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Course Description

Blast-Resistant Design of Steel Buildings

Part 1

March 17, 2016

This lecture will provide architects and engineers with an introduction to blast analysis. The physics of explosions will be explained, including types of explosions and the effects of blast. Blast loads will be introduced along with their interaction with buildings and structures. Tools to predict blast will be introduced through example problems.

6

Learning Objectives

- Become familiar with types and sources of explosions
- Recognize blast effects due to explosions
- Understand how blast loads interact with structures
- Become familiar with blast prediction tools

7

There's always a solution in steel.

Blast-Resistant Design of Steel Buildings Part 1: Blast Loads and Their Interaction with Buildings

March 17, 2016

Presented by
Kirk Marchand, P.E.
Managing Principal
Protection Engineering Consultants
San Antonio, Texas

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BLAST-RESISTANT DESIGN OF STEEL BUILDINGS

Part I: *Blast Loads and Their Interaction with Buildings*

March 17, 2016

Kirk Marchand, P.E.

Aldo E. McKay, P.E

Protection Engineering CONSULTANTS

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Explosions and Blast Loads

- Introduction to blast loads
  - definitions
  - blast effects
- Blast loads and structure interaction
  - focus on high explosives
- Computation of blast loads
  - tools (BEC, ConWep, BlastX)
  - example problems

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Definition of an Explosion

- A sudden and violent release of mechanical, chemical, or nuclear energy, usually accompanied with the generation of high temperature and the release of gases
  - explosion is created by a runaway exothermic chemical reaction (i.e., produces heat)
  - heat of reaction = heat of combustion

Types of Explosives

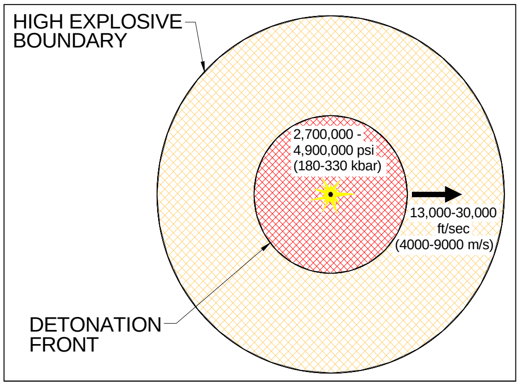
- Four general categories of explosives (Baker et al. 1983):
  1. unstable explosives
     - nitrogen trichloride, some organic peroxides
     - “laboratory curiosities”
  2. primary explosives
     - lead azide
     - shock and spark sensitive
     - used for initiation of high explosives
  3. high explosives (HE)
     - TNT, RDX, C-4, pentolite
     - can be handled safely and stored for long times
  4. propellants
     - black powder, solid rocket fuels
     - difficult to detonate (but can…)

Sources of Explosions

- High explosives (HE)
- Vapor cloud explosions
- Pressure vessel explosions
- Other sources

HE Detonation

- A very rapid and stable chemical reaction moves through the explosive material at supersonic velocity, called the ***detonation velocity*** (22,000 to 29,000-ft/sec for most HE)



HE Detonation

- The boundary between the detonated and undetonated material is known as the ***detonation front***
- Detonation causes a phase change in the liquid or solid explosive material, rapidly converting it to a very hot and dense high-pressure gas

Bridge Pier Tests

VIDEO

HE Detonation

- Common misconception:
  - shock is like wind and the flow can be “redirected” — WRONG!
  - the shock moves faster than the wave speed of the air particles (that’s the definition of a shock)
  - the shock will travel great distances, but the air particles are only displaced on the order of millimeters during shock transmission
    - winds can develop later as the rest of the reaction is completed and the air moves into low pressure areas and in reaction to turbulence—on the order of tenths of a second
- Shock is a 1000-psi gorilla that leans on your structure for a few milliseconds and then moves off

Sources of Explosions

- High explosives (HE)
- Vapor cloud explosions (hazardous materials)
- Pressure vessel explosions
- Other sources

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Vapor Cloud Explosions (VCE)

- Release of flammable chemicals or fuels
  - large vessels and piping – petrochemical
  - smaller vessels – chemical processes, batteries, etc.
- Formation of a flammable vapor cloud (released material is within stoichiometric limits)
  - an ignition source is required
  - resulting flame accelerates, leading to pressure wave transmission
  - blast pressure is determined by flame speed
    - flames accelerate in areas of confinement and congestion (process equip, pipes, structural members)
    - flames decelerate in the open (deflagration)

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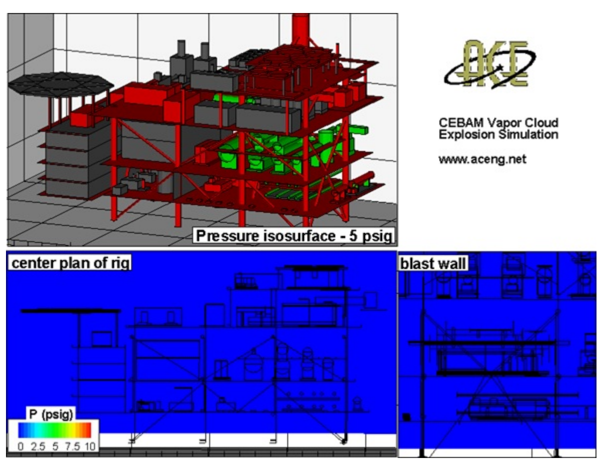
VCE Modeling

- TNT equivalent method
  - assumes a TNT charge of equivalent energy:

    $E_{TNT} = E_{VCE}$
  - TNT is much “stronger” than a VCE and is usually a poor representation of a VCE
- VCE blast curves
  - 1-dimensional (spherical explosion)
  - 2-dimensional (pancake, hemi-ellipsoid shape, confined)
  - reasonably accurate pressures/impulses
- Numerical models
  - computational fluid dynamics (CFD); often include release and dispersion

VCE Modeling

CFD Codes



VIDEO

Sources of Explosions

- High explosives (HE)
- Vapor cloud explosions (hazardous materials)
- Pressure vessel explosions
- Other sources

Pressure Vessel Explosions

- Overpressure of vessels with nonreactive gaseous content (mechanical explosion of pressure tanks and piping)
- Enclosed combustion deflagrations (subsonic) or detonations (supersonic)
  - weak enclosures (or insufficient venting) cannot sustain pressure from the combustion
- Boiling liquid expanding vapor explosions (BLEVE)
  - venting of pressurized flammable liquid as a result of vessel rupture (often weakened by excessive heating from external fire)

Sources of Explosions

- High explosives (HE)
- Vapor cloud explosions (hazardous materials)
- Pressure vessel explosions
- Other sources

Other sources

- Dust explosions
  - Fine particles of combustible solids (flammable dust) can explode in the same manner as flammable gases
  - small concentrations of flammable gas in a dust suspension can produce a more severe explosion than that of dust alone (hybrid mix)
- Steam explosions
  - sudden mix of two streams of widely differing temperatures (e.g. water into hot oil or molten metal)
- Electrical arc
  - high energy electrical arc (arc flash) can rapidly vaporize metal and insulation material, blasting the molten material with extreme force

