White Paper: Performance Limits of Blast Resistant Electrical Equipment Centers (Part 2)

Our first article, "*Blast Resistant Electrical Equipment Centers*," focused on the history, background and key considerations of blast resistant modules (BRMs) and blast resistant electrical equipment centers (BRECs), designed to protect personnel and vital electrical controls, respectively. The article went on to outline the benefits of utilizing protective shelters at hydrocarbon processing (HP) plants.

The premise for greater concern with regard to both personnel safety and process safety was established. Whereas the discussion gave light to both types of shelter, this article will focus specifically on the detailed aspects of BRECs: design, construction, analysis, blast load testing, test results and conclusions.

Following the Texas City incident of March 23, 2005, a special panel headed by former Secretary of State James Baker was convened. The findings of this panel are documented in what became known as the Baker Report of January 2007. One of the most notable sets of statements made in the report places process safety on par with personnel safety:

"Not all refining hazards are caused by the same factors or involve the same degree of potential damage. Personal or occupational safety hazards give rise to incidents—such as slips, falls, and vehicle accidents—that primarily affect one individual worker for each occurrence. Process safety hazards can give rise to major accidents involving the release of potentially dangerous materials, the release of energy (such as fires and explosions), or both. Process safety incidents can have catastrophic effects and can result in multiple injuries and fatalities, as well as substantial economic, property, and environmental damage. Process safety refinery incidents can affect workers inside the refinery and members of the public who reside nearby. Process safety in a refinery involves the prevention of leaks, spills, equipment malfunctions, over-pressures, excessive temperatures, corrosion, metal fatigue, and other similar conditions. Process safety programs focus on the design and engineering of facilities, hazard assessments, management of change, inspection, testing, and maintenance of equipment, effective alarms, effective process control, procedures, training of personnel, and human factors. The Texas City tragedy in March 2005 was a process safety accident."

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The Baker Report

This underscores the need for risk managers, planners and engineers at HP plants to put as much emphasis on providing process safety as they are for personnel safety. It naturally follows that the implementation and utilization of BRECs at refineries directly impacts process safety. In addition to maintaining critical process operations during and after an overpressure incident, blast resistant equipment shelters can limit extensive downtime and prevent ever having to replace critical equipment rendered inoperable or destroyed due to the effects of a blast event.

Demonstrating the Strength Quotient and Viability of BREC Technology

With respect to the current response to market demand for BRECs, the most important challenge is industry awareness and acceptance. Owners and engineers in the chemical and petrochemical industries are identifying the need for blast-rated protection of essential and critical equipment, especially in light of recent refinery overpressure incidents such as those cited here and in our first article.

The precedent and need for BRECs are without argument, and formed the basis of an extensive research and development program culminating in the establishment of three specific equipment center construction types—two being of interlocking steel panel construction and the third utilizing fully-welded, crimped steel plate. Now a verifiable revolution in the industry, the use of interlocking steel panel construction for BRECs addresses both cost effectiveness and critical protection factors.

First Considerations

As discussed previously, the most desirable location for an electrical equipment center at HP facilities is as close to the processing operation and maintenance personnel as possible. Therefore, in establishing baseline criteria for BREC performance and system design, the first step taken is typically a Siting Analysis.

Siting Analyses

Site maps of refining facilities containing concentric rings that depict various levels of explosive potential are used in required siting analyses. The rings indicate levels of overpressure in psi, with the higher pressures appearing at the potential blast sources or at positions between blast potentials. Blast sources and reflective convergences appear in much the same manner as do the peaks on a topographical map. The site map of the Texas City refinery is shown in Figure 1.

Standoff Distances

The best way to protect a building from blast loads is to ensure that it is kept as far from the origin of a blast load as possible. By contrast, the structures which shelter equipment required to maintain essential or critical systems are often required to be inside the potential blast zone. Close proximity for equipment is also often a function of cost since the power losses and de-rating of equipment, as well as the heavy power cables connecting the equipment, may be more costly than the equipment or the shelter itself (if required to reach a point outside the blast zone pressure potential).

