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Package Boiler Siting Calculations - Vessel Overpressurization and Fuel Oil Fire

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Abstract: The purpose of this calculation note is to provide the basis for the siting of a package boiler outside the Plutonium Finishing Plant.

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**Package Boiler Siting
Calculations - Vessel
Overpressurization and
Fuel Oil Fire**

R. M. Marusich
Fluor Daniel Northwest

June 6, 1997

I. Purpose

The purpose of this calculation is to provide the basis for the siting of a package boiler to be used to supply steam to the Plutonium Finishing Plant.

II. Methodology

Standard engineering textbooks and handbooks supplied the equations and figures used in the analysis.

A standard methodology taken from the explosives manual used at the Pantax plant (DOE 1992) is used to determine the shock overpressure, impulse and their effect on steel panels, block walls and people. The methodology relates shock overpressure and the impulse as a function of distance to experiments on bursting vessels. The methodology uses scaled dimensionless parameters.

A standard methodology taken from DOE (1992) is used to determine the initial fragment velocity for fragments from the burst vessel. Data showing an empirical fit to TNT casing data is used to determine the initial velocity. A standard method from the Army Handbook for effects of the use of conventional explosives (Army 1986) is used to determine breach thickness as a function of striking velocity and striking velocity as a function of initial velocity and fragment size.

The methodology for the effects of a large diesel fuel fire is taken from a chapter of the Fire Protection Handbook concerning this subject. The methodology uses a number of empirical correlations and charts to determine the radiant heat flux and the effect of radiant heating on people.

Simple heat transfer equations are used to determine wall temperature and heat losses.

The methodology used to determine the overpressure due to a deflagration resulting from ignition of a large stoichiometric quantity of fuel oil aerosol was taken from experiments. In these experiments, stoichiometric quantities of flammable gas are ignited inside balloons. The pressure is recorded at varying distances. An empirical fit is made to the data (Kogarko 1966).

A copy of the pertinent pages of the references used are on file with the author. These references must be consulted in any effort to upgrade or change these calculations as almost all of the data comes from graphs which provide the results of a series of experiments or graphs having scaled dimensionless parameters for axes.

III. Assumptions

The following is assumed:

- A. The fuel oil tank can hold 40,000 gallons of No. 2 diesel fuel oil (per vendor).

- B. The boiler tank dimensions are per the vendor (78 inch ID, 79 inch OD, 225 inch long).
- C. The major siting concerns are shockwave due to boiler vessel burst as a result of overpressurization, fire due to diesel fuel tank leak, and deflagration due to ignition of diesel fuel oil vapor or aerosol.
- D. The boiler is assumed to be empty at the start of the overpressurization accident so as to maximize the energy at burst. The boiler vessel is assumed to burst at its peak bursting pressure. The peak pressure occurs when the cylindrical shell ruptures at a location away from the seam. The head will separate from the vessel at a lower pressure. A seam in the cylindrical shell will also rupture at a lower pressure.
- E. The diesel fuel tank is assumed to rupture with flow outside the berm. The pool is assumed to form quickly, spread until it is one inch deep and be ignited at that point. A separate case is also analyzed in which the fuel remains in the berm, and is ignited there.
- F. The building that houses the package boiler is assumed to contain a stoichiometric concentration of fuel oil vapor or aerosol prior to ignition.
- G. No credit is taken for the effect of the sheet steel building which encloses the boiler. Note that should vessel overpressurization, external fuel tank rupture event (e.g., seismic event, vehicle impact or external missile), or fuel oil deflagration occur, the building will afford little protection.
- H. No formal hazards identification procedure was performed to identify the potential fire and explosion hazards. Instead it was postulated that the accidents having the greatest potential for damage were the 40,000 gallon diesel fuel oil fire, vessel overpressurization followed by rupture, and deflagration of a large quantity of diesel fuel oil vapor or aerosol.

IV. Input Data

See attached calculations.

V. Calculations

See attached.

VI. Results and Conclusions

Three conclusions came as a result of this study. The first conclusion is that the boiler must be located at least 50m from an important building made up of corrugated steel sheet walls and at least 30m from important buildings made up of block walls to prevent collapse of these walls due to shock pressure.

The second conclusion is that a one inch deep pool containing 40,000 gallons of fuel oil centered 50m from a sheet steel wall insulated on one side produces unacceptable wall temperatures and effects on people near the wall. Therefore the berm must be protected or shown to have adequate structural capacity against all accidents that cause berm and tank failure. Examples of such accidents are vehicle impact, seismic event and external missiles.

The third conclusion is that it is possible for shrapnel to penetrate steel walls that are 50m away. The calculational methods are such that protection against this event is not afforded by placement further away. Instead standard boiler overpressure controls coupled with a discussion of the conservative nature of the calculation (discussed in the attached calculation) and orientation of the boiler such that the vessel heads as well as small equipment (e.g., valves) attached to the vessel are not pointing at an important building is all that can be done to show adequate protection.