Steam Explosion

VIDEO

Blast Effects

- Airblast
- Fragmentation
- Cratering
- Ground shock
- Thermal

Blast Effects

- In most cases…
  - in industrial settings or where gov't anti-terrorism requirements apply…*airblast only*
- In some special purpose gov't facilities…
  - for law enforcement and justice facilities…*ballistic protection may be required*
- In some Industrial settings…
  - ruptured pressure vessels, transformers or steam explosions…*debris penetration and loads*

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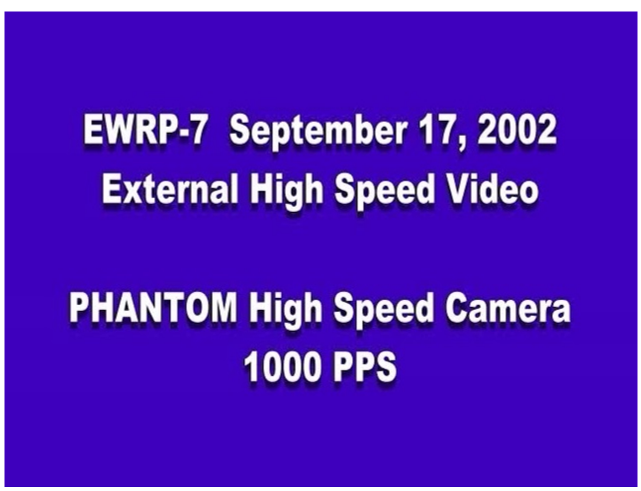
Blast Wave



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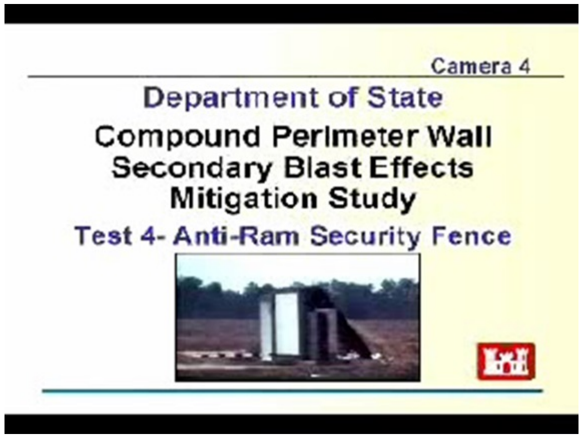
VIDEO

Blast Effects

- Airblast
- Fragmentation
- Cratering
- Ground shock
- Thermal

Fragments and Debris



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VIDEO

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Blast Effects

- Airblast
- Fragmentation
- Cratering
- Ground shock
- Thermal

Cratering

- Importance of crater size is relatively small compared to range of airblast effects
  - size depends on soil properties
  - for 220-lbs TNT
    - crater depth from 3.6 to 8.2-ft
    - crater diameter from 13 to 27-ft
- Refer to UFC 3-340-01

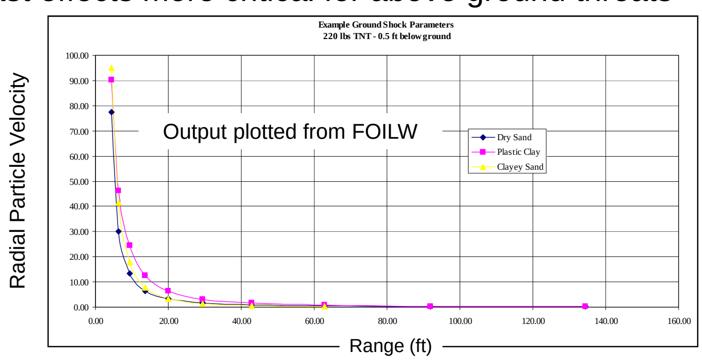
Blast Effects

- Airblast
- Fragmentation
- Cratering
- Ground shock
- Thermal

Ground Shock

- Generated by buried charges
- Applied to buried structures
- Airblast effects more critical for above ground threats

Refer to UFC 3-340-01



Blast Effects

- Airblast
- Fragmentation
- Cratering
- Ground shock
- Thermal

Thermal Effects

- Thermal/flame/fire risks are usually small to non-existent.
  - fire ball is too fast and short-lived and most of the available oxygen gets consumed.
- This is contrary to the popular misconception propagated by the movie industry, which likes to show big orange fireballs and follow-on scenes with burning debris.
- Fire can be a risk if the building contains flammable materials…
  - if gas lines are ruptured and if there is an ignition source

Blast Loads and Structures Interaction

Topics

- TNT Equivalency
- Ideal blast waves
- Air bursts and surface bursts
- Blast loads on structures

TNT Equivalencies

- TNT is not the optimal material to use to define equivalencies but is used for historical reasons
  - most modern HE contains enough oxidizer (oxygen) to support the entire reaction
    - can be used for underwater demolition
  - TNT is oxygen deficient and requires oxygen from the environment to complete the detonation.
    - results are variable

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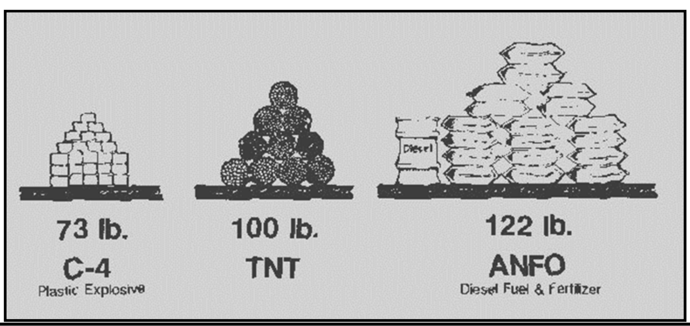
TNT Equivalency



P_{eq} = TNT P for 1.30 x C-4 wt

I_{eq} = TNT I for 1.19 x C-4 wt

P_{eq} = TNT P for 0.87 x ANFO wt

I_{eq} = TNT I for 0.87 x ANFO wt

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TNT Equivalencies Based on Energy