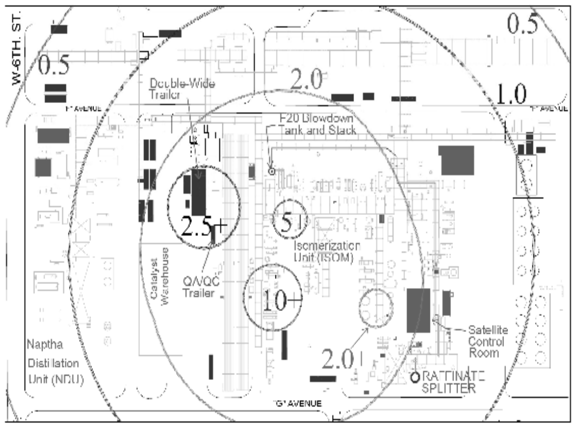

Figure 1- Site Map of the Texas City, TX Refinery

Blast Loads

The load on a structure from a nearby explosion takes the form of an almost instantaneous increase in pressure to a maximum value, followed by a brief period during which the pressure decays back to its ambient value. Pressures are measured in pounds per square inch (psi) and metric equivalents known as Pascal Units, e.g., kilopascals (kPa).

A free-field blast load is the measurement of a blast pressure that radiates equally in all directions with no reflections. The side-on pressure is equivalent to the un-reflected pressure of the wave at the point where it reaches the structure. This is the “rating” pressure used to map the site and position the blast-rated structures. A free-field blast is the usual result of a Vapor Cloud Explosion (VCE). The pressure wave generated by the VCE impacts the structure on the facing wall, creating a peak reflected pressure due to the Doppler effect (change in the observed frequency of a wave) of the pressure reflecting off the structure’s wall.

Blast Pressure Effects

The VCE experienced during the Texas City Incident in 2005 produced a 2.49 psi (17.2 kPa) free-field blast, which in turn produced an equivalent side-on pressure. This level of pressure was sufficient to destroy construction trailers positioned within the blast zone and in fact, trailers nearly 1000 feet from the center of the blast area sustained damage to varying degrees.

Table 1 describes three levels of blast pressure damage on buildings in HP facilities subject to blast loads. As information, the terms *damage level* and *response level* are often used interchangeably, as shown in Table 2.

Table 1- Building Damage Level/Response Level Descriptions

Building Damage Level	Component Consequence
1 (Low)	Localized building damage. Building can be used, however repairs are required to restore integrity of structural envelope. Total cost of repairs is moderate.
2 (Medium)	Widespread building damage. Building cannot be used until repaired. Total cost of repairs is significant.
3 (High)	Building has lost structural integrity and may collapse due to environmental conditions (i.e., wind, snow, rain). Total cost of repairs approaches replacement cost of building.

Research & Development: Optimal Blast Resistance and Affordability

Recently, a highly advanced team of designers and engineering managers with decades of experience in blast resistant structures made a decision that is significantly impacting the HP industry: it was determined that a thorough program of research, analyses and testing would be undertaken to rate the performance limits of existing electrical equipment center designs. It was also understood that test results would, at the same time, provide needed feedback leading to improvements in the construction of blast resistant structures, and determine the best possible combination of materials and design technology for the most advanced equipment shelters.

Analysis Phase: Complete BREC and Components

Computer analysis began using a Single Degree of Freedom (SDOF) approach, analyzing the maximum response of BREC components at various blast loadings.
SDOF was used to determine the blast load capacities for various pressure-impulse (P-i) combinations. P-i diagrams (See Figure 2) are commonly used in the preliminary design of protective structures to establish safe response limits for given blast-loading scenarios. Considered here was the potential peak pressure experienced by wall panels in the blast facing wall. The impulse was the blast duration in milliseconds times the peak pressure in psi (or kPa). This value is measured in psi-msec.

The complete Electrical Equipment Center as an assembly was also evaluated using Finite Element Analysis (FEA). Using FEA, a computer model of the BREC was generated to verify resistance to a 2.5 psi blast load at 200 milliseconds (equivalent to the destructive Texas City blast load). Validations were performed to compare the FEA results to the SDOF model's results, and verify the SDOF calculations.

Figure 2 - Side-On Pressure-Impulse Diagram for 2.7 Mm Wall Panels

Using the SDOF approach, engineers conducted a series of single panel evaluations on a 3-meter long, 81-cm wide steel wall panel section at the point of maximum deflection; the measured results were critical in modeling the BREC using FEA.