An important observation that also came out of the review of the references was that the diesel fuel oil tank must be protected from heating from long duration heat sources such as range fires or large vehicle fires. Prolonged heating of the tank could result in a BLEVE (boiling liquid expanding vapor explosion) which could result in greater than acceptable overpressures and radiant heat loads.

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Detailed Calculations

I. The Effects of Overpressurization of the Boiler.

A. Burst Pressure

The manufacture shows the boiler to be

2m (78 inches) inside diameter
(Dimension T)

5.7m (225 inches) long
(Dimension B+E)

2m (79 inches) outside diameter
(Dimension X-R)

The volume is then

$$\frac{\pi}{4} \left(\frac{78 \text{ in.}}{12 \text{ in/ft}} \right)^2 \left(\frac{225 \text{ in.}}{12 \text{ in/ft}} \right) = 622 \text{ ft}^3 \\ = 17.63 \text{ m}^3$$

The wall thickness is 1.3 cm (0.5 in)
(Dimension X-R-S divided by 2)

The material of construction is assumed to be carbon steel.

The burst pressure is found from Halverson (1986) pg 11.

$$U = PD/2t$$

where P = burst pressure, psi

D = outside diameter of vessel, in

$t = .79$ in wall thickness, in = 0.5 in.

U = ultimate strength, psi (tensile strength)

= 65,000 psi (Halverson 1986, pg 11)

Solving for " P " yields 823 psi

This equation assumes that the split is longitudinal (Megyesy 1973, pg 14) and the shell is seamless

If the split was circumferential, the

equation is (Megyesy 1973) and the shell is seamless

$$U = PD/4t$$

Solving for " P " yields 1646 psi

Megyesy 1973 pg 18 gives other possible splitting points.

Cylindrical shell, long seam

$$P = \frac{SEt}{R + 0.6t}$$

where S = ultimate stress or ultimate strength
 = 65,000 psi (tensile)
 E = joint efficiency

assume butt joint, spot examined
 = 0.85

t = wall thickness = 0.5 in

R = inside radius

= 78 in. / 2 = 39 in

Solving for "P" yields 703 psig

Ellipsoidal Head

$$P = \frac{2SEt}{D + 0.2t}$$

where S, E, t are as above

D = inside diameter, in
 = 78 in.

Solving for "P" yields 707 psig

For purposes of this calculation, the burst pressure is taken to be 1000 psig

which is larger than the pressure at which
 a long seam splits (703 psig)

the head splits off (707 psig)

the seamless splits
 longitudinally (823 psig)

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B. Shock Wave from Bursting Vessel

To calculate all of the parameters needed, a burst scenario is needed. The term scenario is not an indication that this is a credible sequence of events. It indicates a possible sequence. Scenario 1.

Assume the vessel is filled with air and leaked until 1000 psig is reached.

Assume initial conditions are 14.7 psig and 70 F

Using the ideal gas law

$$PV = nRT \quad \text{with} \quad R = 1544 \frac{\text{lb-ft}}{\text{lb-mole} \cdot \text{R}}$$

with $P = 14.7 \text{ psia} = 2116.8 \text{ lbf/ft}^2$

$$V = 622 \text{ ft}^3$$

$$T = 70 \text{ F or } 530 \text{ R}$$

"n" is found to be 1.6 lb moles of air or 46.4 lb of air

Ignore compressibility. When "P" equals 1000 psig (1014.7 psia), "T" would be 36,790 R. This is unrealistic.

Scenario 2. Assume the flue outlet is blocked and the flue gas inlet lets in air but does not allow gas to escape. Assume that the tubes carrying the flue gas fail and that the flue gas mixes with the air. Assume that the air and gas reach the burner temperature. Assume a burner (that is flame) temperature of 3000 R ("Producer gas" or "blast furnace gas" flame temperature per Avallone and Baummeister 1987, pg 4-33)

This results in a value for "n" of

$$n = 19.62 \text{ lb-moles (1.6 is air)}$$

$$T = 3000 \text{ R}$$

$$V = 622 \text{ ft}^3$$

$$P = 1014.7 \text{ psia}$$

This is what will be used in the calculations for shock pressure.

The equations for shock overpressure and impulse for a bursting sphere come from Baker (1983) p 9 145 - 153 and the sample problem on pg 205 - 206.

The problem involves determining a number of scaled parameters in a step-wise manner.

