RECYCLING SPENT RESIDUE UPGRADE CATALYST
ENABLING A GREENER FUTURE

THOMAS CENTA

Recycling Metals Conference 2019
Indianapolis, IN

AMG VANADIUM LLC
June 2019
AMG IS A CRITICAL MATERIALS COMPANY

GLOBAL TRENDS
CO₂ emission reduction, population growth, increasing affluence, and energy efficiency

SUPPLY
AMG sources, processes, and supplies the critical materials that the market demands

DEMAND
Innovative new products that are lighter, stronger, and resistant to higher temperatures
AMG: MITIGATING TECHNOLOGIES

Products and processes saving raw materials, energy and CO₂ emissions during manufacturing (e.g., recycling of Ferrovanadium)

AMG: ENABLING TECHNOLOGIES

Products and processes saving CO₂ emissions during use (e.g., light-weighting and fuel efficiency in the aerospace and automotive industries)

LEADER IN ADVANCED TECHNOLOGIES TO ADDRESS CO₂ REDUCTION

CO₂ REDUCTION

A GLOBAL IMPERATIVE FOR THE 21ST CENTURY
AMG AT A GLANCE

AMG IS A GLOBAL SUPPLIER OF CRITICAL MATERIALS TO:

- ENERGY
- TRANSPORTATION
- INFRASTRUCTURE
- SPECIALTY METALS AND CHEMICALS

FY 2018 REVENUE

BY SEGMENT:
- 67% Critical Materials
- 33% Technologies

BY END MARKET:
- 40% Transportation
- 21% Specialty Metals & Chemicals
- 30% Infrastructure
- 9% Energy

BY REGION:
- 42% Europe
- 37% North America
- 16% Asia
- 5% ROW

Market leading producer of highly engineered specialty metals and vacuum furnace systems

~3,300 Employees

~$1 billion Annual Revenues

At the forefront of CO₂ Reduction
AMG BUSINESS SEGMENTS

AMG CRITICAL MATERIALS

- AMG’s conversion, mining, and recycling businesses
  - Vanadium
    - Spent Catalyst Recycling
  - Superalloys (Chrome)
  - Aluminum Master Alloys
  - Brazil (Tantalum & Lithium)
  - Antimony
  - Graphite
  - Silicon Metal

AMG TECHNOLOGIES

- AMG’s titanium alloys, vacuum systems and services business
  - Titanium Alloys & Coatings
  - Furnaces
  - Heat treatment services

- Infrastructure: 36%
- Speciality Metals & Chemicals: 22%
- Transportation: 32%
- Energy: 10%
- Infrastructure: 15%
- Speciality Metals & Chemicals: 70%
- Transportation: 4%
- Energy: 11%
- Infrastructure: 4%
- Speciality Metals & Chemicals: 15%
- Transportation: 70%
- Energy: 11%
The EU identified 27 critical raw materials* to the European economy in 2017, focusing on two determinants: economic importance and supply risk.

The US identified 35 critical materials* which are vital to national security and the economy, primarily through assessing supply risk.

AMG has a unique critical materials portfolio comprising:
- 7 EU critical raw materials
- 10 US critical raw materials

* 2017 list of Critical Raw Materials for the EU, September 2017; US draft list of Critical Materials per February 16, 2018 announcement by U.S. Department of the Interior. ** Chromium Metal (a subcategory of chrome ore) is not identified by the EU report. *** AMG possesses technology license patent for production of Magnesium products.
AMG VANADIUM’S VISION AND MISSION

VISION

AMG Vanadium is committed to being the leading hazardous waste processor in the world converting this waste into valuable products.

MISSION

To acquire Vanadium (V), Nickel (Ni) and Molybdenum (Mo) bearing waste materials and convert them, in an environmentally beneficial manner, into valuable goods for the benefit of our stakeholders.