A half-symmetry model of the entire BREC structure, as shown in Figure 3, was also used and measured the blast resistance and integrity of the walls, as well as the global response of the entire structure. Although the front wall must resist the reflected load, the side wall panels also play an important role: they are essential to the transfer of the roof loads to the foundation. Both the roof and ceiling were modeled as double-panel systems as described for the wall, and material properties were identical to those used in the validation phase of the analyses. The reflected load as tested used a peak pressure of 36.5 kPa (5.29 psi) at 200 milliseconds, applied to the exterior panel of the front wall. The side wall, back wall and roof were subjected to side-on pressures, with a time lag included to the back wall in the analysis, to effectively capture the blast wave surrounding the building. The highest stresses tended to occur at either the panel mid-span or at its end connections with the roof and base steel. The testing and recording of results for these FEA building models effectively completed the computer analysis phase.

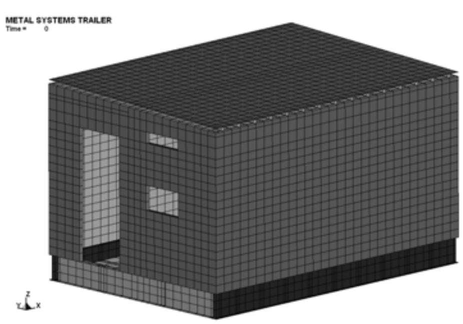

Figure 3 - Half-Symmetry Building Model

Physical Test Specimen Preparation

Subsequent to the engineering team's completion of the SDOF and FEA phase, Baker Engineering and Risk Consultants, Inc. (BakerRisk) was contracted to evaluate a series of wall panel units by subjecting them to actual, physical blast pressures, using a powerful device known as the BakerRisk shock tube. It may be said that the shock tube is to research and testing of blast resistant designs what actual wind tunnel testing is to the aeronautical and automotive industries.

Fifteen tests were conducted on six different wall panel designs, using seven different wall specimens and combinations of 16-gauge, 12-gauge and 11-gauge steel. Multiple units were built up for the 16 in wide × 3 in deep, 12 gauge G90 wall panel, and single specimens were provided for the five remaining panel designs. Three equipment access doors using three different gauges (14, 16 and 18) and methods of construction were installed on one panel to test their performance limits.

Test Specimen Construction

The physical test phase involved the wall, roof and floor systems, and equipment doors. Cross-section drawings of the floor, wall and roof systems are shown in Figures 4 and 5. Included in the analyses and testing was an optional inner wall comprised of 50 mm studs with a 1.2 mm steel liner panel. Other options for equipment support include unistruts and structural tube steel. The ceiling has a set-up similar to the walls, but without the insulation and inner liner panel. The floor system consists of 6.3 to 9.5 mm metal plate fastened above various hot-rolled steel beams and angles.

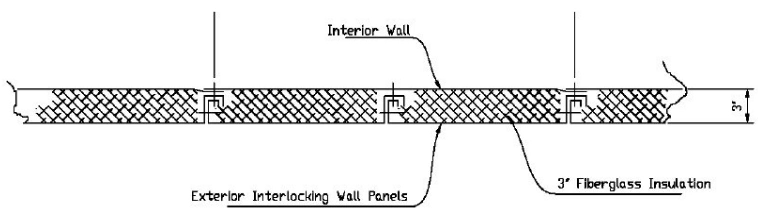

Figure 4 - Typical Interlocking Wall Panel Section

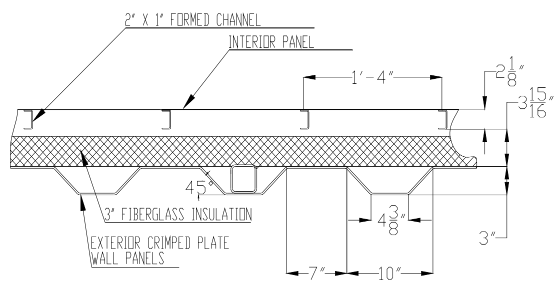

Figure 5 - Typical Crimped Plate, Seam-Welded Wall Section

Wall panels used in the analysis and testing were modeled as ASTM A36 steel. It should be noted that BRECs are actually constructed of A653CQ Grade 38 steel; therefore, the material cited in the analyses is on the conservative side. The majority of panels were wall panels of interlocking steel construction as shown in Figures 4 and 6; one panel was constructed to validate 6.3 mm seam-welded, crimped plate (SWCP) construction, as shown in Figures 5 & 7.