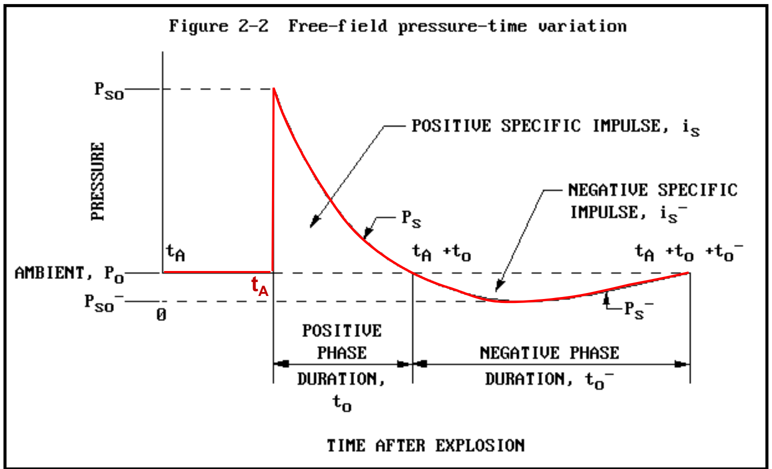
- TNT equivalent weight (W_{TNT}) can be determined by comparing the heat of detonation (ΔH_{EXP}) of the explosive to that of TNT (ΔH_{TNT})

$$W_{TNT} = \left(\frac{\Delta H_{EXP}}{\Delta H_{TNT}} \right) \bullet W_{EXP}$$

Topics

- TNT Equivalency
- Ideal blast waves
- Air bursts and surface bursts
- Blast loads on structures

Ideal Blast Wave



Ref: UFC 3-340-02

Side-on = SO = Incident = Free Field

Ideal Blast Wave (terms)

- P_{so} = incident, side-on or free field peak pressure
- i_s = incident, side-on or free field specific impulse
  = area under pressure vs time curve
  - "specific" because impulse (force x time) is over a unit area (length^2)
  - units of pressure x time, often psi-msec
- t_A = time of arrival

Topics

- TNT Equivalency
- Ideal blast waves
- Air bursts and surface bursts
- Blast loads on structures

Air Bursts

- **Free air bursts** occur at such an elevation that ground reflections are not a consideration.
- **Air bursts** are still above the ground surface but are lower and reflection effects must be considered.
- **Surface bursts** occur when the charge is on the ground surface.
- Air bursts and Surface bursts are discussed in detail in this presentation.

Air Burst Phenomena – Mach Stem Formation

- Shock waves from an air burst detonation interact with a plane reflecting surface (the ground).
- A region of Mach reflection develops due to nonlinear blast wave interaction; the incident and reflected waves merge into a single pulse called the **Mach Stem or Mach Front**.

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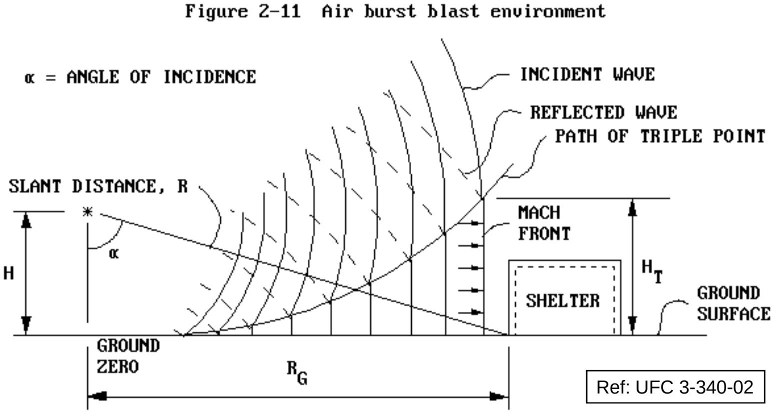
Air Burst Phenomena – Mach Stem Formation

Figure 2-11 Air burst blast environment



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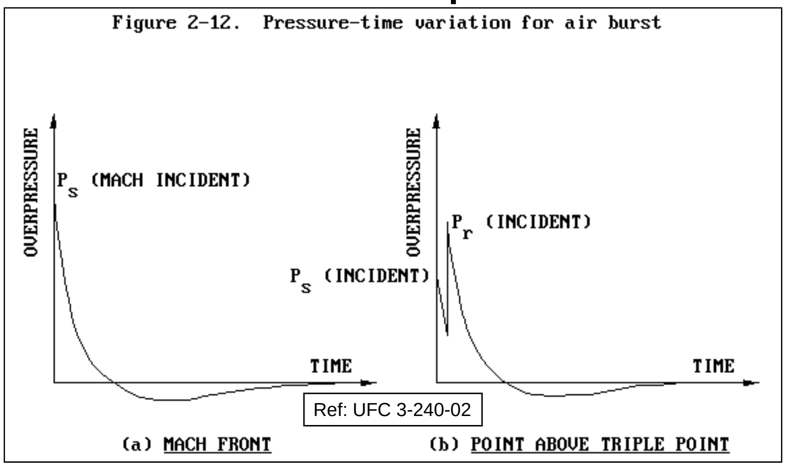
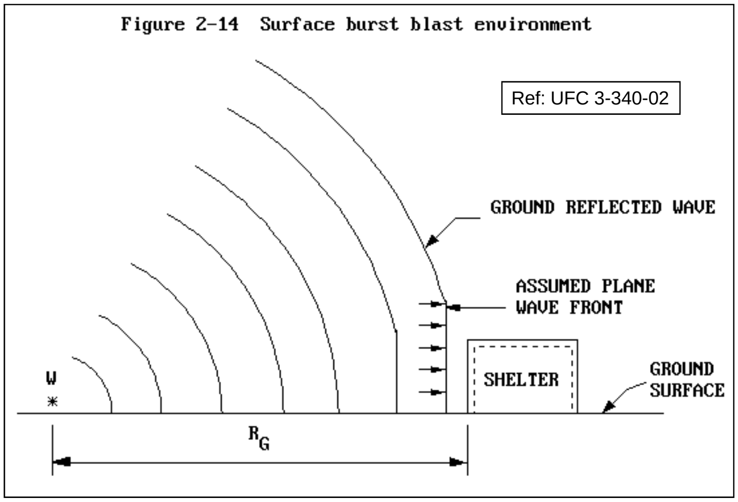
Shock Profile Above and Below the Triple Point



Surface Bursts

- For **surface bursts,** the explosive is at or on the surface
  - the initial wave of the explosion is reflected and reinforced by the ground surface to produce a reflected wave.
  - unlike the free-air burst, the reflected wave merges with the incident wave at the point of detonation to form a single wave similar to the reflected wave of the free-air burst, but essentially hemispherical in shape.
  - often referred to as “**hemispherical surface burst”**

Surface Burst Blast

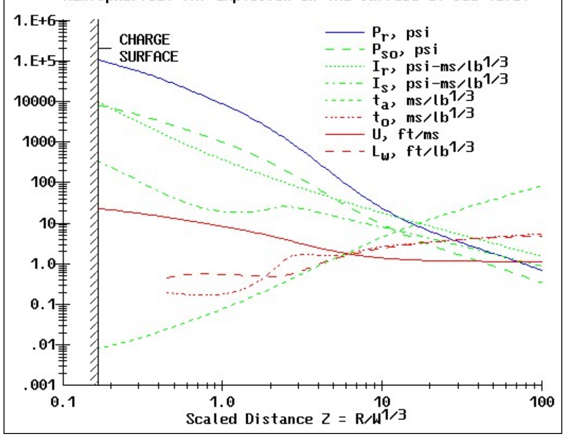


Hemispherical Surface Burst Blast Curves

- Explosive charge assumed to be at or on the ground
- Structure elements are perpendicular or parallel to the direction of the shock wave
- Blast curves account for ground as reflecting surface for shock wave
- TNT is the reference explosive
- Typically used for design of blast-resistant buildings (with a few exceptions)

