Explosion Risks in a Casthouse

Presented by:
Gus Hornsby
What we will cover!

• General reactivity of molten aluminium
• Things to remember about molten aluminium explosions
• Industry statistics (historical)
• Fundamental properties of molten aluminium
• Some factors that influence explosions
• Explosive reactions
• Protection & reporting
• Key areas of control
• Emergency procedures
• Conclusion
General reactivity of molten aluminium

- Bring together any two liquids at different temperatures

Possible Explosion !!!!!!!!

(The greater the difference in temperature, the greater the probability)

- With aluminium, one additional factor = CHEMICAL REACTIVITY !!!
Things to remember

➤ Casthouse explosions kill, on average, 3 people per year in the aluminium industry

➤ Casthouse explosions are caused by:
  ➤ Steam formation and containment
  ➤ Reactions between molten Al and contaminants
  ➤ Ignition of gases
  ➤ Ignition of certain dust

➤ The force of an explosion is unpredictable, therefore prevention is essential

➤ Rapid initiation: less than 0.5 milliseconds

➤ Mechanical shock can act as a trigger
Aluminum Association Nomenclature & Statistics
## Explosion Category

### Some basic principles

<table>
<thead>
<tr>
<th>Property Damage</th>
<th>FORCE</th>
<th>FORCE</th>
<th>FORCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Min</td>
<td>Flash</td>
<td>Intense</td>
</tr>
<tr>
<td>Sound</td>
<td>Short cracking</td>
<td>Loud report</td>
<td>Painful</td>
</tr>
<tr>
<td>Vibration</td>
<td>Short sharp</td>
<td>Brief rolling</td>
<td>Massive structural</td>
</tr>
<tr>
<td>Metal dispersion radius</td>
<td>5 m</td>
<td>5-15 m</td>
<td>15 m</td>
</tr>
</tbody>
</table>
### Analysis of reported incidents (1980-2003)

<table>
<thead>
<tr>
<th>Operation</th>
<th>Total</th>
<th>Activities</th>
<th>Causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remelting</td>
<td>821</td>
<td>Charging (626)</td>
<td>Moisture</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alloying (77)</td>
<td>Contamination</td>
</tr>
<tr>
<td>Casting</td>
<td>671</td>
<td>Start-up (415)</td>
<td>Bleed outs</td>
</tr>
<tr>
<td>– DC</td>
<td>545</td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Non-DC</td>
<td>126</td>
<td>Foundry, pigs, small form</td>
<td>Moisture in mould</td>
</tr>
<tr>
<td>Transfer</td>
<td>443</td>
<td>Drain pan (181)</td>
<td>Moisture</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trough (137)</td>
<td>Moisture</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crucibles (72)</td>
<td>Moisture</td>
</tr>
</tbody>
</table>
Fundamental properties of Aluminium
Molten Al\textsuperscript{Liq} : Physical & chemical properties

- High chemical reactivity $\rightarrow$ Large Energy release
- High heat of fusion $\rightarrow$ Energy release
- 12% Shrinkage during solidification $\rightarrow$ Cavity formation, clings, burns deeply
- Low viscosity/ high fluidity $\rightarrow$ Leaks, splashes, flows
- Low emissivity $\rightarrow$ No visual detection of overheating
Some factors that can influence explosions (From early explosion work – Hess, Brondyke & others)

◆ Metal orifice stream – no explosions up to approx. 50mm

◆ Quantity of metal not critical (explosions even with little metal)

◆ Distance of metal stream fall is critical
  - explosions at approx. 450mm & 1.2m
  - none at e.g. 3m
Some influencing factors (cont)

◆ Water temp. important
  • although explosions less frequent above 32C, still can occur even above 60C under certain conditions.

◆ Surface coatings
  • lime, rust - promote explosions
  • sludge - promotes explosions
  • Grease, oil - prevents explosions
  • Organic coatings - prevent explosions
Some influencing factors (cont)

- Depth of water pool relative (temperature dependant)

  - Pool approx. 70 to 150mm - explosions at temp. as low as 670C
  - Pool approx. 250mm - no explosions at 670C, but explosions at 750C
  - Pool 25mm or less - no explosions at different temps.
    (Not license to have water lying around,
Explosion definition (sudden release of energy)

- Generation of gas and sudden increase in volume
- Shock wave
  - Speed of propagation > Speed of sound in medium
  - Amplified when passing through explosive substance
Explosion Violence Mechanism

\[ 4\text{Al} + 3\text{O}_2 = 2\text{Al}_2\text{O}_3 + \text{ENERGY} \]

- Al converts much more rapidly if molten, at high temperature and/or finely dispersed !!
- Fully reacting 0.5kg aluminium is equivalent to reacting 1.5kg TNT.
Steam formation