First we need to find which curve of the family of curves relating $\bar{P}_s$ to $\bar{R}$ we are on.

$$\bar{R} = r P_0^{1/3} / E^{1/3}$$

where r = distance to the point of interest, in
In this case " r " is
the edge of our boiler
assuming it was
spherical

$$17.63 \text{ m}^3 = \frac{4}{3} \pi r^3$$

$$= 1.6 \text{ m}$$

$$P_0 = \text{atmospheric pressure, } P_a$$

$$= 1.013 \times 10^5 \text{ Pa}$$

$$E = \left(\frac{P_1 - P_0}{\gamma - 1} \right) V$$

$$P_1 = \text{burst pressure, } P_a$$

$$= 7 \times 10^6 \text{ Pa}$$

$$(1000 \text{ psig})$$

$$P_g 12 \text{ of } 39$$

γ = ratio of specific heats
assume it is the same as air

1.4

$$V = \text{volume} = 17.63 \text{ m}^3$$

$$E = 3.04 \times 10^8 \text{ N-m}$$

Solving for $\bar{R}$ yields 0.11

Step 2 find $\bar{P}_{S0}$ initial shock pressure

Figure 2-16 of Baker 1983 provides
a curve of $\bar{P}_{S0}$ as a function
of P_1/P_0 and a_1/a_0 .

where P_1 = burst pressure 1014.7 psia
(1000 psig)

P_0 = atmospheric pressure 14.7 psia

$$P_1/P_0 = 69$$

a_1 = speed of sound at burst

a_0 = speed of sound initially

Baumertner (1987) shows that

$$a \sim \sqrt{T}$$

$$\text{So } \frac{a_1/a_0}{(a_1/a_0)^2} = \sqrt{3000R/530R} = 2.4$$

Using Figure 2-16, $\bar{P}_{S0} = 12 \text{ psi}$

Going to Figure 2-15 with $\bar{P}_S = 12$

$$\bar{R} = 0.11$$

Shows that the curve to use is
the 5th from the top.

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Step 3 Now solve for P given values of R .

$$\text{Recall } \bar{R} = r P_0^{1/3} / E^{1/3} \\ = r (0.07)$$

$$\bar{P}_s = (P_s - P_0) / P_0 \quad \text{pg 206}$$

$P_s =$ ~~over~~ pressure at "r"

$P_0 =$ atmospheric pressure

$$\bar{P}_s(P_0) = P_s - P_0 = \text{over pressure or differential pressure}$$

Using Figure 2-15

r, m	$\bar{R}$	$\bar{P}_s$ (Note 1)	over-pressure, P_{sig}	$\bar{i}$ (See next page and below)	$i, Pa-s$	$i, Psi-s$
10	0.7	1	14.7	0.1	435	0.063
30	2.1	0.15	2.2	0.037	161	0.023
50	3.5	0.1	1.5	0.022	96	0.014
70	4.9	0.063	0.9	0.015	65	0.009

Note 1 values of $\bar{R}$ above 3 use $\log(\bar{P}_s) = -1.3 \log \bar{R} - 0.3$
(extrapolation of top curve of Fig 2-15)

The impulse will be needed for calculations involving effects on people. The impulse is found on Figure 2-19

Between $\bar{R} = 2$ and 10^3

The curve in Figure 2-19 is approximated by

$$\log \bar{i} = -1.04 \log \bar{R} - 1.1$$

$$\bar{i} = i a_0 / (P_0^{2/3} E^{1/3})$$

i = impulse, Pa-s

a_0 = speed of sound

$$= 331 \text{ m/s} \quad (\text{Baker pg 206})$$

P_0, E are as before

$$\bar{i} = i (2.3 \times 10^{-4})$$

To get " i " in units of psi-s (the normal unit) divide by 6895.

c. Building Damage

Overpressure from blast waves that result in damage are taken from Brasie (1968). Brasie took data from actual explosions and developed a Table of blast over pressure vs damage.

For our case his table shows:

Corrugated steel panel (234-52)	connection failure	1-2 psi
---------------------------------	--------------------	---------

Concrete or cinder block walls (not reinforced) (231-7)	shattering	2-3 psi
---	------------	---------

Assume that failure occurs at the mid point of the range.

Therefore

boiler over pressurization	can fail
steel panels	50m (164ft) away
block walls	30m (98ft) away

It is possible that the vessel overpressurizes based on steam not air. The next page considers the changes in the values due to the switch from air to steam.

It was also found during the course of these calculations that the stored energy of a vessel half filled with water and half steam is about 10 times that of a vessel filled with just steam.

For the case of a vessel filled with steam at 1000psig, 546 F

$$u_i - u_f = (H + PV)_i - (H + PV)_f = \frac{(622 \text{ Ft}^3)}{0.44 \text{ lb/ft}^3} \times 1192.5 + \frac{(1014.7 \text{ psi})(144)(622 \text{ Ft}^3)}{790 \text{ ft} \cdot 16.18 \text{ lb}} - \frac{(622 \text{ Ft}^3)}{0.44 \text{ lb/ft}^3} \times 1092.5 + (14.7) \frac{(144)(622)}{790} = 2.6 \times 10^5 \text{ Btu}$$

For the case of a vessel filled with half water (15465 lb) + half steam (561 lb) and isentropic expansion to 70 F, 14.7 psia (33% of water turned to steam)

$$u_i - u_f = (H_w + H_s + PV)_i - (H_w + H_s + PV)_f = 15465(544.4) + 561(1192.5) + \frac{1014.7(144)(622)}{790} - 10206(38) + 5819(1092.1) + \frac{14.7(144)(622)}{790} = 2.5 \times 10^6 \text{ Btu}$$

using steam table data and $H = m h$

However, Baker (1983) states that in tests that he did with pressurized liquid Freon (that flashed when depressurized) vessel failures produced minimal blast overpressures due to the relatively long time it takes to flash the liquid. This was borne out in actual tests performed by Baker.

