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Exh 62

Exhibit #68

An Analysis of the Probable Cause of the August 8, 2000 Explosion at the Hudson Bay Mining and Smelting Co., Limited Reverberatory Furnace in Flin Flon, Manitoba

Prepared by

Dr. John H.S. Lee
and
Hoi Dick Ng

SWACER INC.

Prepared for

Thompson Dorfman Sweatman
Barristers and Solicitors

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3.0 ANALYSIS OF THE AUGUST 8 INCIDENT AT FLIN FLON

Although the indications surrounding the explosion at Flin Flon point to a stratified steam explosion. confirmation of this conclusion requires a number of questions to be answered. Theoretical analyses were carried out to answer these questions.

3.1 Estimate of the optimum ratio of matte to water.

It is important to estimate the amount of molten matte (and water) that is required to result in an explosion such as the one that happened on August 8. The approach used is to first calculate the mass ratio of water to matte that can give rise to an energetic steam explosion. For example, considering 1 kg of liquid matte and a very small amount of water mixed with it, the volume of steam generated would not be significant enough to give rise to an explosion. The equilibrium temperature after mixing is too high and little of the thermal energy of the matte is converted to steam.

Alternatively, if a large amount of water is mixed with the given 1 kg of liquid matte, then no explosion can occur since the equilibrium temperature of the water is now too low and would not even evaporate to form steam. Hence, there exists a range of the mass ratio of water to molten matte in which the resultant formation of superheated steam can be significant enough for an explosive event.

A thermodynamic model was developed to compute first the equilibrium state when "x" kg amount of water is mixed with "y" kg of molten matte to form superheated steam. Computation is made of the subsequent work done by the isentropic expansion of the superheated steam that is formed. On the basis of this isentropic work of the expanding steam; the optimum range of the mass ratio x/y in which an energetic event (steam explosion) can be established. This analysis shows that the mass ratio range of $0.2 \le \frac{x}{y} \le 0.5$ will give rise to a significant work potential of the steam (hence an explosion). Taking the mass ratio of $\frac{x}{y} \cong 0.3$, the maximum work potential is about 180 kJ/kg matte.

In other words, when 0.3 kg of water is mixed with 1 kg of molten matte, the maximum work that can be obtained from the expansion of the superheated steam generated is about 180 kJ/kg matte. For a comparison to the explosive energy from a chemical explosion, 1 kg of TNT releases about 4.2×10^6 joules. Hence, molten matte is thus equivalent to only about 4% of the explosive yield of TNT.

From the nature of the explosive event, we estimated that the amount of steam generated is probably of the order of one volume of the reverberatory furnace (i.e., ~ 608 m^3). If a much larger volume of steam was generated in the August 8th incident, the roof of the furnace would not be intact because the explosive work potential of a larger volume of steam would result in more significant damage to the hanging roof of the reverberatory furnace. For 608 m^3 of steam generated, the corresponding amount of water is about 359 kg.

Thus, assuming the optimum condition of a mass ratio of 0.3, the amount of molten matte required computed from the theoretical model is about 1077 kg. In terms of the volume, the amount of water required is about 0.360 m^3 (or 360 litres) and the corresponding volume of molten matte is about 0.207 m^3 (207 litres) for the explosive event of August 8th.

A mass ratio that is the optimum has been considered. Hence, the amount of water and matte estimated corresponds to the minimum values required

It should be noted that there may have been more water and/or matte present.

3.2 Conditions required to establish a stable stratified condition.

To obtain a stratified configuration of water on top of molten matte, we have to have water accumulated. If the evaporation rate is greater than the rate in which water was introduced into the furnace, then no water could be accumulated to generate the stratified configuration.

To determine the appropriate heat transfer coefficient to use, it must be established whether a steam layer is present. Assuming an averaged surface temperature of about 1000°K (727°C) for the surface of the contents of the furnace, which is much above the Leidenfrost temperature of about 546°K (273°C), a stable steam layer exists. Thus, the film boiling heat transfer coeffcient is applicable when the water is introduced. Taking a typical value for the heat transfer coefficient of 500 watt/m^2 °K, the rate of evaporation is estimated to be about 0.25 kg/sec m^2.

Thus, if a fire hose with an output of about 75 gal/min or (4.72 kg/sec) were to discharge into a cylindrical pool of molten matte of a surface area of about 4m^2 (about 2.25 m diameter), the rate of water accumulation would be about 3.72 kg/sec. Hence, in 2 minutes, a water depth of about 10 cm would be accumulated on top of the pool of about 2.25 metres diameter, sufficient for sustaining a stratified steam explosion. Details of this evaporation analysis are given in Appendix Four.

