Magic R

Seismic Evaluation of Tanks

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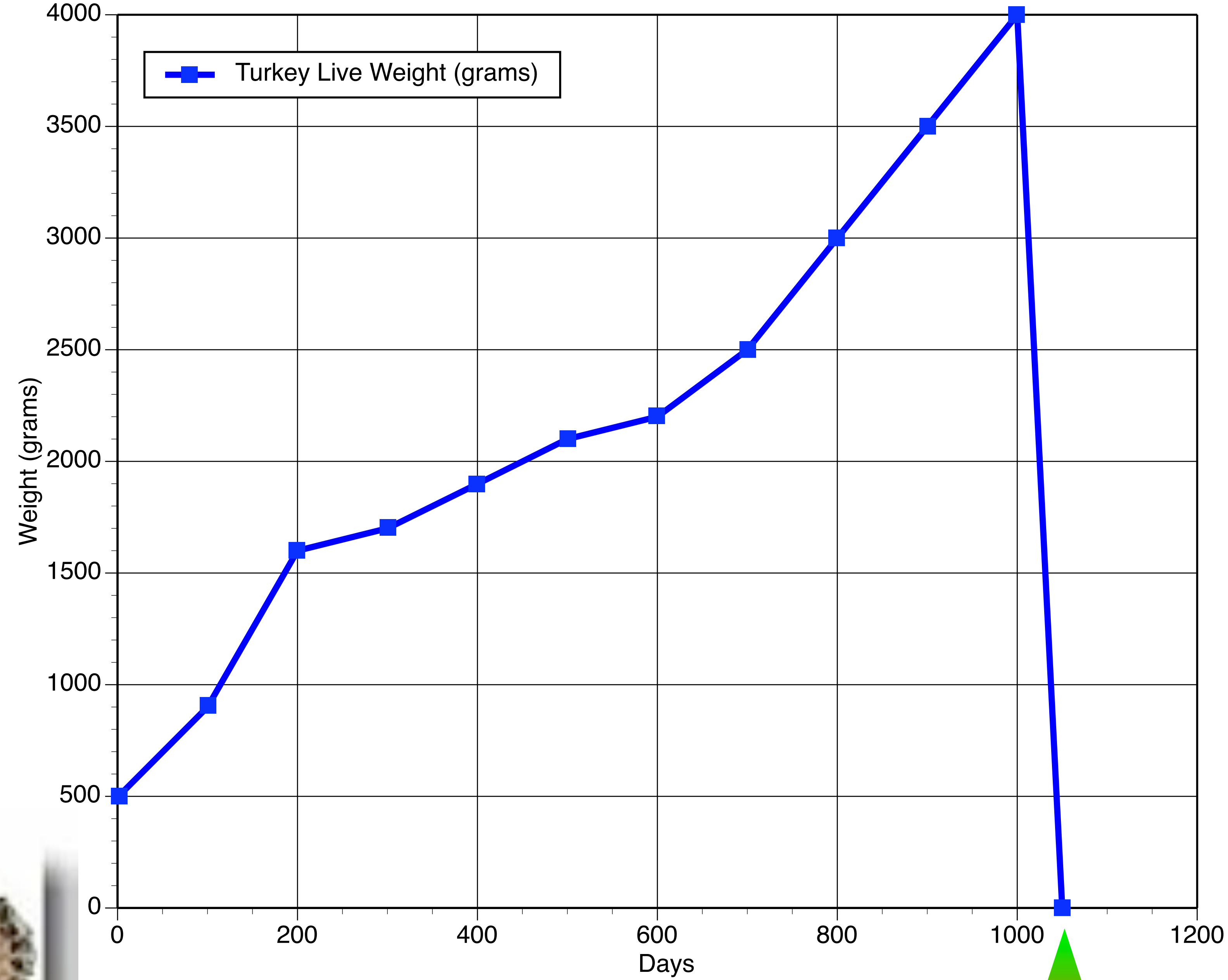
Consider

- Steel is ductile! R = 4.5 by Tank Fabricators on Code ! (helps sells tanks)
- Steel connections crack! R should be reduced to 2

Which Statement is True?

