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Secondary Containment Design for a High Speed Centrifuge

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Abstract

Secondary containment for high speed rotating machinery, such as a centrifuge, is extremely important for operating personnel safety. Containment techniques can be very costly, ungainly and time consuming to construct. A novel containment concept is introduced which is fabricated out of modular sections of polycarbonate glazed into a *Unistrut* metal frame. A containment study for a high speed centrifuge is performed which includes the development of parameters for secondary containment design. The *Unistrut*/polycarbonate shield framing concept is presented including design details and proof testing procedures. The economical fabrication and modularity of the design indicates a usefulness for this shielding system in a wide variety of containment scenarios.

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Secondary Containment Design for a High Speed Centrifuge

Introduction

Any type of rotating machinery subjects operating personnel to danger from flying projectiles. High speed centrifuges are particularly dangerous since their purpose is to spin test objects, sometimes on center, but usually at the end of a rotating arm. If the test object should be released from the arm, it can leave the centrifuge tangentially with a high kinetic energy. Most centrifuges are designed with some sort of primary containment or enclosure surrounding the rotating components of the machine. One can hope that the original designers of the centrifuge built the primary containment to contain any form of fragment that might be released from the machine. However, there are always entry breaches of the primary containment for loading test parts, temperature conditioning, or machine maintenance. If these entry points are not closed and interlocked properly, or if the interlocks are purposely bypassed, or if the machine would fail in a mode not completely understood by the designers, a catastrophic failure of the primary containment can occur causing part fragments to be thrown from the machine with a high kinetic energy. Accidents of this type were documented fairly well by Sonnichsen (1993).

Any failure mode of a high speed centrifuge can cause damage to equipment in the vicinity and also personnel injury or death. These failure modes are common to all centrifuges and basically any high speed rotating machinery. Because of a history of machine failures and uncertain methods in determining failure criteria, it is this author's belief, and becoming an industry standard, that all rotating machinery should be surrounded, not only with primary containment, but with a secondary method of containment to protect operating personnel. The secondary containment should be designed to contain any fragments that could breach the primary containment. Controls, both interlocking and procedural, should be placed to prevent machine operation when personnel are within the secondary containment.

Given the task of installing a Genisco 1082 centrifuge at the Sandia Weapons Evaluation Test Laboratory (WETL) at the Pantex facility in Amarillo, Texas, secondary containment was a requirement. An investigation of secondary containment options was performed by analyzing the centrifuge attachment to the floor and examining several alternative barrier designs. Typical barrier designs include steel plate/frame structures, reinforced concrete walls, concrete block walls, and a concrete walled excavated pit with either a steel or concrete roof.

It was determined, during the preliminary analysis, that all of the rotational energy of the centrifuge would be transferred to the base anchor bolts, if a failure in which the test object was lodged between the rotating arm and the primary containment wall occurred. This would cause the centrifuge to shear from the anchors and "walk" across the floor until the energy was dissipated. Because of anchoring constraints, it proved to be prudent to design the secondary containment to handle an impact from the centrifuge itself. An assumption was made that any containment designed to contain the maximum size fragment released from the centrifuge at its maximum tangential velocity would be stout enough to contain the machine should the anchor bolts fail. It was also determined that the energy required to shear the anchor bolts along with the mass of the machine itself would dissipate most of the energy of the rotating arm.

The classical machine barrier designs proved to be quite expensive to fabricate and install, especially at the highly access restricted Pantex facility. Installation costs were especially high, because of the need for specialized construction crews. An idea for a innovative and economical approach to machine containment was needed. Having had some experience and knowledge of polycarbonate and it’s high impact strength properties, the author decided to examine the possibility of using polycarbonate shielding as a method of secondary containment.

