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Integrity of Pipes and Vessels
Subject to Internal Explosions
an overview

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BWR Explosions

On November 7, 2001, a hydrogen explosion ruptured and fragmented a 6 inch steam condensate pipe elbow at the Hamaoka-1 boiling water reactor (BWR) nuclear power plant in Japan, while the plant was in operation, Figure 1. A month later, on December 14, 2001, a hydrogen explosion ruptured an approximately eight foot long section of a 4 inch spray line at the Brunsbuttel BWR nuclear power plant in Germany, also while the plant was in operation, Figure 2. In both cases the cause of the explosion was believed to be the accumulation and detonation of hydrogen gases created by radiolysis of water or steam. The ignition source was not conclusively identified [1,2].

Figure 1 - Six-inch Elbow Rupture at Hamaoka-1, Japan.

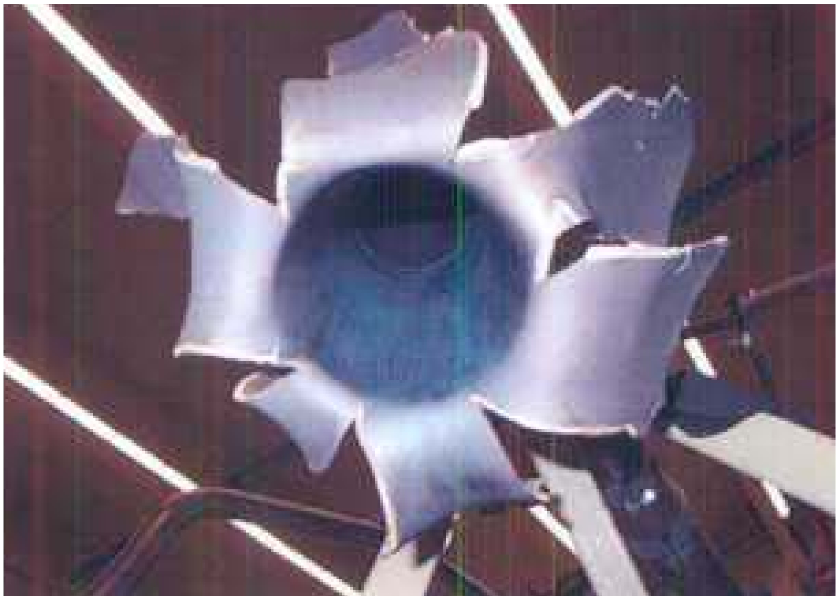

Figure 2 - Four-inch Pipe Rupture at Brunsbuttel, Germany.

Overview of the Assessment Process

The two BWR accidents point to the need to assess the risks associated with the accumulation and explosion of hydrogen by radiolysis. A six-step approach for such an assessment is presented in the logic diagram of Figure 3.

Step 1 determines which systems are susceptible to hydrogen accumulation by radiolysis, and their initial conditions (hydrogen-oxygen mixtures, their location and their initial pressures and temperatures). This step also groups the systems into classes by similarity of materials and designs.

Step 2 determines whether the explosion is a deflagration (subsonic pressure wave), a detonation (supersonic pressure wave), or a deflagration that transitions into a detonation (referred to as deflagration-to-detonation transition or DDT). Having established the initial conditions and the explosion regime, this step develops the explosion pressure time histories (pressure vs. time) and peak temperatures. This is the fluid dynamics aspect of the assessment.

Step 3 calculates the structural capacity of systems, equipment and components subject to the explosion loads of Step 2. Step 4 compares the demand (pressure and temperature) to the capacity. These are the stress-strain analysis and fracture analysis aspects of the assessment.

If in Step 4 the demand exceeds the capacity, Step 5 investigates the failure mode to help understand the consequences of such an explosion, which is the final step, Step 6.

