\text{e_cover_block}} = 51.114 \cdot \text{in}$$

$$N_p = 0.84$$

$$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

Maximum drop height to preclude perforation or punching shear failure of concrete target (for soft missile impact).

$$t_{\text{e_cover_block}}(h) := t_c(f_c, W_{\text{cover_block}}, d_{\text{e_cover_block}}, h, N_p, E_c)$$

Perpendicular flat end drop

$$\text{For Pit + Dome concrete thickness } h_{\text{e_cover_block}} := \text{root}(t_c - t_{\text{e_cover_block}}(h), h) \quad h_{\text{e_cover_block}} = 839 \cdot \text{ft}$$

$$t_c = 30 \cdot \text{in}$$

$$x/d = x_d(h_{\text{e_cover_block}}) = 0.16$$

Corresponding initial impact velocity.

Corresponding initial potential energy of missile.

$$V(h_{\text{e_cover_block}}) = 232 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{cover_block}}, h_{\text{e_cover_block}}) = 2.618 \cdot 10^7 \cdot \text{ft} \cdot \text{lbf}$$

For Pit only

$$h_{\text{e_cover_block}} := \text{root}(t_{\text{pit_floor}} - t_{\text{e_cover_block}}(h), h) \quad h_{\text{e_cover_block}} = 172 \cdot \text{ft}$$

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$$x/d = x_d(h_{\text{e_cover_block}}) = 0.08$$

$$V(h_{\text{e_cover_block}}) = 105 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{cover_block}}, h_{\text{e_cover_block}}) = 5.356 \cdot 10^6 \cdot \text{ft} \cdot \text{lbf}$$

Maximum drop height to preclude scabbing of concrete target (for hard missile impact).

$$t_{\text{s_cover_block}}(h) := t_s(f_c, W_{\text{cover_block}}, d_{\text{e_cover_block}}, h, N_p, E_c)$$

$$\text{For Pit + Dome concrete thickness } h_{\text{s_cover_block}} := \text{root}(t_c - t_{\text{s_cover_block}}(h), h) \quad h_{\text{s_cover_block}} = 323 \cdot \text{ft}$$

$$t_c = 30 \cdot \text{in}$$

$$x/d = x_d(h_{\text{s_cover_block}}) = 0.1$$

Corresponding initial impact velocity.

Corresponding initial potential energy of missile.

$$V(h_{\text{s_cover_block}}) = 144 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{cover_block}}, h_{\text{s_cover_block}}) = 1.007 \cdot 10^7 \cdot \text{ft} \cdot \text{lbf}$$

For Pit only

$$h_{\text{s_cover_block}} := \text{root}(t_{\text{pit_floor}} - t_{\text{s_cover_block}}(h), h) \quad h_{\text{s_cover_block}} = 63.8 \cdot \text{ft}$$

$$t_{\text{pit_floor}} = 15 \cdot \text{in}$$

$$x/d = x_d(h_{\text{s_cover_block}}) = 0.05$$

$$V(h_{\text{s_cover_block}}) = 64.1 \cdot \frac{\text{ft}}{\text{sec}}$$

$$PE(W_{\text{cover_block}}, h_{\text{s_cover_block}}) = 1.991 \cdot 10^6 \cdot \text{ft} \cdot \text{lbf}$$

$$h := 0.1 \cdot \text{ft}, 2 \cdot \text{ft} \dots 900 \cdot \text{ft}$$

Cover Block - Tank C106 Pump Pit Cover Block Drop in Pit of Tank Perforation/Scabbing of Concrete Target

Cover Block Drop - Tank C106 Pump Pit Cover Block - SST

$$t_{e_cover_block}(h, d_e) = t_e(f_c, W_{cover_block}, d_e, h, N_p, E_c)$$

$$h = 0.1\text{-ft}, 1\text{-ft}, 300\text{-ft}$$

$$t_{s_cover_block}(h, d_e) = t_s(f_c, W_{cover_block}, d_e, h, N_p, E_c)$$

Cover Block - Tank C106 Pump Pit Cover Block Drop in Pit of Tank Perforation/Scabbing of Concrete Target

Cover Block Drop - Tank C106 Pump Pit Cover Block - SST

Perpendicular flat end drop

Penetration into Concrete Pit of Tank for Hard Missile Impact

$$x_{\text{cover_block}}(h) := x(f_c, W_{\text{cover_block}}, d_{\text{e_cover_block}}, h, N_p, E_c)$$

Penetration

$$t_{\text{d_cover_block}}(h) := t_d(f_c, W_{\text{cover_block}}, d_{\text{e_cover_block}}, h, N_p, E_c)$$

Duration of impact

$$F_{A_cover_block}(h) := F_A(f_c, W_{\text{cover_block}}, d_{\text{e_cover_block}}, h, N_p, E_c)$$

Average constant impact force

$$h := 1 \cdot \text{ft} \quad h_{\text{c_cover_block}} := \text{root}(P_{\text{c_cover_block}} - F_{A_cover_block}(h), h)$$

Missile crush load drop height

$$h_{\text{c_cover_block}} = 28.138 \cdot \text{ft}$$

$$h := 0.01 \cdot \text{ft}, 2 \cdot \text{ft}, 20 \cdot \text{ft}$$

Penetration

Duration of impact

Missile crush load

Average Constant Impact Force

$$P_{\text{c_cover_block}} = 5.976 \cdot 10^6 \cdot \text{lbf}$$

Cover Block Drop - Tank C106 Pump Pit Cover Block - SST

Drop on Soil above Tank

$t_{\text{soil}} = 5 \text{ ft}$ minimum soil cover depth

$S = 5$ approximate soil factor for dry sandy soil conditions at Hanford

$$W_{\text{cover_block}} = 31200 \cdot \text{lb}_f$$

$$A_{\text{cover_block}} = 2.052 \cdot 10^3 \cdot \text{in}^2$$

$$N_p = 0.84$$

Maximum drop height to just perforate minimum soil cover.

$$x_{\text{soil_cover_block}}(h, S, A) = x_{\text{soil}}(W_{\text{cover_block}}, A, h, S, N_p)$$

$$h_{\text{soil_cover_block}} = \text{root}(t_{\text{soil}} - x_{\text{soil_cover_block}}(h, S, A_{\text{cover_block}}), h) \quad h_{\text{soil_cover_block}} = 605 \cdot \text{ft}$$

Corresponding initial impact velocity.

$$V(h_{\text{soil_cover_block}}) = 197.351 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{cover_block}}, h_{\text{soil_cover_block}}) = 1.888 \cdot 10^7 \cdot \text{ft} \cdot \text{lb}_f$$

Cover Block - Tank C106 Pump Pit Cover Block Drop on Soil above Tank Penetration into Soil

$h = 0.1 \text{ ft}, 2 \text{ ft}.. 800 \text{ ft}$

Turbine Transfer Pump Drop - DCRT

$$W_{\text{turbine_pump}} := 1000 \cdot \text{lbf} \quad L_{\text{turbine_pump}} := 25 \cdot \text{ft}$$

$$d_{\text{turbine_pump}} := 4.5 \cdot \text{in} \quad \text{4-in. Schedule-40 304L pipe}$$

$$t_{\text{turbine_pump}} := 0.237 \cdot \text{in}$$

$$A_{\text{turbine_pump}} = A_{\text{pipe}}(d_{\text{turbine_pump}}, t_{\text{turbine_pump}}) \quad A_{\text{turbine_pump}} = 3.174 \cdot \text{in}^2$$

$$d_{\text{p_turbine_pump}} := 4.5 \cdot \text{in} \quad \text{open pipe - contacting impact end}$$

$$t_{\text{p_turbine_pump}} := 0.237 \cdot \text{in}$$

$$A_{\text{p_turbine_pump}} := A_{\text{pipe}}(d_{\text{p_turbine_pump}}, t_{\text{p_turbine_pump}})$$

Frontal (projected) area of projectile

$$A_{\text{p_turbine_pump}} = 3.174 \cdot \text{in}^2$$

$$d_{\text{e_turbine_pump}} := d_{\text{e}}(A_{\text{p_turbine_pump}})$$

Effective missile diameter

$$d_{\text{e_turbine_pump}} = 2.01 \cdot \text{in}$$

$$I_{\text{turbine_pump}} := I_{\text{pipe}}(d_{\text{turbine_pump}}, t_{\text{turbine_pump}})$$

$$I_{\text{turbine_pump}} = 7.233 \cdot \text{in}^4$$

$$\gamma_{\text{turbine_pump}} := \frac{W_{\text{turbine_pump}}}{A_{\text{turbine_pump}} \cdot L_{\text{turbine_pump}}}$$

Specific weight

$$\gamma_{\text{turbine_pump}} = 1.05 \cdot \frac{\text{lbf}}{\text{in}^3}$$

$$\rho_{\text{turbine_pump}} := \frac{\gamma_{\text{turbine_pump}}}{g}$$

Density

$$\rho_{\text{turbine_pump}} = 0.003 \cdot \frac{\text{lbf} \cdot \text{sec}^2}{\text{in}^4}$$

$$c_{\text{o_turbine_pump}} := c_{\text{o}}(E_{\text{s}}, \rho_{\text{turbine_pump}}) \quad \text{Velocity of stress wave in impacting missile}$$

$$c_{\text{o_turbine_pump}} = 8.605 \cdot 10^3 \cdot \frac{\text{ft}}{\text{sec}}$$

$$P_{\text{y_turbine_pump}} := P_{\text{y}}(S_{\text{y304L}}, A_{\text{turbine_pump}})$$

$$P_{\text{y_turbine_pump}} = 7.935 \cdot 10^4 \cdot \text{lbf}$$

$$K_{\text{bc}} := 1$$

Buckling/Crush Load Evaluation for Missile

$$P_{\text{b_turbine_pump}} := P_{\text{buckling}}(K_{\text{bc}}, E_{\text{s}}, I_{\text{turbine_pump}}, L_{\text{turbine_pump}})$$

$$P_{\text{b_turbine_pump}} = 2.3 \cdot 10^4 \cdot \text{lbf}$$

$$P_{\text{c_turbine_pump}} := P_{\text{c}}(P_{\text{b_turbine_pump}}, P_{\text{y_turbine_pump}})$$

$$P_{\text{c_turbine_pump}} = 1.783 \cdot 10^4 \cdot \text{lbf}$$

$$\sigma_{\text{p_turbine_pump}} := \sigma_{\text{p}}(P_{\text{c_turbine_pump}}, A_{\text{turbine_pump}})$$

$$\sigma_{\text{p_turbine_pump}} = 5618 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$f_{\text{c}} = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$\sigma_{\text{t}} = 6000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