There has been limited testing of polycarbonate used in a shielding application. Most of the data available is for the ballistic regime at velocities of 1000 - 3000 ft/s. Most of the research performed on characterizing polycarbonate began in the 1960’s and was classified and therefore not included in this report. The US Air Force performed a minor amount of ballistic testing to determine the material’s applicability to transparent armor. The research also included early bonding agents to bond polycarbonate with glass. One of the most significant conclusions from this early work was the determination that the ballistic performance of polycarbonate is not related to its low-rate impact properties (Ball et al. 1970). This is significant in that there has not been a great amount of testing performed on low-rate impacts. The US Army Ballistic Research Laboratory investigated the impact resistance of various glazing materials including polycarbonate for improving safety in railroad vehicles. Limited low impact testing was performed with .22 caliber ballistic testing being the preferred method (Rakaczky 1979). Proof testing of polycarbonate shields for laboratory protection was stressed by Ciolek (1986) who performed some limited impact testing on the material. The targets impacted were all 12 inch square without much detail given on support methods. The US Naval Civil Engineering Laboratory was concerned with protecting building occupants from an external terrorist threat, such as an explosive blast. Keenan and Meyers (1987) developed a cable suspended polycarbonate window shield to absorb blast energy and shield against fragments from such explosions. This design concept was formulated into a development plan sometime later (Shope and Keenan, 1991), however the author could find no reference to further work being performed. The use of polycarbonate as an ocular protective device against ballistic fragments was studied by Masso (1992). He performed research under the direction of the US Army Medical Research and Development Command while actually collaborating with American Optical on developing processes for fabricating a wide variety of protective eyewear. More recently, Mewes et al. (1998) have been investigating the use of polycarbonate for shielding personnel from machine tools. They have performed testing with smaller masses, (0.22 - 11)lb, striking a clamped 19.5 inch square target.

Because of the lack of impact data in the lower velocity regime (50 - 500 ft/s), impact proof testing of polycarbonate sheets was performed to determine it's ability to stop the centrifuge's maximum energetic fragment. In addition to determining the polycarbonate's impact strength, a method of securing the polycarbonate in some sort of frame was developed. A design suitable for secondary containment with polycarbonate shielding, for the Genisco 1082 Centrifuge, is presented in this paper along with the shield frame's suitability to be adapted for a myriad of containment applications.

NOMENCLATURE

A	area normal to direction of projectile impact
C	constant (Westine equation)
c	THOR empirical constant
I	moment of inertia
I_D	moment of inertia of the centrifuge door
K	kinetic energy
k	radius of gyration
m	mass
m_p	mass of projectile
r	radius of rotation from edge of door to hinge
T	toughness
U	total strain energy
V	volume of material which undergoes ductile failure
v_f	final velocity
v_s	starting velocity
v_{P1}	initial velocity of the projectile
v_{P2}	final velocity of the projectile
W_S	initial weight of projectile
α	THOR empirical constant
β	THOR empirical constant
γ	THOR empirical constant
λ	THOR imperialist constant
ω	angular velocity
ω_{D1}	initial angular velocity of the centrifuge door
ω_{D2}	final angular velocity of the centrifuge door

Containment Study

The Genisco 1082 centrifuge has a weight capacity of 80 lb, with a top speed of 700 rpm. The radius of gyration k is given as 23 inches. This centrifuge is illustrated in Figure 1. As is evident in Figure 1, the rotating test mount is surrounded by a temperature chamber, which acts as the primary containment. This chamber is a 4 inch thick composite layup, consisting of an interior of 16 gauge stainless steel and an exterior of 1/4 inch hot rolled steel, with the space between filled with urethane foam insulation. The temperature chamber is secured to the base, with (4) 1/2 inch bolts, which is then secured to the floor with another (4) 1/2 inch bolts.

Figure 1.
Genisco 1082 Centrifuge

As was mentioned in the introduction of this paper, preliminary calculations showed that the rotational kinetic energy of this centrifuge far surpassed the energy required to shear the anchor bolts, therefore anchor bolt design was deemed immaterial to centrifuge safety. The anchor bolt calculations were performed by Southwest Research Institute (SwRI) in San Antonio, Texas under Sandia Contract #AU-7998. The SwRI project number was 06-8555. A summary of some of those calculations follows.

