

PROGRAM CRITERIA

The BS in Metallurgical program satisfies the program criterion for Metallurgical Engineering as described in Criterion 5 and described here in greater detail.

A. Curriculum

The curriculum requires students to have completed basic courses in chemistry and physics and engineering principles before they embark on upper division required metallurgical engineering courses. For example, students must complete one half of their required eight credit hours of college level chemistry (CHEM 112, 112L, 114, 114L) and six credits of college level physics (PHYS 211, 213) before enrolling in the junior-level Metallurgical Thermodynamics course (MET 320). They are also required to complete Statics (EM 214) and either Mechanics of Materials (EM 321) or Introduction to Solid Mechanics (ME 216) before enrolling in Mechanical Metallurgy (MET 440). MET 422 (Transport Phenomena in Metallurgical Engineering) and MET 433 (Process Control) both require completion of the two college-level Calculus I and Calculus II (MATH 123 and MATH 125) and Differential Equations (MATH 321). The advanced chemistry, physics, and engineering principles derived from these courses are applied to the production, shaping, forming, treating, and performance of metals. Every capstone senior design projects involve only the production or processing of metals.

The four major elements of the field are the focus of the curriculum. The development of these criteria originated in the early 1990's from efforts led by Dr. Gerald Liedl serving as chair of the TMS Accreditation and Education and Professional Affairs committees. TMS is the lead society for Materials and Metallurgical Engineering. The difficulty of describing an educational criteria for both the extractive and physical branches of metallurgical engineering was resolved by applying the seemingly physical metallurgical terms of structure, properties, processing and performance to extractive processes as well. As Dr. Liedl described it, "an iron blast furnace has both *structural* and *properties* critical to its *processing* and *performance* that every extractive metallurgical engineer should know." The same applies to every chemical process employed by extractive metallurgists from the mineral processor, to chemical metallurgist as well as to physical metallurgists for which the terms are familiar. Each metallurgical engineer relies on these four elements of the field to solve materials selection and design problems.

Table 9-1 shows a quality deployment matrix for how each required and elective MET engineering course. The importance of each course in satisfying the metallurgical engineering criteria is indicated with a rating of 9 if it is highly important; a 3 if it is moderately important; and 1 if it is of low importance. The specific curricular details for each course are available in the course syllabi, but the *highly important* items (score of 9) are summarized for convenience below for each of the four elements: structure, properties, processing, and performance.

Table 9-1 Quality Function Deployment Matrix for meeting the program criteria

| Course | Description | Structure | Properties | Processing | Performance |
|------------------|-------------------------------|-----------|------------|------------|-------------|
| Required | | | | | |
| MET 220 | Min Proc & Resource Rec | 9 | 3 | 9 | 1 |
| MET 220L | Min Proc & Resource Rec Lab | 1 | 3 | 9 | 3 |
| MET 231 | Structures & Prop of Mat Lab | 3 | 9 | 3 | 9 |
| MET 232 | Prop of Materials | 9 | 9 | 3 | 1 |
| MET 310 | Aqueous Extract/Conc/Rec | 3 | 3 | 9 | 9 |
| MET 310L | Aq. Extract/Conc/Rec Lab | 1 | 3 | 9 | 9 |
| MET 320 | Metallurgical Thermodynamics | 1 | 9 | 3 | 1 |
| MET 321 | High Temp Extract/Conc/Rec | 9 | 3 | 9 | 3 |
| MET 330 | Physics of Metals | 9 | 3 | 9 | 3 |
| MET 330L | Physics of Metals Lab | 9 | 9 | 3 | 3 |
| MET 332 | Thermomechanical Processing. | 3 | 3 | 9 | 9 |
| MET 422 | Transport Phenomena | 1 | 3 | 9 | 9 |
| MET 433 | Process Control | 3 | 3 | 3 | 9 |
| MET 440 | Mechanical Metallurgy | 9 | 9 | 9 | 9 |
| MET 440L | Mechanical Metallurgy Lab | 3 | 9 | 3 | 9 |
| MET 351 | Engineering Design I | 1 | 9 | 3 | 9 |
| MET 352 | Engineering Design II | 1 | 9 | 3 | 9 |
| MET 464 | Engineering Design III | 1 | 9 | 3 | 9 |
| MET 465 | Engineering Design IV | 1 | 9 | 3 | 9 |
| | | 75 | 111 | 111 | 123 |
| Electives | | | | | |
| MET 426 | Steelmaking | 9 | 3 | 9 | 3 |
| MET 430 | Weld Eng & Design, Structures | 3 | 9 | 9 | 3 |
| MET 443 | Composite Materials* | 9 | 9 | 3 | 3 |
| MET 450 | Forensic Engineering | 9 | 3 | 9 | 3 |
| MET 445 | Oxidation and Corr. of Metals | 1 | 9 | 3 | 9 |
| MET 491 | Security Printing Technology | 3 | 9 | 3 | 3 |
| | | 26 | 34 | 34 | 30 |