Type of impact (hard/soft) predicted

$$\sigma_{\text{p_turbine_pump}} < \sigma_{\text{t}} \Rightarrow \text{soft impact}$$

Thickness of concrete target = thickness of pit slab

$$t_{\text{pit_slab}} := 12 \cdot \text{in}$$

$$N_{\text{p}} := 0.84 \quad \text{assume blunt nose projectile}$$

Petration of missile to missile effective diameter ratio (x/d)

$$x_{\text{d}}(h) := \frac{x(f_{\text{c}}, W_{\text{turbine_pump}}, d_{\text{e_turbine_pump}}, h, N_{\text{p}}, E_{\text{s}})}{d_{\text{e_turbine_pump}}}$$

Turbine Transfer Pump Drop - DCRT

$$W_{\text{turbine_pump}} = 1000 \cdot \text{lb} \cdot \text{f}$$

Drop in Concrete Pit of Tank

$$d_{\text{e_turbine_pump}} = 2.01 \cdot \text{in}$$

$$N_p = 0.84$$

$$f_c = 3000 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2}$$

Maximum drop height to preclude perforation or punching shear failure of concrete target (for soft missile impact).

$$t_{\text{e_turbine_pump}}(h) := t_e(f_c, W_{\text{turbine_pump}}, d_{\text{e_turbine_pump}}, h, N_p, E_s)$$

For Pit Slab concrete thickness

$$h_{\text{e_turbine_pump}} := \text{root}(t_{\text{pit_slab}} - t_{\text{e_turbine_pump}}(h), h) \quad h_{\text{e_turbine_pump}} = 43 \cdot \text{ft}$$

$$t_{\text{pit_slab}} = 12 \cdot \text{in}$$

$$x/d = x_d(h_{\text{e_turbine_pump}}) = 2.95$$

Corresponding initial impact velocity.

$$V(h_{\text{e_turbine_pump}}) = 52.6 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$\text{PE}(W_{\text{turbine_pump}}, h_{\text{e_turbine_pump}}) = 4.297 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

Maximum drop height to preclude scabbing of concrete target (for hard missile impact).

$$t_{\text{s_turbine_pump}}(h) := t_s(f_c, W_{\text{turbine_pump}}, d_{\text{e_turbine_pump}}, h, N_p, E_s)$$

For Pit Slab concrete thickness

$$h_{\text{s_turbine_pump}} := \text{root}(t_{\text{pit_slab}} - t_{\text{s_turbine_pump}}(h), h) \quad h_{\text{s_turbine_pump}} = 22.7 \cdot \text{ft}$$

$$t_{\text{pit_slab}} = 12 \cdot \text{in}$$

$$x/d = x_d(h_{\text{s_turbine_pump}}) = 2.1$$

Corresponding initial impact velocity.

$$V(h_{\text{s_turbine_pump}}) = 38.3 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$\text{PE}(W_{\text{turbine_pump}}, h_{\text{s_turbine_pump}}) = 2.274 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

Turbine Transfer Pump Drop in DCRT Pit Perforation/Scabbing of Concrete Target

$$h := 0.01 \cdot \text{ft}, 0.5 \cdot \text{ft} \dots 50 \cdot \text{ft}$$

Turbine Transfer Pump Drop - DCRT

Penetration into Concrete Pit of Tank for Hard Missile Impact

$$\begin{aligned} x_{\text{turbine_pump}}(h) &:= x(f_c, W_{\text{turbine_pump}}, d_{\text{e_turbine_pump}}, h, N_p, E_s) && \text{Penetration} \\ t_{\text{d_turbine_pump}}(h) &:= t_d(f_c, W_{\text{turbine_pump}}, d_{\text{e_turbine_pump}}, h, N_p, E_s) && \text{Duration of impact} \\ F_{A_turbine_pump}(h) &:= F_A(f_c, W_{\text{turbine_pump}}, d_{\text{e_turbine_pump}}, h, N_p, E_s) && \text{Average constant impact force} \end{aligned}$$

$$h := 1 \cdot \text{ft} \quad h_{\text{c_turbine_pump}} := \text{root}(P_{\text{c_turbine_pump}} - F_{A_turbine_pump}(h), h) \quad \text{Missile crush load drop height}$$

$$h_{\text{c_turbine_pump}} = 2.179 \cdot \text{ft}$$

$$h := 0.01 \cdot \text{ft}, 2 \cdot \text{ft}..20 \cdot \text{ft}$$

Penetration

Duration of impact

Missile crush load

$$P_{\text{c_turbine_pump}} = 1.783 \cdot 10^4 \cdot \text{lbf}$$

Average Constant Impact Force

Submersible Transfer Pump Drop - DCRT

$$W_{\text{submersible_pump}} := 1000 \cdot \text{lb} \cdot \text{f} \quad L_{\text{submersible_pump}} := 25 \cdot \text{ft}$$

$$d_{\text{submersible_pump}} := 2.875 \cdot \text{in} \quad \text{2.5-in. Schedule-40 304L pipe}$$

$$t_{\text{submersible_pump}} := 0.203 \cdot \text{in}$$

$$A_{\text{submersible_pump}} := A_{\text{pipe}}(d_{\text{submersible_pump}}, t_{\text{submersible_pump}}) \quad A_{\text{submersible_pump}} = 1.704 \cdot \text{in}^2$$

$$d_{\text{p_submersible_pump}} := 6 \cdot \text{in} \quad \text{contacting impact end - closed pipe}$$

$$t_{\text{p_submersible_pump}} := \frac{d_{\text{p_submersible_pump}}}{2}$$

$$A_{\text{p_submersible_pump}} := A_{\text{pipe}}(d_{\text{p_submersible_pump}}, t_{\text{p_submersible_pump}})$$

Frontal (projected) area of projectile

$$A_{\text{p_submersible_pump}} = 28.274 \cdot \text{in}^2$$

$$d_{\text{e_submersible_pump}} := d_{\text{e}}(A_{\text{p_submersible_pump}})$$

Effective missile diameter

$$d_{\text{e_submersible_pump}} = 6 \cdot \text{in}$$

$$I_{\text{submersible_pump}} := I_{\text{pipe}}(d_{\text{submersible_pump}}, t_{\text{submersible_pump}})$$

$$I_{\text{submersible_pump}} = 1.53 \cdot \text{in}^4$$

$$\gamma_{\text{submersible_pump}} := \frac{W_{\text{submersible_pump}}}{A_{\text{submersible_pump}} \cdot L_{\text{submersible_pump}}} \quad \text{Specific weight}$$

$$\gamma_{\text{submersible_pump}} = 1.956 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^3}$$

$$\rho_{\text{submersible_pump}} := \frac{\gamma_{\text{submersible_pump}}}{g} \quad \text{Density}$$

$$\rho_{\text{submersible_pump}} = 0.005 \cdot \frac{\text{lb} \cdot \text{f} \cdot \text{sec}^2}{\text{in}^4}$$

$$c_{\text{o_submersible_pump}} := c_{\text{o}}(E_{\text{s}}, \rho_{\text{submersible_pump}}) \quad \text{Velocity of stress wave in impacting missile}$$

$$c_{\text{o_submersible_pump}} = 6.305 \cdot 10^3 \cdot \frac{\text{ft}}{\text{sec}}$$

$$P_{\text{y_submersible_pump}} := P_{\text{y}}(S_{\text{y304L}}, A_{\text{submersible_pump}})$$

$$P_{\text{y_submersible_pump}} = 4.26 \cdot 10^4 \cdot \text{lb} \cdot \text{f}$$

$$K_{\text{bc}} := 1$$

Buckling/Crush Load Evaluation for Missile

$$P_{\text{b_submersible_pump}} := P_{\text{buckling}}(K_{\text{bc}}, E_{\text{s}}, I_{\text{submersible_pump}}, L_{\text{submersible_pump}})$$

$$P_{\text{b_submersible_pump}} = 4.864 \cdot 10^3 \cdot \text{lb} \cdot \text{f}$$

$$P_{\text{c_submersible_pump}} := P_{\text{c}}(P_{\text{b_submersible_pump}}, P_{\text{y_submersible_pump}})$$

$$P_{\text{c_submersible_pump}} = 4.366 \cdot 10^3 \cdot \text{lb} \cdot \text{f}$$

$$\sigma_{\text{p_submersible_pump}} := \sigma_{\text{p}}(P_{\text{c_submersible_pump}}, A_{\text{submersible_pump}})$$

$$\sigma_{\text{p_submersible_pump}} = 2562 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2}$$

$$f_{\text{c}} = 3000 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2} \quad \sigma_{\text{t}} = 6000 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2}$$

Type of impact (hard/soft) predicted

$$\sigma_{\text{p_submersible_pump}} < \sigma_{\text{t}} \Rightarrow \text{soft impact}$$

Thickness of concrete target = thickness of pit slab

$$t_{\text{pit_slab}} := 12 \cdot \text{in}$$

$$N_{\text{p}} := 0.84 \quad \text{assume blunt nose projectile}$$

Penetration of missile to missile effective diameter ratio (x/d)

$$x_{\text{d}}(h) := \frac{x(f_{\text{c}}, W_{\text{submersible_pump}}, d_{\text{e_submersible_pump}}, h, N_{\text{p}}, E_{\text{s}})}{d_{\text{e_submersible_pump}}}$$

Submersible Transfer Pump Drop - DCRT

$$W_{\text{submersible_pump}} = 1000 \cdot \text{lb} \cdot \text{f}$$

Drop in Concrete Pit of Tank

$$d_{\text{e_submersible_pump}} = 6 \cdot \text{in}$$

$$N_p = 0.84$$

$$f_c = 3000 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2}$$

Maximum drop height to preclude perforation or punching shear failure of concrete target (for soft missile impact).

$$t_{\text{e_submersible_pump}}(h) := t_e(f_c, W_{\text{submersible_pump}}, d_{\text{e_submersible_pump}}, h, N_p, E_s)$$

For Pit Slab concrete thickness

$$h_{\text{e_submersible_pump}} := \text{root}(t_{\text{pit_slab}} - t_{\text{e_submersible_pump}}(h), h)$$

$$t_{\text{pit_slab}} = 12 \cdot \text{in}$$

$$x/d = x_d(h_{\text{e_submersible_pump}}) = 0.6$$

$$h_{\text{e_submersible_pump}} = 43 \cdot \text{ft}$$

Corresponding initial impact velocity.

$$V(h_{\text{e_submersible_pump}}) = 52.6 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{submersible_pump}}, h_{\text{e_submersible_pump}}) = 4.3 \cdot 10^4 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