Positive Phase Parameters for Hemispherical TNT Charge

Figure 2-15. Positive phase shock wave parameters for a hemispherical TNT explosion on the surface at sea level



Ref: UFC 3-340-02

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Negative Phase Parameters for Hemispherical TNT Charge on the

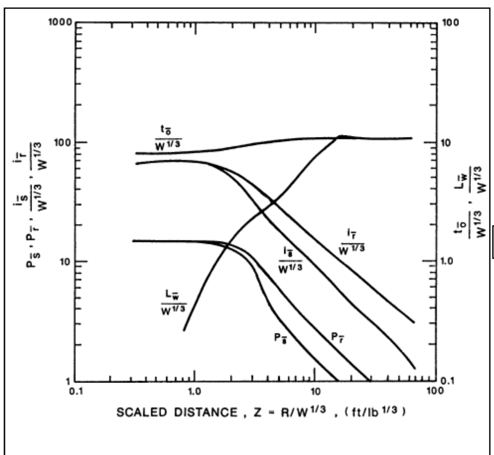

Figure 2-16. Negative Phase Shock Wave Parameter for Hemispherical TNT Explosions on the Surface at Sea Level

Ref: UFC 3-340-02

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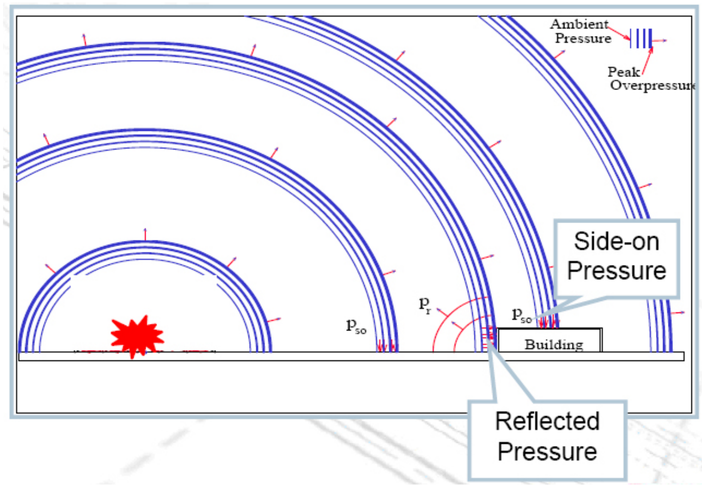
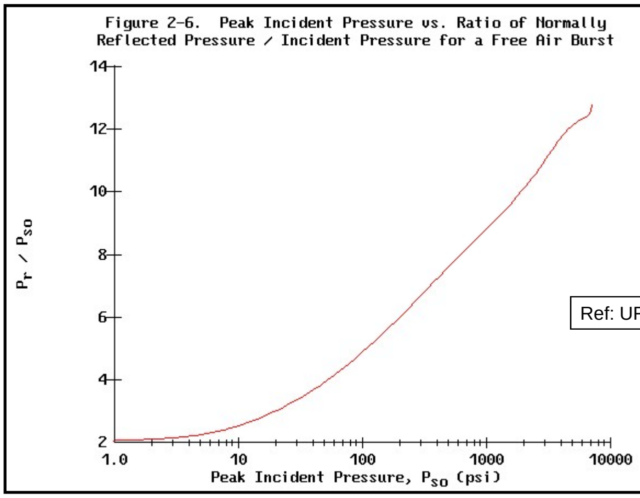
Reflected vs. Side-on Loads



Reflected vs. Side-on Loads

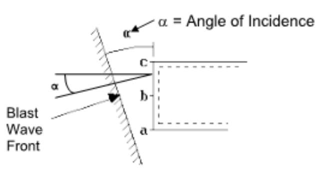
- When a blast wave propagates into a rigid surface:
  - incident particle velocity becomes zero
  - pressure, density, and temperature are increased to values greater than those for the incident blast wave
- The enhanced “reflected” overpressure is approximately twice the incident pressure for weak peak incident pressures less than 15 psi (one atmosphere), but can be over 12 P_{so} for very strong shocks above ten atmospheres

Ratio of Peak Reflected Pressure to Side-on (Incident) Pressure



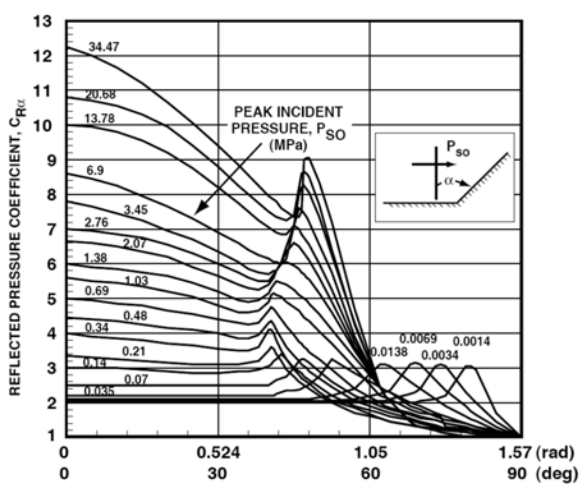
Ref: UFC 3-340-02

Reflected Pressure vs. Angle of Incidence

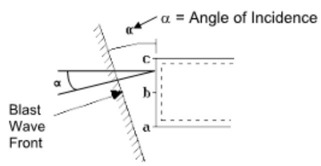


$P_{r\alpha}$ = reflected pressure at angle of incidence α

Ref: PDC TR-06-01

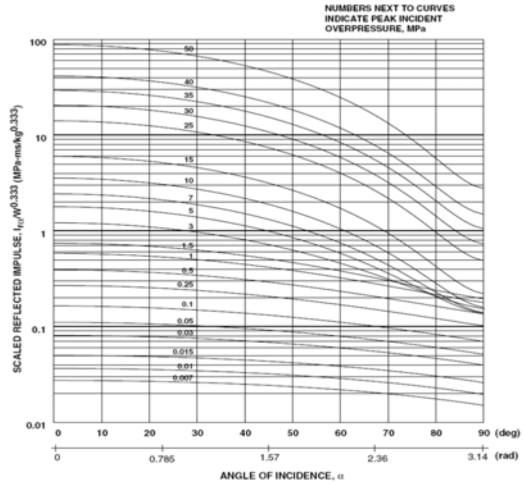


Reflected Impulse vs. Angle of Incidence



$I_{r\alpha}$ = reflected impulse at angle of incidence α

Ref: PDC TR-06-01



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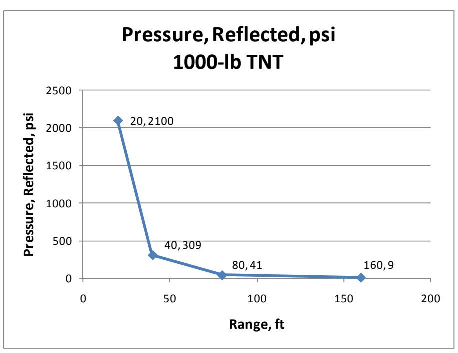
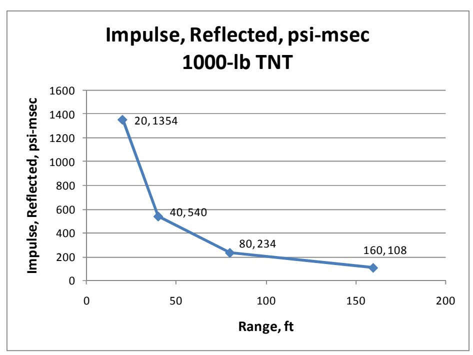
Reflected Pressure vs. Range