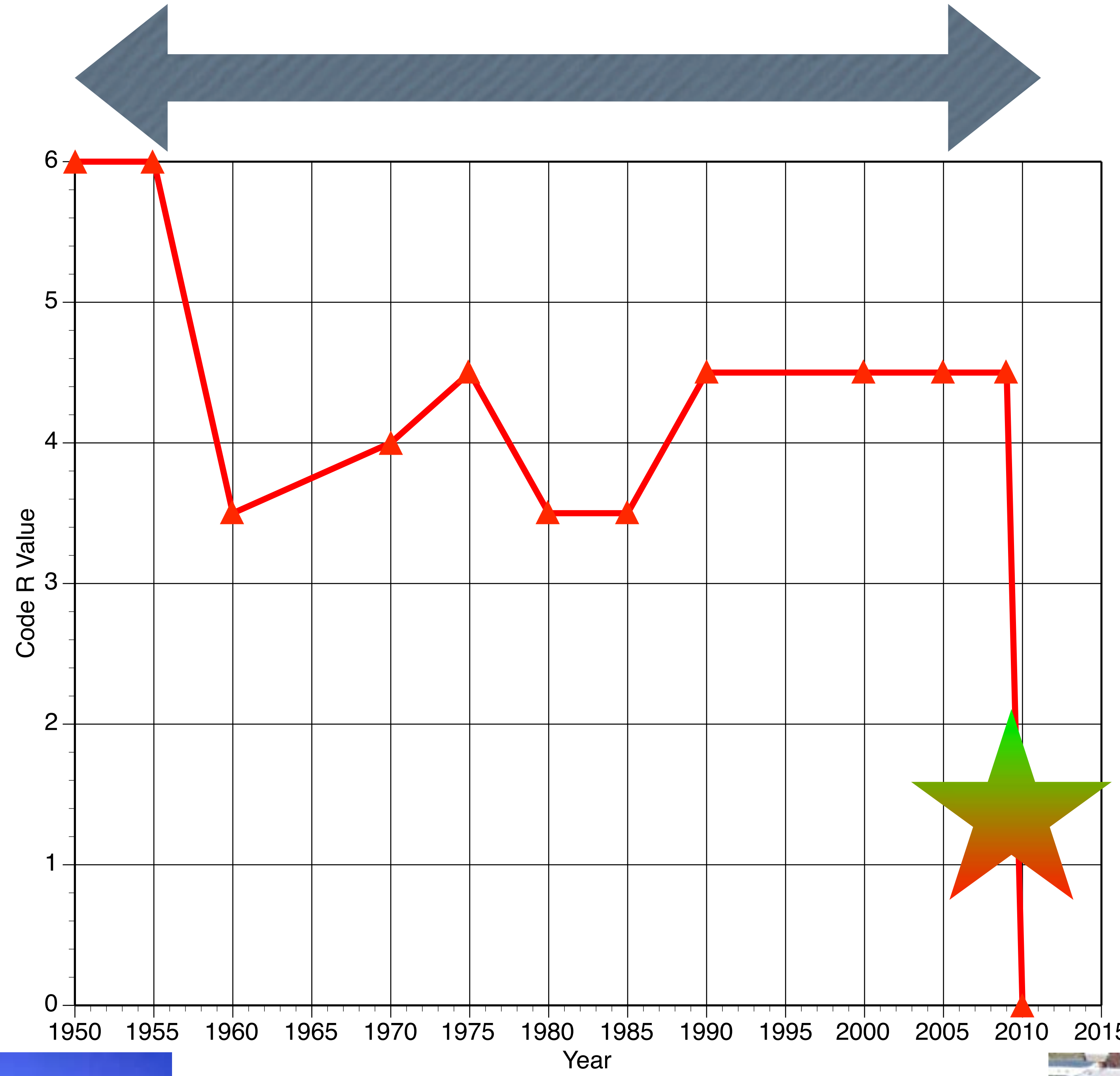
- Both appear to be false!

Happy Feeding Cycle



Thanksgiving

Happy Water Tank Performance



Disaster Occurs

What Happened?

- Owner's (Turkey's) Perspective
- Engineer's (Butcher's) Perspective

Opposing Views

- 100% sure that the Turkey will be slaughtered

- The Farmer has fed me every day for 1,000 days! He is a nice guy! I can sure trust him!

Opposing Views

- Earthquakes don't care what R the code says. They only care how the tank is built!