Maximum drop height to preclude scabbing of concrete target (for hard missile impact).

$$t_{\text{s_submersible_pump}}(h) := t_s(f_c, W_{\text{submersible_pump}}, d_{\text{e_submersible_pump}}, h, N_p, E_s)$$

For Pit + Dome concrete thickness

$$h_{\text{s_submersible_pump}} := \text{root}(t_{\text{pit_slab}} - t_{\text{s_submersible_pump}}(h), h)$$

$$t_{\text{pit_slab}} = 12 \cdot \text{in}$$

$$x/d = x_d(h_{\text{s_submersible_pump}}) = 0.25$$

$$h_{\text{s_submersible_pump}} = 6.1 \cdot \text{ft}$$

Corresponding initial impact velocity.

$$V(h_{\text{s_submersible_pump}}) = 19.8 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{submersible_pump}}, h_{\text{s_submersible_pump}}) = 6.095 \cdot 10^3 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

Submersible Transfer Pump Drop in Pit of DCRT Perforation/Scabbing of Concrete Target

$$h := 0.01 \cdot \text{ft}, 0.5 \cdot \text{ft}.. 50 \cdot \text{ft}$$

Submersible Transfer Pump Drop - DCRT Penetration into Concrete Pit of Tank for Hard Missile Impact

$$\begin{aligned} x_{\text{submersible_pump}}(h) &:= x(f_c, W_{\text{submersible_pump}}, d_{\text{e_submersible_pump}}, h, N_p, E_s) && \text{Penetration} \\ t_{\text{d_submersible_pump}}(h) &:= t_d(f_c, W_{\text{submersible_pump}}, d_{\text{e_submersible_pump}}, h, N_p, E_s) && \text{Duration of impact} \\ F_{A_submersible_pump}(h) &:= F_A(f_c, W_{\text{submersible_pump}}, d_{\text{e_submersible_pump}}, h, N_p, E_s) && \text{Average constant impact force} \end{aligned}$$

$$\begin{aligned} h &= 1 \text{ ft} && h_{\text{c_submersible_pump}} = \text{root}(P_{\text{c_submersible_pump}} - F_{A_submersible_pump}(h), h) \\ &&& h_{\text{c_submersible_pump}} = 0.914 \text{ in} && \text{Missile crush load drop height} \end{aligned}$$

$$h = 0.01 \text{ ft}, 2 \text{ ft}, 20 \text{ ft}$$

Penetration

Duration of impact

Missile crush load

Average Constant Impact Force

$$P_{\text{c_submersible_pump}} = 4.366 \cdot 10^3 \text{ lbf}$$

Cover Block Drop - DCRT

$$W_{\text{cover_block}} = 26875 \cdot \text{lb} \cdot \text{f} \quad L_{\text{cover_block}} = 20 \cdot \text{ft}$$

$$d_{\text{cover_block}} = 4 \cdot \text{ft} + 5.75 \cdot \text{in} \quad \text{end dimension}$$

$$t_{\text{cover_block}} = 2 \cdot \text{ft}$$

$$A_{\text{cover_block}} = d_{\text{cover_block}} \cdot t_{\text{cover_block}}$$

$$A_{\text{cover_block}} = 1.29 \cdot 10^3 \cdot \text{in}^2$$

$$d_{\text{p_cover_block}} = d_{\text{cover_block}}$$

$$t_{\text{p_cover_block}} = t_{\text{cover_block}}$$

$$A_{\text{p_cover_block}} = d_{\text{p_cover_block}} \cdot t_{\text{p_cover_block}}$$

Frontal (projected) area of projectile

$$A_{\text{p_cover_block}} = 1.29 \cdot 10^3 \cdot \text{in}^2$$

$$d_{\text{e_cover_block}} = d_e(A_{\text{p_cover_block}})$$

Effective missile diameter

$$d_{\text{e_cover_block}} = 40.528 \cdot \text{in}$$

$$I_{\text{cover_block}} = \frac{1}{12} \cdot d_{\text{cover_block}} \cdot t_{\text{cover_block}}^3$$

$$I_{\text{cover_block}} = 6.192 \cdot 10^4 \cdot \text{in}^4$$

$$\gamma_{\text{cover_block}} = \frac{W_{\text{cover_block}}}{A_{\text{cover_block}} \cdot L_{\text{cover_block}}}$$

Specific weight

$$\gamma_{\text{cover_block}} = 0.087 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^3}$$

$$\rho_{\text{cover_block}} = \frac{\gamma_{\text{cover_block}}}{g}$$

Density

$$\rho_{\text{cover_block}} = 2.248 \cdot 10^{-4} \cdot \frac{\text{lb} \cdot \text{f} \cdot \text{sec}^2}{\text{in}^4}$$

$$c_{\text{o_cover_block}} = c_o(E_c, \rho_{\text{cover_block}})$$

Velocity of stress wave in impacting missile

$$c_{\text{o_cover_block}} = 9.82 \cdot 10^3 \cdot \frac{\text{ft}}{\text{sec}}$$

$$P_{\text{y_cover_block}} = P_y(f_c, A_{\text{cover_block}})$$

$$P_{\text{y_cover_block}} = 3.87 \cdot 10^6 \cdot \text{lb} \cdot \text{f}$$

$$K_{bc} = 1$$

Buckling/Crush Load Evaluation for Missile

$$P_{\text{b_cover_block}} = P_{\text{buckling}}(K_{bc}, E_s, I_{\text{cover_block}}, L_{\text{cover_block}})$$

$$P_{\text{b_cover_block}} = 3.077 \cdot 10^8 \cdot \text{lb} \cdot \text{f}$$

$$P_{\text{c_cover_block}} = P_c(P_{\text{b_cover_block}}, P_{\text{y_cover_block}})$$

$$P_{\text{c_cover_block}} = 3.822 \cdot 10^6 \cdot \text{lb} \cdot \text{f}$$

$$\sigma_{\text{p_cover_block}} = \sigma_p(P_{\text{c_cover_block}}, A_{\text{cover_block}})$$

$$\sigma_{\text{p_cover_block}} = 2963 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2} \quad \sigma_t = 6000 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2}$$

Type of impact (hard/soft) predicted

$$\sigma_{\text{p_cover_block}} < \sigma_t \Rightarrow \text{soft impact}$$

Thickness of concrete target = thickness of pit slab

$$t_{\text{pit_slab}} = 12 \cdot \text{in}$$

$$N_p = 0.84 \quad \text{assume blunt nose projectile}$$

Penetration of missile to missile effective diameter ratio (x/d)

$$x_d(h) = \frac{x(f_c, W_{\text{cover_block}}, d_{\text{e_cover_block}}, h, N_p, E_c)}{d_{\text{e_cover_block}}}$$

Cover Block Drop - DCRT

$$W_{\text{cover_block}} = 26875 \cdot \text{lb} \cdot \text{f}$$

Drop in Concrete Pit of Tank

$$d_{\text{e_cover_block}} = 40.528 \cdot \text{in} \quad N_p = 0.84$$

$$f_c = 3000 \cdot \frac{\text{lb} \cdot \text{f}}{\text{in}^2}$$

Maximum drop height to preclude perforation or punching shear failure of concrete target (for soft missile impact).

$$t_{\text{e_cover_block}}(h) = t_e(f_c, W_{\text{cover_block}}, d_{\text{e_cover_block}}, h, N_p, E_c)$$

Perpendicular flat end drop

For Pit Slab concrete thickness

$$h_{\text{e_cover_block}} = \text{root}(t_{\text{pit_slab}} - t_{\text{e_cover_block}}(h), h) \quad h_{\text{e_cover_block}} = 101 \cdot \text{ft}$$

$$t_{\text{pit_slab}} = 12 \cdot \text{in}$$

$$x/d = x_d(h_{\text{e_cover_block}}) = 0.08$$

Corresponding initial impact velocity.

$$V(h_{\text{e_cover_block}}) = 80.5 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{cover_block}}, h_{\text{e_cover_block}}) = 2.707 \cdot 10^6 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

Maximum drop height to preclude scabbing of concrete target (for hard missile impact).

$$t_{\text{s_cover_block}}(h) = t_s(f_c, W_{\text{cover_block}}, d_{\text{e_cover_block}}, h, N_p, E_c)$$

For Pit + Dome concrete thickness

$$h_{\text{s_cover_block}} = \text{root}(t_{\text{pit_slab}} - t_{\text{s_cover_block}}(h), h) \quad h_{\text{s_cover_block}} = 37.3 \cdot \text{ft}$$

$$t_{\text{pit_slab}} = 12 \cdot \text{in}$$

$$x/d = x_d(h_{\text{s_cover_block}}) = 0.05$$

Corresponding initial impact velocity.

$$V(h_{\text{s_cover_block}}) = 49 \cdot \frac{\text{ft}}{\text{sec}}$$

Corresponding initial potential energy of missile.

$$PE(W_{\text{cover_block}}, h_{\text{s_cover_block}}) = 1.004 \cdot 10^6 \cdot \text{ft} \cdot \text{lb} \cdot \text{f}$$

**Cover Block Drop in DCRT Concrete Pit
Perforation/Scabbing of Concrete Target**

$$h = 0.1 \cdot \text{ft}, 1 \cdot \text{ft}, \dots, 100 \cdot \text{ft}$$

Cover Block Drop - DCRT

$$t_{e_cover_block}(h, d_e) = t_e(f_c, W_{cover_block}, d_e, h, N_p, E_c)$$

$$t_{s_cover_block}(h, d_e) = t_s(f_c, W_{cover_block}, d_e, h, N_p, E_c)$$

$$h = 0.1\text{-ft. to } 100\text{-ft}$$

APPENDIX B

PARAMETRIC RESULTS FOR STEEL OR CONCRETE PROJECTILE IMPACTING CONCRETE ($f_c = 3,000 \text{ lb/in}^2$) OR SOIL

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ICF Kaiser Hanford

EVALUATION ANALYSIS

Calc. No. _____

Revision: _____

Page No. B-1 of B-33Client: Westinghouse Hanford Company

WO/Job No. _____

Subject: Tank Farm Drop Load EvaluationDate: Sept 13, 1996By: L. J. JulykLocation: 200 Area - Hanford SiteChecked: 9-24-96By: K.H. Zund

Revised: _____

By: _____

APPENDIX B

Parametric Results for Steel or Concrete Projectile Impacting Concrete Target ($f_c = 3,000 \text{ lbf/in}^2$) or Soil

NDRC Equations - Local Effects for Concrete Target Impacted by Steel or Concrete Projectile