Spent Catalyst  
Ferrovanadium  
Ferronickel-molybdenum  
HSLA Steel  
Stainless Steel
INDUSTRY-LEADING ENVIRONMENTAL SOLUTION

- **Recycled Raw Materials**
  - Utilize vanadium-bearing secondary materials and hazardous wastes
  - 100% secondary aluminum
- **Industry-Leading Process**
  - No waste water
  - Lowest overall emissions (solid waste, air emissions, waste water) in the industry
  - Highest industry conversion: 99% of solids produced are saleable material, only 1% are landfilled
- **FeV is an Energy Efficient Microalloy**
  - Vanadium alloy steels reduce steel requirements by 20-40% thereby drastically reducing CO₂ emissions in construction and infrastructure projects worldwide
- **Refineries view AMG as the premier spent catalyst recycling facility in the world**

AMG’s process is the gold standard in spent catalyst recycling
Vanadium is a chemical element with symbol V and atomic number 23.

Vanadium occurs naturally in about 65 minerals and in fossil fuel.

It is produced in China and Russia from steel smelter slag, in South Africa and Brazil from magnetite directly, and other countries from the recycling of spent catalyst and ashes resulting from the refining, gasification or burning of heavy oil.

Vanadium was discovered in 1801.

The first large-scale industrial use of vanadium was in the steel alloy chassis of the Ford Model T.
FERROVANADIUM PRODUCTION PROCESSES

Primary Route
Ore → Mineral Processing → V2O5 → FeV → Chemical → Ti Master Alloys

Co-Product Route (Steel Producers)
Ore → Steel Production → Slag → FeV → V2O5

Secondary Route
Oil → Spent Refinery Catalyst → Processor → V2O5 → FeV (Powder) → Chemicals → Ti Master Alloys
Oil → Power Plant Slags/Flyashes → FeV

Primary 16%
Co-Product 67%
Secondary 17%

Red = Current AMG V Processing Route
WHAT IS SPENT CATALYST?

Distillation of Crude Oil

Residual Upgrading

Catalyst removes metals and sulfur from crude oil during refining process

AMG Vanadium then recovers these metals from the spent catalyst

Metals include Vanadium (V), Nickel (Ni), Molybdenum (Mo) and Aluminum Oxide (Al₂O₃)

Nickel and molybdenum are contained in the fresh catalyst; all vanadium and part of nickel come from the oil

**Fresh Catalyst Composition**

<table>
<thead>
<tr>
<th></th>
<th>Aluminum Oxide</th>
<th>Vanadium</th>
<th>Nickel</th>
<th>Molybdenum</th>
<th>Sulfur</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80-90%</td>
<td>0-0.3%</td>
<td>1-10%</td>
<td>1-10%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

**Spent Catalyst Composition**

<table>
<thead>
<tr>
<th></th>
<th>Aluminum Oxide</th>
<th>Vanadium</th>
<th>Nickel</th>
<th>Molybdenum</th>
<th>Sulfur</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30-40%</td>
<td>8-15%</td>
<td>3-5%</td>
<td>1.5-3%</td>
<td>5-12%</td>
<td>20-30%</td>
</tr>
</tbody>
</table>

Source: AMG-Vanadium Management
# AMG VANADIUM’S PRODUCTS

<table>
<thead>
<tr>
<th>PRODUCTS &gt;</th>
<th>VALUE PROPOSITION &gt;</th>
<th>APPLICATIONS &gt;</th>
</tr>
</thead>
</table>
| Ferovan® (Ferrovanadium) | • High strength low alloy (HSLA) steel used for construction, shipbuilding, pipeline, bridges, energy, automotive, etc.  
• Rail steels, tool and die steels  
• Rebar | ![Image](image1.jpg) |
| FeNiMoly® (Ferronickel-molybdenum) | Alloy addition for stainless steel and NiMo low-alloy steels | ![Image](image2.jpg) |
| Revan™ (Calcium Aluminate) | Slag-conditioner for the steel industry | ![Image](image3.jpg) |
| LimeAdd™ (Calcium Sulfate) | Solidification and stabilization | ![Image](image4.jpg) |
| Future Product High Purity V₂O₅ (Vanadium Pentoxide) | Vanadium redox flow batteries (VRFBs) require vanadium electrolyte to store energy and enable sustained use of renewable power sources | ![Image](image5.jpg) |
RAW MATERIAL STORAGE BUILDING (OIL CONTAINMENT)

