# A Missile System Design Engineering Model Graduate Curriculum

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## Abstract

A missile system design engineering design model graduate curriculum is presented for discussion. The rationale for the program is discussed in detail. Three levels of educational objectives which support the program are addressed. A course matrix for a master's level degree is presented as is a shorter missile engineering certification program matrix. Course descriptions are provided, as are representative instructional objectives which support them. Program assessment is discussed in terms of program objectives and accreditation.

## Introduction

The missile segment of the aerospace industry is quite small compared to the airplane and space segments. In 2003 missile segment sales were 13,489 million dollars compared to the total aerospace industry sales of 148,928 million dollars; the missile segment was about nine percent of the total. In terms of 2003 employment, the missile and space segment employed some 70,000 people, whereas the total aerospace industry employed some 583,000 people; the missile segment employed less than twelve percent of the total aerospace work force [1]. The squeaky wheel comprising airplane and space engineering graduate demands overshadows the missile community needs wheel for specialized expertise in missile system design engineering.

The paucity of missile engineering degree programs at universities within the United States suggests that the development of a model graduate missile engineering system design curriculum would be of interest to both academe and industry. Accordingly, a model graduate missile engineering system design curriculum is presented for discussion.

A model curriculum can be expected to provide a template for what should be an ideal specification of learning behaviors required in a given field of endeavor. These learning behaviors may or may not be grouped into specific courses. Such a template provides any given educational institution with set of minimum learning behaviors that can then be tailored and/or adjusted to meet the needs of that institution and the particular communities or constituencies that it serves. For the purposes of this paper, behavioral (instructional) objectives are generally grouped within specific course boundaries.

Universities with existing missile engineering programs can use the model curriculum to determine whether or not changes in their current curriculum should be made. Universities developing new missile programs can use the model curriculum to guide their own particular curriculum development. Some programs may wish to package the various topics in the proposed model curriculum in a somewhat different manner. Model curricula should be viewed as a time and knowledge sensitive assessment of minimum educational requirements.

The presented curriculum assumes an academic quarter system as opposed to a semester system. It would need to be repackaged for a semester based system. A quarter based program, as opposed to a semester based program, may be more appealing to industry-based students. Such a preference may allow industry-based students to better accommodate required corporate or agency travel time to their classroom schedule.

Program admission issues and possible transfer courses or credits are not addressed in this model program. Refresher courses (carrying no graduate credit) have been considered for students who have been away from a formal classroom environment for several years. These refresher courses, as needed, are discussed below.

Although most university engineering programs are accredited at the basic (undergraduate) level, there are a few that are accredited at the advanced level. Accordingly, accreditation issues related to both levels are addressed. Industry concerns and feedback are also addressed.

## Missile System Design Engineering Model Graduate Curriculum

Very few universities in the United States provide students with the opportunity to complete a program, at any level (undergraduate or graduate) in missile system engineering. To the writer's knowledge, these programs number less than the usual number of fingers on one hand. One might presume that either the demand for such programs is small or that the existing programs in aerospace engineering prepare students, equally well, for careers in space, airplane or missile engineering. There are significant differences between airplane and missile engineering.

### Airplane/Missile Mission Differences

Missiles and airplanes have different missions. Typically, airplanes carry a non-lethal payload of some sort from point A to point B, or perform some sort of surveillance. Airplanes are characterized by their relatively frequent ***takeoffs*** and ***landings***. Aircraft are generally ***reuseable***. Missiles, with some notable exceptions, are typically used as weapons of war. They are usually launched in an instantaneous manner (no taxi or takeoff run) from an airplane or a ground station, and explode with some degree of lethality at their terminus (instant landing). Moreover, missiles are generally not reuseable.

Airplane wings generally have higher aspect ratios than missile fins, although some fighters might be viewed as exceptions. Airplanes are usually powered by reciprocating or jet engines. With some exceptions, missiles are typically powered by either liquid or solid rockets. Airplanes are usually manned, with appropriate attention given to cockpit design and crew or passenger comfort. Missiles are typically unmanned, although appropriate attention is given to sensor installation requirements. Missiles can generally be designed to sustain higher load factors than airplanes. Aerodynamic heating is almost a non-problem for most airplanes, whereas, it can be of substantial concern in missile design.