Determination of the penetration of the projectile into the concrete using modified NDRC formula (see ASCE 1980, Section 6.4.1, Equation 6.33) assuming nondeformable projectile impacting massive concrete target:

$$g = 32.174 \frac{\text{ft}}{\text{sec}^2} \quad \text{acceleration due to gravity} \quad E_m = 29 \cdot 10^6 \frac{\text{lbf}}{\text{in}^2} \quad \text{reference modulus of elasticity for mild steel missile}$$

$$V(h) = \sqrt{2 \cdot g \cdot h} \quad \text{initial impact velocity (ft/sec) of projectile dropped from height, h, above target}$$

$$K_{cp}(f_c, E) = \frac{180}{\sqrt{f_c}} \left(\frac{1}{\text{lbf}} \left(\frac{E}{E_m} \right) \right)^{1.25} \quad \text{modified concrete penetrability factor by Kar (Adeli and Amin 1985)}$$

$$x_1(f_c, W, d, h, N_p, E) = \sqrt[4]{4 K_{cp}(f_c, E) \cdot N_p \cdot W \cdot d \left(\frac{V(h)}{1000 \frac{\text{ft}}{\text{sec}} \frac{d}{\text{in}}} \right)^{1.80}} \quad \text{for } x/d < 2.0$$

$$x_2(f_c, W, d, h, N_p, E) = K_{cp}(f_c, E) \cdot N_p \cdot W \cdot \left(\frac{V(h)}{1000 \frac{\text{ft}}{\text{sec}} \frac{d}{\text{in}}} \right)^{1.80} + d \quad \text{for } x/d > 2.0$$

$$x(f_c, W, d, h, N_p, E) = \text{if} \left(\frac{x_1(f_c, W, d, h, N_p, E)}{d} \leq 2, x_1(f_c, W, d, h, N_p, E), x_2(f_c, W, d, h, N_p, E) \right)$$

where

x = Total penetration depth (in), i.e., the depth which a projectile will penetrate into an infinitely thick target. As defined herein, the penetration depth neglects all rear boundary effects and is applicable only when the target thickness is sufficiently great to prevent rear face scabbing.

h = Initial drop height (ft) of projectile above target

N_p = Nose-shape factor for projectile
 = 0.72 for flat nosed projectile
 = 0.84 for blunt nosed projectile
 = 1.0 for average bullet nosed (spherical end) projectile
 = 1.14 for very sharp nosed projectile

W = Weight of projectile (lbf)

A_p = Frontal (projected) area of projectile (in^2)

$V(h)$ = Projectile initial impact velocity (ft/s)

f_c = Ultimate compressive strength (lbf/in^2) of concrete target

$$d = d_c(A_p) = \sqrt{\frac{4 \cdot A_p}{\pi}} \quad \text{Effective missile diameter (in.)}$$

E = Modulus of elasticity of missile material

Perforation Thickness for Soft Missiles Impact

Soft missiles will not cause local penetration with the exception of possible punching shear. However, punching shear can be prevented by requiring that the concrete thickness is at least 1.2 times that required at perforation as obtained for hard missile impact. The minimum concrete target thickness for perforation is

$$e_1(f_c, W, d, h, N_p, E) = d \left(1.32 + 1.24 \frac{x(f_c, W, d, h, N_p, E)}{d} \right) \quad \text{for } 1.35 < x/d < 13.5$$

$$e_2(f_c, W, d, h, N_p, E) = d \left[3.19 \frac{x(f_c, W, d, h, N_p, E)}{d} - 0.718 \left(\frac{x(f_c, W, d, h, N_p, E)}{d} \right)^2 \right] \quad \text{for } x/d < 1.35$$

$$e(f_c, W, d, h, N_p, E) = \text{if} \left(\frac{x(f_c, W, d, h, N_p, E)}{d} \leq 1.35, e_2(f_c, W, d, h, N_p, E), e_1(f_c, W, d, h, N_p, E) \right)$$

The minimum concrete target thickness to prevent perforation or punching shear failure for soft missile impact is

$$t_e(f_c, W, d, h, N_p, E) = 1.2 \cdot e(f_c, W, d, h, N_p, E)$$

For Hard Missile Impact

$$t_d(f_c, W, d, h, N_p, E) = \frac{2 \cdot x(f_c, W, d, h, N_p, E)}{V(h)} \quad \text{duration of impact}$$

$$F_A(f_c, W, d, h, N_p, E) = \frac{W}{g} \frac{V(h)}{t_d(f_c, W, d, h, N_p, E)} \quad \text{average constant impact force}$$

Scabbing Thickness for Hard Missile Impact

The concrete thickness required to resist hard missile impact should be at least 1.2 times the scabbing thickness. The minimum concrete target thickness for scabbing with Kar correction (Adeli and Amin 1985) is

$$s_1(f_c, W, d, h, N_p, E) = d \left(2.12 + 1.36 \frac{x(f_c, W, d, h, N_p, E)}{d} \right) \left(\frac{E}{E_m} \right)^{0.2} \quad \text{for } 0.65 < x/d < 11.75$$

$$s_2(f_c, W, d, h, N_p, E) = d \left[7.91 \frac{x(f_c, W, d, h, N_p, E)}{d} - 5.06 \left(\frac{x(f_c, W, d, h, N_p, E)}{d} \right)^2 \right] \left(\frac{E}{E_m} \right)^{0.2} \quad \text{for } x/d < 0.65$$

$$s(f_c, W, d, h, N_p, E) = \text{if} \left(\frac{x(f_c, W, d, h, N_p, E)}{d} \leq 0.65, s_2(f_c, W, d, h, N_p, E), s_1(f_c, W, d, h, N_p, E) \right)$$

The minimum concrete target thickness to prevent scabbing failure for hard missile impact is

$$t_s(f_c, W, d, h, N_p, E) = 1.2 \cdot s(f_c, W, d, h, N_p, E)$$

Warning, the NDRC equations only consider the local effects on the concrete target from an impacting projectile. These equations were developed from impact tests using essentially nondeforming projectiles impacting massive concrete targets. Test velocities were generally much higher than would be expected from equipment drops over Hanford underground waste storage tanks. The results from application of the NDRC equations are expected to give conservative predictions for maximum drop height restrictions with respect to local effects on the concrete target. However, these results should not be applied without considering the global response of the structure to the resulting impulse loading associated with the impact.

Young's Equation for Depth of Soil Penetration by Impacting Projectile

The penetration of a missile into soil is estimated from empirical equation given by Young (1969) as

$$x_{s1}(W, A_p, h, S, N_p) = 0.53 \cdot S \cdot N_p \cdot \sqrt{\frac{W}{A_p}} \cdot \ln \left[1 + 2 \cdot 10^5 \cdot \left[\frac{V(h)}{\left(\frac{ft}{sec} \right)} \right]^2 \right] \quad \text{for } V < 200 \text{ ft/sec}$$

$$x_{s2}(W, A_p, h, S, N_p) = 0.0031 \cdot S \cdot N_p \cdot \sqrt{\frac{W}{A_p}} \cdot \ln \left[\left[\frac{V(h)}{\left(\frac{ft}{sec} \right)} \right] - 100 \right] \cdot ft \quad \text{for } V > 200 \text{ ft/sec}$$

$$x_{soil}(W, A_p, h, S, N_p) = \text{if} \left(V(h) < 200 \cdot \frac{ft}{sec}, x_{s1}(W, A_p, h, S, N_p), x_{s2}(W, A_p, h, S, N_p) \right)$$

where

x_{soil} = Penetration depth (ft) into soil

h = Initial drop height (ft) of projectile above target

N_p = Nose-shape factor for projectile

= 0.72 for flat nosed projectile

= 0.84 for blunt nosed projectile

= 1.0 for average bullet nosed (spherical end) projectile

= 1.14 for very sharp nosed projectile

W = Weight of projectile (lbf)

A_p = Frontal (projected) area of projectile (in²)

$V(h)$ = Projectile initial impact velocity (ft/s)

S = Soil coefficient, range for Hanford soil conditions is estimated at 4 to 6 on basis of data given in Young (1969).

Modulus and ultimate compressive strength of concrete

$$f_c := 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$E_c := 57000 \cdot \sqrt{f_c \cdot \frac{\text{lbf}}{\text{in}^2}}$$

$$E_c = 3.122 \cdot 10^6 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$E_s := E_m$$

Check: AZ Mixer Pump

$$N_p := 0.84$$

$$S := 5 \quad t_{\text{soil}} := 5 \cdot \text{ft}$$

$$t_c := 30 \cdot \text{in}$$

$$W := 27000 \cdot \text{lbf}$$

$$d := 29.933 \cdot \text{in}$$

$$h = 1 \cdot \text{ft}$$

Maximum Drop Height to just Perforate Minimum Soil Cover Depth

$$h_{\text{soil}}(t_{\text{soil}}, W, d, S, N_p) := \text{root}\left(t_{\text{soil}} - x_{\text{soil}}\left(W, \frac{\pi d^2}{4}, h, S, N_p\right), h\right)$$

$$h_{\text{soil}}(t_{\text{soil}}, W, d, S, N_p) = 339.393 \cdot \text{ft}$$

$$h = 0.05 \cdot \text{ft}$$

Maximum Drop Height to Perforate Concrete Target

$$h_s(t_c, f_c, W, d, N_p, E) := \text{root}(t_c - t_s(f_c, W, d, h, N_p, E), h)$$

$$h_s(t_c, f_c, W, d, N_p, E_s) = 4.022 \cdot \text{ft}$$

$$h = 1 \cdot \text{ft}$$

Maximum Drop Height to Cause Scabbing Failure of Concrete Target

$$h_e(t_c, f_c, W, d, N_p, E) := \text{root}(t_c - t_e(f_c, W, d, h, N_p, E), h)$$

$$h_e(t_c, f_c, W, d, N_p, E_s) = 29.53 \cdot \text{ft}$$

$$x_s(t_c, f_c, W, d, N_p, E) := x(f_c, W, d, h_s(t_c, f_c, W, d, N_p, E), N_p, E)$$

$$\frac{x_s(t_c, f_c, W, d, N_p, E_s)}{d} = 0.114$$

$$x_e(t_c, f_c, W, d, N_p, E) := x(f_c, W, d, h_e(t_c, f_c, W, d, N_p, E), N_p, E)$$

$$\frac{x_e(t_c, f_c, W, d, N_p, E_s)}{d} = 0.279$$

Duration of impact for scabbing and perforation failure of concrete target, respectively

$$t_{ds}(t_c, f_c, W, d, N_p, E) := t_d(f_c, W, d, h_s(t_c, f_c, W, d, N_p, E), N_p, E)$$