* Replaced after 2010 by the 2 credit hour Advances in Processing and Nanoengineering of Polymers (MES 475) and the one credit hour Composites Manufacturing MET 489)

Structure

The fundamental scientific and engineering principles associated with the microstructure of metallurgical elements and alloys are taught the following requires undergraduate lecture and laboratory courses.

Required

- MET 220 (Mineral Processing)
Students examine the crystallography and stoichiometry related to minerals used for metal content and/or industrial mineral value. Students also examine how mineral crystallography influences comminution behavior.
- MET 232 (Properties of Materials)
Students examine microstructure and bonding and its relationship to polymer, ceramic, and metal properties.
- MET 321 (High Temperature Extractive, Concentration, and Recycling)
Students learn the structure of a number of selected metal production process equipment such as the iron blast furnace and how such structures work to produce metals from 1) metal-based compounds and 2) the recycling of materials.
- MET 330 (Physics of Metals)
Students study in detail the crystal structure of metals. Students also study important defect structure that influence behavior of metals including grain structure, solidification structure, and dislocation structure.
- MET 330L (Physics of Metals Laboratory)
Students make extensive use of metallography to examine the physical structure of metals including grain structure, phase structure, and precipitate structure.
- MET 440 (Mechanical Metallurgy)
Students learn the influence of metal structure (e.g. crystal structure, dislocations, grain boundaries, precipitates) on elastic deformation, plastic deformation, and fracture

Electives

- MET 426 (Steelmaking)
This course covers the unit operations in integrated steel mills, mini-mills, and direct reduction processes. The structure of these unit operations provides the basis for the thermochemical and thermomechanical process analysis.
- MET 443 (Composite Materials)[†]
This course prepares students in the basics of materials, design, and selection of materials for critical applications such as defense, crash protection and aerospace.
- MET 450 (Forensic Engineering)
Students in detail the structure related to fracture surfaces and metal failures. Students also use various advanced characterization techniques that are common to looking at the structure of materials including optical and electron microscopy.

[†] Replaced after 2010 by the 2 credit hour Advances in Processing and Nanoengineering of Polymers (MES 475) and the one credit hour Composites Manufacturing (MET 489)

Properties

The fundamental principles associated with material properties and their application to solving engineering problems and material selection is taught in the following required courses.

Required

- MET 231 (Structure and Properties of Materials Laboratory)
Students learn the to measure material properties including hardness, strength, and toughness. Students also learn about relative standards for testing properties.
- MET 232 (Properties of Materials)
Students learn the fundamentals of accurately defining and describing material properties including hardness, strength, toughness, fracture toughness, and fatigue. Students are introduced to performance properties including hardness, tensile strength, toughness, fatigue limits, brittle-ductile transition temperature, fracture toughness, and ductility.
- MET 320 (Metallurgical Thermodynamics)
Students learn the rigorous definition of thermochemical terms such as heat capacity, Enthalpy, Gibb's energy, etc. They learn the fundamentals needed to perform heat balances and determine conditions for chemical equilibrium and the propensity for chemical reaction and phase change. Students gain a fundamental understanding and learn to compute chemical and phase stability using Gibb's energy and perform simple heat balances for physical and chemical processes.
- MET 330L (Physics of Metals Laboratory)
Students perform detailed hardness, microhardness, and other mechanical property tests on metal alloys in a variety of conditions.
- MET 440 (Mechanical Metallurgy)
Students learn the rigorous definition of mechanical properties of metals (e.g. yield strength, tensile strength, fatigue strength, fracture toughness) and how these properties are controlled by the processing and structure of metals.
- MET 440L (Mechanical Metallurgy Laboratory)
Students conduct advanced mechanical property tests to measure tensile, fatigue and fracture properties. Emphasis is placed on understanding relevant testing standards.