- High R value = low cost construction. "It has not failed in 40 years, so why worry?"

$$V = \frac{ZIC}{R} W$$

- Z = peak ground acceleration (say, Z = 0.60 g)
- I = Importance Factor (say, I = 1.00)
- C = Spectra Amplification (say, C = 2.5)
- W = Weight of tank plus contents
- R = Magic factor (R = 1 for elastic response)
- V = (0.6 x 1.00 x 2.5 / 1) = 1.50W (elastic)

$$V = \frac{ZIC}{R} W$$

Regular Steel Buildings

- V = 0.02W to 0.10W (1943, Los Angeles)
- V = 0.06W (1957, Los Angeles)
- V = 0.10W (1974, San Francisco)
- V = 0.17W (1975, San Francisco, Steel Building)
- V = 0.40W (2009, Retrofit of Critical Steel Buildings)

$$V = \frac{ZIC_i}{R_i} W_i + \frac{ZIC_s}{R_s} W_s$$

$$W = W_i + W_s$$

Water Tanks in Zone 4 (California)

- V = 0.25W (1954, Housner)
- V = 0.11W (1978, AWWA anchored, I = 1.0)
- V = 0.138W (1978, AWWA unanchored, I = 1.0)
- V = 0.454W (2009 NRC, elastic, I = 1.0)
- AWWA (1978) implies R = 4.13 (anchored) or R = 3.29 (unanchored)

Latest AWWA Codes (1984, 1996 and 2005)

Committee Personnel

The D100 Revision Task Force that developed this standard had the following personnel at that time:

Robert S. Wozniak, *Chair*

K.A. Alms	A.M. DeVaul
R.G. Biale	R.P. Kennedy
Richard Blaisdell	Ron Kern
L.E. Bower	E.C. Knoy
J.R. Buzek	B.E. Kromer
F.M. Couch	Y.T. Lin
Ray Crosno	S.W. Meier
D.G. Cull	Chris Sundberg
R.J. Davis	L.R. Todd

Table 25 Force reduction coefficient R_w for type of tank

Structure	Force Reduction Coefficient R_w
Cross-braced elevated tank	4.0
Pedestal-type elevated tank	3.0
Anchored flat-bottom tank	4.5
Unanchored flat-bottom tank	3.5

2009: Bob Kennedy says: he never approved this! these R values are too high!

Empirical Evidence

Table 1. Tank Database

PGA (g)	All Tanks	DS = 1	DS = 2	DS = 3	DS = 4	DS = 5
0.10	8	4	4	0	0	0
0.16	263	196	42	13	8	4
0.26	65	32	18	11	4	0
0.36	56	22	19	8	6	1
0.47	47	32	11	3	1	0
0.56	53	26	15	7	3	2
0.67	25	9	5	5	3	3
0.87	14	10	0	1	3	0
1.18	10	1	3	0	0	6
Total (542)	532	331	112	47	25	16

	No damage	Roof, ladders et.	Buckled	Buckled, Pipes Broken	Collapse
Holds water?	Yes	Yes	Yes	No	No

Tank Fragility vs. Fill Level

Table 2. Fragility Curves, Tanks, As a Function of Fill Level

DS	A, g	Beta	A, g	Beta	A, g	Beta	A, g	Beta	A, g	Beta
DS≥2	0.38	0.80	0.56	0.80	0.18	0.80	0.22	0.80	0.13	0.07
DS≥3	0.86	0.80	>2.00	0.40	0.73	0.80	0.70	0.80	0.67	0.80
DS≥4	1.18	0.61			1.14	0.80	1.09	0.80	1.01	0.80
DS=5	1.16	0.07			1.16	0.40	1.16	0.41	1.15	0.10
	All Tanks N=531		Fill < 50% N=95		Fill ≥ 50% N=251		Fill ≥ 60% N=209		Fill ≥ 90% N=120	

1. Median PGA ~1.10g to fail (lose water) 50% of AWWA-designed tanks (when mostly full)

2. Empty tanks do not fail (but, so what?)

Tank Fragility vs. Anchorage

Table 3. Fragility Curves, Tanks, As a Function of Fill Level and Anchorage (through 1994)

