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TRUTHS AND FALSEHOODS OF MOLTEN METAL EXPLOSIONS IN THE ALUMINIUM INDUSTRY

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Abstract

Hess & Brondyke's studies of molten metal explosions proved molten aluminium could explode upon contact with moisture and various substrates. Over forty years later, their findings have been mostly forgotten. This paper will review Hess & Brondyke's findings as well as other studies with a special attention to the various specific substrates that upon contact with molten metal generate an explosion. I argue that Hess & Brondyke's research is still valid today and if followed will result in a decrease in the number of molten metal explosions occurring in our industry.

Introduction

Out of all the hazards the aluminium industry deals with on a daily basis, molten metal explosions has had the greatest impact in terms of financial losses and worker injuries and fatalities. Explosions occurred almost immediately in late 1940's and early 1950's when the first direct chill castings was performed. The severity of the explosions varied from small (equipment damaged) to severe (cast houses were destroyed). Aluminium companies soon realized that understanding the mechanisms associated with causing an explosion could be the key to the future of our industry. Without controlling molten metal explosions, our industry would be curtailed in terms of production and have a limited future. Many of the industry's pioneering aluminium companies performed research on molten metal explosions. Aluminium Company of America (ALCOA) began researching molten metal explosions in the 1950's. That research continued for the next 50 years and produced results that are the basis of our industry's best practices toward safety. Some of their findings have been forgotten with time to the detriment of our industry. This paper will review some notable papers and highlight findings that our industry needs to reincorporate into our industries best safety practices.

George Long

The opening sentence of George Long's 1957 "Explosion of Molten Aluminum in Water – Cause and Prevention" [1] publication still resonates 67 years later. "Accidental spilling of molten materials into water or onto a wet surface is a serious industrial hazard." George Long pioneered the research into molten aluminum explosions and many of his findings are valid today. He and his associates at the Alcoa Technical Center developed the testing apparatus for molten metal explosions. The procedures were well documented and subsequent studies followed his design for testing apparatuses. Utilizing the same design in subsequent tests allowed data to be compared between studies. A total of 880 tests were carried out by Mr. Long studying various factors that might affect the explosions. "The procedure consisted of suspending a crucible containing a weighted amount – usually 50 lb. – of molten, commercially pure aluminum above a container partially filled with water." The water containers were constructed of steel plate and concrete. The explosions were described as a violent, bursting action. Many tests resulted in explosions that destroyed the steel and concrete water containers. Molten metal was routinely propelled hundreds of feet away after an explosion. George Long's observations and hypothesis regarding the mechanism of metal explosions were later proven to be correct. He believed that the "triggering action" in minor explosions was due to the quick transformation to steam of a very thin layer of water trapped below the incoming metal. In shallow water, this explosion "merely blows molten metal and water out of the container." Finally, he brought forth the discussion of the critical chemical reaction.

$$2Al+3H_20 \rightarrow Al_2O_3+3H2$$

Figure 1 William L. Bonnell Company, Newnan, Georgia explosion of December 27, 1956 which was heard 15 miles away resulted in two workers killed, windows broken in residences, and tops of pine trees broken more than ½ mile away.

Hess & Brondyke

Paul D. Hess and Kenneth J. Brondyke's 1969 Metal Progress article, "Causes of Molten Aluminum-Water Explosions" [2] expanded on the foundation that George Long laid a decade earlier. Through a series of tests, they concluded that they knew the mechanism involved in the explosions. They proposed "efficient ways" to prevent explosions on the different substrates on which molten metal could come into contact. Substrates such as rust and bare concrete (lime) were repeatedly tested and found that they "greatly increased the likelihood and violence of the explosions." In subsequent studies, Hess & Brondyke would focus on the minimum area of exposed rust that could generate a molten metal explosion. The researchers were the first to utilize high speed video to record the explosions. Recording 700 to 1000 frames per second showed three types of explosions. These findings are the basis of the Aluminium Associations molten metal explosion classification system used today.

Thermocouples were employed to "study the influence of temperatures on explosions." Results showed that metal with an original temperature of 1170 F that the temperature at the bottom of the water container would rise instantaneously to 1,400 to 1,800 within .25 second after an explosion. In several tests the water temperature rose from 69 F to 1,280 F in only 0.06 seconds and quickly (0.25 seconds) went off the scale (1400 F).