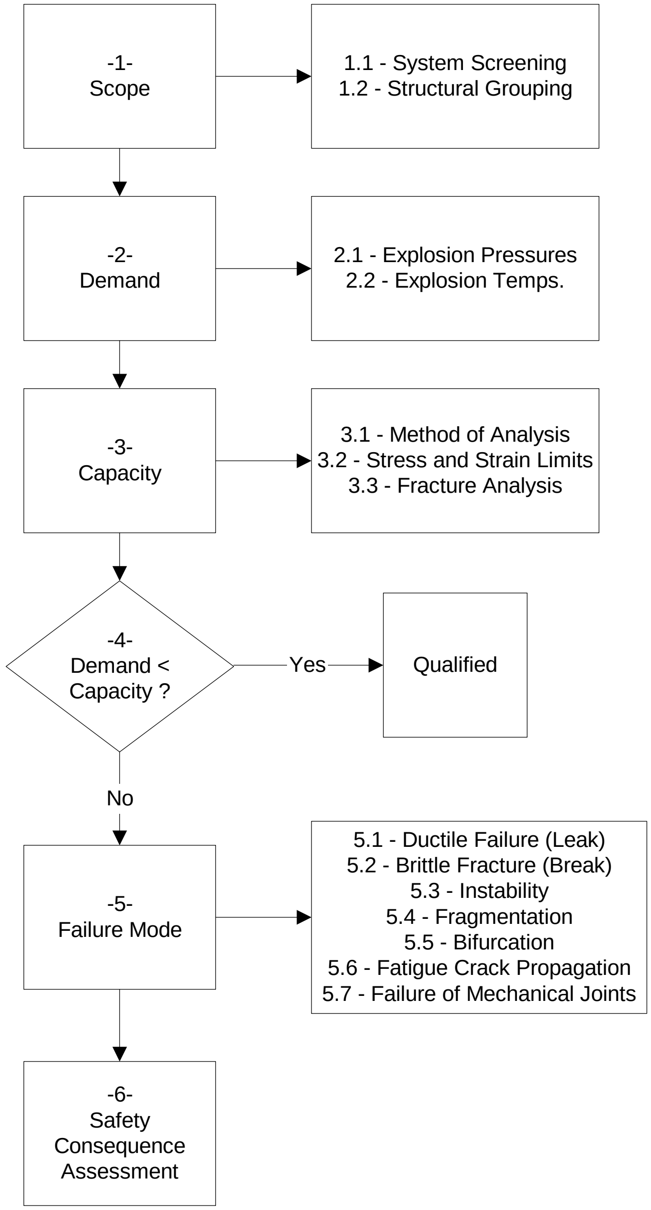

Figure 3 - Assessment Logic for Hydrogen Explosions

Demand: Pressure Pulse

An explosion is a sudden and violent release of energy [3]. When it is due to the combustion of flammable gases, an explosion takes the form of either a deflagration or a detonation. Table 1 compares the two phenomena:

Table 1 - Comparison of Deflagration and Detonation Characteristics

Parameter	Deflagration	Detonation
Propagation Velocity	< 740 mph in air $< 2,800$ mph in H_2	~ 4,500 mph

Peak Pressure (absolute)	~ 6 x $P_{initial}$	~ 16 x $P_{initial}$
Pressure vs Time	Figure 4	Figure 5

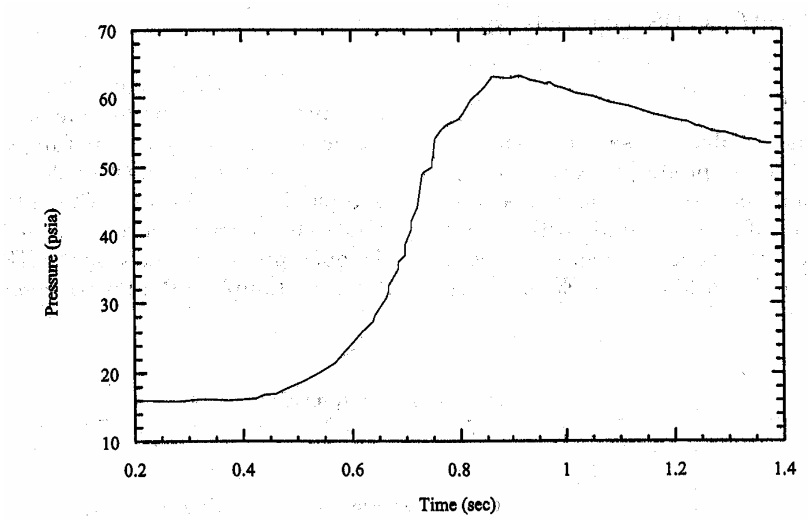

Figure 4 - Deflagration Time History [4]