DS	A, g	Beta	A, g	Beta	A, g	Beta
DS≥2	0.18	0.80	0.71	0.80	0.15	0.12
DS≥3	0.73	0.80	2.36	0.80	0.62	0.80
DS≥4	1.14	0.80	3.72	0.80	1.06	0.80
DS=5	1.16	0.80	4.26	0.80	1.13	0.10
	Fill ≥ 50% All N=251		Fill ≥ 50% Anchored N=46		Fill ≥ 50% Unanchored N=205	

1. Anchored Tanks have MUCH higher capacity than Unanchored Tanks

2. Should Unanchored Tanks be Eliminated from the Code?

Roof Damage

- Code requires roof to be designed for dead load only
- If the tank wall uplifts, the roof rafter can easily fail. This is observed!
- Water sloshing impacts not likely the main cause of roof damage.

Test Data

- Niwa (1978) tested water tanks on the Berkeley Shake table
- Anchored tanks: stress = Moment / S is "reasonable". Test/Code = -18%, -7%, +64%.
- Unanchored tanks: stress = Moment / S is not "reasonable". Test/Code ≥200%
- Code allowable buckling stress = 1,560 psi. Actual measured stress = 3,698 psi, but no buckling occurred.

Conclusions

- R values in the code have NOTHING to do with reality.
- R values are NOT supported by test data.
- R values are NOT supported by empirical data.
- R values are NOT supported by the original author of the code.

Conclusions

- Code R values for Steel Tanks were set to match R values for Buildings.
- NRC does not allow R! NRC is pretty smart...
- Consensus R value for water utilities (not nuclear) is $R(max) = 2.0$ to 2.5, tanks should be anchored, attached pipes must be able to accommodate uplift if $R > 1$.
- Unanchored tanks must check compression stresses as the sum of cantilever (M/S), lift off and hoop breathing modes.

Conclusions

- If an owner MUST have an unanchored tank, then:
  - Compute vertical shell stresses using accurate methods
  - Include the soil / concrete ring foundation under the tank wall (compliant soil may result in lower stresses than a rigid concrete ring beam)
  - Provide for adequate tank wall uplift for pipes

M6.5 Earthquake, December 2003

4.0 Million Gallons

Built in 1972

130 feet diameter (40 m)

41 feet height (12.5 m)


12/23/2003

4.0 Million Gallons

Built in 2001

132 feet diameter (40 m)

41.6 feet height (12.7 m)


12/23/2003


12/23/2003


12/23/2003

Site Overflow Drain


12/23/2003


Elastic rebound of buckle
Buckle impacts fence post


'03 12 26


02 12 26

Only Tank that had Zero Damage (one of ten)