• 1 cm$^3$ (water) = 1700 cm$^3$ of steam
Thermite reaction

Some basic principles

Al (liquid or powder) + Oxygen → \( \text{Al}_2\text{O}_3 \) + Metal + ENERGY

High chemical affinity
### Thermite reaction

Al + Metal Oxide → Al₂O₃ + Metal + ENERGY

<table>
<thead>
<tr>
<th>REACTION</th>
<th>ENERGY (KJ/g)</th>
<th>EQUIVALENCE IN TNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>2Al + 3H₂O → Al₂O₃ + 3H₂</td>
<td>17 (/g H₂O)</td>
<td>4.3 X</td>
</tr>
<tr>
<td>2Al + 3/2 O₂ → Al₂O₃</td>
<td>31 (/g Al)</td>
<td>7.4 X</td>
</tr>
<tr>
<td>2Al + Fe₂O₃ → Al₂O₃ + 2Fe</td>
<td>16 (/g Al)</td>
<td>3.8 X</td>
</tr>
<tr>
<td>6Al + 3NH₄NO₃ → 3Al₂O₃ + 4NH₃ + N₂</td>
<td>25 (/g Al)</td>
<td>6 X</td>
</tr>
</tbody>
</table>
Explosions

Water trapped in molten Al
Explosions – Al\textsubscript{Liq} + water

Water trapped in Al\textsubscript{Liq}

- Steam explosion
- Intensity varies from bubbling to massive explosion
Water trapped in $\text{Al}_{\text{Liq}}$ (cont’d)

- Materials charged in furnace
- Damp tools
- Ingots
- Containers
- Voids
- Condensation Cracks
- Bottles
- Cans
- Pinched-off tubing
- Etc.

Explosions – $\text{Al}_{\text{Liq}} + \text{water}$
Water trapped in $\text{Al}_{\text{Liq}}$ (cont’d)

- Water: liquid $\rightarrow$ Gas
  - $T_{\text{Al}} = 700 \, ^\circ\text{C}$

- Gas pressure build-up

- Steam explosion
  - 1 litre water $\rightarrow$ 4.4 m$^3$ vapour $\rightarrow$ 0.8 kg TNT

- Al - vapour cloud
- Blast / shock wave
Water trapped in $\text{Al}_{\text{Liq}}$: Catastrophic reactions

**Secondary**

$$2 \text{Al}_{\text{Liq}} + 3 \text{H}_2\text{O}_{(g)} \rightarrow \text{Al}_2\text{O}_3 + 3 \text{H}_2$$

(4.3 X TNT)

**Tertiary**

$$3 \text{H}_2 + 3/2 \text{O}_2 \rightarrow 3 \text{H}_2\text{O}$$

(3.2 X TNT)

$$2 \text{Al}_{\text{Dust}} + 3/2 \text{O}_2 \rightarrow \text{Al}_2\text{O}_3$$

(3.2 X TNT)
Explosions

Water trapped by molten Al on a surface
Steam explosion: Entrapment mechanism

Explosions – Water trapped by Al\textsubscript{Liq} on a surface

Water is trapped

Boiling begins

Steam expands
Steam explosion: Entrapment mechanism

- Prevention through design so that water cannot be entrapped
  - Sloped baseplates to let water and metal run into the pit
  - Open grid table / baseplate design to let metal and water pass through

- Bottom blocks can trap molten metal and water, therefore proper design necessary (e.g. drain plugs)!
Explosions – Water trapped by Al\textsubscript{Liq} on a surface

**View of a DC machine after an explosion**
Metal bled through the bottom of the solidified shell due to loss of contact with the bottom block. This metal entrapped water on the surface of the bottom block which resulted in an explosion.
Explosions – Water trapped by $\text{Al}_{\text{Liq}}$ on a surface

Aspect of ingot #2 after the explosion

- Initial melt through on south side
- Hole created by the explosion on the north side
Explosions

Oxidized materials + molten Al
Explosions – $\text{Al}_{\text{Liq}} + \text{oxidized materials}$

$\text{Al}_{\text{Liq}} + \text{oxidized materials}$

- **Rust**
  - $2 \text{Al} + \text{Fe}_2\text{O}_3 \rightarrow \text{Al}_2\text{O}_3 + 2 \text{Fe} + \text{ENERGY}$

- **Residual fertilizers**
  - $6 \text{Al} + 3\text{NH}_4\text{NO}_3 \rightarrow 3\text{Al}_2\text{O}_3 + \text{N}_2 + 4 \text{NH}_3 + \text{ENERGY}$

- **Salt fluxes containing**
  - Nitrates
  - Sulfates
  - Other oxidizing chemicals
Al<sub>Liq</sub> + oxidized materials (cont’d)

- No need for external agent
  - Good contact: Al<sub>Liq</sub>/oxidized material
- Energy release

Heat → VIOLENT EXPLOSION

Flying Al<sub>Liq</sub>

Blast wave
Explosions

Molten Al + hydrocarbons & gases
$\text{Al}_{\text{Liq}} + \text{butane}$

- Butane lighter

Heat + Lighter = ± 3 sticks
Explosions – $\text{Al}_{\text{Liq}} + \text{hydrocarbons } \& \text{gases}$

$\text{Al}_{\text{Liq}} + \text{gases}$

- Accumulation of combustion gases in a furnace
  - The explosion of combustion gases accumulated in the furnaces is eliminated by automatic control systems (air/gas ratio adjustment, pilot flame, purge cycles, etc.)

