MONTANA TECHNOLOGICAL UNIVERSITY

Pyrometallurgy and Thermal Processing

COURSE LEVEL OBJECTIVES

- **CO1** – Calculate mass balances and process heat requirements for industrial applications
- **CO2** – Apply metallurgical thermodynamics and process fundamentals to solve complex thermal processing problems and evaluate process equipment

COURSE MODULES

- **M1** – Material Balances and Thermodynamics Review
- **M2** – Metallurgical Diagrams
- **M3** – Combustion
- **M4** – Drying and Calcining
- **M5** – Roasting
- **M6** – Vapor Metallurgy
- **M7** – Slags and Refractories
- **M8** – Smelting
- **M9** – Converting
- **M10** – Molten Salt, Halide Metallurgy, and Metallothermic Processes
- **M11** – Refining
- **M12** – Safety and Environmental Considerations
- **M13** – Processing Schemes/Case Studies

MODULE 1: Material Balances and Thermodynamics Review OBJECTIVES

- **MO1** – Setup and calculate a mass, or mole, balance for a system.
- **MO2** – Determine enthalpy, entropy, and free energy values for a given system to demonstrate the basics of chemistry and chemical thermodynamics used in pyrometallurgy and thermal processing.
- **MO3** – Calculate the heat of reaction/process heat requirement for a system.

MODULE 1 ACTIVITIES and ASSESSMENTS	
ACTIVITIES	**ASSESSMENTS**
• Learning Activity 1 – Lecture material/learning content on process fundamentals and mass balances • Video Example – Solving a mass balance problem • Learning Activity 2 – Lecture material/learning content on the basics of chemical thermodynamics in pyrometallurgy • Video Examples – Solving enthalpy increment problem using Kubaschweski, entropy increments • Learning Activity 3 – Lecture material/learning content on solving heats of reaction and determining process heat requirements • Video Example – Solving a heat of reaction problem, calculating ΔG • Resources: ΔH, ΔS, C_p data tables (Kubaschewski)	• Homework Assignments: 1-3 • Quizzes: 1-3 • Discussion Question (participation) • Learning Activity Questions (participation)

MODULE 2: Metallurgical Diagrams OBJECTIVES
• **MO1** – Interpret and construct predominance area diagrams to evaluate stable phases and processing conditions • **MO2** – Interpret Ellingham diagrams to determine Gibbs free energy values, process feasibility, and gas phase partial pressure ratios • **MO3** – Evaluate binary phase diagrams by applying principles of thermodynamics

MODULE 2 ACTIVITIES and ASSESSMENTS	
ACTIVITIES	**ASSESSMENTS**
• Learning Activity 4 – Lecture material on constructing/using predominance area diagrams • Video Example – Determining boundary line equations • Learning Activity 5 – Lecture material on utilizing/interpreting Ellingham diagrams	• Homework Assignments: 4-6 • Quizzes: 4-6 • Discussion Question (participation) • Learning Activity Questions (participation)

• Video Example – Determining ΔG, PO_2, CO/CO_2 ratios (ELMO) • Learning Activity 6 – Lecture material on utilizing/interpreting phase diagrams • Video Example – Lever law (ELMO) • Resource: PDF of Ellingham diagrams (oxide + sulfide) • Resource: PDF of binary phase diagrams (Slag Atlas?)	

MODULE 3: Combustion **OBJECTIVES**
• **MO1** – Conduct mass and energy balances for the combustion of a given fuel source, accounting for all constituents. • **MO2** – Determine heating values for a given fuel source.

MODULE 3 ACTIVITIES and ASSESSMENTS	
ACTIVITIES	**ASSESSMENTS**
• Learning Activity 7 – Lecture material on fuel types, heating values, and proximate/ultimate analyses • Learning Activity 8 - Lecture material on solving combustion problems and determining adiabatic/theoretical flame temperatures • Video Example – Solving a combustion problem • Resources – eia.gov/coal/annual and/or usgs.gov (coal resource and reserves assessment)	• Homework Assignments: 7, 8 • Quiz: 7 • Discussion Question (participation) • Learning Activity Questions (participation)

MODULE 4: Drying and Calcining **OBJECTIVES**
• **MO1** – Outline process considerations for drying and calcination operations; describe process terminology, equipment, and thermodynamic/kinetic considerations. • **MO2** – Prepare van't Hoff plots for decomposition temperature determination.

MODULE 4 ACTIVITIES and ASSESSMENTS

ACTIVITIES	ASSESSMENTS
• Learning Activity 9 – Lecture material on process equipment: rotary kilns • Learning Activity 10 – Lecture material on drying processes • Learning Activity 11 – Lecture material on calcination processes, with a focus on limestone calcination • Supplemental: Material and Process Factors for Dryer Selection (pdf)	• Homework Assignments: 9, 10 • Quiz: 8 • Discussion Question (participation) • Learning Activity Questions (participation) • Exam # 1 (covering material from Modules 1-4)

MODULE 5: Roasting OBJECTIVES
• **MO1** – Distinguish between the different types of roasting operations, as well as evaluate process methodologies. • **MO3** – Describe the process considerations for fluidized-bed reactors and calculate design parameters for a fluidized-bed.