KEY FEATURES

- 78,000 square feet
- Segregated inventory bins
- Multi-layer subfloor liner system to capture free-flowing liquids

Felt Liner Protection

Concrete Slab – 8”

Gravel – 8”

Concrete Base – 36”

Upper Liner

Drainage Net

Lower Liner

Multi-layer subfloor liner system cutaway

Exterior View

Rebar Installation

Spent Catalyst Storage
SPENT CATALYST MUST BE PROPERLY MANAGED

• The Goal: safe, environmentally sound recycling of spent catalyst

• Spent catalyst has unique properties that must be taken into account by the generator to ensure management – recycling – reclamation is performed in a way that is protective of the environment.

• K171/172 Listed Hazardous Waste in the U.S.

• High sulfide content
  • Self-heating
  • Pyrophoric
  • Reactive

• High polynuclear aromatic hydrocarbon (PAH)

• High oil content

• High metals content
### SPENT CATALYST LEACHABILITY

#### Roasted vs As Received Spent Catalyst (start)

- **Roasted Catalyst**
- **Raw Catalyst**

#### Roasted vs As Received Spent Catalyst (72 hours)

---

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Water Analysis</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roasted Catalyst</td>
<td>Raw Catalyst</td>
<td>Tap Water</td>
</tr>
<tr>
<td>Sulfur</td>
<td>814</td>
<td>44</td>
<td>32.1</td>
</tr>
<tr>
<td>Nickel</td>
<td>600</td>
<td>0</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>475</td>
<td>0</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Sodium</td>
<td>268</td>
<td>121</td>
<td>123</td>
</tr>
<tr>
<td>Calcium</td>
<td>260</td>
<td>51</td>
<td>29.4</td>
</tr>
<tr>
<td>Vanadium</td>
<td>69</td>
<td>1</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Aluminum</td>
<td>29</td>
<td>0</td>
<td>0.046</td>
</tr>
<tr>
<td>Magnesium</td>
<td>15</td>
<td>14</td>
<td>10.6</td>
</tr>
</tbody>
</table>
OPTIONS AVAILABLE TO REFINERIES IN NORTH AMERICA TODAY

Environmental Considerations
- Environmentally beneficial
- Mitigates refinery's risk

- Leachable
- Pyrophoric
- Creates ongoing refinery liability and risk

Oil Refinery Spent Residue Upgrading Catalyst

- Full Metals Reclamation
- AMG Vanadium LLC

Thermal Desorption/ Hydrocarbon Stripping

- Export to Asia

- Leachable
- Pyrophoric
- Creates ongoing refinery liability and risk

Landfill (US)

Landfill (Canada)
| **BEST IN CLASS SPENT CATALYST TREATMENT** |
|-----------------|-----------------|-----------------|-----------------|
| **Raw Material Storage** | **Totally enclosed building and conveyors built to RCRA standards** | **Outside in totes or roll-off boxes** | **Outside in steel tank or railcar** |
| **Oil Containment** | **Dual liner system under entire floor for oil containment** | **No identified secondary containment.** | **Tray under outdoor silo. Poor secondary containment.** |
| **Elimination of Pyrophoric Status** | **Conversion of metal sulphides to oxides eliminates pyrophoric nature** | **Sulphur is not removed in this process. Significant pyrophoric risk exists.** | **Sulphur is not removed in this process. Significant pyrophoric risk exists.** |
| **SO₂ Control** | **Flue Gas Desulphurization unit with over 96% control** | **Desulphurization occurs in future processing with unknown controls. Some SO₂ generation likely occurs due to uncontrolled self heating.** | **Desulphurization occurs in future processing with unknown controls. Some SO₂ generation likely occurs due to uncontrolled self heating.** |
| **Control of Leachability** | **Roasted catalyst is stored indoors prior to conversion to ferroalloys** | **Desorbed catalyst is stored in supersacks. Fire risk exists.** | **Stripped catalyst is stored in supersacks. Fire risk exists.** |
| **Metals Reclamation** | **Full recovery of vanadium, nickel, and molybdenum. Alumina recovery as well** | **None. Material must still be roasted (convert sulphides to oxides) before metals reclamation.** | **None. Material must still be roasted (convert sulphides to oxides) before metals reclamation.** |
| **Final Product Destination** | **Metals sold to steel mills as alloys. Alumina sold as slag refiner.** | **Desorbed catalyst shipped to reclaimers in Asia for desulphurization and metals reclamation** | **Desorbed catalyst shipped to reclaimers in Asia for desulphurization and metals reclamation** |
In 1987, the UN Brundtland Commission defined sustainable development as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." (Report of the World Commission on Environment and Development.)