While experimenting with elevating metal temperatures (above 1800 F), the molten metal detonated "before it was poured, indicating that a chemical reaction had taken place". When testing a water container with a rusted surface a flash proceeded the explosion. They surmised that the flash, the dispersal of large quantities of aluminum oxide particles over the area, and the fact that the maximum temperatures within the container were above that of the incoming metal clearly indicated that the most violent explosions involve a chemical reaction.

The three mechanisms Hess & Brondyke listed are the basis of today's Force 1, Force 2, and Force 3 molten metal explosion classification system. They put forth that catastrophic explosions (Force 3 classification) which destroyed the water container and were accompanied by a flash were associated with a thermite reaction. This was the exact opposite of George Long's belief that a thermite reaction played "a minor part" in the most severe explosion. They concluded their paper by proposing two ways to prevent explosions. The first is by having sufficient depth of water and second by applying a protective coating on exposed surfaces. Today's best industry practice toward safety of having a minimum 3 feet of water above the bottom of the casting pit or debris was developed by Hess & Brondyke.

Absence from their Metal Progress publication was research that Hess & Brondyke performed in 1968 investigating the "maximum size of bare spot" in the protective coating surface exposing the bare substrate underneath. In a series of tests they determined that "any bare spot larger than 2" x 2" on steel or concrete surfaces in casting operations represents an explosive hazard and should be patched immediately." Many fail to acknowledge this important contribution from Hess & Brondyke resulting in explosions that could easily be prevented with proper maintenance.

Hess & Miller

Paul Hess and Ron Miller, Alcoa Technical Center researchers headed an Aluminum Association sponsored research project in 1980 [3]. The project was "undertaken to extend the margin of safety in casting operations by improving the engineering solutions to the inherently hazardous casting operations where molten aluminum and water are often in close proximity." Back then, our industry acknowledged the seriousness of molten metal explosions. Overtime our industry has forgotten some of Hess and Miller's findings. A total of over 503 explosion tests were performed in this study. Previous studies by Hess & Brondyke resulted in the widespread use of Tarset, a catalyzed coal tar epoxy. Complaints of Tarset arose, overtime, regarding difficulty of application on wet surfaces, maintenance, repair and premature failures. In addition, the black color of Tarset had the unintended consequence of camouflaging damage that molten metal exposure left making it difficult to visually see exposed bare substrate. This study evaluated other coatings that had properties including, but not limited to; ease of application, short drying time, ease of repair, durability. Some coatings were added to the list because some member companies were already using them (e.g., Wise Chem E-212-F). The white colored Wise Chem E-212-F was tested over 55 times resulting in zero explosions. Wise Chem was quickly adopted throughout the industry because it could be applied on concrete, steel, and stainless steel substrates.

Water containers were constructed out of a variety of substrates during the testing (e.g., plywood, tar impregnated brick, concrete, etc). When George Long tested stainless steel water containers no explosions occurred. But "moderate" explosions were observed by Hess & Miller on stainless steel substrates. This resulted in the researchers making the unusually forceful statement "that bare stainless steel should not be used". This recommendation seems mostly forgotten in our industry now. Some believe bare stainless substrates are safe while bare concrete and steel are dangerous in close proximity of molten metal. Hess & Miller and numerous other researchers have proven time and time again that bare concrete, bare steel ***and*** bare stainless steel can all generate explosions with molten metal. It is common place now to see bare stainless steel in close proximity of molten metal in cast houses. Several vertical casting pits have been constructed over the past few years out of stainless steel. Each and every stainless casting pit that was recently built was eventually coated with Wise Chem E-212-F or Wise Chem E-115.

Figure 2 Stainless steel vertical casting pit built in 2012 coated with Wise Chem E-115

One particular coating, Rustoleum 769, was added to the testing because some member companies were applying it in their casthouses. Hess & Miller's testing showed that Rustoleum 769 "did not prevent explosions". "During impact testing, pan coated with Rustoleum 769, exploded before the mechanical impact could be delivered." Previous research studies had obtained an explosion by setting off a small explosive charge inside a mixture of molten aluminum and water in a Tarset coated water container. Hess & Miller wondered if a purely mechanical [impact] was also able to initiate an explosion under otherwise protected conditions (e.g., use of Tarset). Tarset and Wise Chem E-212-F passed the mechanical impact test while many of the other coatings being evaluated failed because an explosion occurred.