An estimate of the breakup depth of the water jet from a fire hose when it directly impinges onto the pool of molten matte is of the order of 11 cm. Since the Weber number of the water jet is 3820, we would expect that the jet would fragment into fine droplets. Assuming that all the water from the jet were to be "instantaneously" vapourized, the maximum mass rate of steam generation would correspond to the mass flow rate of water (4.72 kg/sec) giving a volumetric rate of steam generation of about 8 m^3/sec (at 100°C and 1 atm). However, the rate of steam generation in a stratified steam explosion is of the order ~12,160 m^3/sec, about 1000 times higher! Therefore, from a comparison of the rate of steam generation of the two processes, we may conclude that direct impingement of a water jet from one fire hose onto a pool of molten matte would not be of an explosive nature as that of a stratified steam explosion.

3.3 Estimate of crust thickness.

To obtain a stable, stratified configuration for steam explosion, we must have a vapour and/or solid crust layer separating the water from the molten matte. Since it is most likely that a layer of slag is present on top of the molten matte, we must estimate the thickness of the solid crust of slag that is formed for a time of the order of about 3 hours between the time when the burners were turned off and the explosion itself.

Performing the heat transfer and solidification calculations, it is found that a conservative estimate of the solid slag crust is of the order of 12.5 cm thick after a cooling period of 3 hours. This is the theoretical maximum thickness of slag crust that could form. In reality, the crust would be less than this thickness.

Thus, the molten matte would be insulated by up to a 12.5 cm layer of a poor heat conducting slag that allowed the water to accumulate on top of the solid layer of slag to form a stable, stratified configuration.

The trigger event would require a fairly substantial perturbation to fracture a layer of solid slag to bring the water into direct contact with the molten matte. Once fractured, water would be brought into direct contact with the molten matte to generate a local precursory steam explosion. The explosive energy of this precursory event could serve to bring about further destruction of the crust, bringing more water into contact with the molten matte. Thus, the event escalated and eventually led to the main explosion. These precursory explosions are typical of a stratified steam explosion. Witness reports confirmed that a number of "pops" were heard in rapid succession prior to the main event of August 8th.

3.4 Comparison of the ability of slag and matte to fragment.

It would be important to determine if molten slag alone can also participate in a stratified steam explosion. As pointed out steam explosion requires the fragmentation of the hot liquid into fine droplets so that the surface area for heat transfer to vapourize the cold liquid is significantly increased. The typical size of the fragments in a molten metal explosion is of the order of 500 μm.

From experiments, the propagation speed of a stratified explosion is of the order of 50 m/s and, assuming a stratification of 10 cm of water and 5 cm of molten matte (or slag), the intermixing velocity of the two liquids is of the order of 3 m/s. The surface tension of molten matte is typically 20 dynes/cm resulting in a Weber number of about 1170. For such a high Weber number, the molten matte is expected to be able to breakup into the fine droplets required for the rapid heat transfer.

For molten slag, the surface tension is an order of magnitude greater at about 300 dynes/cm. The corresponding Weber number would be of the order of about 45, and fragmentation to fine droplets is not possible. Thus, it may be concluded from this analysis that molten matte is probably involved in the incident and not slag alone.

From the above analyses, it can be confirm that the necessary conditions for a stratified steam explosion were be met under the conditions that existed prior to the explosion of August 8th at the reverberatory furnace at Flin Flon.

4.0 CONCLUSION

From the physical evidence obtained after the explosion, the nature of the injuries to the workers in the immediate vicinity of the reverberatory furnace, and the theoretical analyses carried out, it may be concluded that the most probable cause of the August 8th incident is one of a stratified steam explosion.

It is postulated that a solid crust of slag was formed on top of a pool of molten matte while the "wash down" operation was taking place. The solid crust of slag, possibly in combination with a layer of steam, served as an insulating blanket. This permitted the water from the fire hoses entering into the furnace to accumulate on top of the slag crust.

This eventually formed a stable, stratified configuration of water on top of the molten matte separated by an insulating layer of a solid crust of slag and possibly steam. A significant trigger event fractured the solid crust layer, which permitted the water to come into contact with molten matte and started an initial precursory explosion. This precursory explosion caused further fragmentation of the crust bringing more water into contact with the molten matte. The precursory explosions escalated rapidly and brought about the final major event.

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SWACER Inc.

Prof. J.H.S. LEE