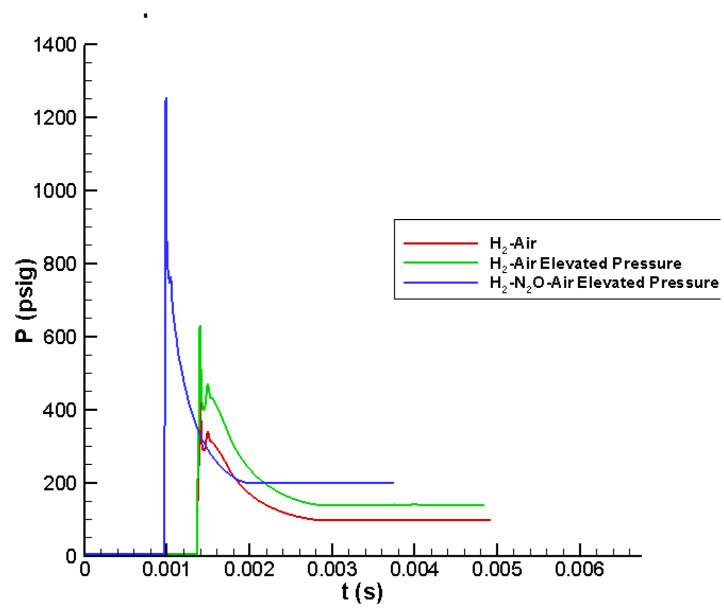

Figure 5 - Detonation Time Histories for Three Initial Gas Mixture Conditions [5]

In the detonation profile of Figure 5, the narrow peak pressure is the Chapman-Jouguet (C-J) pressure, the remnant exponential decay following the C-J pressure is the Taylor-Zeldovich pressure profile. Not shown is the Von Neumann pressure, a very narrow spike concurrent with the C-J pressure and nearly twice as large as C-J.

Further:

- When the pressure wave reflects on a solid surface or at a gas-liquid interface it is amplified by a factor of 2 to 2.5.
- When a deflagration transitions to a detonation, the C-J pressure is further amplified.

Dynamic Response Regime

For the simplest of shapes, a straight cylindrical pipe, the explosion causes an outward radial expansion (breathing) of the pipe wall. The magnitude of the dynamic response in the form of radial expansion of the component depends not only on the magnitude of the explosion pressure but also on its duration. Two dynamic response regimes are possible [3,6]:

Quasi-Static Regime: In this case, the peak pressure lasts a sufficiently long time to fully strain the pipe wall, and the effect of the pressure is predicted by increasing the peak pressure by a dynamic load factor (DLF) of 2 maximum. The quasi-static regime takes place if

$$T_{pulse} > 25\% \times T_{comp}$$

T_{pulse} = duration of the pressure pulse, sec
T_{comp} = natural period of the first response mode of the component, sec

For a cylindrical steel pipe this condition can be written as

$$T_{pulse} > \frac{D}{66{,}000}$$

D = pipe diameter, in

For example, for a 2 inch pipe (D = 2.375”) the explosion is quasi-static if the pressure spike lasts more than 2.375 / 66,000 = 35 micro-seconds. The pipe will sense twice the peak pressure.

Impulsive Regime: In this case, the peak pressure is of such short duration that the metal has no time to fully strain before the pressure has dropped. In this case the component response does not depend on the magnitude of the peak pressure, instead the response depends on the pressure impulse (the area under the pressure vs. time curve). The impulsive regime takes place if

$$T_{pulse} < 25\% \times T_{comp}$$

Note that Baker places the quasi-static regime at $T_{pulse} > 40\ T_{comp}$ and the impulsive regime at $T_{pulse} < 0.4\ T_{comp}$, and between these two regimes is the dynamic regime [6].

Method of Analysis

Given the explosion pressure time history (pressure vs time), four decisions must be made regarding the structural capacity analysis:

- Closed-form solution or finite elements: The closed-form solution is suitable for simple shapes such as cylindrical pipes, bends and flat end plates. For more complex shapes the analysis is conducted by finite element analysis.

- Static or dynamic: If the dynamic response regime is quasi-static, then the explosion pressures can be applied statically, with a dynamic load factor. If the dynamic regime is impulsive, a dynamic analysis is more appropriate (pressure vs time applied to the model).

- Elastic or plastic: If the stresses remain below yield, or if an ASME B31 or ASME III elastic stress criterion will be applied, the analysis must be elastic (linear stress-strain). If the evaluation will be based on strain limits or ASME III Appendix F plastic criteria, the analysis must be plastic.

- Material properties: Under explosive loads, the strain rates are large and the strength properties of steel (yield stress and ultimate strength) increase. This strengthening effect could be included in the structural model, or conservatively ignored [7].