Hess & Miller's study was able to confirm many of the results of previous studies and produced new findings that are still resonant today. Our industry should heed their findings including especially that "explosions occur with stainless steel containers", and "that purely mechanical impact caused explosions in pans coated with Rustoleum 769".

Taleyarkhan & Kim

Rusi Taleyarkhan and Seokho Kim with the Oak Ridge National Laboratory (ORNL), U.S. Department of Energy in the United States worked in conjuncture with another Aluminum Association study in 1997 evaluating protective coatings [4]. The ORNL researchers developed a unique experimental apparatus called the Steam Explosion Triggering Studies (SETS) facility.

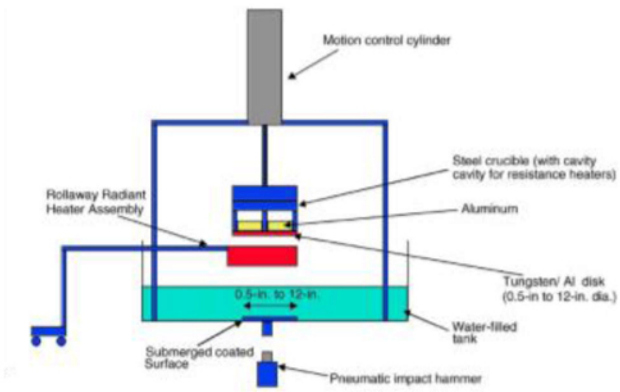

Figure 3 Steam Explosion Triggering Studies (SETS) facility

In this facility, molten aluminum never comes in contact with water in a tank so there is no danger of a steam explosion. However, the facility accurately simulated heat transfer from molten aluminum moving over submerged surfaces using tungsten as a replacement interface material. This technology was able to produce test results quicker than the Aluminum Associations ongoing study that involved molten metal. The SETS facility corroborated Hess & Miller's results that explosions can be generated from stainless steel substrates. Taleyarkhan & Kim reported that molten metal coming into contact with bare stainless steel was "very explosive".

The researchers also tested the amount of gases released upon pyrolyze from the protective coatings upon contact with hot metal. It was found that certain organic coatings that gave off significant non-condensable gases during attack by hot metals also gave assistance in avoiding explosive shocks. Wise Chem E-115 was found to "retain the highest gas generation potential" in the study. Taleyarkhan & Kim's testing proved once again that the maximum area of bare substrate in a protective coating that would generate an explosion was 2" by 2".

Conclusions

Our industry should be commended for acknowledging the hazard of molten metal explosions. Research has been conducted on this hazard for over 65 years. The researchers cited in this publication along with a multitude of others should be acknowledged for their contributions to making our industry safety. It is impossible to calculate the number of injuries and lives saved by our industry incorporating past research findings. It seems unfortunate that some of what was learned from past research studies is no longer followed today. Future explosions could be prevented if our industry incorporated the following into best safety practices:

- Stainless steel substrates can generate explosions
- Rustoleum 769 coated pan exploded during impact testing before the mechanical could be delivered.
- The maximum area of bare substrate exposed in a protective coating is 2" x 2"

References

1. G. Long "Explosions of Molten Aluminum in Water – Cause and Prevention," Metal Progress, 5 (1959), 107-112

2. P. Hess, K. Brondyke "Causes of Molten Aluminum-Water Explosions and Their Prevention," Metal Progress, 4(1969), 76-84

3. P. Hess, R. Miller, W. Wahnsiedler, C. Cochran "Molten Aluminum Water Explosions -1979 for Aluminum Association" (Report No. 28290, Alcoa Technical Center, (1980).

4. R. Taleyarkhan, S. Kim, "Understanding Prevention & Mitigation of Molten Metal-Water Explosions in DC Casting Pits, ORNL/TM-13769, for Oak Ridge National Laboratory, (2000).

5. R. Taleyarkhan, "Vapor Explosion Studies for Nuclear and Non-nuclear Industries," Elsevier B.V., (2005)