Greater emphasis is placed upon non-linear aerodynamics in missile design than in airplane design. Compared to airplane system design, missile system design requires more attention to maneuverability, agility if you will, different sensors, more positive command and control, different types of propulsion subsystems, warheads, lethality, miss distance, different guidance issues, different trajectory (or flight path) analysis, emphasis on different cost components, a different type of design space, different payload packaging requirements, and different development time-lines. These subtle differences can be significant. For example, proportional navigation is a topic of special interest in the missile community but seldom discussed in an airplane curriculum. Also, wing body interference is usually of great importance in missile aerodynamics, but rarely discussed in detail in an undergraduate airplane oriented curriculum.

Although there are many similarities between airplane and missile design, there are also many differences. Industry and government often overcome these differences by resorting to in-house missile related courses or simply on-the-job training - methods initially used by the airplane industry. In-house course work has the advantage of addressing the latest, as well as proprietary and classified methodologies. However, in-house course work may not be cost effective (small employee/student numbers) or as broadening or comprehensive as a more formal educational program. Cost effectiveness can be enhanced if the student service area is enlarged from one specific company to include students and/or employees from several closely sited organizations interested in missile system engineering. If a formal education program is viable, of what components should it be comprised? Furthermore, how should be program be delivered?

**Program Delivery**

The apparent need for university executive leadership to reduce the number of quarter- or semester-hour requirements to graduate, reduce the number of classes taken in any given quarter or semester, and increase the number of non-professional (social science and humanities) credit hours in existing undergraduate engineering programs makes it increasingly difficult for university aerospace engineering departments to meet the professional technical needs of both the airplane and space communities, to say nothing of the needs of the missile community. More and more topics have been added to such curricula in recent years, e.g., modern control theory, probability and statistics, management, higher level computer programming, software competency, ethics, additional topics in the social sciences and the humanities, as well as new technologies; which is not to say that these additions are not needed. Most current aerospace engineering curricula have little room in which the special needs of the missile community can be met. Ten pounds of engineering education are already stuffed into a five pound curriculum box.

Thus, the needs of the missile community are probably best met in some type of graduate program. Ideally, such a graduate program would be based upon an undergraduate program in aerospace engineering. However, government agencies and the missile industry employ a wide variety of engineers and scientists. The missile system design engineering model graduate curriculum should account for this wide variation in student background preparation. Furthermore, the missile community needs can be expected to vary somewhat from one geographical region to another and from one segment of the missile industry to another. A full-blown missile engineering master's degree program may be required in some instances, while something less, such as a smaller (in terms of the number of courses) certification program may suffice in other circumstances.

**University Campus Programs.** For students going directly from their undergraduate work to graduate school, a formal university setting for graduate missile engineering study is not generally difficult. Universities wishing to offer a missile engineering program will probably need to develop a number of missile engineering related courses. Also, they may need to hire additional missile oriented faculty members.

However, for individuals who have left the university and entered government or industrial employment, there may not be a temporal window through which they can return to such a setting. Accordingly, another delivery system may need to be developed to satisfy the needs of the missile community. Distance learning represents one alternative. Another alternative is a company or agency sponsored on-site external degree program administered by a university.

**External Degree Programs.** The corporate or government agency sponsored on-site delivery system has one big advantage over the formal university system. Companies and government agencies typically have a number of individuals who are qualified to teach graduate level missile engineering courses, often these individuals are former university professors. These non-university individuals can bring real world system implementation experience into the classroom to emphasize the theoretical concepts developed in any course; practical missile engineering experience generally not possessed by university faculty members who, more often than not, have been exposed only to the research side of the missile community. A significant percentage of the professors for an on-site program usually can be obtained from the corporation or agency sponsoring the program to the advantage of both the company and the university.

A number of these on-site programs have been developed for the airplane segment of the aerospace community, e.g., the external degree master's program developed at California State Polytechnic University, Pomona. This program has been utilized by the employees of a number of companies including Northrop, Lockheed, and Rockwell [2, 3].