Rotational kinetic energy is given as

$$K = \frac{1}{2}I\omega^2, \tag{1}$$

where I is given as

$$I = mk^2. \tag{2}$$

Substituting equation (2) into equation (1) yields

$$K = \frac{1}{2}mk^2\omega^2. \tag{3}$$

Substituting operating data for the Genisco 1082 centrifuge into equation (3) yields a maximum rotational kinetic energy of

$$K = \frac{1}{2}\left(\frac{80\text{ lb}}{384\text{ in/s}^2}\right)(23\text{ in})^2(73.3\text{ rad/s})^2 = 296,099.6\text{ in lb}.$$

As given in the SwRI report, Westine and Kineke (1978) showed that the energy absorbed by a cantilever beam that fails from strong blast loading is equal to

$$U = CTV \tag{4}$$

where C is a constant given as 0.5 for ductile shear of a beam. For the calculation, the material was assumed to be steel with a yield stress of 100,000 psi and a failure strain of 10%, giving a toughness of 10,000 psi. It was further assumed that the volume of material in the bolt that would undergo ductile failure when it is sheared by the base flange is based on a bolt length equal to the 1.0 inch centrifuge floor flange thickness plus one bolt diameter (due to additional deformation in the floor). This gives a total strain energy absorbed by a 1/2 inch bolt of

$$U = 0.5(10{,}000\text{ psi})(0.295\text{ in}^3) = 1472.6\text{ in lb}$$

Equating this energy, times the number of bolts, to the maximum rotational kinetic energy of the centrifuge given above, we find that approximately 200 bolts are required. Since this number of bolts is impractical, the centrifuge anchorage was not modified, thus, the secondary containment would be designed to contain the centrifuge if it broke loose from the floor. However, since the centrifuge weighs approximately 2500 lb, the rotational energy would be dissipated through trying to move this mass and floor friction. The secondary containment would be subtly bumped by the centrifuge, if even, under this worst case scenario.

Before designing secondary containment, one must examine the strength and fragment breaching scenarios of the primary containment. SwRI also performed impact studies on the temperature chamber primary containment under Sandia Contract #AU-7998. The calculations performed are too extensive to be all be repeated here, however they predicted no perforation of the temperature chamber wall when struck by the highest energetic projectile. An examination of impact penetration of the 1/4 inch steel outer shell of the temperature chamber may be determined through the use of the empirical THOR equations. A discussion of the development of the THOR equations and their references may be found in “A Manual for the Prediction of Blast and Fragment Loadings on Structures,” SwRI, 1992.

The THOR equation for residual velocity of a projectile which perforates a target is given as

$$v_f = v_s - 10^c (hA)^\alpha (7000 W_s)^\beta (\sec\theta)^\gamma v_s^\lambda \tag{5}$$

where for hard steel, the empirical constants are given as c = 6.475, $\alpha = 0.889$, $\beta = -0.945$, $\gamma = 1.262$, and $\lambda = 0.019$.

Assuming a 36 inch diameter centrifuge arm yields a maximum tangential velocity of approximately 110 ft/s. And assuming a small projectile such as a 1/2 inch bolt being released with an impact area of 0.2 inches, weighing 0.2 lb and impacting at 0°, and substituting into equation 5 yields

$$\begin{aligned} v_f &= 110 \text{ ft/s - } (10)^{6.475}[(0.25)(0.1963)]^{0.889}[(7000)(0.2)]^{-0.945} \\ &\quad (\sec 0°)^{1.262}(110 \text{ ft/s})^{0.019} \\ &= -128.16 \text{ ft/s} \end{aligned}$$

A negative velocity result indicates that the bolt does not penetrate the target.

If we assume a large 32 lb projectile, which represents the largest possible test package based on the Genisco 1082 centrifuge capacity, with an impact area of 11 inches, and substitute into equation (6) we get

$$\begin{aligned} v_f &= 110 \text{ ft/s - } (10)^{6.475}[(0.25)(0.92)]^{0.889}[(7000)(32)]^{-0.945} \\ &\quad (\sec 0°)^{1.262}(110 \text{ ft/s})^{0.019} \\ &= 102.23 \text{ ft/s} \end{aligned}$$

This result indicates that, not only does the projectile penetrate the target, but it also hardly slows down. The problem in using these equations is that they were developed empirically at ballistic velocities or velocities in the 1000 - 3000 ft/s range. Since the maximum centrifuge tangential velocity is only 110 ft /s, these results cannot be taken as accurate. This is a problem with analyzing penetration in this lower velocity regime, empirical equations do not exist since most research is of a ballistic nature. However, from these results one can assume that the larger projectile causes a greater penetration problem than the smaller one. Thus, a proof test with the larger projectile would prove containment of anything that could be released from the centrifuge arm.