$$t_{ds}(t_c, f_c, W, d, N_p, E_s) = 0.035 \cdot \text{sec}$$

$$t_{de}(t_c, f_c, W, d, N_p, E) := t_d(f_c, W, d, h_e(t_c, f_c, W, d, N_p, E), N_p, E)$$

$$t_{de}(t_c, f_c, W, d, N_p, E_s) = 0.032 \cdot \text{sec}$$

Average constant impact force for scabbing and perforation failure of concrete target, respectively

$$F_{As}(t_c, f_c, W, d, N_p, E) := F_A(f_c, W, d, h_s(t_c, f_c, W, d, N_p, E), N_p, E)$$

$$F_{As}(t_c, f_c, W, d, N_p, E_s) = 3.823 \cdot 10^5 \cdot \text{lb}$$

$$F_{Ae}(t_c, f_c, W, d, N_p, E) := F_A(f_c, W, d, h_e(t_c, f_c, W, d, N_p, E), N_p, E)$$

$$F_{Ae}(t_c, f_c, W, d, N_p, E_s) = 1.144 \cdot 10^6 \cdot \text{lb}$$

Initial impact velocity for scabbing and perforation failure of concrete target, respectively

$$V_s(t_c, f_c, W, d, N_p, E) := V(h_s(t_c, f_c, W, d, N_p, E))$$

$$V_s(t_c, f_c, W, d, N_p, E_s) = 16.088 \cdot \frac{\text{ft}}{\text{sec}}$$

$$V_e(t_c, f_c, W, d, N_p, E) := V(h_e(t_c, f_c, W, d, N_p, E))$$

$$V_e(t_c, f_c, W, d, N_p, E_s) = 43.591 \cdot \frac{\text{ft}}{\text{sec}}$$

**Check OK (see Appendix A,
AZ Mixer Pump Drop)**

The following plots provide a sensitivity of the weight of the projectile, its effective contact diameter, the thickness of the concrete target, and material of the projectile (steel equipment or concrete cover blocks) to the predicted maximum drop height on the basis of the perforation and scabbing local effects criteria. Any application of these curves must also consider the global effect of the impact on the concrete structure.

Steel Projectile Impacting Concrete Structure

$W = 1000 \text{ lbf}$ **Missile Weight** $E_s = E_m$ $f_c = 3000 \frac{\text{lbf}}{\text{in}^2}$ $t_c = 30 \text{ in}$ **Concrete Target Thickness**
 $d = 1 \text{ in}, 1.5 \text{ in}, 20 \text{ in}$ $N_p = 0.84$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Steel Projectile Impacting Concrete Structure

W = 5000·lbf
Missile Weight

Missile Weight

$E_s = 2.9 \cdot 10^7 \cdot \frac{\text{lbf}}{\text{in}^2}$

$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$

$t_c = 30 \cdot \text{in}$

Concrete Target Thickness

$N_p = 0.84$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Steel Projectile Impacting Concrete Structure

W = 10000-lbf

Missile Weight

$$E_s = 2.9 \cdot 10^7 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$t_c = 30 \cdot \text{in}$$

Concrete Target Thickness

$$N_p = 0.84$$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Steel Projectile Impacting Concrete Structure

$W = 15000 \cdot \text{lbf}$ **Missile Weight** $E_s = 2.9 \cdot 10^7 \cdot \frac{\text{lbf}}{\text{in}^2}$ $f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$ $t_c = 30 \cdot \text{in}$ **Concrete Target Thickness**
 $N_p = 0.84$

Steel Projectile Impacting Concrete Structure

$W = 20000\text{-lbf}$

Missile Weight

$E_s = 2.9 \cdot 10^7 \cdot \frac{\text{lbf}}{\text{in}^2}$

$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$

$t_c = 30\text{-in}$

Concrete Target Thickness

$N_p = 0.84$

Steel Projectile Impacting Concrete Structure

$W = 25000 \cdot \text{lb}$

Missile Weight

$E_s = 2.9 \cdot 10^7 \cdot \frac{\text{lb}}{\text{in}^2}$

$f'_c = 3000 \cdot \frac{\text{lb}}{\text{in}^2}$

$t_c = 30 \cdot \text{in}$

Concrete Target Thickness

$N_p = 0.84$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lb)

Initial Impact Velocity (ft/sec)

Steel Projectile Impacting Concrete Structure

$W = 30000 \cdot \text{lb}$

Missile Weight

$E_s = 2.9 \cdot 10^7$

$\cdot \frac{\text{lb}}{\text{in}^2}$

$f_c = 3000 \cdot \frac{\text{lb}}{\text{in}^2}$

$t_c = 30 \cdot \text{in}$

Concrete Target Thickness

$N_p = 0.84$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Steel Projectile Impacting Concrete Structure

$W = 1000\text{-lbf}$

Missile Weight

$E_s = E_m$

$f_c = 3000 \frac{\text{lbf}}{\text{in}^2}$

$t_c = 15\text{ in}$

Concrete Target Thickness

$N_p = 0.84$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Steel Projectile Impacting Concrete Structure

$W = 5000 \cdot \text{lbf}$ **Missile Weight**
 $E_s = 2.9 \cdot 10^7 \cdot \frac{\text{lbf}}{\text{in}^2}$
 $f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$
 $t_c = 15 \cdot \text{in}$ **Concrete Target Thickness**

$N_p = 0.84$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Steel Projectile Impacting Concrete Structure

$W = 10000 \cdot \text{lbf}$ **Missile Weight** $E_s = 2.9 \cdot 10^7 \cdot \frac{\text{lbf}}{\text{in}^2}$ $f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$ $t_c = 15 \cdot \text{in}$ **Concrete Target Thickness**

$N_p = 0.84$

Steel Projectile Impacting Concrete Structure

$W = 15000 \cdot \text{lb}$

Missile Weight

$E_s = 2.9 \cdot 10^7$

$\cdot \frac{\text{lb}}{\text{in}^2}$

$f_c = 3000$

$\cdot \frac{\text{lb}}{\text{in}^2}$

$t_c = 15 \cdot \text{in}$

Concrete Target Thickness

$N_p = 0.84$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lb)

Initial Impact Velocity (ft/sec)

Steel Projectile Impacting Concrete Structure

$W := 20000 \cdot \text{lb}$
 $d := 1 \cdot \text{in}, 1.5 \cdot \text{in} \dots 20 \cdot \text{in}$

Missile Weight

$E_s = 2.9 \cdot 10^7 \cdot \frac{\text{lb}}{\text{in}^2}$

$f_c = 3000 \cdot \frac{\text{lb}}{\text{in}^2}$

Concrete Target Thickness

$t_c = 15 \cdot \text{in}$

$N_p = 0.84$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Steel Projectile Impacting Concrete Structure

$W = 25000 \cdot \text{lb}$
 $d = 1 \cdot \text{in}, 1.5 \cdot \text{in}, 20 \cdot \text{in}$
Missile Weight
 $E_s = 2.9 \cdot 10^7 \cdot \frac{\text{lb}}{\text{in}^2}$
 $N_p = 0.84$
 $f_c = 3000 \cdot \frac{\text{lb}}{\text{in}^2}$
Concrete Target Thickness
 $t_c = 15 \cdot \text{in}$

Steel Projectile Impacting Concrete Structure

$W = 30000 \cdot \text{lb}$ **Missile Weight** $E_s = 2.9 \cdot 10^7 \cdot \frac{\text{lb}}{\text{in}^2}$ $f_c = 3000 \cdot \frac{\text{lb}}{\text{in}^2}$ $t_c = 15 \cdot \text{in}$ **Concrete Target Thickness**
 $d = 1 \cdot \text{in}, 1.5 \cdot \text{in}.. 20 \cdot \text{in}$ $N_p = 0.84$

Concrete Projectile Impacting Concrete Structure

$W := 1000\text{-lb}$ **Missile Weight** $E_s = E_c$ $f_c = 3000\frac{\text{lb}}{\text{in}^2}$ $t_c = 30\text{-in}$ **Concrete Target Thickness**
 $d := 10\text{-in}, 10.5\text{-in}, 40\text{-in}$ $N_p = 0.84$

Concrete Projectile Impacting Concrete Structure

$W = 5000 \cdot \text{lb} \cdot \text{ft}$

Missile Weight

$$E_s = 3.122 \cdot 10^6 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

$$t_c = 30 \cdot \text{in}$$

Concrete Target Thickness

$$N_p = 0.84$$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lb)

Initial Impact Velocity (ft/sec)

Concrete Projectile Impacting Concrete Structure

$W = 10000 \text{ lbf}$

Missile Weight

$$E_s = 3.122 \cdot 10^6 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$t_c = 30 \cdot \text{in}$$

Concrete Target Thickness

$$N_p = 0.84$$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Concrete Projectile Impacting Concrete Structure

$W = 15000 \text{ lbf}$

Missile Weight

$E_s = 3.122 \cdot 10^6 \cdot \frac{\text{lbf}}{\text{in}^2}$

$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$

$t_c = 30 \cdot \text{in}$

Concrete Target Thickness

$N_p = 0.84$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Concrete Projectile Impacting Concrete Structure

$W = 20000 \text{ lbf}$ **Missile Weight**
 $E_s = 3.122 \cdot 10^6 \cdot \frac{\text{lbf}}{\text{in}^2}$
 $f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$
 $t_c = 30 \cdot \text{in}$ **Concrete Target Thickness**
 $N_p = 0.84$

Concrete Projectile Impacting Concrete Structure

$$W = 25000\text{-lbf}$$

Missile
Weight

$$E_s = 3.122 \cdot 10^6$$

$$\cdot \frac{\text{lbf}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$t_c = 30 \cdot \text{in}$$

Concrete Target
Thickness

$$N_p = 0.84$$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Concrete Projectile Impacting Concrete Structure

$$W = 30000 \cdot \text{lb} \cdot \text{ft}$$

Missile Weight

$$E_s = 3.122 \cdot 10^6 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

$$t_c = 30 \cdot \text{in}$$

Concrete Target Thickness

Maximum Drop Height (ft)

$$N_p = 0.84$$

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Concrete Projectile Impacting Concrete Structure

$W = 1000 \text{ lbf}$

Missile Weight

$E_s = E_c$

$f'_c = 3000 \frac{\text{lbf}}{\text{in}^2}$

$t_c = 15 \text{ in}$

Concrete Target Thickness

$N_p = 0.84$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Concrete Projectile Impacting Concrete Structure

W = 5000-lbf

Missile Weight

$$E_s = 3.122 \cdot 10^6 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$t_c = 15 \cdot \text{in}$$

Concrete Target Thickness

$$N_p = 0.84$$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Concrete Projectile Impacting Concrete Structure