Steel Tank Failure, 2008

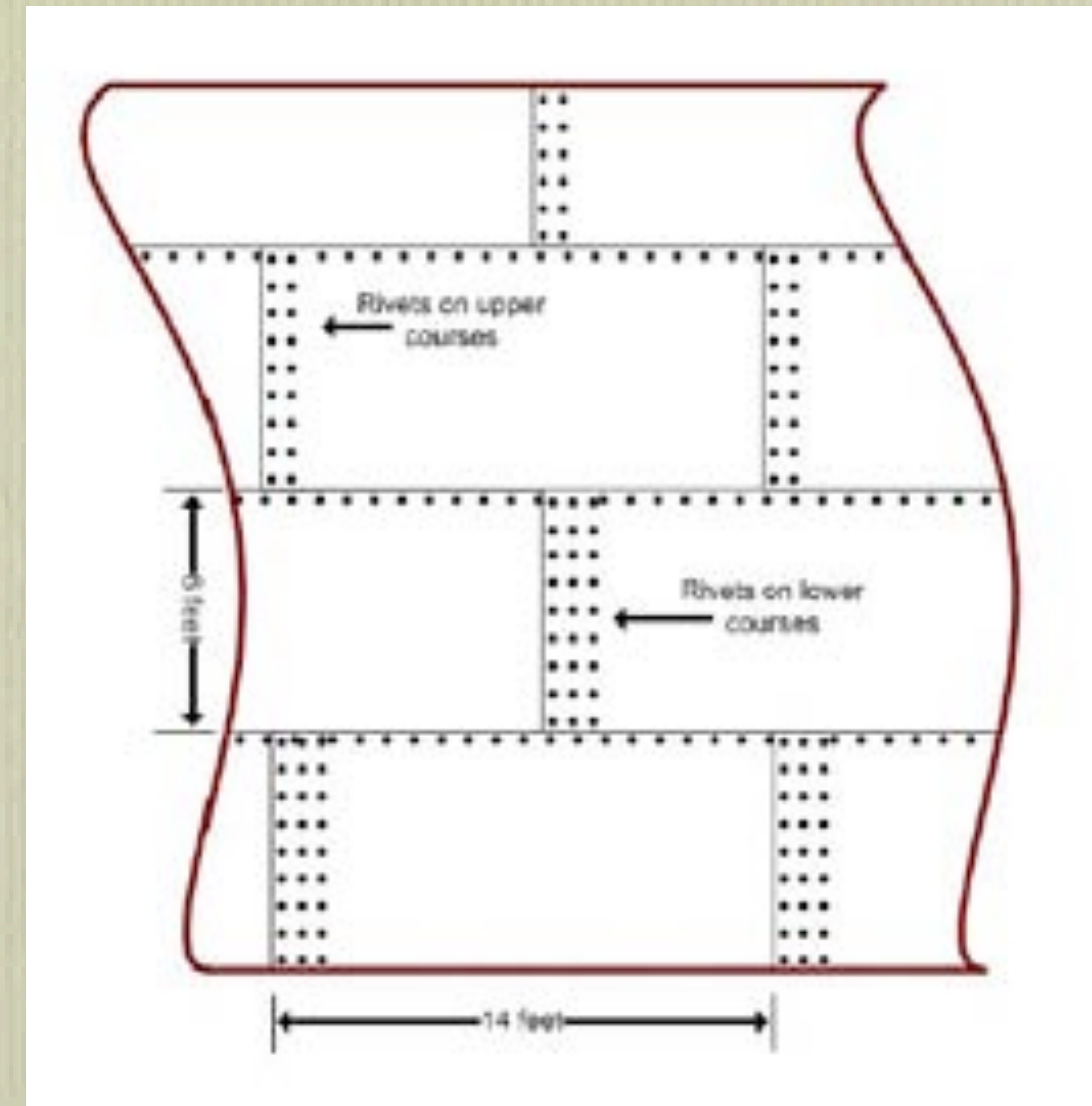
Date	Location	Number of failures	Details	Cause (if known)	Consequences reported
1995	Poneto, Indiana	1	500,000-gallon fertilizer tank rupture	Faulty welds	
March 1997	Pacific Junction, Iowa	3	1-million gallon fertilizer tank rupture and cascading failure of two other tanks	Faulty welds	Temporary dike prevented release to Missouri River
February 1999	Dixon, California	1	Tank rupture during transfer out of leaking tank; 250,000 gallons released		One killed, two hospitalized
July 1999	Maumee, Ohio	2	Failure of two fertilizer storage tanks	Faulty welds	
July 1999	Webberville, Michigan	1	1-millon gallon fertilizer tank rupture at seams	Faulty welds	Two hospitalized
January 8, 2000	Cincinnati, Ohio	1	Million-gallon tank rupture, 379,000 gallons released	Faulty welds	Release to Ohio River, containing walls and two vehicles destroyed
January 26, 2000	Morral, Ohio	1	1.5-million gallon tank rupture	Faulty welds	
March 3 and March 8, 2000	Morral, Ohio	2	Two separate fertilizer tank ruptures days apart	Faulty welds	Community and school evacuation
November 7, 2008	Wilmington, North Carolina	1	Fertilizer tank failure at seam between shell and bottom	Failure at weld, corrosion	Release to waterway
November 12, 2008†	Chesapeake, Virginia	1	Catastrophic failure of fertilizer tank	Faulty welds due to lack of weld penetration	Community evacuation, two hospitalized, release to Elizabeth River
December 16, 2008	Ashkym, Illinois	3	500,000-gallon release due to storage tank catastrophic failure and cascading failure of two smaller tanks		