A proof test was performed at SwRi with a 32 lb projectile being fired at a test panel mock-up of the temperature chamber at 125% of the maximum tangential velocity, or approximately 137 ft/s. Figure 2 is an illustration of the results of that proof test. As is evident in Figure 2, the projectile pierced the inner stainless steel liner compressing the foam, but did not breach the outer 1/4 inch steel plate. Thus the primary containment held.

Figure 2.
Result of Primary Containment Proof Test

However, because of reasons mentioned in the introduction of this paper and upon examining the centrifuge illustrated in Figure 1., one can see that secondary containment is still required due to door hinges and latches and temperature control access holes to the temperature chamber, all of which provide weak points in the primary containment

At the time of this primary containment proof test, a preliminary test shot was performed on 1/2 inch polycarbonate sheeting to access it’s impact strength in the velocity regime of the Genisco 1082 centrifuge. However, since the primary containment must be breached for a projectile to impact the polycarbonate secondary containment, temperature chamber failure was examined to determine a suitable velocity for secondary containment design. Other than after a ricochet, which would considerably lower the energy of the projectile, the only direct path of projectile release from the centrifuge arm through the primary containment could be through the door. Since the door latch was the weakest point of the door, calculations were performed to determine the loss in velocity from impact and movement of the door mass to the open position, assuming that the door wasn't even latched.

A conservation of momentum calculation can be performed to determine the reduction in velocity after the projectile impacts the door. Conservation of momentum provides a more accurate determination of velocity over conservation of energy in that energy absorption and loss upon impact are ignored. As discussed in Tipler (1976) and in Serway (1982), total momentum is always conserved during a collision whereas total kinetic energy is not because some of the kinetic energy is converted into heat and internal potential energy when the bodies are deformed during impact.

Therefore

$$m_P v_{P1} + \cancelto{0}{I_D \omega_{D1}} = m_P v_{P2} + I_D \omega_{D2} \tag{6}$$

where P and D represent the projectile and the door, respectively

Since the velocity of the projectile after pushing the door open can be equated to the tangential velocity of the door edge, equation (6) can be rewritten as

$$m_P v_{P1} = m_P v_{P2} + I_D \frac{v_{P2}}{r^2} \tag{7}$$

or

$$v_{P2} = \frac{m_P v_{P1}}{\left(m_P + \frac{I_D}{r^2}\right)} = \frac{v_{P1}}{\left(1 + \frac{I_D}{m_P r^2}\right)} \tag{8}$$

With the 27 inch door moment of inertia given as 41.14 in lb s^2, and the projectile weighing 32 lb, equation (8) solves as

$$v_{P2} = \frac{137.5 \text{ ft/s}}{\left(1 + \frac{41.14 \text{ in lb s}^2}{\frac{32 \text{ lb}}{386 \text{ in/s}^2}(27 \text{ in})^2}\right)} = 81.81 \text{ ft/s}$$

So the test velocity of the polycarbonate secondary containment proof test was set at 82 ft/s, which is still considered a 25% overtest. Since the initial test was a preliminary shot, a 4 ft square sheet of polycarbonate was simple bolted to a test frame in a random bolting pattern. A large number of bolts were used since a rigid end connection was assumed to be beneficial to the impact resistance. Figure 3 illustrates the results of that test.

Figure 3.
Result of Preliminary Polycarbonate Impact Test

Note that the projectile did not penetrate or even crack the polycarbonate sheet. The projectile only produced a slight plastic deformation in the region of impact. Some cracking is seen, however, at the bolted interface near the number 6. This indicated that the rigid connection was probably not the most suitable for this application, a more flexible hold on the polycarbonate would be more desirable.