- Accumulation of hydrogen in a transfer crucible
  - The explosion of hydrogen that has built-up in molten metal transfer crucibles is eliminated by:
    - airtight dome preventing water vapour from entering
    - work procedures – open the hatch and wait 10 minutes before pouring the molten metal
    - Venting valve
Explosions

Metal dusts / Al dust + air + ignition
Metal dust / $A_{\text{Dust}}$

- Certain metals in fine particle form = COMBUSTIBLE
- Mg and Al = Most common combustible metals in casting & remelt
- Scalping & degassing = Some sources of combustible metal in particle form
Dust explosion mechanism

\[ \text{Metal dust/Al} + \text{Air} + \text{Ignition source} \]

- Specific dusts (Al, Mg, coal, flour, etc.)
- Spark, flame, hot surface, etc.

- Heat (+ gas of reaction)

- Pressure increase

- Material damage, injuries
Explosiveness of different dusts

– The occurrence and severity of a dust explosion depends on the following factors:
  » type of dust
  » dust concentration
  » size and shape of dust particles
  » type of ignition
Explosiveness of different dusts (cont’d)

– Dusts are classified according to their explosion index. Explosion index = 1 for Pittsburgh coal

<table>
<thead>
<tr>
<th>Relative explosion risk</th>
<th>Explosion index</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0</td>
</tr>
<tr>
<td>Small</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.1 - 1.0</td>
</tr>
<tr>
<td>Powerful</td>
<td>1.0 - 10.0</td>
</tr>
<tr>
<td>Severe</td>
<td>&gt; 10</td>
</tr>
</tbody>
</table>
Explosiveness of different dusts (cont’d)

<table>
<thead>
<tr>
<th>Material</th>
<th>Explosion Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomized Al</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Magnesium</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.9</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.1</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.1</td>
</tr>
<tr>
<td>Iron</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Zinc</td>
<td>&lt; 0.1</td>
</tr>
</tbody>
</table>

- 200 Mesh (74 microns and under) powder ((some sources claim 420 microns and less !))
Explosions – Metal dust/Al_{Dust} + air

An illustration of the power of the Al_{Dust} + O_2 reaction

Solid fuel = mixture of aluminium powder and ammonium perchlorate.
The white fume = alumina (Al_2O_3)
Explosion and fire caused by ignition of dust
Safety around dross handling

◆ AIN, AIC4, Al in DROSS + Water = Liberate

1. NH3
2. H2
3. CH4

Noxious OR EXPLOSIVE
Protection and Reporting
Two key areas of control

• **Plant & equipment design**
  - minimise risk
  - allow safe operation
  - allow safe shutdown

• **Operations**
  - good equipment condition
  - good operating procedures & practices
  - good housekeeping (incl. dust) & common sense
How to prevent explosions during charging

• Inspect incoming materials for moisture and contaminants (fertilizers, other oxidising materials, radioactive materials etc.)

• Indoor storage is recommended for:
  - Primary ingot & scrap ingots
  - Remelt & fabrication scrap
  - Purchased scrap & alloying materials

• Drying is recommended for (unless charged to a dry hearth):
  - Sows not cast in house
  - Sows cast in house but put outside (or in a cold place)
  - Primary ingot cast elsewhere
  - Mg ingot

• Charge all suspect material to a dry hearth
How to prevent explosions during melting, skimming, sampling & alloying

• Ensure combustion systems operating correctly (avoid accumulation of combustion gases in furnace)

• Temperature controls adequate – avoid overheating metal (spontaneous explosions), avoid overheating dross (skim fires)

• Furnace tools free of rust, coated & dried

• Sampling tools free of rust, coated & dried

• Alloying tools (e.g. steels magnesium alloying cages) free of rust, coated & dried

• Oxidised alloying materials not to be charged (Mg, Cu wire etc. Example of explosion while skimming after alloying Cu wire)

• Wet alloying materials not to be charged.
How to prevent explosions during DC casting