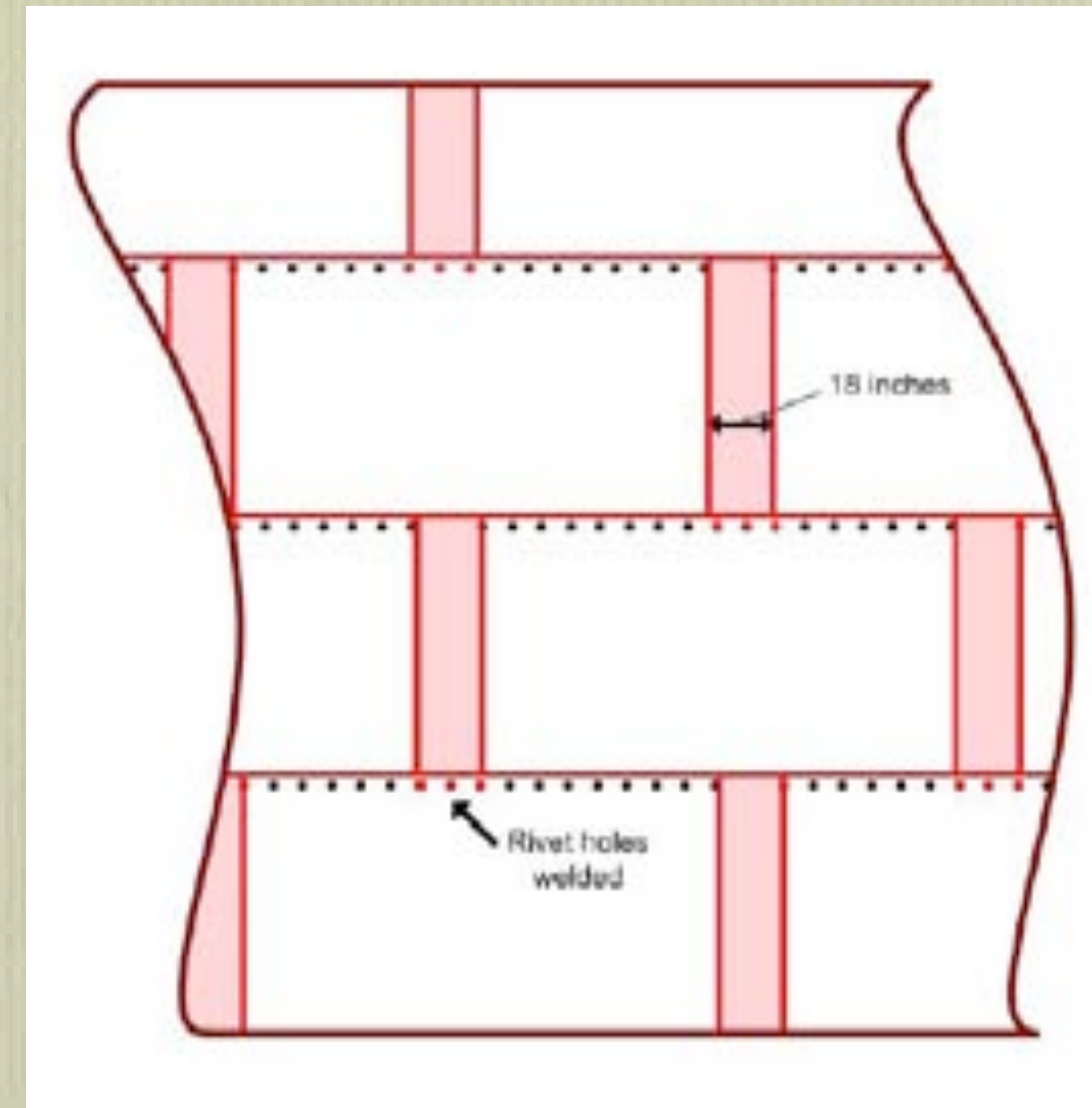

202
205
201
209
Banks St
Rosemont Ave
Middle St
Hill St
Roosevelt Ave
Park Row
Hill St
Rosemont Ave
464

Tank Before it Failed

Tank After it Failed


Man-lift basket
Tank stairs


Rivets on upper courses
Rivets on lower courses
6 feet
14 feet


18 inches
Rivet holes
welded


Unfused plate
material

Observations

- R for hoop failure: NEVER let static hoop force exceed weld (bolt, rivet) capacity
- Poor welds = low R!
- Rivets and Bolts = low R!

Questions or Comments?