Figure 6 – Interior And Exterior Wall Panels Used In Physical Test Phase

Figure 7 – Wall Panel Of SWCP Construction Used In Physical Test Phase

Test Procedure

Actual physical response of the structural system to simulated blast loads was the next step. Full-scale blast tests were conducted by subjecting complete wall/roof sections and equipment doors to known, controlled blast pressures. Actual pressures of up to 8 psi were applied. The physical test program served a dual purpose:

- to evaluate each wall panel unit under three blast loadings: near the low damage level threshold, near the medium damage level threshold, and at or near the failure limit of the specimen, and to follow up with documented test results.

- to provide a basis for comparison to and validation of the SDOF and FEA analyses, thereby allowing for a computer modeling and blast load analysis program of this nature to serve as the sole criterion for testing of blast resistant electrical equipment centers.

BakerRisk designed their shock tube to provide an applied blast load to a structural specimen without the use of explosives. A significant advantage of the shock tube over open-air blast testing with high explosives is its ability to deliver long-duration blast loads typical of industrial explosions, without requiring explosives or the use of open land area.

To simulate the blast pressure of a free-field VCE, the shock tube applied pressure to the test panel. The tests were conducted on 3-meter by 3-meter wall and roof sections. Each test section was fixed to the front of the shock tube where a controlled release of pressurized air impacts the wall surface. The test samples were subjected to increasing blast pressures for varying levels of duration and impulse. Tests were gauged to precipitate low, medium, or high damage responses. Component damage response levels as shown in Table 3 follow the same pattern as the building level responses. The test panel configurations represent those used in current BREC designs.

Panel Damage Level

Support rotations were also used in determining the damage/response levels of the panels. The maximum dynamic deflection of each component was calculated, providing the ranges used in the three damage/response levels shown in Table 2.

Each component was also analyzed for various Pressure-Impulse (P-i) combinations to determine an overall P-i diagram for the entire electrical equipment center, in terms of building response level. The definitions of the building response levels are provided in Table 2. Results for the FEA model using 12-gauge wall and roof panels are also indexed in Figure 2 for side-on or free-field blast loads.

Table 2 - Component Response Levels and Range Of Deflection - Inches

Component	Damage Level 1 (Low)	Damage Level 2 (Medium)	Damage Level 3 (High)
Stiffened Wall and Roof Panels	**Less than 2.1 in.** Onset of visible damage; component can be repaired.	**2.1 to 4.2 in.** Permanent deformation of components requiring replacement.	**4.2 to 8.4 in.** Substantial plastic deformation approaching incipient collapse. Replacement is required. Component failure is possible, although not probable.

Test Results

Selected test configurations and test results are shown in Table 3.

Table 3 - Shock Tube Test Results

Specimen	Test	Panel Type	Screw Size	Peak Applied Test Pressure 1,2 (psi)	Equivalent Right Triangular Peak Pressure (psi)	Peak Applied Impulse (psi-ms)	Duration (ms)	Peak Dynamic Deflection (in)	Observed Damage Level
A	1A	16" wide 3" deep 16Ga G90	#10	0.9	0.8	26	58	None Visible	Low
A	1B	16" wide 3" deep 16Ga G90	#10	2.8	2.4	97	69	5.5	High
B	1B	12" wide, 4" deep 12Ga G90	#10	3.4	2.6	167	98	0.75	Low
B	2B	12" wide, 4" deep 12Ga G90	#10	5.3	4.3	213	80	1.5	Low
B	3B	12" wide, 4" deep 12Ga G90	#10	6.8	5.4	290	85	4	Medium
C	1C	12" wide, 4" deep 11Ga G90	¼ inch	7.6	5.9	314	83	2	Low
C	2C	12" wide, 4" deep 11Ga G90	¼ inch	8.5	6.2	462	109	4	Medium
D	1D	1/4" Crimped Plate	N/A	6.8	5	277	81	2.5	Medium
D	2D	1/4" Crimped Plate	N/A	12	8.7	755	126	7	High
E	1E	3 Equipment Doors	N/A	4.4	4	114	52	N/A	Doors remained attached

The test results establish effective side-on pressure ratings for the tested panel configurations. Table 4 shows the side-on ratings for the each BREC construction type as well.