MODULE 5 ACTIVITIES and ASSESSMENTS	
ACTIVITIES	**ASSESSMENTS**
• Learning Activity 12 – Lecture material on roasting processes • Learning Activity 13 – Lecture material on fluidized bed reactors • Supplemental: Introduction to Fluidization (pdf)	• Homework Assignments: • Quiz: • Discussion Question (participation) • Learning Activity Questions (participation)

MODULE 6: Vapor Metallurgy OBJECTIVES
• **MO1** – Explain the phenomenon of vapor metallurgy, and outline process considerations for processing volatile metal species, such as zinc • **MO2** – Determine metal vapor pressures through calculations or analyzing vapor pressure diagrams

MODULE 6 ACTIVITIES and ASSESSMENTS	
ACTIVITIES	**ASSESSMENTS**
• Learning Activity – Lecture material on vapor chemistry/ thermodynamics	• Homework Assignments: • Quiz: • Discussion Question (participation)

• Learning Activity – Lecture material on volatile metal processes	• Learning Activity Questions (participation)

MODULE 7: Slags and Refractories OBJECTIVES
• **MO1** – Identify slag types, describe the purpose of slags in smelting operations, and explain how their properties influence their function. • **MO2** – Describe the types of refractories and evaluate their properties for selection in thermal processing.

MODULE 7 ACTIVITIES and ASSESSMENTS	
ACTIVITIES	**ASSESSMENTS**
• Learning Activity – Lecture material on ternary phase diagrams • Learning Activity – Lecture material on slags • Learning Activity – Lecture material on refractories • Resources: PDF of ternary phase diagrams	• Homework Assignments: • Quiz: • Discussion Question (participation) • Learning Activity Questions (participation)

MODULE 8: Smelting OBJECTIVES
• **MO1** – Identify different types of smelting furnaces • **MO2** – Establish process considerations for flash smelting, and explain the benefits compared to other smelting furnaces • **MO3** – Calculate process variables for a given system using fundamental mass and energy balance (thermodynamic) principles

MODULE 8 ACTIVITIES and ASSESSMENTS	
ACTIVITIES	**ASSESSMENTS**
• Learning Activity – Lecture material on smelting • Learning Activity – Lecture material on flash smelters	• Homework Assignments: • Quiz: • Discussion Question (participation) • Learning Activity Questions (participation) • Exam #2 (covering material from Modules 5-8)

MODULE 9: Converting OBJECTIVES
• **MO1** – Identify and outline process considerations for different types of converters, such as Peirce-Smith and top blown rotary converters. • **MO2**– Evaluate the thermodynamics of converting, and explain the benefits of each type of converter

MODULE 9 ACTIVITIES and ASSESSMENTS	
ACTIVITIES	**ASSESSMENTS**
• Learning Activity – Lecture material on converting fundamentals • Learning Activity – Lecture material on process considerations for Peirce-Smith, top blown, and flash converters	• Homework Assignments: • Quiz: • Discussion Question (participation) • Learning Activity Questions (participation)

MODULE 10: Molten Salt, Halide Metallurgy, and Metallothermic Processes OBJECTIVES
• **MO1** – Summarize the principles of molten salt pyrometallurgical processes; evaluate the Hall-Héroult process for aluminum production and detail key thermodynamic and process considerations. • **MO2 –** Evaluate halide metallurgy processes, specifically the Kroll process for titanium production, detailing key processing steps. • **MO3** – Determine metals amenable to metallothermic processes (i.e. those that have reductive capabilities).

MODULE 10 ACTIVITIES and ASSESSMENTS	
ACTIVITIES	**ASSESSMENTS**
• Learning Activity – Lecture material on molten salt processes: highlighting the Hall-Héroult process • Learning Activity – Lecture material on halide metallurgy: highlighting the Kroll process • Learning Activity – Lecture material on metallothermic processes	• Homework Assignments: • Quiz: • Discussion Question (participation) • Learning Activity Questions (participation)

MODULE 11: Refining OBJECTIVES

- **MO1** – Assess refining operations based on the presence of impurities and the system under consideration (metal-slag, metal-metal, or metal-gas)
- **MO2** – Analyze a metal-slag system to evaluate whether the results of fire-refining would be favorable to remove an undesirable constituent
- **MO3** – Outline process considerations for zone refining and vacuum refining; determine whether a system is amenable to these types of refining operations

MODULE 11 ACTIVITIES and ASSESSMENTS	
ACTIVITIES	**ASSESSMENTS**
• Learning Activity – Lecture material on refining operations/purpose • Learning Activity – Lecture material on fire, zone, and vacuum refining processes	• Homework Assignments: • Quiz: • Discussion Question (participation) • Learning Activity Questions (participation)

MODULE 12: Safety and Environmental Considerations
OBJECTIVES

- **MO1** – Establish safety objectives for pyrometallurgical and thermal processing operations
- **MO2** – Assess operating parameters, with environmental considerations in mind. (Example: combustion/burner parameters – NOx)
- **MO3** – Evaluate methods of dust collection and gas cleaning
- **MO4** – Assess methods of heat recovery

MODULE 12 ACTIVITIES and ASSESSMENTS	
ACTIVITIES	**ASSESSMENTS**
• Learning Activity – Lecture material on environmental considerations during metallurgical processes and operations • Learning Activity – Lecture material on safety in metallurgical operations • Resources: EPA – NOx, etc.	• Homework Assignments: • Quiz: • Discussion Question (participation) • Learning Activity Questions (participation) • Exam # 3 (covering material from Modules 9-12)

MODULE 13: Processing Schemes and Case Studies
OBJECTIVES

- **MO1** – Perform mass and energy balances for an extractive metallurgy operation (roasting, smelting, converting, etc.), explain key processing variables, and describe process equipment. Prepare a final report detailing the extractive processes.

MODULE 13 ACTIVITIES and ASSESSMENTS	
ACTIVITIES	**ASSESSMENTS**
• Learning Activity – Lecture material on select case studies/processes	• Final Project