It is interesting to solve the THOR equation for 1/2 inch polycarbonate, using the large 32 lb projectile, where the empirical constants are given as c = 2.908, $\alpha = 0.72$, $\beta = -0.657$, $\gamma = 0.773$, and $\lambda = 0.603$.

Thus

$$\begin{aligned} v_f &= 82 \text{ ft/s} - (10)^{2.908}[(0.5)0.92)]^{0.72}[(7000)(32)]^{-0.657} \\ &\qquad (\sec 0^\circ)^{0.773}(82 \text{ ft/s})^{0.603} \\ &= 79.99 \text{ ft/s} \end{aligned}$$

This indicates that the 1/2 inch polycarbonate would hardly even slow the projectile, let alone stop it from penetrating. Again it needs to be reiterated that the THOR equations were developed empirically for ballistic velocities and aren’t very applicable to much lower velocities. This illustrates how testing is really the only method for determining the impact properties of polycarbonate at velocities in the (50 - 500) ft/s range. Empirical equations have never been developed in this velocity regime.

Shield and Frame Design

Since shielded protection completely surrounding the centrifuge was required, a rigid frame was needed to support the polycarbonate. However, as was mentioned before, the edges of the polycarbonate favored a more flexible connection to the frame. Also, searching for an economical solution to the shield concept, ease of assembly was preferred over construction which would prove to be labor extensive.

Unistrut metal framing was chosen for it's strength, durability, ease of assembly, and prefabricated two-channel width. The double channel framing members allowed one channel for polycarbonate glazing and another channel for frame assembly. The double channel *Unistrut* framing concept is illustrated in Figure 4. One can visualize the polycarbonate glazed into the near channel while the farther channel allows bolting of the various framing members.

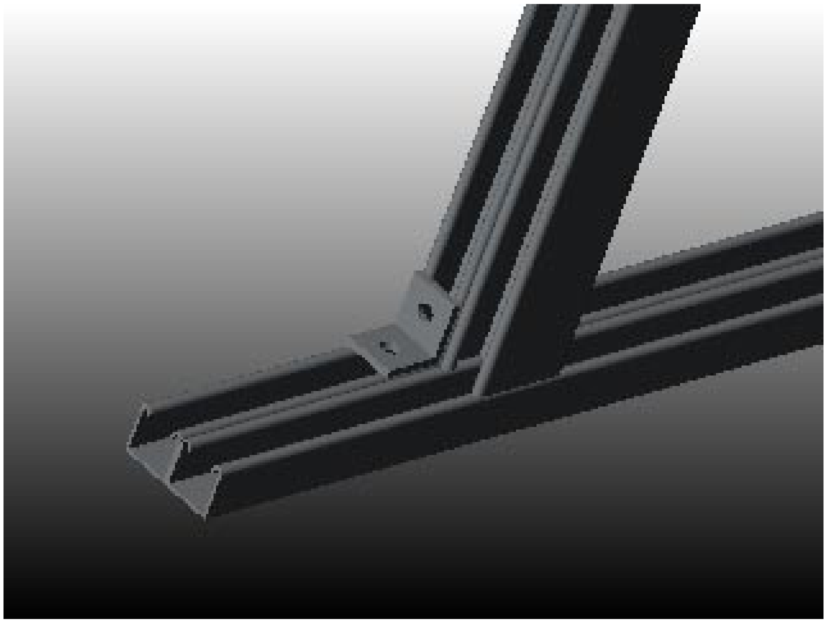

Figure 4.
***Unistrut* Shield Framing Concept**

To create a polycarbonate shield design that is truly economical, one would rather utilize standard size sheets of polycarbonate to avoid cutting and fitting at the assembly site. For the centrifuge secondary containment, an 8 ft high shield proved to be of adequate height for personnel protection. Thus, standard 4 ft wide by 8 ft high polycarbonate sheets were incorporated into the shield frame design, creating a modular containment framing concept consisting of 4 ft x 8 ft sections. This frame section is illustrated in Figure 5. When the entire containment structure is built, the top and bottom frame channels are continuous. The vertical frame channels are spaced every 4 ft to accommodate the 4 ft wide polycarbonate sheets. The center brace is assembled behind the continuous polycarbonate sheet, in each 4 ft wide section, to provide additional impact bracing. This will be covered in more detail in the next section.