Decreases roughly as 1/(Range ^2.8)



Decreases roughly as 1/(Range ^1.25)

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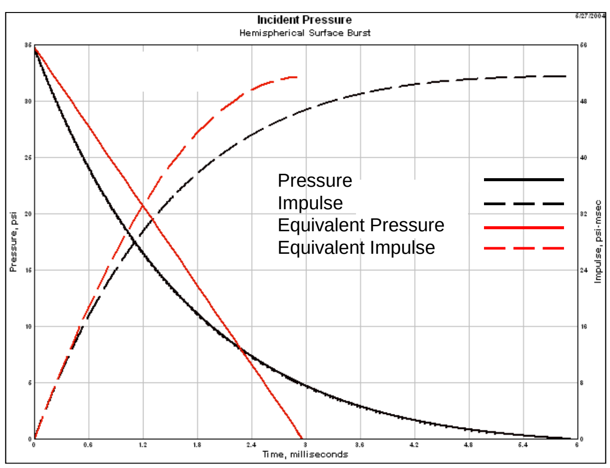
Topics

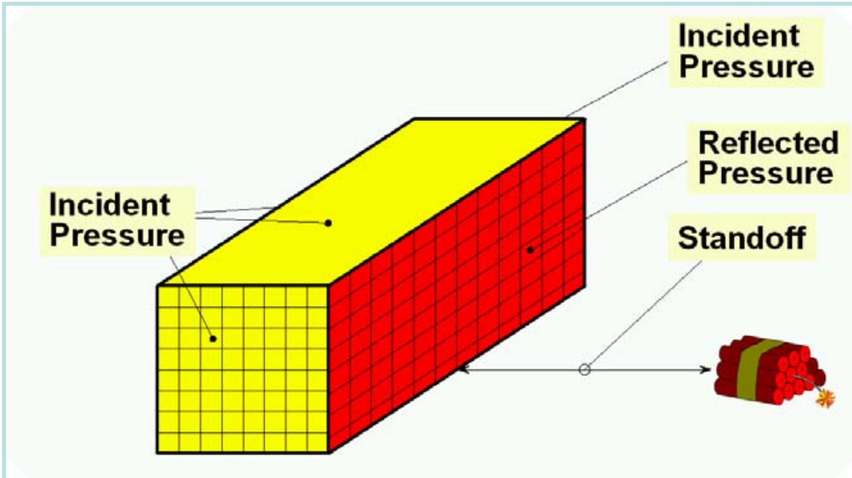
- TNT Equivalency
- Ideal blast waves
- Air bursts and surface bursts
- Blast loads on structures

Equivalent Triangular Load

- *Right triangular* is a typical assumption for pressure history shape…appropriate in many cases; not all
- *Adjust duration* to maintain peak pressure & impulse
  - $t_d = 2 * I / P_{max}$
- *Negative phase is ignored*
- Numerous design aids are based on this simplified history



Loads on Structures



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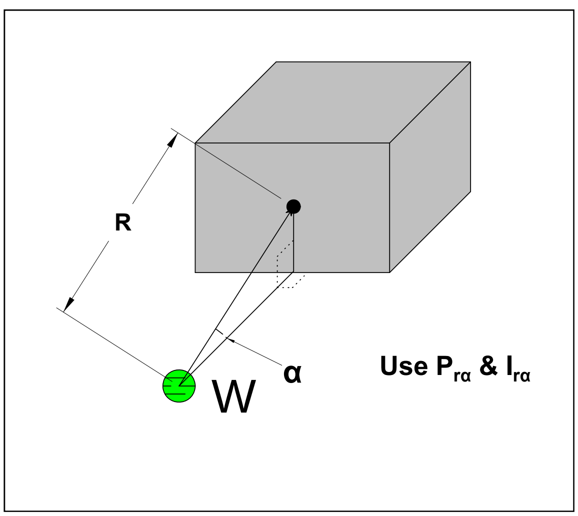
Loads on Structures – Front Wall



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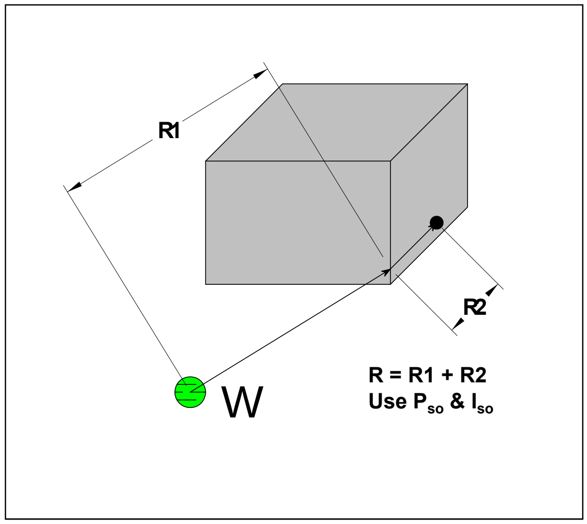
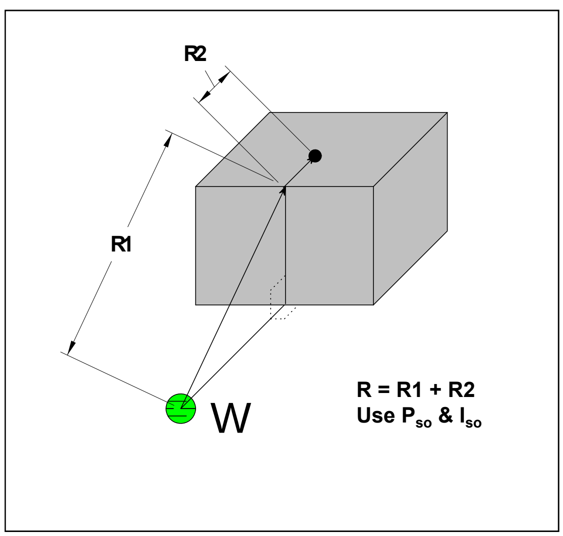
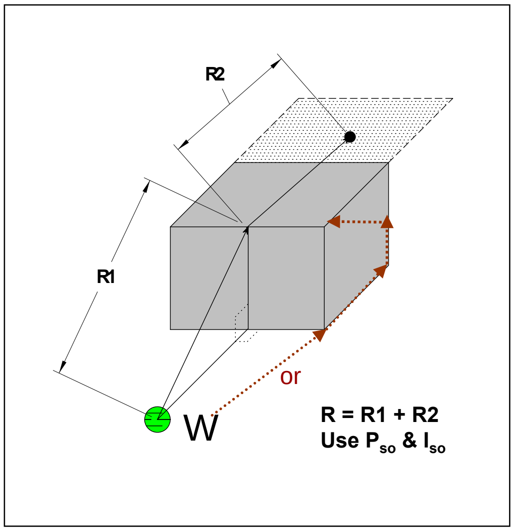
Loads on Structures – Side Wall