W = 10000·lbf

Missile Weight

$$E_s = 3.122 \cdot 10^6 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$t_c = 15 \cdot \text{in}$$

Concrete Target Thickness

$$N_p = 0.84$$

Concrete Projectile Impacting Concrete Structure

 $W = 15000 \text{ lbf}$ **Missile Weight**

$$E_s = 3.122 \cdot 10^6 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$t_c = 15 \cdot \text{in}$$

Concrete Target Thickness

$$N_p = 0.84$$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Concrete Projectile Impacting Concrete Structure $W = 20000 \text{ lbf}$ **Missile
Weight**

$$E_s = 3.122 \cdot 10^6 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$$

$$t_c = 15 \cdot \text{in}$$

**Concrete Target
Thickness****Maximum Drop Height (ft)**

$$N_p = 0.84$$

Duration of Impact (sec) **x/d Ratio** **Average Constant Impact Force (lbf)** **Initial Impact Velocity (ft/sec)**

Concrete Projectile Impacting Concrete Structure

 $W = 25000 \cdot \text{lb}$ **Missile
Weight**

$$E_s = 3.122 \cdot 10^6 \cdot \frac{\text{lb} \cdot \text{ft}}{\text{in}^2}$$

$$f_c = 3000 \cdot \frac{\text{lb}}{\text{in}^2}$$

$$t_c = 15 \cdot \text{in}$$

**Concrete Target
Thickness**

$$N_p = 0.84$$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Concrete Projectile Impacting Concrete Structure

$W = 30000 \text{ lbf}$

Missile Weight

$E_s = 3.122 \cdot 10^6 \cdot \frac{\text{lbf}}{\text{in}^2}$

$f_c = 3000 \cdot \frac{\text{lbf}}{\text{in}^2}$

$t_c = 15 \cdot \text{in}$

Concrete Target Thickness

$N_p = 0.84$

Maximum Drop Height (ft)

Duration of Impact (sec)

x/d Ratio

Average Constant Impact Force (lbf)

Initial Impact Velocity (ft/sec)

Concrete or Steel Projectile Impacting Soil

$d = 1\text{-in.}, 1.5\text{-in.}, 20\text{-in.}$

$N_p = 0.84$

$t_{\text{soil}} = 5\text{-ft}$

$S = 6$

Maximum Drop Height (ft) to just Perforate Through Minimum Soil Cover Depth of 5 ft

W (lbf) = 1000, 5000, 10000, 15000, 20000, 25000, 30000

$d = 20\text{-in.}, 20.5\text{-in.}, 40\text{-in.}$

W (lbf) = 1000

APPENDIX C

ADDITIONAL PARAMETRIC RESULTS FOR STEEL PROJECTILE IMPACTING CONCRETE TARGET ($f_c = 5,000, 4,000, 3000, 2,500 \text{ lb/in}^2$)

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ICF Kaiser Hanford

EVALUATION ANALYSIS

Calc. No. _____

Revision: _____

Page No. C-1 of C-46Client: Westinghouse Hanford Company

WO/Job No. _____

Subject: Tank Farm Drop Load EvaluationDate: Sept 13, 1996By: L. J. JulykLocation: 200 Area - Hanford SiteChecked: 9-24-96By: H. H. E. E. E.

Revised: _____

By: _____

APPENDIX C

Additional Parametric Results for Steel Projectile Impacting Concrete Target with Compressive Strength $f_c = 5,000, 4,000, 3,000$, and $2,500$ lbf/in²**NDRC Equations - Local Effects for Concrete Target Impacted by Steel Projectile**

Determination of the penetration of the projectile into the concrete using modified NDRC formula (see ASCE 1980, Section 6.4.1, Equation 6.33) assuming nondeformable projectile impacting massive concrete target:

$$g = 32.174 \cdot \frac{\text{ft}}{\text{sec}^2} \quad \text{acceleration due to gravity} \quad E_m = 29 \cdot 10^6 \cdot \frac{\text{lbf}}{\text{in}^2} \quad \text{reference modulus of elasticity for mild steel missile}$$

$$V(h) = \sqrt{2 \cdot g \cdot h} \quad \text{initial impact velocity (ft/sec) of projectile dropped from height, h, above target}$$

$$K_{cp}(f_c, E) = \frac{180}{\sqrt{f_c}} \cdot \sqrt{\frac{1}{\text{lbf}} \cdot \left(\frac{E}{E_m} \right)^{1.25}} \quad \text{modified concrete penetrability factor by Kar (Adeli and Amin 1985)}$$

$$x_1(f_c, W, d, h, N_p, E) = \sqrt[4]{4 \cdot K_{cp}(f_c, E) \cdot N_p \cdot W \cdot d \cdot \left(\frac{V(h)}{1000 \cdot \frac{\text{ft}}{\text{sec}} \cdot \frac{\text{d}}{\text{in}}} \right)^{1.80}} \quad \text{for } x/d < 2.0$$

$$x_2(f_c, W, d, h, N_p, E) = K_{cp}(f_c, E) \cdot N_p \cdot W \cdot \left(\frac{V(h)}{1000 \cdot \frac{\text{ft}}{\text{sec}} \cdot \frac{\text{d}}{\text{in}}} \right)^{1.80} + d \quad \text{for } x/d > 2.0$$

$$x(f_c, W, d, h, N_p, E) = \text{if} \left(\frac{x_1(f_c, W, d, h, N_p, E)}{d} \leq 2, x_1(f_c, W, d, h, N_p, E), x_2(f_c, W, d, h, N_p, E) \right)$$

where

x = Total penetration depth (in), i.e., the depth which a projectile will penetrate into an infinitely thick target. As defined herein, the penetration depth neglects all rear boundary effects and is applicable only when the target thickness is sufficiently great to prevent rear face scabbing.

h = Initial drop height (ft) of projectile above target

N_p = Nose-shape factor for projectile
 = 0.72 for flat nosed projectile
 = 0.84 for blunt nosed projectile
 = 1.0 for average bullet nosed (spherical end) projectile
 = 1.14 for very sharp nosed projectile

W = Weight of projectile (lbf)

A_p = Frontal (projected) area of projectile (in²)

$V(h)$ = Projectile initial impact velocity (ft/s)

f_c = Ultimate compressive strength (lbf/in²) of concrete target

$$d = d_e(A_p) = \sqrt{\frac{4 \cdot A_p}{\pi}} = \text{Effective missile diameter (in.)}$$

E = Modulus of elasticity of missile material

Perforation Thickness for Soft Missiles Impact

Soft missiles will not cause local penetration with the exception of possible punching shear. However, punching shear can be prevented by requiring that the concrete thickness is at least 1.2 times that required at perforation as obtained for hard missile impact. The minimum concrete target thickness for perforation is

$$e_1(f_c, W, d, h, N_p, E) = d \left(1.32 + 1.24 \frac{x(f_c, W, d, h, N_p, E)}{d} \right) \quad \text{for } 1.35 < x/d < 13.5$$

$$e_2(f_c, W, d, h, N_p, E) = d \left[3.19 \frac{x(f_c, W, d, h, N_p, E)}{d} - 0.718 \left(\frac{x(f_c, W, d, h, N_p, E)}{d} \right)^2 \right] \quad \text{for } x/d < 1.35$$

$$e(f_c, W, d, h, N_p, E) = \text{if} \left(\frac{x(f_c, W, d, h, N_p, E)}{d} \leq 1.35, e_2(f_c, W, d, h, N_p, E), e_1(f_c, W, d, h, N_p, E) \right)$$

The minimum concrete target thickness to prevent perforation or punching shear failure for soft missile impact is

$$t_c(f_c, W, d, h, N_p, E) = 1.2 \cdot e(f_c, W, d, h, N_p, E)$$

For Hard Missile Impact

$$t_d(f_c, W, d, h, N_p, E) = \frac{2 \cdot x(f_c, W, d, h, N_p, E)}{V(h)} \quad \text{duration of impact}$$

$$F_A(f_c, W, d, h, N_p, E) = \frac{W}{g \cdot t_d(f_c, W, d, h, N_p, E)} \quad \text{average constant impact force}$$

Scabbing Thickness for Hard Missile Impact

The concrete thickness required to resist hard missile impact should be at least 1.2 times the scabbing thickness. The minimum concrete target thickness for scabbing with Kar correction (Adell and Amin 1985) is

$$s_1(f_c, W, d, h, N_p, E) = d \left(2.12 + 1.36 \frac{x(f_c, W, d, h, N_p, E)}{d} \right) \cdot \left(\frac{E}{E_m} \right)^{0.2} \quad \text{for } 0.65 < x/d < 11.75$$

$$s_2(f_c, W, d, h, N_p, E) = d \left[7.91 \frac{x(f_c, W, d, h, N_p, E)}{d} - 5.06 \left(\frac{x(f_c, W, d, h, N_p, E)}{d} \right)^2 \right] \cdot \left(\frac{E}{E_m} \right)^{0.2} \quad \text{for } x/d < 0.65$$

$$s(f_c, W, d, h, N_p, E) = \text{if} \left(\frac{x(f_c, W, d, h, N_p, E)}{d} \leq 0.65, s_2(f_c, W, d, h, N_p, E), s_1(f_c, W, d, h, N_p, E) \right)$$

The minimum concrete target thickness to prevent scabbing failure for hard missile impact is

$$t_s(f_c, W, d, h, N_p, E) = 1.2 \cdot s(f_c, W, d, h, N_p, E)$$

Warning, the NDRC equations only consider the local effects on the concrete target from an impacting projectile. These equations were developed from impact tests using essentially nondeforming projectiles impacting massive concrete targets. Test velocities were generally much higher than would be expected from equipment drops over Hanford underground waste storage tanks. The results from application of the NDRC equations are expected to give conservative predictions for maximum drop height restrictions with respect to local effects on the concrete target. However, these results should not be applied without considering the global response of the structure to the resulting impulse loading associated with the impact.