Design

- MET 351 (Engineering Design I)
 - MET 352 (Engineering Design I)
 - MET 464 (Engineering Design I)
 - MET 465 (Engineering Design I)
- Students are enrolled in the design sequence during their junior and senior years. They spend considerable time selecting materials or their design projects. Students typically select materials for their projects using a trade table in which material properties are a major consideration. This is true whether the project is a physical metallurgy project or an extractive processing project. Both have unique material selection requirements.

Electives

- MET 430 (Weld Eng & Design, Structures)
Students study in detail the effect of different welding techniques on the physical and mechanical properties of metals. Emphasis is placed on consideration of weld design with respect to change in mechanical properties.
- MET 443 (Composite Materials)[†]
This course prepares students in the basics of materials, design, and selection of materials for critical applications such as defense, crash protection and aerospace.
- MET 445 (Oxidation and Corrosion)
Students learn about the corrosion properties and relative galvanic response of metal alloys. Students also perform corrosion testing to measure the corrosion properties of metals in different media.
- MET 491 (Security Printing Technology)
The students learn how to relate fundamental concepts of interfacial chemistry to understand ink manufacture for specific printing applications, and to combine inks, printing and substrates to make security end products for a variety of overt, covert, and forensic applications

[†] Replaced after 2010 by the 2 credit hour Advances in Processing and Nanoengineering of Polymers (MES 475) and the one credit hour Composites Manufacturing MET 489)

Processing

The fundamental principles and application to engineering problems of metallurgical processing is taught in the following required courses.

Required

- MET 220 (Mineral Processing)
Students learn the fundamentals of minerals processing including comminution; separations by gravity, electrostatic, magnetic, flotation, size fractionation and heavy media; dewatering processing including thickeners and filtration; and environmental considerations.
- MET 220L (Mineral Processing)
The student applies the fundamentals learned in MET 220 to conduct mineral concentration by gravity, electrostatic, magnetic, and flotation. This laboratory culminates in an experiential learning project where students apply these processing techniques to a real world industrial mineral separation.
- MET 310 (Aqueous Extraction, Concentration, and Recycling)
The students learn the fundamentals of liberation analysis and to understand and solve complex problems related to the concentration, solution purification, and recovery of metals from minerals in aqueous solution.
- MET 310L (Aqueous Extraction, Concentration, and Recycling)
The student will be able to design a set of leaching process experiments, to understand important parameters affecting the leaching of metals, and to understand the principles of solvent extraction, cementation, ion exchange and solution precipitation.

- MET 321 (High Temperature Extractive, Concentration, and Recycling)
Students learn the operating characteristics and methods for analyzing extractive metallurgical unit operations including oxidations, reduction, and refining processes ranging from carbothermic to electrochemical processes. They perform heat and mass balances on metal production processes.
- MET 330 (Physics of Metals)
Students learn the fundamental effects of heat on recovery, recrystallization and grain growth in metals. They also study the effect of solidification rates on the substructure of metals along with the effect of heating and cooling rates on phase transformations.
- MET 332 (Thermomechanical Processing)
Students learn fundamental heat treatment methods and mechanical processes used in the production of many metal alloys. These include annealing, quenching, and precipitation treatments. Students also learn the fundamentals of surface hardening through carburization and other treatments.
- MET 422 (Transport Phenomena)
Students learn the fundamentals of heat and mass transfer and how they influence heat treating processes and control the composition of metals during surface modification processes.
- MET 440 (Mechanical Metallurgy)
Students learn how the theory of elasticity and theory of plasticity are used in mechanical processing of metals.

Electives

- MET 426 (Steelmaking)
This course covers the unit operations in integrated steel mills, mini-mills, and direct reduction processes. The structure of these unit operations provides the basis for the thermochemical and thermomechanical process analysis.
- MET 430 (Weld Eng & Design, Structures)
Students learn about the difference in heat input and energy density for many welding techniques. Students also learn the fundamental strategies of choosing a particular joining process for an application.
- MET 450 (Forensic Engineering)
The students learn the influence of materials processing (e.g. heat treatment, casting, forging) on failure of metals and how to use this information to conduct failure analysis.