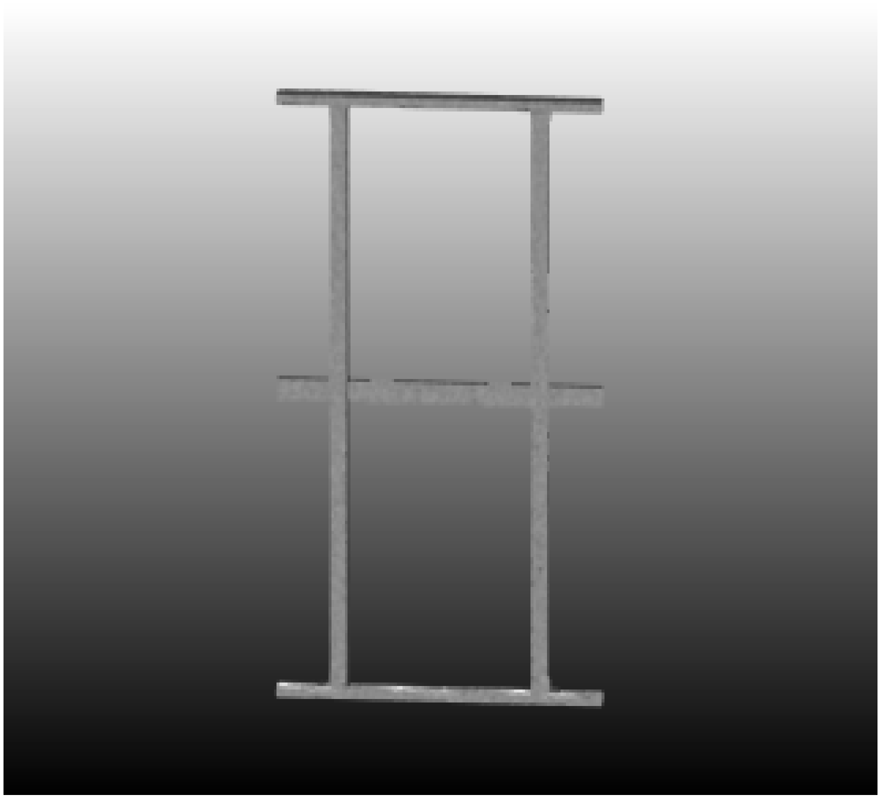

Figure 5.
Standard 4 ft Wide by 8 ft High Shield Frame Section

To glaze the polycarbonate sheets into the *Unistrut* channel, neoprene gasketing material was used. This gasketing provides centering and a flexible edge support for the polycarbonate sheet. Neoprene gasketing is used because of it's compatibility with polycarbonate. Polyvinyl chloride (PVC) must not be used with polycarbonate since contact will result in surface cracking. The neoprene gasketing material used in this shield design was obtained with pressure sensitive tape for ease of assembly. After fitting the glazing channel with gasketing on all three surfaces and wetting, the polycarbonate is simply slipped into place. To assemble the entire structure, the bottom floor *Unistrut* channel frame is placed in position initially. Then the shield walls are assembled, starting at one end moving towards the other, alternately bolting uprights in place and glazing in the polycarbonate sheets. Once a shield wall is completed, the top *Unistrut* channel is bolted on, completing the structure. The secondary containment structure surrounding the Genisco 1082 centrifuge measures 12 ft on a side. This is illustrated in Figure 6. Note the labyrinth entrance to the secondary containment. This enables easy access to the centrifuge without a breach in the continuous polycarbonate shielding, while allowing no direct projectile escape path.