Young's Equation for Depth of Soil Penetration by Impacting Projectile

The penetration of a missile into soil is estimated from empirical equation given by Young (1969) as

$$x_{s1}(W, A_p, h, S, N_p) = 0.53 \cdot S \cdot N_p \cdot \sqrt{\frac{W}{A_p}} \cdot \frac{\text{in}^2}{\text{lb}} \cdot \ln \left[1 + 2 \cdot 10^{-5} \cdot \left[\frac{V(h)}{\left(\frac{\text{ft}}{\text{sec}} \right)} \right]^2 \right] \text{ ft} \quad \text{for } V < 200 \text{ ft/sec}$$

$$x_{s2}(W, A_p, h, S, N_p) = 0.0031 \cdot S \cdot N_p \cdot \sqrt{\frac{W}{A_p}} \cdot \frac{\text{in}^2}{\text{lb}} \cdot \left[\left[\frac{V(h)}{\left(\frac{\text{ft}}{\text{sec}} \right)} \right] - 100 \right] \text{ ft} \quad \text{for } V > 200 \text{ ft/sec}$$

$$x_{\text{soil}}(W, A_p, h, S, N_p) = \text{if} \left(V(h) < 200 \cdot \frac{\text{ft}}{\text{sec}}, x_{s1}(W, A_p, h, S, N_p), x_{s2}(W, A_p, h, S, N_p) \right)$$

where

- x_{soil} = Penetration depth (ft) into soil
- h = Initial drop height (ft) of projectile above target
- N_p = Nose-shape factor for projectile
 - = 0.72 for flat nosed projectile
 - = 0.84 for blunt nosed projectile
 - = 1.0 for average bullet nosed (spherical end) projectile
 - = 1.14 for very sharp nosed projectile
- W = Weight of projectile (lbf)
- A_p = Frontal (projected) area of projectile (in²)
- $V(h)$ = Projectile initial impact velocity (ft/s)
- S = Soil coefficient, range for Hanford soil conditions is estimated at 4 to 6 on basis of data given in Young (1969).

Modulus and ultimate compressive strength of concrete

$$f_c := 3000 \cdot \frac{\text{lbf}}{\text{in}^2} \quad E_c := 57000 \cdot \sqrt{f_c} \cdot \frac{\text{lbf}}{\text{in}^2} \quad E_c = 3.122 \cdot 10^6 \cdot \frac{\text{lbf}}{\text{in}^2} \quad E_s := E_m$$

Check: AZ Mixer Pump

$$N_p := 0.84 \quad S := 5 \quad t_{\text{soil}} := 5 \cdot \text{ft} \quad t_c := 30 \cdot \text{in} \quad W := 27000 \cdot \text{lbf}$$

$$d := 29.933 \cdot \text{in}$$

$$h := 1 \cdot \text{ft}$$

Maximum Drop Height to just Perforate Minimum Soil Cover Depth

$$h_{\text{soil}}(t_{\text{soil}}, W, d, S, N_p) := \text{root}\left(t_{\text{soil}} - x_{\text{soil}}\left(W, \frac{\pi \cdot d^2}{4}, h, S, N_p\right), h\right) \quad h_{\text{soil}}(t_{\text{soil}}, W, d, S, N_p) = 339.393 \cdot \text{ft}$$

$$h := 0.05 \cdot \text{ft}$$

Maximum Drop Height to Perforate Concrete Target

$$h_s(t_c, f_c, W, d, N_p, E) := \text{root}(t_c - t_s(f_c, W, d, h, N_p, E), h) \quad h_s(t_c, f_c, W, d, N_p, E_s) = 4.022 \cdot \text{ft}$$

$$h := 1 \cdot \text{ft}$$

Maximum Drop Height to Cause Scabbing Failure of Concrete Target

$$h_e(t_c, f_c, W, d, N_p, E) := \text{root}(t_c - t_e(f_c, W, d, h, N_p, E), h) \quad h_e(t_c, f_c, W, d, N_p, E_s) = 29.53 \cdot \text{ft}$$

$$x_s(t_c, f_c, W, d, N_p, E) := x(f_c, W, d, h_s(t_c, f_c, W, d, N_p, E), N_p, E) \quad \frac{x_s(t_c, f_c, W, d, N_p, E_s)}{d} = 0.114$$

$$x_e(t_c, f_c, W, d, N_p, E) := x(f_c, W, d, h_e(t_c, f_c, W, d, N_p, E), N_p, E) \quad \frac{x_e(t_c, f_c, W, d, N_p, E_s)}{d} = 0.279$$

Duration of impact for scabbing and perforation failure of concrete target, respectively

$$t_{ds}(t_c, f_c, W, d, N_p, E) := t_d(f_c, W, d, h_s(t_c, f_c, W, d, N_p, E), N_p, E) \quad t_{ds}(t_c, f_c, W, d, N_p, E_s) = 0.035 \cdot \text{sec}$$

$$t_{de}(t_c, f_c, W, d, N_p, E) := t_d(f_c, W, d, h_e(t_c, f_c, W, d, N_p, E), N_p, E) \quad t_{de}(t_c, f_c, W, d, N_p, E_s) = 0.032 \cdot \text{sec}$$

Average constant impact force for scabbing and perforation failure of concrete target, respectively

$$F_{As}(t_c, f_c, W, d, N_p, E) := F_A(f_c, W, d, h_s(t_c, f_c, W, d, N_p, E), N_p, E) \quad F_{As}(t_c, f_c, W, d, N_p, E_s) = 3.823 \cdot 10^5 \cdot \text{lb}$$

$$F_{Ae}(t_c, f_c, W, d, N_p, E) := F_A(f_c, W, d, h_e(t_c, f_c, W, d, N_p, E), N_p, E) \quad F_{Ae}(t_c, f_c, W, d, N_p, E_s) = 1.144 \cdot 10^6 \cdot \text{lb}$$

Initial impact velocity for scabbing and perforation failure of concrete target, respectively

$$V_s(t_c, f_c, W, d, N_p, E) := V(h_s(t_c, f_c, W, d, N_p, E)) \quad V_s(t_c, f_c, W, d, N_p, E_s) = 16.088 \cdot \frac{\text{ft}}{\text{sec}}$$

$$V_e(t_c, f_c, W, d, N_p, E) := V(h_e(t_c, f_c, W, d, N_p, E)) \quad V_e(t_c, f_c, W, d, N_p, E_s) = 43.591 \cdot \frac{\text{ft}}{\text{sec}}$$

**Check OK (see Appendix A,
AZ Mixer Pump Drop)**

The following plots provide a sensitivity of the weight of the projectile, its effective contact diameter, the thickness of the concrete target, and material of the projectile (steel equipment or concrete cover blocks) to the predicted maximum drop height on the basis of the perforation and scabbing local effects criteria. Any application of these curves must also consider the global effect of the impact on the concrete structure.

Steel Projectile Impacting Concrete Structure

$$f_c = 5000 - \frac{\text{lb}_f}{\text{in}^2}$$

Concrete
Compressive
Strength

$$E = E_m$$

$$N_p = 0.84$$

$$t_c = 30\text{-in}$$

Concrete Target
Thickness

$$d = 1\text{-in}, 1.5\text{-in}, 20\text{-in}$$

Maximum Drop Height (ft) on Basis of Scabbing Criterion

Duration of Impact (sec)

Average Constant Impact Force (lb_f)

Steel Projectile Impacting Concrete Structure

$$f'_c = 5000 \frac{\text{lb}}{\text{in}^2}$$

**Concrete
Compressive
Strength**

$$E = E_m$$

$$N_p = 0.84$$

$$t_c = 30 \text{ in}$$

**Concrete Target
Thickness**

$$d = 1 \text{ in}, 1.5 \text{ in}, 20 \text{ in}$$

Maximum Drop Height (ft) on Basis of **Perforation Criterion**

Duration of Impact (sec)

Average Constant Impact Force (lb)

Steel Projectile Impacting Concrete Structure

$f_c = 5000 \frac{\text{lb}}{\text{in}^2}$ **Concrete Compressive Strength**

$E = E_m$

$t_c = 15 \text{ in}$ **Concrete Target Thickness**

$N_p = 0.84$

$d = 1\text{-in}, 1.5\text{-in}, 20\text{-in}$

Maximum Drop Height (ft) on Basis of Scabbing Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure

$$f_c := 5000 \cdot \frac{\text{lbf}}{\text{in}^2} \quad \text{Concrete Compressive Strength}$$

$$E := E_m \quad N_p := 0.84$$

$$t_c := 15 \text{ in}$$

Concrete Target Thickness

$$d := 1\text{-in}, 1.5\text{-in}, 20\text{-in}$$

Maximum Drop Height (ft) on Basis of Perforation Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure

$$f_c = 5000 \frac{\text{lbf}}{\text{in}^2} \quad \text{Concrete Compressive Strength}$$

$$E = E_m \quad N_p = 0.84$$

$$t_c = 12 \text{ in}$$

$$\text{Concrete Target Thickness}$$

$$d = 1 \text{ in}, 1.5 \text{ in}, 20 \text{ in}$$

Maximum Drop Height (ft) on Basis of Scabbing Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure

Concrete Compressive Strength $f_c := 5000 \frac{\text{lb}}{\text{in}^2}$ $E = E_m$ $N_p := 0.84$ $t_c := 12 \cdot \text{in}$ Concrete Target Thickness $d := 1 \cdot \text{in}, 1.5 \cdot \text{in}, 20 \cdot \text{in}$

Maximum Drop Height (ft) on Basis of Perforation Criterion

Duration of Impact (sec)

Average Constant Impact Force (lb)

Steel Projectile Impacting Concrete Structure

$$f_c := 4000 \frac{\text{lb}}{\text{in}^2}$$

**Concrete
Compressive
Strength**

$$E = E_m$$

$$N_p = 0.84$$

$$t_c := 30 \text{ in}$$

**Concrete Target
Thickness**

$$d := 1 \text{ in}, 1.5 \text{ in}.. 20 \text{ in}$$

Maximum Drop Height (ft) on Basis of Scabbing Criterion

Duration of Impact (sec)

Average Constant Impact Force (lb)

Steel Projectile Impacting Concrete Structure

$$f_c = 4000 \frac{\text{lb}_f}{\text{in}^2}$$

Concrete
Compressive
Strength

$$E = E_m$$

$$N_p = 0.84$$

$$t_c = 30 \text{ in}$$

Concrete Target
Thickness

$$d = 1 \text{ in}, 1.5 \text{ in}, 20 \text{ in}$$

Maximum Drop Height (ft) on Basis of Perforation Criterion

Duration of Impact (sec)

Average Constant Impact Force (lb_f)