- Dry starting heads / blocks (AA additionally recommends oiling)
- Starting blocks to have ‘minimal’ cracking – establish standards
- Metal delivery system in good condition and preheated
- MLC system calibrated and verified
- Moulds in good condition, good water distribution
- Correct practice for alloy and size
- Equipment centered and gaps not excessive
- Equipment coated with recommended coatings (everything below the moulds)
- Adequate minimum water level in the pit
How to prevent explosions during transfer operations

- Dry, preheat refractories in the launders / troughs
- No leaky joints
- Preheat any repairs
- Preheated (above dew point) drain pans (AA recommends oiling)
- Drains pans with minimal cracking, no rust
- Drain pans clean – no skulls, garbage etc.
- In-line fluxing units with dry and preferably preheated rotors when coated with MgCl$_2$
- Preheated transfer crucibles
Explosion prevention: Casting pit

- Adequate depth of water in the pit to freeze metal before it hits the bottom

- Approved Organic coating on all surfaces:
  - give off noncondensable gases at a temperature below the boiling point of water that blow holes in the molten aluminium thus permitting the rapidly forming steam to escape without causing an explosion.
  - to prevent any contact with rust and molten aluminium
  - to facilitate the spreading of the molten Al over the surface
Explosions – Water trapped by $\text{Al}_{\text{Liq}}$ on a surface

Explosion prevention: DC Pit

Water level in DC Casting pit

Minimum over any spill = 1 m (40 in)
Explosion prevention: DC Pits / Mould Tooling

Approved Coatings

Interturf 132 HS
Multi-Gard 955 CP
WiseChem E-115
WiseChem E-212 F

Rule of thumb: If it is below the mould it should be coated

DO NOT USE UN-TESTED / UN-APPROVED COATINGS!
How to prevent dust explosions

• Area classification to categorise and identify high risk areas – explosive dusts, electrical risks etc.

• Dust prevention strategies (work permits etc.)

• Good regimen for cleaning accumulated dust (managed by good systems to flag when due etc.)

• Proper equipment (dust collection systems) / training to deal with dust fires

• Explicit material purchasing policies e.g. specify minimum ‘dust’ in alloying materials etc.
How to prevent explosions with hot dross

• Dross pans free of rust, coated & preheated. Do not prod dross with rusty steel implements e.g. to mix in cover flux.

• Cool dross if possible (pressing, argon cooling etc.)

• Store, handle & transport dross undercover

• Hot dross never stored outside in open

• Manage & control dust formation
Protection and documentation

• Awareness and vigilance
  – Attitude (Behaviour-based safety)
  – Development & implementation of rules and procedures

• Personal protective equipment - PPE (last line of defense)

• Reporting

Adherence to SOP’s, safety guidelines is CRITICAL
Approved Safety glasses, helmet, face shield, bib, snood etc.

Example of incident where operator avoided serious injury due to a molten metal splash on face shield & safety glasses
Protection and documentation

Flame-retardant clothing (inherent flame retardant – not treated) with minimum D2 rating (D3 preferred)
# Molten metal incident report

**ALUMINUM ASSOCIATION**  
**MOLTEN METAL INCIDENT REPORT**

Date of Incident: ____________________________ Type of Plant: ____________________________
(Reduction, Recycling, Rolling, Extrusion, etc.)

Explosion Characterization* (see explanation below): Force 1 ___________ Force 2 ___________ Force 3 ___________

## OPERATION

<table>
<thead>
<tr>
<th>Charging/Melting</th>
<th>Type of Furnace</th>
<th>(Reverb, Topcharging, Induction, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Furnace capacity       | ___________ lbs          | % Full ___________                      | Alloy ____________________ |
|------------------------|--------------------------|----------------------------------------|

| Metal Temperature      | ___________ °F           | Approximate amount of metal involved   | ___________ lbs            |
|------------------------|--------------------------|----------------------------------------|

<table>
<thead>
<tr>
<th>Materials Charged</th>
<th>_________________________</th>
<th></th>
</tr>
</thead>
</table>

Outside storage? Yes _____ No _____  
Preheat? Yes _____ No _____  
Preheat time & temp: _____ hrs _____ °F
Emergency procedures

• Emergency shower ??
• Fire emergency plan ??
• Medical emergency plan ??
• Environmental emergency plan ??
• Trained in operation & location of
  - Hydraulic & water shut-off
  - Gas shut-off (chlorine, LPG, argon, nitrogen)
  - Electric breaker
Conclusion !!!

- Accidents can happen if we do not take all necessary precautions!
  1. Aim to prevent incidents / accidents
  2. Maintain best housekeeping standards
  3. Maintain equipment in best condition, particularly equipment that controls hazardous conditions
  4. Contain incidents if safe to do so to minimize damage
  5. Always follow S.O.P’s
  6. Last line of defence => wear correct FR PPE
Any questions / comments?

- Have a safe day
- Gus Hornsby
  - (Sincere acknowledgement to all material resources)