Scenario 3 -

There is little water in the vessel. The vessel is assumed to overpressureize based on the boiling of the remaining liquid. The boiler is assumed to be plugged.

Using the same method as in Scenario 2, the following is found

$$\gamma = 1.3 \quad \text{not } 1.4$$

$$E = 4.05 \times 10^8 \text{ Nm} \quad \text{not } 3.04 \times 10^8 \text{ Nm}$$

$$\bar{R} = 0.1 \quad \text{not } 0.11$$

a.1/a. as the same as the speed of sound as per prior a.1 to $\sqrt{T}$ and both a.1 and a.9 are measured in steam atmosphere
 Figure 2-16 of Baker is for $\gamma = 1.4$.
 There is also a curve for $\gamma = 1.667$.

Extrapolating yields $\bar{P}_{50}$ as 13 not 12 with $\bar{P}_0$ as 13 and $\bar{R}$ as 0.1 the same curve is used.

Now determine the over pressure at 50 m,

$$\bar{R} = 3.15 \quad \text{not } 3.5$$

$$\text{So } \bar{P} = 0.11 \quad \text{not } 0.1$$

The over pressure is 1.6 psi not 1.5

no significant difference here.

The equations for impulse also use $E^{0.33}$ so there would be no significant difference there either.

D. Fragments

Fragmentation data comes from DOE (1992)
Pg 6-49 to 6-53

The velocity of the fragments comes from a curve that relates pressure and velocity

$$\text{pressure term} = \frac{(P - P_0) V_0}{M_c a^2}$$

where P = burst pressure, P_0

P_0 = atmospheric pressure, P_a

V_0 = volume of container, m^3 of air

M_c = mass of container, kg of metal

a = speed of sound of gas at burst.

In this case

$$P = 7 \times 10^6 P_a$$

$$P_0 = 1.013 \times 10^5 P_a$$

$$V_0 = 17.63 m^3$$

} from previous calculations in section IA, IB, IC

$$\begin{aligned} a &= 331 m/s (\sqrt{T_0/T_0}) \quad (\text{From Section IB}) \\ &= 331 m/s (\sqrt{3000R/560R}) \\ &= 766 m/s \end{aligned}$$

m_c is found by the following
(obtain the volume of metal then multiply by the density)
density steel 489 lb/ft³

volume of shell

$$V = \frac{\pi}{4} \left[\left(\frac{79}{12} \right)^2 - \left(\frac{78}{12} \right)^2 \right] \left(\frac{225}{12} \right)$$

$$= 16 \text{ ft}^3 \text{ of metal}$$

Volume of 2 ends (assume 0.5 inch thick)

$$V = \frac{\pi}{4} \left(\frac{79}{12} \right)^2 \left(\frac{0.5}{12} \right)$$

$$= 1.4 \text{ ft}^3 \text{ each of metal}$$

$$m_c = (16 \text{ ft}^3 + 1.4 \text{ ft}^3 + 1.4 \text{ ft}^3) 489 \frac{\text{lb}}{\text{ft}^3}$$

$$= 9193 \text{ lb of metal}$$

$$= 4179 \text{ kg of metal}$$

Pressure term equals 0.05

velocity term = $u / K a$

assume equal fragments. Then $K=1$

velocity term = $u / 766$

where u = fragment velocity

Using Figure 6.16 of DOE 1992

with Pressure term of 0.05

assume 100 cylindrical fragments

then velocity term equals 0.3

$$u = (766 \text{ m/s})(0.3) = 230 \text{ m/s}$$

The ability of the fragment to penetrate walls is taken from Army (1986)

The value $u = 230 \text{ m/s}$ is the initial velocity of the particle. The particle will slow over time.

Figure 6-5 pg 6-10 of Army 1986 shows the ratio of the velocity as a function of fragment weight.

At 50m (164 ft) large fragments (>100oz) lose little of their velocity. The

Figure provides the following information

<u>Wt, oz</u>	<u>$V_{\text{strike}} / V_{\text{initial}}$</u>
100	0.87
10	0.75
1	0.55

Assume that the strike velocity equals the initial velocity. This is close to true for large fragments that weigh alot (eg 100 oz or so).

Figure 6-7 pg 6-13 shows the penetration depth as a function of weight and velocity.

At 230 m/s (754 ft/s) large fragments (40oz) can penetrate up to 1 inch of steel.