In 1987, sustainability might have been seen as a nice thing to do

In 2019, sustainability is seen as a must-do
CLIMATE CHANGE

Two numbers to remember:

3 – the middle class is expected to grow by 3.3 billion people (from 2 billion to over 5 billion) by 2030

2 – The predicted average global temperature increase by 2030 is two degrees Celsius (2°C)

The need to act is urgent!

US EPA regulations promulgated under the Resource Conservation Act (RCRA) on August 6, 1998 (63 FR 42110) listed as hazardous wastes:

- spent hydrotreating catalysts (K171); and
- spent hydrorefining catalysts (K172)
CARBON FOOTPRINT OF FERROVANADIUM

Estimated CO₂ Emission by Process

Primary Mining
63.4 kg CO₂ eq per kg FeV

AMG Process
12.6 kg CO₂ eq per kg FeV

FeV represents AMG’s average ferrovanadium chemistry of 57.8%

Source: Environmental Resource Management (ERM) AMG Ferovan® Carbon Footprint Interim Report dated October 1, 2018
Ferrovanadium is produced from oil refinery wastes with no mining or raw material beneficiation required.

**Base Technology**
- Primary Mining and Processing
  - Kgs CO₂/kg FeV: 63.4 kg

**Enhanced Technology**
- Spent Refinery Catalyst Recycling
  - Kgs CO₂/kg FeV: 12.6 kg

AMG production mitigates about **239,000 MT** of CO₂ emissions per year.

PYROMETALLURGICAL RECYCLING
Ferrovanadium is produced from oil refinery wastes with no mining or raw material beneficiation required.
ENABLING CO₂ REDUCTION – FERROVANADIUM IN HSLA STEEL

Ferrovanadium can be added to structural steel to reduce the quantity of steel required to perform the same function.

- A steel alloy containing vanadium results in a 20 - 40% reduction in mass.
- CO₂ is reduced through the value chain with lighter weight steel, enabling more efficient transportation and fabrication.

**Table: CO₂ Emissions Comparison**

<table>
<thead>
<tr>
<th>Material</th>
<th>CO₂/kg steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>2.00 kg</td>
</tr>
<tr>
<td>Enhanced Technology</td>
<td>1.50 kg</td>
</tr>
</tbody>
</table>

HSLA Steel using AMG vanadium enables the saving of more than 3.1 million metric tons of CO₂ per year.

Source: Environmental Resource Management (ERM) AMG Ferovan Carbon Footprint Interim Report dated October 1, 2018
AMG: MITIGATING TECHNOLOGIES
Products and processes saving raw materials, energy and CO₂ emissions during manufacturing (e.g., recycling of Ferrovanadium)

AMG: ENABLING TECHNOLOGIES
Products and processes saving CO₂ emissions during use (e.g., light-weighting and fuel efficiency in the aerospace and automotive industries)

AMG has developed into a leader in enabling technologies
THANK YOU

for your time and attention

to Heritage for hosting and inviting us

Thomas Centa
Executive Vice President
AMG Vanadium LLC
60790 Southgate Road
Cambridge, OH 43725 USA
Tel +1 740 435 4656  |  Cell 740 630 4492
tcenta@amg-v.com
www.amg-v.com