Evaluation Criteria: Codes and Standards

The design of vessels "to accommodate loadings produced by deflagration" is addressed in ASME VIII Non-Mandatory Appendix H, which in turn refers to ASME III Division 1, in particular "Level D" plastic design [10, 11]. ASME III Division 1 Appendix F plastic analysis design rules limit primary membrane stresses to 70% of ultimate and maximum stresses to 90% of ultimate. For stainless steel, these limits correspond to strain limits in the order of 5% membrane and 15% peak. The actual failure strain is larger, as evidenced in Figure 6, where the bulging (membrane) strain is in the order of 30%.

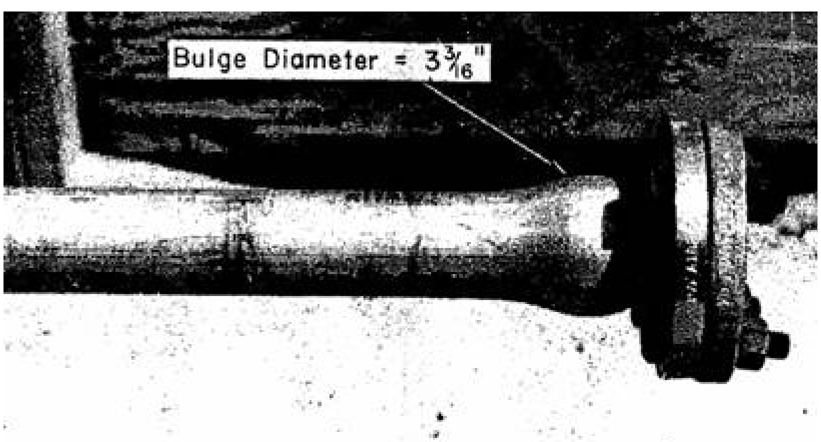

Figure 6 - Pipe Bulging from Hydrogen Detonation

An ASME VIII Division 3 code case is currently being drafted for the design of pressure vessels subject to impulsive loads, based primarily on US and UK experience in the design of detonation-containing vessels [12, 13, 14]. The proposed strain limits are 0.2% (elastic limit) for membrane (average) strain and 2.5% and 5% for peak strains in welds and base metal respectively.

For piping systems, the ASME B31 code does not explicitly address design for explosions [15]. However, there is a large body of studies on detonations in cylindrical tubes and pipes, particularly related to the development of pulse detonation engines [16 to 23]. Similar design rules would apply as for pressure vessels, in addition to having to address the effects of pipe whip as the explosive wave travels through the system.

Failure Mode

Explosions in pipes and vessels can have several effects:

- No perceptible deformation if the stresses generated by the explosion are below yield.
- Blowout of gaskets, packing and mechanical joints by overpressure.
- Bulging, as illustrated in Figure 6, when the material behaves in a ductile manner and stresses exceed yield but are below the ultimate strength.
- Brittle fracture, with little deformation, when the material is brittle (such as cast iron or plastic).
- Fish-mouth rupture as illustrated in Figure 7. Here the stresses exceed the ultimate strength of the material, but there is insufficient explosive energy to drive the fracture beyond the split.
- Fish-Mouth rupture, with bifurcation as illustrated in Figure 8. The bifurcated cracks may wrap around the pipe and separate (guillotine break) the section.
- Long rupture along a weak seam or a flaw, such as the weld between the tank shell and roof in Figure 9.
- Fracture in two or more fragments as illustrated in Figures 1, 2 and 10.