Steel Projectile Impacting Concrete Structure

$f_c := 4000 \frac{\text{lb}}{\text{in}^2}$ **Concrete Compressive Strength**

$E := E_m$
 $N_p := 0.84$

$t_c := 15 \text{ in}$

Concrete Target Thickness

$d = 1 \text{ in}, 1.5 \text{ in}.. 20 \text{ in}$

Maximum Drop Height (ft) on Basis of Scabbing Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure

$$f_c = 4000 \frac{\text{lbf}}{\text{in}^2} \quad \text{Concrete Compressive Strength}$$

$$E = E_m \quad N_p = 0.84$$

$$t_c = 15 \text{ in}$$

$$\text{Concrete Target Thickness}$$

$$d = 1 \text{ in}, 1.5 \text{ in}, 20 \text{ in}$$

Maximum Drop Height (ft) on Basis of Perforation Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure

$$f_c = 4000 \frac{\text{lb}_f}{\text{in}^2}$$

**Concrete
Compressive
Strength**

$$E = E_m$$

$$N_p = 0.84$$

$$t_c = 12 \text{ in}$$

**Concrete Target
Thickness**

$$d = 1 \text{ in}, 1.5 \text{ in}, 20 \text{ in}$$

Maximum Drop Height (ft) on Basis of Scabbing Criterion

Duration of Impact (sec)

Average Constant Impact Force (lb_f)

Steel Projectile Impacting Concrete Structure

$$f_c = 4000 \frac{\text{lb}}{\text{in}^2}$$

**Concrete
Compressive
Strength**

$$E = E_m$$

$$N_p = 0.84$$

$$t_c = 12 \text{ in}$$

**Concrete Target
Thickness**

$$d = 1 \text{ in}, 1.5 \text{ in}, 20 \text{ in}$$

Maximum Drop Height (ft) on Basis of Perforation Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure

$f_c := 3000 \cdot \frac{\text{lb}}{\text{in}^2}$ **Concrete Compressive Strength**

$E := E_m$
 $N_p := 0.84$

$t_c := 30 \cdot \text{in}$ **Concrete Target Thickness**

$d := 1 \cdot \text{in}, 1.5 \cdot \text{in}, 20 \cdot \text{in}$

Maximum Drop Height (ft) on Basis of Scabbing Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure

Concrete Compressive Strength $f_c = 3000 \frac{\text{lb}}{\text{in}^2}$ $E = E_m$ $t_c = 30 \text{ in}$ Concrete Target Thickness $d = 1 \text{ in}, 1.5 \text{ in}.. 20 \text{ in}$
 $N_p = 0.84$

Maximum Drop Height (ft) on Basis of Perforation Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure

$$f_c := 3000 \frac{\text{lb}}{\text{in}^2} \quad \text{Concrete Compressive Strength}$$

$$E := E_m \quad N_p := 0.84$$

$$t_c := 15\text{-in} \quad \text{Concrete Target Thickness}$$

$$d := 1\text{-in}, 1.5\text{-in}, 20\text{-in}$$

Maximum Drop Height (ft) on Basis of Scabbing Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure

Concrete
Compressive
Strength
 $f_c = 3000 \frac{\text{lb}}{\text{in}^2}$

$E = E_m$
 $N_p = 0.84$

Concrete Target
Thickness
 $t_c = 15 \text{ in}$

$d = 1 \text{ in}, 1.5 \text{ in}, 20 \text{ in}$

Maximum Drop Height (ft) on Basis of Perforation Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure

$f_c = 3000 \frac{\text{lb}}{\text{in}^2}$ **Concrete Compressive Strength**

$E = E_m$
 $N_p = 0.84$

$t_c = 12\text{-in}$ **Concrete Target Thickness**

$d = 1\text{-in}, 1.5\text{-in}, 20\text{-in}$

Maximum Drop Height (ft) on Basis of Scabbing Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure

 $W := 10000 \text{ lbf}$ **Missile
Weight** $E := E_m$ $N_p := 0.84$ $t_c := 30 \text{ in}$ **Concrete Target
Thickness** $d := 1 \text{ in}, 1.5 \text{ in}, 20 \text{ in}$

Maximum Drop Height (ft) on Basis of Scabbing Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure $W = 10000 \text{ lbf}$ **Missile
Weight** $E = E_m$ $N_p = 0.84$ $t_c = 30 \text{ in}$ **Concrete Target
Thickness** $d = 1 \text{ in}, 1.5 \text{ in}, 20 \text{ in}$ **Maximum Drop Height (ft) on Basis of Perforation Criterion** **Duration of Impact (sec)** **Average Constant Impact Force (lbf)**

Steel Projectile Impacting Concrete Structure

W = 10000-lbf

Missile
Weight $E = E_m$ $N_p = 0.84$ $t_c = 15\text{-in}$ Concrete Target
Thickness

d = 1-in, 1.5-in, 20-in

Maximum Drop Height (ft) on Basis of Scabbing Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure $W := 10000\text{-lb}$ **Missile
Weight** $E := E_m$ $N_p := 0.84$ $t_c := 15\text{-in}$ **Concrete Target
Thickness** $d := 1\text{-in}, 1.5\text{-in}, 20\text{-in}$ **Maximum Drop Height (ft) on Basis of Perforation Criterion** **Duration of Impact (sec)** **Average Constant Impact Force (lbf)**

Steel Projectile Impacting Concrete Structure

 $W := 10000\text{-lb}$ **Missile
Weight** $E := E_m$ $t_c := 12\text{-in}$ **Concrete Target
Thickness** $d := 1\text{-in}, 1.5\text{-in}, 20\text{-in}$ $N_p := 0.84$ Maximum Drop Height (ft) on Basis of **Scabbing** Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure $W = 10000\text{-lb}$ **Missile
Weight** $E = E_m$ $N_p = 0.84$ $t_c = 12\text{-in}$ **Concrete Target
Thickness** $d = 1\text{-in}, 1.5\text{-in}, 20\text{-in}$ **Maximum Drop Height (ft) on Basis of Perforation Criterion** **Duration of Impact (sec)** **Average Constant Impact Force (lb)**

Steel Projectile Impacting Concrete Structure $W := 20000\text{-lb}$ **Missile
Weight** $E := E_m$ $N_p := 0.84$ $t_c := 30\text{-in}$ **Concrete Target
Thickness** $d := 1\text{-in}, 1.5\text{-in}, 20\text{-in}$ **Maximum Drop Height (ft) on Basis of Scabbing Criterion** **Duration of Impact (sec)** **Average Constant Impact Force (lb)**

Steel Projectile Impacting Concrete Structure $W = 20000\text{-lbf}$ **Missile
Weight** $E = E_m$ $t_c = 30\text{-in}$ **Concrete Target
Thickness** $d = 1\text{-in}, 1.5\text{-in}, 20\text{-in}$ $N_p = 0.84$ **Maximum Drop Height (ft) on Basis of Perforation Criterion** **Duration of Impact (sec)** **Average Constant Impact Force (lbf)**

Steel Projectile Impacting Concrete Structure

$W = 20000\text{-lb}$ **Missile Weight** $E = E_m$ $t_c = 15\text{-in}$ **Concrete Target Thickness** $d = 1\text{-in}, 1.5\text{-in}, 20\text{-in}$
 $N_p = 0.84$

Maximum Drop Height (ft) on Basis of Scabbing Criterion

Duration of Impact (sec)

Average Constant Impact Force (lb)

Steel Projectile Impacting Concrete Structure

W = 20000-lbf

**Missile
Weight** $E = E_m$ $N_p = 0.84$ $t_c = 15\text{ in}$ **Concrete Target
Thickness** $d = 1\text{ in}, 1.5\text{ in}, 20\text{ in}$ **Maximum Drop Height (ft) on Basis of Perforation Criterion** **Duration of Impact (sec)** **Average Constant Impact Force (lbf)**

Steel Projectile Impacting Concrete Structure $W = 20000 \text{ lbf}$ **Missile
Weight** $E = E_m$ $t_c = 12 \text{ in}$ **Concrete Target
Thickness** $d = 1 \text{ in}, 1.5 \text{ in} \dots 20 \text{ in}$ $N_p = 0.84$ **Maximum Drop Height (ft) on Basis of Scabbing Criterion** **Duration of Impact (sec)** **Average Constant Impact Force (lbf)**

Steel Projectile Impacting Concrete Structure $W = 20000 \text{ lbf}$ **Missile
Weight** $E = E_m$ $N_p = 0.84$ $t_c = 12 \text{ in}$ **Concrete Target
Thickness** $d = 1 \text{ in}, 1.5 \text{ in}, 20 \text{ in}$ **Maximum Drop Height (ft) on Basis of Perforation Criterion** **Duration of Impact (sec)** **Average Constant Impact Force (lbf)**

Steel Projectile Impacting Concrete Structure $W := 30000\text{-lb}$ **Missile
Weight** $E := E_m$ $N_p := 0.84$ $t_c := 30\text{-in}$ **Concrete Target
Thickness** $d := 1\text{-in}, 1.5\text{-in}, 20\text{-in}$ **Maximum Drop Height (ft) on Basis of Scabbing Criterion** **Duration of Impact (sec)** **Average Constant Impact Force (lbf)**

Steel Projectile Impacting Concrete Structure

W = 30000-lbf

**Missile
Weight**

$E = E_m$

$t_c = 30\text{-in}$

**Concrete Target
Thickness**

d = 1-in, 1.5-in.. 20-in

$N_p = 0.84$

Maximum Drop Height (ft) on Basis of **Perforation Criterion**

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure

 $W = 30000 \text{ lbf}$ **Missile
Weight** $E = E_m$
 $N_p = 0.84$ $t_c = 15 \text{ in}$ **Concrete Target
Thickness** $d = 1 \text{ in}, 1.5 \text{ in}, 20 \text{ in}$ Maximum Drop Height (ft) on Basis of **Scabbing Criterion**

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure $W = 30000\text{-lbf}$ **Missile
Weight** $E = E_m$ $N_p = 0.84$ $t_c = 15\text{-in}$ **Concrete Target
Thickness** $d = 1\text{-in}, 1.5\text{-in}, 20\text{-in}$ **Maximum Drop Height (ft) on Basis of Perforation Criterion** **Duration of Impact (sec)** **Average Constant Impact Force (lbf)**

Steel Projectile Impacting Concrete Structure

 $W := 30000 \text{ lbf}$ **Missile
Weight** $E := E_m$ $N_p := 0.84$ $t_c := 12 \text{ in}$ **Concrete Target
Thickness** $d := 1 \text{ in}, 1.5 \text{ in}, 20 \text{ in}$

Maximum Drop Height (ft) on Basis of Scabbing Criterion

Duration of Impact (sec)

Average Constant Impact Force (lbf)

Steel Projectile Impacting Concrete Structure $W = 30000\text{-lbf}$ **Missile
Weight** $E = E_m$ $t_c = 12\text{-in}$ **Concrete Target
Thickness** $d = 1\text{-in}, 1.5\text{-in}, 20\text{-in}$ $N_p = 0.84$ **Maximum Drop Height (ft) on Basis of Perforation Criterion** **Duration of Impact (sec)** **Average Constant Impact Force (lbf)**

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