Loads on Structures - Roof



Loads on Structures – Back Wall



Design Considerations

- When deciding on the loading to consider for a wall (front, side, or back) consider *future potential threat location* not just the current threat
- Discuss future plans for the area with the Installation Master Planner
- The Master Planner may have plans for that nice open field currently behind the facility you are designing

Averaging Load Over A Panel

- For close-in charges, the spatial variance in pressure & impulse can be significant
  - using the load at a point at the middle of the span may be conservative
  - however, the degree of conservatism can be significant
- Averaging the load over a panel reduces the conservatism – *equivalent uniform load*

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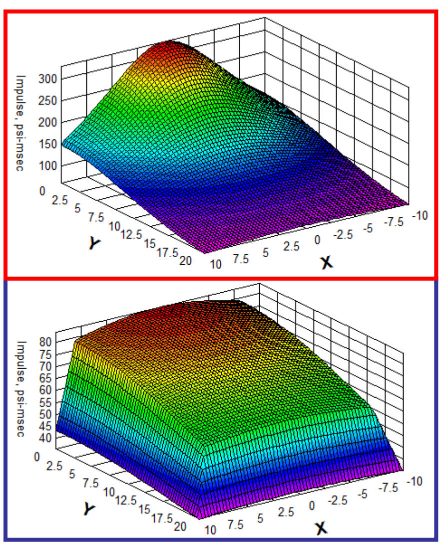
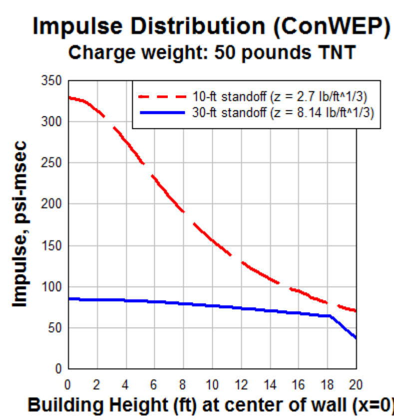
Load Averaging





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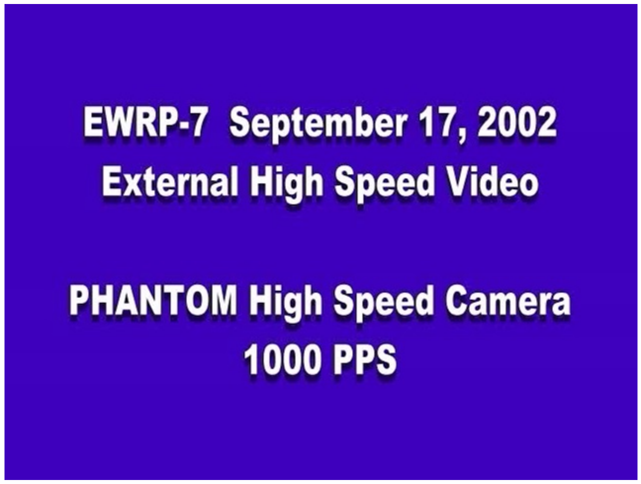
Load Averaging

- Careful conservative judgment should be used when load averaging is required due to large pressure and impulse gradients over the tributary loaded area of a structural component
- Load averaging for *single-degree-of-freedom* calculations is dependent on the gradient and location of a concentrated blast load
  - uniform (large standoff)
  - single point (close-in)
  - triple point

Clearing Effects

- At building edges, a pressure discontinuity exists between the reflected shock and the ongoing incident shock
- The discontinuity creates a relief (rarefaction) wave that propagates inward from the free edges of the reflecting surface of a building
- This relief wave reduces the reflected load on the face of the building, but it does not affect the initial peak reflected pressure applied to the walls

Clearing Effects



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VIDEO

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Computation of Blast Loads

Introduction

- Objective
  - Introduce blast prediction tools and instruct on their usage
- Topics
  - Blast prediction tools
  - Example problems

Blast Prediction Tools

- Simple rules (Kingery-Bulmash, etc) implemented into GUIs or spreadsheets
  - BEC (Blast Effects Computer)
  - ConWep (Conventional Weapons Effects Program)
- Propagation/ray tracing
  - BlastX
- Computational fluid dynamics
  - simplified
    - AIR-3D
  - complicated
    - SHAMRC (ARA)
    - FEFLO (SAIC)

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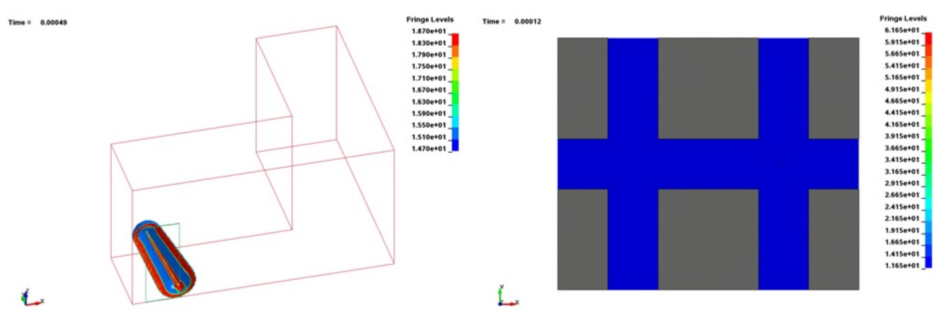
CFD Examples



Urban cityscape

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VIDEO

Blast Prediction Tools

- ***ConWep*** and ***BlastX*** are controlled and supported by the US Army Corps of Engineers
  - distribution is restricted to US government agencies and their contractors
  - both can be found at: https://pdc.usace.army.mil/
  - click on the “Software” icon on the left side and you’ll be taken to a cornucopia of blast- and anti-terrorism-related software

ConWep

- ConWep is a collection of conventional weapon effects calculations based on UFC 3-340-01 (DAHS-CWE). It calculates:
  - airblast
    - free air
    - surface burst calculations
    - loads on surfaces accounting for angle of incidence
  - fragment penetration
  - projectile penetration
  - projectile path into earth
  - shaped charge penetration
  - cratering
  - ground shock