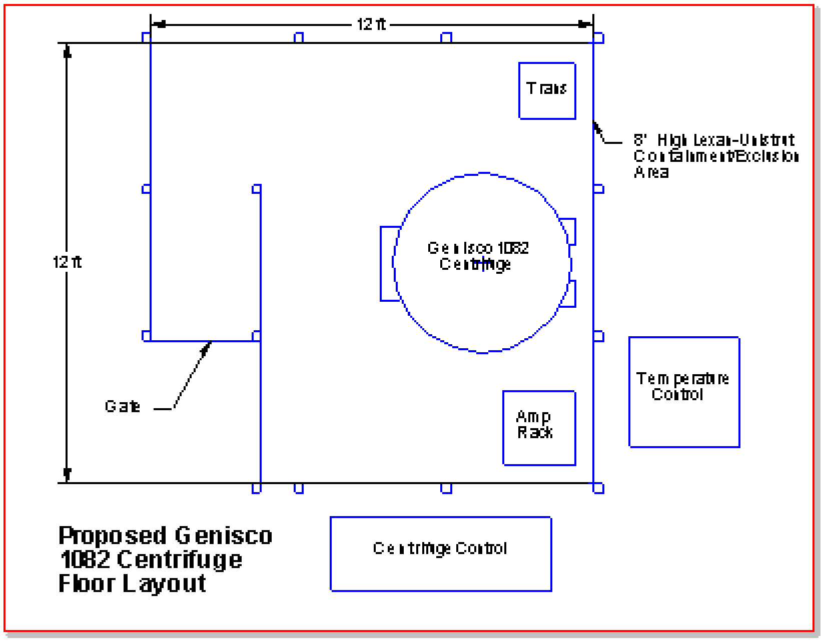

Figure 6.
Proposed Genisco 1082 Centrifuge Floor Layout

Once the entire structure is assembled, it is then bolted to the floor with simple concrete anchors. Since each 4 ft x 8 ft section weighs approximately 250 lb, there is no need for major anchorage, the mass of the structure suffices to keep it in place. Control cabling and temperature control hoses are routed over the top of the *Unistrut*/polycarbonate frame so that the shield is not breached in any way.

Although any type of polycarbonate may be used in this framing system, without a protective coating the material offers limited abrasion resistance. This can lead to poor visible clarity over time. In this application, and wherever aesthetics must be maintained, the author suggests the use of *Margard*, made by the General Electric Company, which is polycarbonate sheet coated with a mar-resistant silicone hardcoat. This material has the same impact properties of regular polycarbonate sheet but also is warranted for 10 years against abrasion and coating delamination.

Testing Procedure

After designing the shield framing concept and sizing the polycarbonate thickness by the preliminary test shot (Figure 3), new test frames were fabricated and assembled at SwRI to enable proof testing of the *Unistrut*/polycarbonate frame itself. As is shown in Figure 5, the shield design for the Genisco 1082 centrifuge included a center brace. The initial test frame was built without a center brace and failed. However, the unique adaptability of this *Unistrut*/polycarbonate framing concept enables the addition of any number of center braces, depending on impact requirements. It just so happened that during the secondary containment proof testing for the Genisco 1082 centrifuge, only one center brace was required in all test shots. Figure 7 illustrates the test frame setup at SwRI for proof testing.

Figure 7.
Test Frame Setup at Southwest Research Institute.

A total of 7 proof test projectile impacts were performed. The polycarbonate was impacted at a velocity of approximately 85 ft/s in the center, edge, and corners. A separate test frame was assembled for each test shot, except in instances where deformation effects were minimal and influences on the reaction to other shots would be negligible. A 30 degree oblique shot was performed to impact the polycarbonate sheet with the edge of the projectile for a cutting effect. The *Unistrut* frame itself was also impacted to test the integrity of the bolted connections. The test frame survived all the proof test impacts. It was interesting to witness how the *Unistrut* frame and the polycarbonate reacted as a system to absorb the energy of the impacts. The neoprene gasketing was very successful at transferring the energy from the polycarbonate to the metal framing.