Table 4 - Effective Side-On Pressure Ratings

Specimen/ Contruction Type	**Panel Type**	Low Response Limiting Applied Load (psi, psi-msec)	**Low Response Limiting Side-On Load (psi, psi-msec)**	Medium Response Limiting Applied Load (psi, psi-msec)	**Medium Response Limiting Side-On Load (psi, psi-msec)**	High Response Limiting Applied Load (psi, psi-msec)	**High Response Limiting Side-On Load (psi, psi-msec)**
A/Type I	16" wide 3" deep 16Ga G90	0.8, 26	0.4, 13	**	**	2.4, 97	1.2, 47
B/Type II	12" wide, 4" deep 12Ga G90	4.3, 213	2.0, 101	5.4, 290	2.5, 136	**	**
C/Type II	12" wide, 4" deep 11Ga G90	5.9, 314	2.8, 147	6.2, 462	2.9, 215	**	**
D/Type III	1/4" Crimped Plate	**	**	5.0, 277	2.4, 131	8.7, 755	4.0, 344
E/Type I & II	3 Equipment Doors	**	**	**	**	4.0, 114	1.9, 54

**** - TEST DATA NOT AVAILABLE**

Conclusions

Both the SDOF and FEA results of the analyses were compared to the shock tube test results shown in Table 3. The tests provide a high degree of validation of the analyses and demonstrate the limits of the panels used to absorb blast forces exceeding those of the Texas City incident, without catastrophic failure. In turn, these findings verify the robustness and efficiency of BREC construction types I, II AND III.

Based on the actual test results, it can be confidently stated that interlocking panel design can be used to resist blasts up to 4 psi side-on pressure. It was also learned that screw type and spacing are critical. Thirdly, equipment doors, such as the ones built for this testing program, can be used.

The primary differences between the standard equipment center and a BREC using Construction Type I or Type II are the gauge and amount of material, screw spacing, door construction and equipment door configuration. A key difference in the layout of a BREC is the addition of a deflection space between the outer blast wall and any interior equipment supports or interior walls. For pressures above 1.0 psi, the use of special blast-rated doors and HVAC units with blast dampers is required. It is also assumed that these designs will be installed on foundations adequate to support the structures and anchor systems effective in holding the BRECs in place during a blast event. With this in mind, power and control cables can be configured to enter the structure through penetration points, preferably in the floor. Penetration points for power cables and wiring should be sealed using glands or other readily available cable sealing systems.

Wrapping It All Up

With a vast amount of design and build experience using both interlocking panel and welded steel construction in blast resistant equipment centers, an expert team of engineers have developed computer-based blast loading and damage profiles. Their ambitious program of evaluations began with Single Degree of Freedom (SDOF) analyses for wall and door components. They then developed computer models of both a complete and half-symmetry building using Finite Element Analysis (FEA). The purpose was to further evaluate and verify the SDOF calculations that showed the limits of blast loadings on the wall panels and other BREC components. Armed with the results of these analyses, actual physical test specimens were prepared using 12-gauge steel sections, after which a battery of physical blast load testing regimes was run on built-up steel wall and door components. The team then compared the results of the physical tests with those of their computer analyses. After they developed a strong correlation between the analyses with the results of the shock tube testing, they were able to conclude that a proper program of computer analyses can be used to accurately predict the response of equipment centers to known blast loads. That knowledge and testing have effectively extended the performance limits of BRECs from less than .5 psi to 4.0 psi.

The state of the industry in equipment centers now allows for the best combination of protection and cost-effectiveness.

What this means for HP companies is that there are now specific design and build parameters for BRECs that can be used to optimize their integration into a program of process safety at every facility. In short, the state of the industry in equipment centers now allows for the best combination of protection and cost-effectiveness.

These factors, combined with the features list found in today's BREC construction, result in benefits that can be directly translated to the client's bottom line: low cost, weather-tight, contaminant-proof buildings that are flexible, easily retrofitted and repaired, and ductile in response to applied loads. The technology, effectiveness and availability of BRECs can provide every refinery with a higher level of safety and security for the process system.

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