Even 1oz fragments can penetrate 0.3 in.

pg 6-9 of Army 1986

provides an equation for striking velocity

$$V_{\text{strike}} = (V_{\text{initial}}) \left(\exp[-0.004(R/w^{0.333})] \right)$$

where R = distance to point of concern, ft

w = fragment wt, oz

Assume a 100 oz fragment,

$V_{\text{strike}}/V_{\text{initial}}$	R
0.88	150 ft
0.77	300 ft
0.65	500 ft

The values of $V_{\text{strike}}/V_{\text{initial}}$ for a 100 oz fragment are still 0.4 at 500 ft.

It is unrealistic to place the boiler back far enough to prevent fragments from entering 234-52 Building of PFP. Instead credit should be taken for event probability, fragment size (gravity, drag, lack of aerodynamics all will cause the fragment to fall to the ground prior to striking) and fragment direction (orientation of boiler with respect to 234-52, fragments will be sent out over a large solid angle).

Figure 6-10 of Army 1986
shows penetration into concrete.
At a velocity of 754 ft/s, large
particles will penetrate 2 inches of
concrete.

The block wall at 231-Z may also be
breached depending on whether or not
the holes in the block are filled and
where the fragment strikes. Credit
should be taken for the same
phenomena as that for strikes onto
234-5Z Building of PFP.

If we viewed the problem from the
point of view of TNT casing being
fractured we would see how bad it
could be. ~~From~~ DOE 1992 pg 6-19, 20
has a sample problem in which
100 lb of TNT having a 10 lb casing is
blown.

For the case of a 0.01 lb fragment
The initial velocity is 9560 ft/s
The velocity at 30 ft is 8590 ft/s
Extended to 160 ft $v = 5400$ ft/s

Figure 6-7 of Army (1986) with 5400 ft/s
and 0.01 lb (0.20±) shows penetration
of about 1 inch of steel.

E. Hazards to Personnel

DoE (1992) pg 179-196 provide the information. Use 2psig as an average of the steel sheet failure pressure and the block value

1. pg 4-181 shows a graph of lung damage vs over pressure and impulse

$$\text{over pressure } \bar{P}_s = P_s / P_0$$

$$= 2 \text{psig} / 14.7$$

$$= 0.136$$

P_s = overpressure psig

P_0 = atmospheric pressure

This value is below the threshold for all values of impulse.

2. pg 4-189 shows skull fracture velocities as a function of P_s and scaled impulse.

In our case

$$P_s = 2 \text{psig}$$

$$\text{scaled impulse } \bar{i} = i / m^{0.33}$$

m = equivalent TNT, lb

From previous calculations $E = 3 \times 10^8 \text{ N-m}$

$$3 \times 10^8 \text{ N-m} = 3 \times 10^8 \text{ J} = 7.2 \times 10^7 \text{ cal}$$

$$\text{energy of TNT} = 1080 \text{ cal/g, TNT}$$

$$7.2 \times 10^7 \text{ cal} = 66,666 \text{ g TNT}$$

$$= 147 \text{ lb TNT}$$

Using the hemispherical TNT curves with

$$W = 147 \text{ lb}, R = 164 \text{ ft}, Z = R / W^{0.333} = 31 \text{ (Baker)}$$

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and $i = 0.014 \text{ psi-s}$ (Baker)

$$S_0 \quad \bar{i} = \frac{0.014 \text{ psi-s}}{1470.33} \\ = 2.6 \times 10^{-3}$$

This is well off the graph.

No skull fracture

3. pg 4-190 shows a graph for whale body translation with the same axis as skull fracture

Again the point is well off the graph indicating no concern.

4. pg 4-196 shows a graph for eardrum damage.

$$\text{using } P_s = 2 \text{ psi-g}$$

$$i_s = 1.4 \times 10^{-2} \text{ psi-s}$$

The point is below the threshold for eardrum rupture but above that for TTS (temporary threshold shift) or hearing loss for a time.

So the only hazard to personnel is a temporary loss of hearing and fragment (shrapnel) injury.

II Effects of a pool fire

Ignore the presence of the berm around the fuel oil tank.

The fuel oil tank holds 40,000 gallons per the purchase spec.

Assume it fails and dumps the entire contents into a pool one inch deep.

(As the calculation proceeds, the effect of pool area and depth will be noted to assure that a one inch pool is the worst case).

The pool area is

$$A = \frac{40,000 \text{ gallons}}{7.48 \text{ gal/ft}^3} \left(\frac{12 \text{ in/ft}}{1 \text{ in.}} \right) = 64,171 \text{ ft}^2$$

$$\text{Diameter} = \left[\frac{64,171 \text{ ft}^2}{\pi/4} \right]^{0.5} = 286 \text{ ft}$$

or 143 ft in radius

Per the bursting tank calculation, the facility is 164 ft from the tank.

Most of the remaining calculation comes from the Fire Protection Handbook (SFPE 1988) pg. 2-45 to 2-87 with the sample problem on pg 2-61
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The burning velocity comes from 109 2-47,
Figure 2-4.2

The burning velocity is 4 mm/min for large liquid
pool areas (up to 30 m diameter)

The pool in this case is

$$D = 286 \text{ ft} / (3.28 \text{ ft/m}) = 87.2 \text{ m}$$

The burning velocity curve is flat from
2 m to 30 m. So use of these values at
87 m should be acceptable.