Performance

Understanding the application of microstructure, properties and processing to the performance of a material in an engineering design is a critical component in the undergraduate curriculum and is inherent in the courses listed above.

Required

- MET 231 (Structure and Properties of Materials Laboratory)
Students gain laboratory experience in performance properties including hardness, tensile strength, toughness, brittle-ductile transition temperature, and ductility.

- MET 310 (Aqueous Extraction, Concentration, and Recycling Laboratory)
Students study the performance of unit operations including concentration, leaching, and recovery from solution.
- MET 310L (Aqueous Extraction, Concentration, and Recycling)
The students apply statistical design and analysis of experiments to optimize a process.
- MET 332 (Thermomechanical Processing)
Students learn the strategy behind alloy development for steels and non-ferrous alloys. Students also focus on the selection of alloys and heat treatments for long term performance.
- MET 422 (Transport Phenomena)
Students learn how to compute the performance of a system undergoing thermal and mass diffusion processes. This is useful to determine heat and mass transfer controlled process rates, heating (and quenching) rates used for chemical processing or heat treatment, and for determining the affected depth of surface treatments.
- MET 433 (Process Control)
Students model the dynamic behavior of physical processes and automatic control systems using algebraic and differential equations; using block diagrams and transfer functions to represent the Laplace transforms of those equations; tune feedback controllers and automatic controllers to illustrate control techniques and response modes
- MET 440 (Mechanical Metallurgy)
The students learn how to calculate yield and failure stresses. Students also study mechanisms, criteria, and prediction for long-term fatigue and creep performance. Students are also introduced to methodologies of failure analysis of metallic components.
- MET 440L (Mechanical Metallurgy Laboratory)
Students perform mechanical testing related to materials lifetime under different loading conditions.

Design

- MET 351 (Engineering Design I)
- MET 352 (Engineering Design I)
- MET 464 (Engineering Design I)
- MET 465 (Engineering Design I)
All student projects are focused on a result; consequently, the performance of the materials selected for their projects become paramount as the project nears completion and evaluation.

Electives

- MET 445 (Oxidation and Corrosion)
Students study the effects of corrosion and oxidation of metals in different aqueous and high temperature environments. Students also learn about passivation and corrosion control techniques used to enhance metal performance.

Applying and Integrating these four fundamental concepts are reinforced by student capstone design projects; applied homework assignments that specifically concentrate on using the principles of microstructure, properties, and/or processing to solve engineering problems specifically applied to metallurgical engineering; and in the required directed met electives courses.

Experimental, statistical, and computational methods are used widely in the metallurgical engineering program in a way consistent with the program educational objectives.

Experimental Experience

The BS metallurgical engineering program requires students complete a robust suite of experimental laboratories that prepare them well for a career in metallurgical engineering. Table 9-2 lists the laboratory courses required in the degree program. The laboratory experience includes the basics of chemistry, materials science, and the specialized and practical aspects needed for entering career in metallurgical engineering.

Computation Experience

Students learn computation methods in MATH 373 (Applied Numerical Analysis). The current computational platform employed in the course is MatLab. MatLab has been the standard for the last three years. Before that MathCad was used extensively. Microsoft Excel is also used extensively. All of this software is available to all students via the laptop computer program. Metallurgical engineering students also use digital resources such as the Metal Handbook now available on-line via the Deveraux Library and perform thermodynamic computations using ThermoCalc[®] or STABCAL[®] computational software. This software is used in MET 320

| Table 9-2 Program laboratory courses (1 credit hour each) | |
|---|--|
| CHEM 112L | General Chemistry I |
| CHEM 114L | General Chemistry II |
| MET 220L | Mineral Processing and Resource Recovery |
| MET 231 | Structure & Properties of Materials |
| MET 310L | Aqueous Extraction, Concentration, and Recycle |
| MET 321 | High Temperature Extraction, Concentration, and Recycle* |
| MET 330L | Physics of Metals |
| MET 440L | Mechanical Metallurgy ** |