BlastX

- BlastX predicts the internal airblast environment in multi-room structures for both internal and external explosions using fast running analytical/empirical models
  - pressure AND temperature histories
  - for external detonations, shock waves dominate the blast environment
  - for internal detonations in multi-room structures, the flow of confined detonation products becomes important

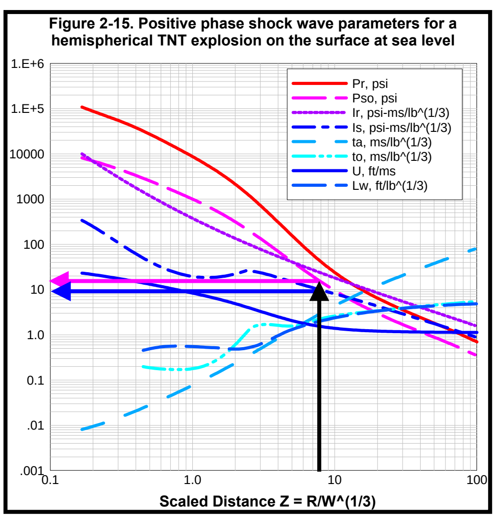
- Shock predictions based on Kingery-Bulmash equations for initial shocks that are combined based on hydrocode simulations

- The blast is assumed to originate from spherical or cylindrical explosions

Example Airblast Calculations – Hemispherical Blast Load

- Hemispherical TNT explosion
  - 50-lb charge weight
  - 30-ft standoff
- Compare
  - A) UFC 3-340-02 curves ("spaghetti curves")
  - B) ConWep

"Spaghetti" Curves Solution



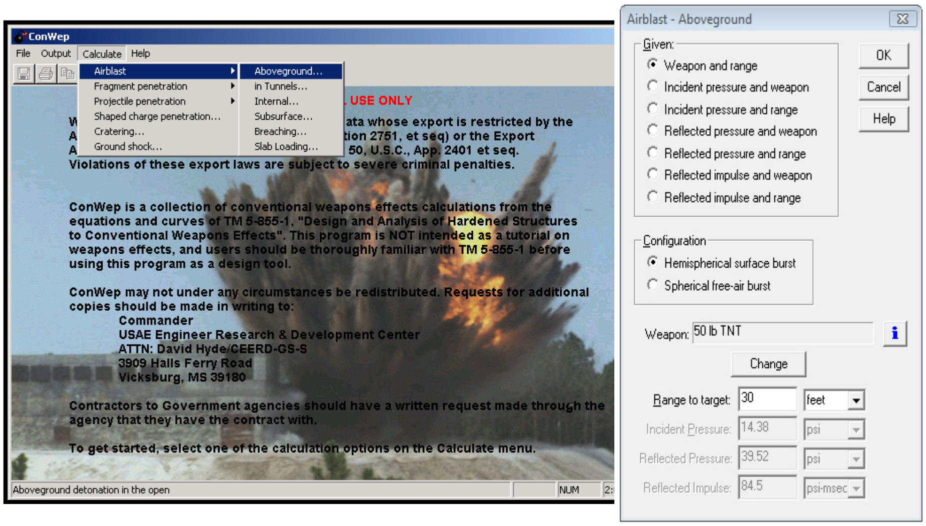
$Z = 30/50^{1/3}$
$= 8.14$

$P_{so} = 14$ psi

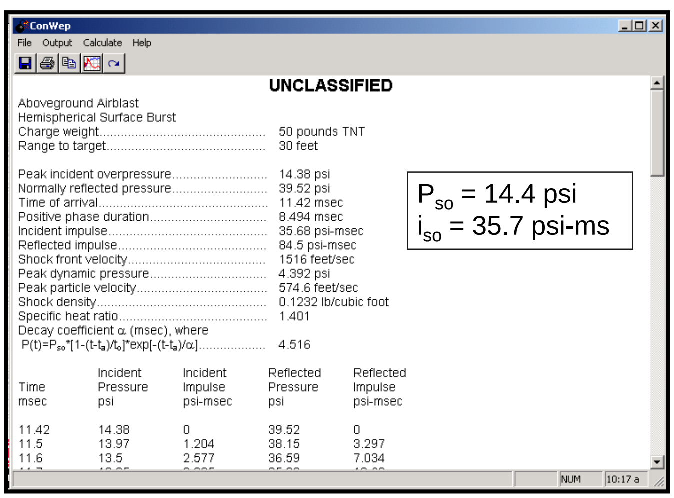
$i_{so} / W^{1/3} = 9.5$
$W^{1/3} = 3.68$
$i_{so} = 35$ psi-ms

Ref: UFC 3-340-02

ConWep Solution



ConWep Solution



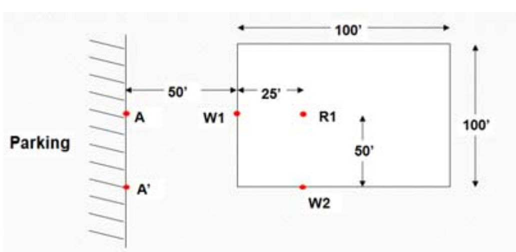
P_{so} = 14.4 psi
i_{so} = 35.7 psi-ms

Comparison of Results

- Spaghetti curves
  - P_{so}= 14 psi, i_{so} = 35 psi-ms
- ConWep
  - P_{so}= 14.38 psi, i_{so} = 35.68 psi-ms

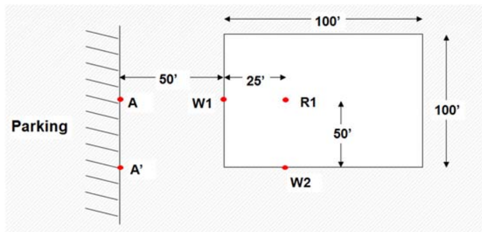
Blast Load on Building - ConWep Example

- Consider a 400 lb TNT charge located in a parking area, which is 50-ft from a building. Building is 100-ft x 100-ft x 14-ft high. Assume a 0-ft height of burst.