Fig 2-51 provides an expression for the
maximum diameter given an instantaneous
release and ignition

$$D_{\max} = 2 [V_L^3 g' / \gamma^2]^{1/8}$$

where V_L = total volume spilled, m^3

$$= \left(\frac{40,000 \text{ gal}}{7.48 \text{ gal/ft}^3} \right) \left(\frac{m^3}{3.28 \text{ ft/m}^3} \right) = 151.5 \text{ m}^3$$

$$g' = g (1 - \rho_L / \rho_w)$$

$$g = \text{acceleration due to gravity } m/s^2$$

$$\rho_L = \text{fuel density}$$

$$\rho_w = \text{water density}$$

The specific gravity is found from
deg. API = $\frac{141.5}{sp\,g} - 131.5$

~~See~~ The deg. API for #2 fuel oil is 26
(Steiner 1950). Solving for spg yields
0.9

$$g' = 32.2 (1 - 0.9) \\ = 3.22$$

$$\dot{y} = \text{burning rate } m/s \\ = 4 \frac{mm}{min} \left(\frac{10^{-3} m}{mm} \right) \left(\frac{min}{60 s} \right) \\ = 6.7 \times 10^{-5} m/s$$

Solving for Dmax yields ~~16.8~~ 16.8 m.

We will stick with the value of 286 ft (87m).

The next step is to determine flame height.
Ignore the effect of the wind.

Pg 2-51 equation 13 provides the
equation for flame height.

$$H/D = 42 [in''/\rho_a \sqrt{gD}]^{0.61}$$

where H = flame height

D = pool diameter

$\dot{m}''$ = mass burning rate, $\text{kg}/\text{m}^2\text{-s}$
 $= \dot{Y}(\rho)$

$\dot{Y}$ = burning velocity
 $= 6.7 \times 10^{-5} \text{ m/s}$

ρ = density = 0.9 (density of water)
 $= 0.9 (1000 \text{ kg}/\text{m}^3)$
 $= 900 \text{ kg}/\text{m}^3$

$\dot{m}'' = 0.06 \text{ kg}/\text{m}^2\text{-s}$

ρ_a = density of ambient air kg/m^3
 $1.2 \text{ kg}/\text{m}^3$

g = acceleration due to gravity
 $= 9.8 \text{ m/s}^2$

Solving for H/D yields 0.82

So flame height = $0.82 (87 \text{ m})$
 $= 71 \text{ m}$

Now to find thermal radiation from the fire.

Follow the sample problem on pg 2-61.

The thermal radiation is given by $q = E \times F$

E = Emissive Power from pg 2-57

use $20 \text{ kW}/\text{m}^2$

F = View Factor

Interested at 164 ft (50 m)

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Use Figure 2-4.13

The non-dimensional distance is given by
 $X / (D/2)$

where X = distance from center of pool
 to point of interest

$$= 50 \text{ m}$$

$$D = \text{pool diameter} = 87 \text{ m}$$

$$\text{Non-Dimensional distance} = 1.15$$

$$\begin{aligned} \text{Height to radius ratio} &= (71 \text{ m tall}) / (87 \text{ m} / 2) \\ &= 1.6 \end{aligned}$$

The view factor equals 0.5

τ = transmissivity

Next the transmissivity is found

Figure 2-4.20 gives the transmissivity
 as a function of path length and
 relative humidity.

Assume a value of 0.8 (low humidity value
 for transmissivity)

The radiant heat flux is given by

$$q = E_p \tau F$$

where E_p = Emissive Power = 20 kW/m^2

τ = transmissivity = 0.8

F = view factor = 0.5

$$q = 8 \text{ kW/m}^2$$

Assume this energy is absorbed by a 1m^2 wall panel at PPP. The final temperature assuming no heat transfer out is

$$m c_p \Delta T = Q$$

m = mass of 1m^2 steel panel

assume $1/8$ inch thick

$$= (1\text{m}^2) \left(3.28 \frac{\text{ft}}{\text{m}} \right)^2 \left(\frac{0.125\text{in}}{12\text{in}/\text{ft}} \right) \left(489 \frac{\text{lb}}{\text{ft}^3} \right) \left(\frac{\text{kg}}{2.2\text{lb}} \right)$$

$$= 25\text{ kg}$$

$$c_p = 0.47\text{ kJ/kg} \cdot \text{C}$$

Q = heat rate

$$= 8\text{ kW (t, s)}$$

t = total burn time

unit area burn rate $0.06\text{ kg/m}^2 \cdot \text{s}$

$$\text{area} = \frac{\pi}{4} (87)^2 = 5942\text{ m}^2$$

$$\text{total burn rate} = 356\text{ kg/s}$$

$$\text{fuel quantity} = \left(\frac{40,000\text{gal}}{7.48\text{gal}/\text{ft}^3} \right) (0.9) \left(62.4\frac{\text{lb}}{\text{ft}^3} \right) \left(\frac{1}{2.2} \right)$$