Summary

Providing secondary containment around rotating machinery is extremely important to operator safety. Without adequate containment, machine failures can cause personnel injury or even death. The design of a containment shielding frame that is safe, aesthetically pleasing, and economical to install, offers engineers an alternative to classical containment methods or risk involved with providing no shielding at all. Through impact testing of polycarbonate supported in a *Unistrut* frame, the author has shown that modular containment may be provided easily for a wide variety of applications.

There are a number of advantages to installing this type of shielding frame. It offers a high impact resistance which can be increased through the addition of more center braces. The *Unistrut* channel itself can accommodate polycarbonate thicknesses in the range of 1/8 inch to 3/4 inch, depending on strength requirements. The frame design is modular, in that any number of 4 ft by 8 ft sections can be erected to form any size containment area. The mar-resistant polycarbonate, *Margard*, is aesthetically ideal, enabling the operator to observe the machine during operation while being located outside the secondary containment. Using *Unistrut* provides a cost effective method of installation since all framing members are pre-cut, pre-finished, and simply bolted together on site. This also improves mobility, in case of temporary shield installations.

In addition to providing containment for machinery, this shielding concept could be utilized wherever there is a need to protect personnel from flying fragments or debris. Secondary containment surrounding explosive test chambers is one application, especially since observation of the chamber is sometimes desired. Shielding personnel from terrorist threats could also be accomplished with this design. It’s portability and adaptability to a 3/4 inch thick polycarbonate sheet make it ideal in this area. General Electric also fabricates a material, *Lexgard*, which is a polycarbonate/acrylic laminate bullet-resistant material, applicable for this application.

The author believes that this design offers a novel approach in personnel shielding. However, because of a lack of empirical equations relating impact strength of this material and frame in a non-ballistic velocity regime, extensive testing is required before this specific shield design or modifications of such should be used in other applications. The responsible engineer providing containment should always proof test the shield design to the maximum energetic fragment release possible for the specific application, providing for a factor of safety. Because of a lack of impact data for algorithm development, the author plans to further characterize this polycarbonate shield framing concept to provide design information on it’s adaptability and limitations.

References

G. L. Ball III, A. Wojtowicz, and I. O. Salyer, 1970, “Evaluation of Improved Transparent Materials and Adhesives for Ballistic and Impact Shields,” *Monsanto Research Corp. Technical Report AFML-TR-70-167*.

W. H. Ciolek, 1986, “Laboratory Shielding for Projectiles,” *Preceedings of the American Institute of Chemical Engineers, National Meeting 1986*, AIChE, New York, Pap 143c, 29p.

W. A. Keenan and G. E. Meyers, 1987, “Suspended Polycarbonate Shield to Defeat Terrorist Threats,” *Proceedings of the Sessions at Structures Congress 1987*, ASCE, New York, 735-748.

Jon D. Masso, 1992, “Fabrication of Ocular Protective Devices Against Laser Radiation and Ballistic Fragments for Evaluation in Military Scenarios,” *U.S Army Medical research and Development Command Report DAMD17-86-C-6079*.

D. Mewes. R. P. Trapp, and H. J. Warlich, 1998, “Strength of Materials under Mechanical Impact,” *Materialwissenschaft und Werkstofftechnik*, Vol. 29, No. 5, 258-262.

J. A. Rakaczky, 1979, “An Investigation of the Impact Resistance of Glazing Materials for Railroad Vehicles,” *US Army Armament Research and Development Command, Ballistic Research Laboratory Report ARBRL-MR-02955*.

R. A. Serway, 1982, Physics: For Scientists and Engineers, Saunders College Publishing, New York.

R. L. Shope and W. A. Keenan, 1991, “Safety Window Shield to Protect Against External Explosions,” *NCEL Report TN-1834*.

H. E. Sonnichsen, 1993, “Ensuring Spin Test Safety,” *Mechanical Engineering*, December 1993.

P. A. Tipler, 1976, Physics, Worth Publishers, Inc., New York.

P. S. Westine and J. H. Kineke, Jr., 1978, “Prediction of Constrained Secondary Fragment Velocities,” *The Shock and Vibration Bulletin 48, Part 2, Isolation and Damping, Impact, Blast*, A publication of the Shock and Vibration Information Center, Naval Research Laboratory, Washington, DC.

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