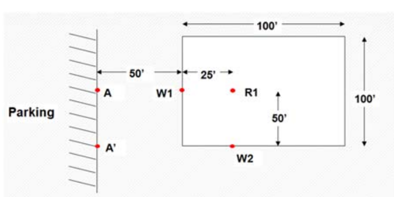
Blast Load on Building - ConWep Example

a) With charge at A, determine the pressure and impulse at W1 (at elevation 0-ft)
b) With charge at A, determine the pressure and impulse at R1 (on roof)
c) With charge at A’, determine pressure and impulse at W2 (at elevation 0-ft)



ConWep Example

a) With charge at A, determine the pressure and impulse at W1 (at elevation 0-ft)



P_r = 64.44 psi
I_r = 209.1 psi-ms

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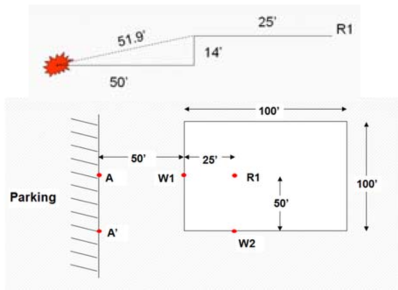
Aboveground Airblast
Hemispherical Surface Burst
Charge weight............ 400 pounds TNT
Range to target............ 50 feet

Peak incident overpressure............ 21.15 psi
Normally reflected pressure............ 64.44 psi
Time of arrival............ 16.55 msec
Positive phase duration............ 14.25 msec
Incident impulse............ 83.86 psi-msec
Reflected impulse............ 209.1 psi-msec
Shock front velocity............ 1670 feet/sec
Peak dynamic pressure............ 8.988 psi
Peak particle velocity............ 767.1 feet/sec
Shock density............ 0.1415 lb/cubic foot
Specific heat ratio............ 1.401
Decay coefficient α (msec), where
$P(t)=P_{sc}*[1-(t-t_a)/t_c]*\exp[-(t-t_a)/\alpha]$............ 6.834

Time msec	Incident Pressure psi	Incident Impulse psi-msec	Reflected Pressure psi	Reflected Impulse psi-msec
16.55	21.15	0	64.44	0
16.6	20.93	1.041	63.55	3.165
16.7	20.48	3.111	61.79	9.431
16.8	20.04	5.136	60.07	15.52
16.9	19.6	7.118	58.4	21.45
17	19.18	9.058	56.77	27.2
17.1	18.77	10.95	55.18	32.8
17.2	18.36	12.81	53.64	38.24
17.3	17.96	14.63	52.14	43.53
17.4	17.57	16.4	50.67	48.67
17.5	17.18	18.14	49.24	53.67
17.6	16.81	19.84	47.86	58.52
17.7	16.44	21.5	46.5	63.24
17.8	16.07	23.13	45.19	67.82
17.9	15.72	24.72	43.9	72.28
18	15.37	26.27	42.66	76.61

ConWep Example

b) With charge at A, determine the pressure and impulse at R1 (on roof)



P_{so} = 8.819 psi
I_{so} = 57.47 psi-ms

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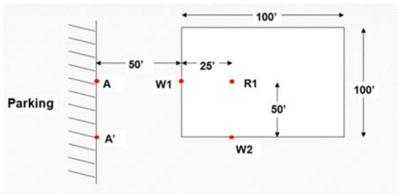
Aboveground Airblast
Hemispherical Surface Burst

Charge weight	400 pounds TNT
Range to target	76.9 feet
Peak incident overpressure	8.819 psi
Normally reflected pressure	21.76 psi
Time of arrival	34.63 msec
Positive phase duration	19.73 msec
Incident impulse	57.47 psi-msec
Reflected impulse	127.3 psi-msec
Shock front velocity	1375 feet/sec
Peak dynamic pressure	1.734 psi
Peak particle velocity	388.2 feet/sec
Shock density	0.1066 lb/cubic foot
Specific heat ratio	1.401
Decay coefficient α (msec), where $P(t)=P_{so}*[1-(t-t_a)/t_c]*exp[-(t-t_a)/\alpha]$	14.14

Time msec	Incident Pressure psi	Incident Impulse psi-msec	Reflected Pressure psi	Reflected Impulse psi-msec
34.63	8.819	0	21.76	0
34.8	8.643	1.447	21.25	3.564
35	8.434	3.154	20.65	7.754
35.2	8.23	4.821	20.06	11.82
35.4	8.03	6.447	19.49	15.78
35.6	7.834	8.033	18.93	19.62
35.8	7.641	9.58	18.39	23.35
36	7.453	11.09	17.86	26.98
36.2	7.268	12.56	17.34	30.5
36.4	7.087	14	16.84	33.92
36.6	6.91	15.4	16.35	37.23
36.8	6.736	16.76	15.87	40.46
37	6.566	18.09	15.4	43.58
37.2	6.399	19.39	14.94	46.62
37.4	6.236	20.65	14.5	49.56
37.6	6.076	21.88	14.07	52.42
37.8	5.919	23.08	13.65	55.19
38	5.765	24.25	13.23	57.87
38.2	5.615	25.39	12.83	60.48
38.4	5.467	26.5	12.44	63.01

ConWep Example

c) With charge at A', determine pressure and impulse at W2 (at elevation 0-ft)



P_{so} = 9.246 psi
I_{so} = 58.74 psi-ms

UNCLASSIFIED

Aboveground Airblast
Hemispherical Surface Burst

Charge weight	400 pounds TNT
Range to target	75 feet
Peak incident overpressure	9.246 psi
Normally reflected pressure	23.02 psi
Time of arrival	33.25 msec
Positive phase duration	19.48 msec
Incident impulse	58.74 psi-msec
Reflected impulse	131 psi-msec
Shock front velocity	1387 feet/sec
Peak dynamic pressure	1.899 psi
Peak particle velocity	403.7 feet/sec
Shock density	0.1079 lb/cubic foot
Specific heat ratio	1.401
Decay coefficient α (msec), where $P(t)=P_{so}*[1-(t-t_a)/t_c]*exp[-(t-t_a)/\alpha]$	13.49

Time msec	Incident Pressure psi	Incident Impulse psi-msec	Reflected Pressure psi	Reflected Impulse psi-msec
33.25	9.246	0	23.02	0
33.4	9.073	1.376	22.52	3.421
33.6	8.847	3.168	21.86	7.859
33.8	8.626	4.915	21.22	12.17
34	8.409	6.619	20.59	16.35
34.2	8.197	8.279	19.98	20.4
34.4	7.989	9.898	19.39	24.34
34.6	7.786	11.48	18.81	28.16
34.8	7.586	13.01	18.24	31.86
35	7.391	14.51	17.69	35.46
35.2	7.2	15.97	17.16	38.94
35.4	7.014	17.39	16.64	42.32
35.6	6.831	18.77	16.13	45.6
35.8	6.652	20.12	15.64	48.78
36	6.476	21.44	15.16	51.85
36.2	6.305	22.71	14.69	54.84
36.4	6.137	23.96	14.24	57.73
36.6	5.972	25.17	13.79	60.53
36.8	5.812	26.35	13.36	63.25

Reference Documents

- AISC
  - Design Guide 26: *Design of Blast Resistant Structures*
  - *Facts for Steel Buildings Number 2 – Blast and Progressive Collapse*
  - Available for download at www.aisc.org; free for members
- DoD
  - *Structures to Resist the Effects of Accidental Explosions* - UFC 3-340-02 (5 December 2008)
  - *Design and Analysis of Hardened Structures to Conventional Weapons Effects* - UFC 3-340-01 (1 June 2002)
- General
  - Baker, W. E. et al, Explosion Hazards and Evaluation, Amsterdam, Elsevier Scientific Publishing Company, 1983.

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