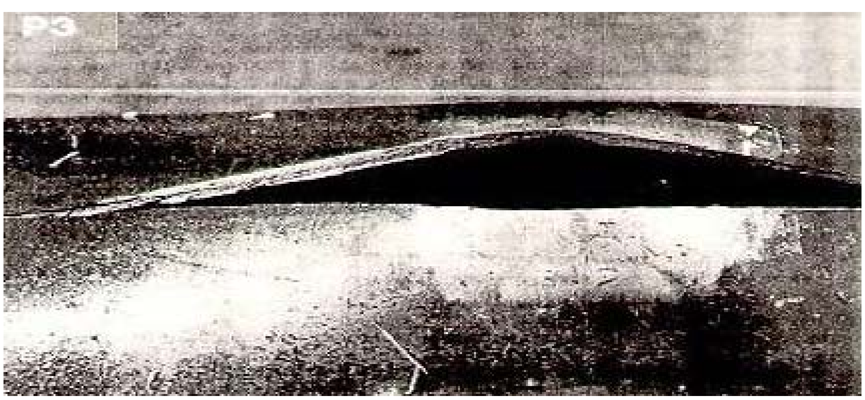

Figure 7 - Typical Ductile Fish-Mouth Rupture by Steady Over-Pressure

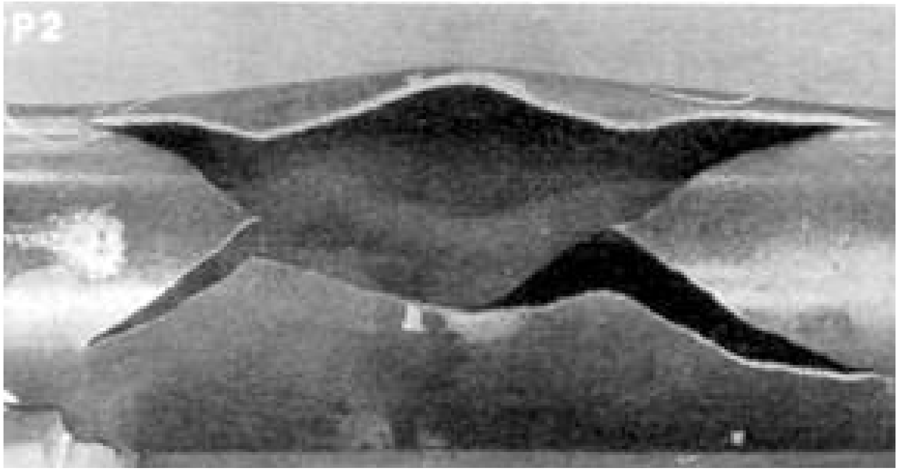

Figure 8 - Typical Large Rupture with Bifurcation of Crack

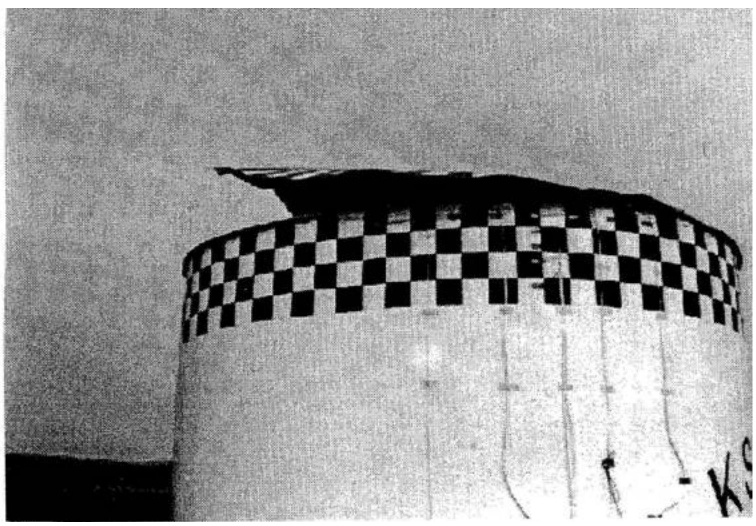

Figure 9 - Vapor Space Explosion in Tank with Weld Failure [8]

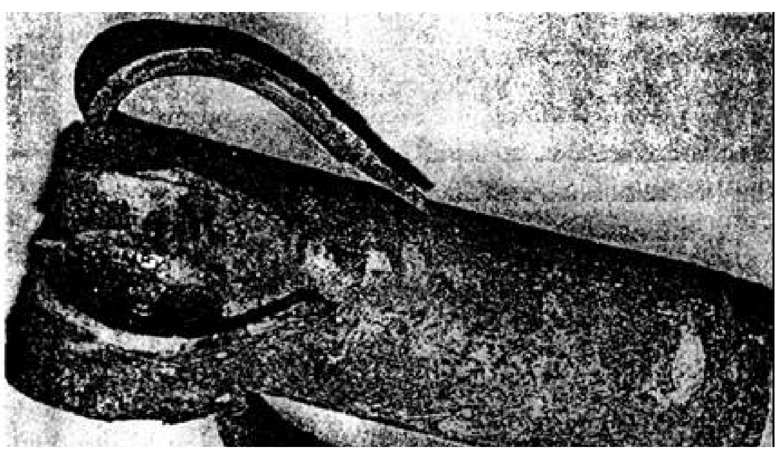

Figure 10 - Fragmentation by Detonation of an Acetylene Gas Cylinder [9]

References

1. Naitoh, M., et. al., Analysis of Pipe Rupture of Steam Condensation Line at Hamaoka-1, Journal of Science and Technology, Vol.40, No.12, December, 2003.