$$= 136,570\text{ kg}$$

$$t_{\text{me}} = 136,570\text{ kg} / 356\text{ kg/s}$$

$$= 383.5\text{ s}$$

$$Q = 8\text{ kW} (383.5\text{ s}) = 3068\text{ kJ}$$

Solving for ΔT

$$\Delta T = \frac{3068 \text{ kJ}}{25 \text{ kg} (0.47 \frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{C}})} = 261^\circ\text{C}$$

check heat loss to see if this is excessive. Assume one side is insulated.

check convection rate out at 261°C

using standard radiation heat transfer equation for a simple situation,

$$q_{\text{rad}} = 5.669 \times 10^{-12} A (T_s^4 - T_a^4) \text{ watts}$$

$$5.669 \times 10^{-12} = \text{ Stefan-Boltzmann constant, } \text{watts/cm}^2 \text{K}^4$$

$$A = \text{area, cm}^2$$

$$= 10^4 \text{ cm}^2$$

$$T_s = 261^\circ\text{C} + 30^\circ\text{C} + 273$$

$$= 564^\circ\text{K}$$

$$T_a = 30^\circ\text{C} + 273 = 303^\circ\text{K}$$

$$q = 5258 \text{ W}$$

$$= 5.26 \frac{\text{kW}}{\text{m}^2} \quad \text{based on a } 1 \text{ m}^2 \text{ area}$$

$$q_{\text{conv}} = h A (T_s - T_a)$$

$$h = \text{heat transfer coefficient } \text{W/m}^2 \text{K}$$

$$= 1.3 (\Delta T)^{1/3}$$

$$\Delta T \text{ is in } ^\circ\text{K}$$

$$h = 1.3 (261)^{1/3} = 8.3$$

$$q_{\text{conv}} = 8.3 (1 \text{ m}^2) (261^\circ\text{K}) = 2166 \text{ W}$$

$$= 2.2 \frac{\text{kW}}{\text{m}^2}$$

based on a
1 m² area

$$q_{\text{out, total}} = \frac{5.26 + 2.2}{0.931 \text{ of } 39} = 7.46 \frac{\text{kW}}{\text{m}^2}$$

This is close to 8 kW/m^2

So the temperature is $261^\circ\text{C} + 30^\circ\text{C} = 291^\circ\text{C}$
 $= 556^\circ\text{F}$

This is probably enough to excessively heat the insulation and possibly have it catch fire. A pool 87m large must be avoided.

Check the berm

The berm is 100 in tall
 16 ft wide (actually 15'8")
 47 ft long

The pool effective diameter is

$$\frac{\pi}{4} D^2 = \frac{(16)(47)}{(3.28)^2}$$

$$D = 9.4 \text{ m}$$

Substituting this into the H/D equation
 yields 1.7

$$H = 1.7 (9.4 \text{ m}) = 16 \text{ m.}$$

$$E = 20 \text{ kW/m}^2$$

To find F •

$$\begin{aligned} X/(D/2) &= 50/(9.4/2) \\ &= 10.6 \\ H/(D/2) &= 16/(9.4/2) = 3.4 \end{aligned}$$

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$$F = 0.015$$

$$r = 0.8$$

$$q = 20 \frac{\text{kw}}{\text{m}^2} (0.015) (0.8) = 0.24 \frac{\text{kw}}{\text{m}^2}$$

burn rate is the same

so

$$\Delta T = \frac{261^\circ\text{C}}{(8 \frac{\text{kw}}{\text{m}^2}) / (0.24 \frac{\text{kw}}{\text{m}^2})} = 7.8^\circ\text{C}$$

no problem with fire in the berm

Effect on People

pg 2-84

Figure 2-4.39 shows the time required for
 pour as a function of flow.

For the large pool fire the flow was

$$Q_{\text{flow}} = 8 \frac{\text{m}^3}{\text{s}}$$

Time was 383.5 s

Thus no well above the line. Personnel
 would feel pain.

Check beam fire

$$g = 0.24 \frac{\text{kg}}{\text{m}^2}$$

Time is 383.5 s

There is no feeling of pain

Figure 2-4.40 and 41 show data for
 skin burn and fatality using the

same axis designations (h, f, f_h)

for the large fire there were no burns
 and fatality at PFP

for the beam fire there are none

From personnel safety point of view
 the large fire must be prohibited
 the beam fire is acceptable (except
 for toxic soot which is commonly
 accepted. pg 34 of 39

III The Effects of Outside-the-Boiler Explosions

A building encloses the boilers.

Assume the building encloses all 3 boilers

The building is assumed to be 5 ft larger than the pad the boilers are on (see Drawings)

The length is then $61' 6'' + 5' = 66.5 \text{ ft}$.

width is then $29' 6'' + 5' = 34.5 \text{ ft}$.