* Computational laboratory is 50 percent /High temperature experimental laboratory is 50 percent

** Contains a segment that includes in-class workshops on statistical instruction

(Metallurgical Thermodynamics) to perform equilibrium calculations in reacting systems and produce tables of thermodynamic data, MET 310L (Aqueous Extraction, Concentration, and Recycle) to create eH-pH diagrams, and MET 321 (High Temp Extraction, Concentration, and Recycle) to compute equilibrium diagrams. Phase diagram are constructed via thermodynamic computations in MET 330 (Physics of Metals). Computational methods used in MET 310 are primarily focused around using Excel and its computational abilities. Specific methods used involved using the add-in Solver to determine equilibrium metal ion concentration values of

multi-mineral pulps by solving multiple solubility product equations and using Goal Seek to solve cubic and higher order equations to determine metal ions concentrations from the solubility product and activity coefficient. Essentially all metallurgical engineering courses rely heavily on Microsoft Excel[®] as a computational platform.

In the coming year a new two-credit course in computation is planned as part of the required curriculum. The credits will be made available by dropping the one-credit of required physical education and another to-be-determined one-credit hour reduction in the curriculum. The content of the new course will replace computational content previously offered by Dr. Howard on programming with VBA's throughout the curriculum (e.g. MET 320, MET 321, MET 422 and MATH 373). The new course also will include instruction on programmable instruments.

Statistical Analysis Experience

Aspects of statistics and statistical data analysis are covered in several courses within the program curriculum. These begin with MET 231 (Properties of Materials Laboratory), usually the first laboratory course MET program students take. Upper division courses with significant statistics and statistical data analysis content are MET 310L (Aqueous Extraction, Purification and Recycling Laboratory) and MET 440L (Mechanical Metallurgy Laboratory). Generally, these are designed so that the experiences in MET 310L (Mineral Processing and Resource Recovery) and MET 440L (Mechanical Metallurgy Laboratory) build upon and extend the materials covered during MET 231 (Properties of Materials Laboratory). At the end of this series, the students are expected to be able to calculate basic statistical measures, such as mean and standard deviation, perform hypothesis testing and determine confidence intervals, and design experiments, including randomization, repeatability and reproducibility, to determine if data sets from experimental procedures are from the same population.

The first laboratory assignment in MET 231 (Properties of Materials Laboratory) involves an introduction to basic statistics calculations, including mean, standard deviation, variance and significance. In addition, later laboratory reports require least squares data fits and the determination and use of means and standard deviation data to properly interpret data. In the MET 310L (Aqueous Extraction, Purification and Recycling Laboratory) course, the background from MET 231 ((Properties of Materials Laboratory) is expanded through inclusion of design and analysis of experiments concepts. This includes factorial design, analysis of variance (ANOVA) and procedures for linking experimentation with analysis. All student group performed laboratories involving designing a set of experiments to test a hypothesis and analyzing the experimental results through proper procedures such as ANOVA or Yates method. In the MET 440L (Mechanical Metallurgy Laboratory) course, the background from MET 231 (Properties of Materials Laboratory) is used and expanded on through three laboratory assignments on the Hardness Reproducibility and Repeatability, Fatigue Analysis, and Statistical Process Control. In addition to using means, standard deviations and confidence intervals, the students learn and use non-parametric statistics and learn six sigma procedures for process control.

Specific topics can be reviewed in the course syllabi contained in Appendix A and in the examples of course examinations and design problems on display during the accreditation visit.

B. Faculty expertise

The metallurgical engineering program faculty all hold PhD degrees in metallurgical engineering or a closely related field of study from recognized accredited USA or UK universities. They maintain active membership in professional mineral, metal, and materials societies ranging including, TMS, SME ASM, AIST, ACeRS, and NACE and publish the results of their research regularly in recognized metallurgical/materials engineering journals, and serve in leadership positions in the professional community. The program faculty members have a combined instructional experience surpassing 100 years and engage in continuous feedback and improvement and continuing personal education opportunities. Faculty hold professional engineering licensure and several are working to gain status as licensed professional engineers. The program faculty members are a cohesive group who interact very well and who put their students' interests first. The faculty members know the undergraduate and graduate students by their first name and value maintaining a close working relationship with the students because it enhances the students' likelihood of success.