2. U.S. Nuclear Regulatory Commission, Information Notice 2002-15 Hydrogen Combustion Events in Foreign BWR Piping, April 12, 2002.

3. Lees, F.P., Loss Prevention in the Process Industries, Volume 2, Section 17 Explosion, Butterworth Heinemann, 2001.

4. Duffey, T.A., Rodriguez, E.A., Romero, C., Design of Pressure Vessels for High Strain Rate Loading: Dynamic Pressure and Failure Criteria, WRC Bulletin 477, December, 2002.

5. Vergara, M., Clutter, J.K., Savannah River Pipe Detonation Study, Analytical & Computational Energetics, Inc. (ACE), July, 2005.

6. Baker, W.E., et. al., Explosion Hazards and Evaluation, Elsevier.

7. Hampton, E.J., Bitner, J.L., Stress or Strain Criteria for Combined Static and Dynamic Loading, WRC Bulletin 500, April, 2005.

8. Antaki, G., Fitness-for-Service and Integrity of Piping, Vessels and Tanks, McGraw-Hill.

9. Price, J.W., An Acetylene Gas Cylinder Explosion, Transactions of the ASME, Vol.120, February, 1998.

10. ASME Boiler and Pressure Vessel Code, section VIII Division 1, Pressure Vessels, American Society of Mechanical Engineers, New York.

11. ASME Boiler and Pressure Vessel Code, section III Division 1, Nuclear Components, American Society of Mechanical Engineers, New York

12. Rodriguez, E.A., Duffey, T.A., Romero, C., Design of Pressure Vessels for High Strain Rate Loading: Dynamic Pressure and Failure Criteria, WRC Bulletin 477, December, 2002.

13. Rodriguez, E.A., and Duffey, T.A., Fracture-Safe and Fatigue Design Criteria for Detonation-Induced Pressure Loading in Containment vessels, WRC Bulletin 494, August, 2004.

14. Clayton, A.M., Forgan, R., The Design of Steel Vessels to Contain Explosions, Proceedings of the ASME Pressure Vessel and Piping Conference, American Society of Mechanical Engineers, New York.

15. ASME B31.3 Process Piping, American Society of Mechanical Engineers, New York.

16. W.M. Beltman, E.N. Burcsu, J.E. Shepherd, L. Zuhal, The Structural Response of Cylindrical Shells to Internal Shock Loading, California Institute of Technology, Graduate Aeronautical laboratories (GAL). *Journal of Pressure Vessel Technology*, pages 315-322, 1999.

17. W.M. Beltman, J.E. Shepherd, Linear Elastic Response of Tubes to Internal detonation Loading, California Institute of Technology, Graduate Aeronautical laboratories (GAL). *Journal of Sound and Vibration*, 252(4):617-655, 2002.

18. T. Chao, J.E. Shepherd, Detonation Loading of Tubes in the Modified Shear Wave Speed Regime, California Institute of Technology, Graduate Aeronautical laboratories (GAL). In Z. Jiang, editor, *Proceedings of the 24th International Symposium on Shock Waves*, volume 2, pages 865-870. Springer, 2005.

19. T.W. Chao and J. E. Shepherd. Fracture response of externally flawed aluminum cylindrical shells under internal gaseous detonation loading. *International Journal of Fracture*, 134(1):59-90, July 2005.

20. E. Wintenberger, J. M. Austin, M. Cooper, S. Jackson, and J. E. Shepherd. An analytical model for the impulse of a single-cycle pulse detonation tube. *Journal of Propulsion and Power*, 19(1):22-38, 2003. and errata.

21. T.W. Chao and J.E. Shepherd, Comparison of Fracture Response of Preeflawed Tubes Under Internal Static and Detonation Loading, California Institute of Technology, Graduate Aeronautical laboratories (GAL). Paper and report.

22. T.W. Chao and J.E. Shepherd, Fracture Response of Externally Flawed Cylindrical Shells to Internal Gaseous detonation Loading, California Institute of Technology, Graduate Aeronautical laboratories (GAL).

23. G.O. Thomas, The Response of Pipes and Supports to Internal Pressure Loads Generated by Gaseous Detonations, Center for Explosion studies, Department of Physics, University of Wales, Aberystwyth, August, 2001.