The height is 18 ft

The volume is therefore $41,300 \text{ ft}^3$ with no credit taken for volume taken up by equipment.

Diesel Fuel can be modelled as being a mixture of cetane (n-hexadecane) and methyl-naphthalene. It is assumed that a 50-50 mix of each is the composition. Cetane ~~and~~ has a ~~cetane~~ cetane number of 100. methyl-naphthalene has a cetane number of 0.

Diesel fuels have a cetane number of 35-65 (Data from pg 375, Kirk-Othmer 1994)

The LFL of cetane is 0.43% by volume (using n-hexadecane for cetane)
or 44mg/l as aerosol droplets.

The UFL is not given

The flammability limits for jet fuel are

LFL	1.4 %	48mg/l
UFL	8 %	330mg/l

(Data from Zabetakis 1965)

Assume that the stoichiometric mixture is
2.8 % (double the LFL) Kanury 1975

The room volume is 41,300 ft³.

The volume of flammable gas is

$$V = 0.028 (41,300 \text{ ft}^3) = 1156 \text{ ft}^3$$

The molecular weight is about 120g/mole

(Kanury 1975 based on gasoline, jet fuel)

The quantity of ~~no~~ vapor is found using the ideal gas law.

$$pV = nRT$$

$$(1 \text{ atm})(1156 \text{ ft}^3) = n \left(0.73 \frac{\text{atm ft}^3}{16\text{-mole R}} \right) (460 + 70 \text{ F})$$

$$n = 2.99 \text{ lb moles}$$

$$= 1357.5 \text{ g moles}$$

$$m = n(\text{Mol. wt.})$$

$$= 1357.5 (120 \text{ g}) = 162,900 \text{ g of gas}$$

If we use double the aerosol loading at LFL as the stoichiometric condition we get

$$m = \left(\frac{88 \text{ mg}}{\text{L}} \right) \left(\frac{9}{1000 \text{ mg}} \right) \left(41,300 \text{ ft}^3 \right) \left(\frac{28.3 \text{ L}}{\text{ft}^3} \right) = 102,900 \text{ g}$$

or just about two-thirds the gas loading.

Since it is more likely that aerosol will be released than gas, the aerosol load will be used.

The energy released is 10.3 kcal/gm (Konury)

The total energy released is 1.06×10^6 kcal.

The overpressure at 50 meters is found from Kogarko (1966)

Kogarko provides pressure as a function of distance from exploding spherical balloons.

The overpressure is given by

$$\Delta p = 0.6 \times 10^{-3} \frac{E^{1/3}}{R} + 1.4 \times 10^{-2} \frac{E^{2/3}}{R^2} + 2.5 \times 10^{-3} \frac{E}{R^3}$$

$$\text{for } \frac{R}{E^{1/3}} > 0.3$$

where R = distance from center to point of interest, m

E = energy, kcal

$\Delta p = \frac{E}{R^3} \sim \text{atm pressure differential}$

In our case

$$E = 1.06 \times 10^6 \text{ kcal}$$

$$R = 50 \text{ m}$$

$$\Delta p = 0.0012 + 0.058 + 0.021$$

$$= 0.08 \text{ atm}$$

$$= 1.2 \text{ psi}$$

This is less than the overpressure due to vessel overpressurization by a small amount (1.5 psi vs 1.2 psi). Therefore 50m siting is acceptable

Use of 160,900 g of gas at 10.3 kcal/g in the method in Kogarko (1966) yields 1.7 psi. This is close enough to 1.5 psi that the site 50m away is still acceptable based on all of the conservativeness in the calculation.

CHECKLIST FOR PEER REVIEW

Document Reviewed: "PACKAGE BOILER SITING CALCULATIONS - VESSEL
OVERPRESSURIZATION," June 5, 1997.

Scope of Review: Entire Document

Yes No NA

- ☐ ☐ ☒ * Previous reviews complete and cover analysis, up to scope of this review, with no gaps.
- ☒ ☐ ☐ Problem completely defined.
- ☒ ☐ ☐ Accident scenarios developed in a clear and logical manner.
- ☒ ☐ ☐ 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. Spreadsheet results should be treated exactly the same as hand calculations.
- ☐ ☐ ☒ Software input correct and consistent with document reviewed.
- ☐ ☐ ☒ Software output consistent with input and with results reported in document reviewed.
- ☒ ☐ ☐ Limits/criteria/guidelines applied to analysis results are appropriate and referenced. Limits/criteria/guidelines checked against references.
- ☒ ☐ ☐ 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.
- ☐ ☐ ☒ Format consistent with appropriate NRC Regulatory Guide or other standards
- ☐ ☒ * Review calculations, comments, and/or notes are attached.
- ☒ ☐ ☐ Document approved.

C. H. HUANG

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6/5/97

Reviewer (Printed Name and Signature)

Date

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