The graduate program espoused herein can be implemented either on a university campus or in an external on-site setting that may be quite far from any university locale. If necessary, it could be implemented by distance learning means.

## Educational Objectives

Curriculum development should begin with general program goals (first level abstract objectives), which are supported by intermediate program objectives (second level, less abstract), which generally describe what students can accomplish when they finish a given course of study. Finally, the first and second level objectives are supported by a foundation of specific instructional objectives, often grouped into specific courses. Assessment of the third level objectives readily provides the theoretical and practical educational mechanism or infrastructure for the assessment of level one and two objectives [4].

The advent of recent engineering accreditation criteria, EC 2000 (and later), espoused by the Accreditation Board for Engineering and Technology (ABET) [5], has required many engineering education professionals to consider the detailed articulation of educational objectives and their assessment for the first time. Accordingly, a number of seminars and symposia have been developed to address these issues [6]. After some six years, many engineering educational professionals still have many questions concerning educational objectives and their assessment; in many cases because they are unaware of the work of, for example, Bloom [7], Krathwohl [8], Harrow [9], and Mager [10,11].

Educational objectives, and methods for their assessment, have been around for many years. Many of our so-called objectives are, in reality, goals and, as such, are difficult, if not impossible, to assess or evaluate with any degree of certainty or accuracy. The missile engineering program presented herein is based upon three levels of educational objectives – from the very general to the very specific. A more detailed discussion of these objectives is presented below.

**Curriculum Summary**

The missile system design engineering model graduate (master's degree) curriculum, summarized below, has four major components: breadth, emphasis area, electives, and degree candidacy. The designation AERO xxx is intended to be a generic designation, within this discussion; the designation MISS xxx, ARO xxx, MSL xxx or some other notation could just as easily have been used. The numbers in parentheses, following the course number and title, indicate the number of quarter credit hours (or units) allocated to the course. The first number inside the parentheses indicates the number of quarter credit hours allocated to course lectures; the second number (after the hyphen) represents the number of quarter credit hours allocated to laboratory activities. The exceptions to this rule are associated with the numbers within the parentheses following the advancement to degree candidacy courses; these numbers simply represent the number of quarter credit hours that ***may*** be allocated to these activities by the student advisor or program coordinator, in consultation with the individual student.

It is expected that a student will complete a course of study that consists of a minimum of 45 graduate quarter credit hours in length. The actual program length could exceed 45 credit units, depending upon the number of electives taken, and the decision by the student to complete either a comprehensive examination or thesis. It is expected that at least two electives will be taken by any student completing the model missile system design engineering program.

It may be noted that this proposed model missile system design engineering curriculum leans to the comprehensive examination option rather than to the thesis option. Detailed course descriptions are provided in Appendix A.

*Breadth Requirements*

| | | |
|---|---|---|
| AERO 500 | Methods of Engineering Analysis | (4-0) |
| AERO 503 | Tensor Analysis for Engineers | (4-0) |
| AERO 536 | Missile Lethality | (4-0) |
| AERO 548 | Missile Cost Analysis | (4-0) |

*Emphasis Area Requirements*

| | | |
|---|---|---|
| AERO 510 | Missile Aerodynamics | (4-0) |
| AERO 513 | Tactical Missile Propulsion | (4-0) |
| AERO 516 | Warhead Design | (4-0) |
| AERO 520 | Missile Flight Analysis | (4-0) |
| AERO 524L | Missile Design I | (4-0) |
| AERO 624L | Missile Design II | (4-0) |

*Electives (any two courses)*

| | | |
|---|---|---|
| AERO 530 | Missile Structures | (4-0) |
| AERO 533 | Hypersonic Aerodynamics | (4-0) |
| AERO 506 | Variational Methods in Engineering | (4-0) |
| AERO 539 | Missile Guidance & Control | (4-0) |
| AERO 542 | Aerodynamic Heating | (4-0) |
| AERO 555 | Sensor Technology | (4-0) |

*Degree Candidacy*

| | | |
|---|---|---|
| AERO 698 | Directed Study for the Comprehensive Examination | (1-2) |
| | or | |
| AERO 699 | Design or Research Thesis | (0-8) |
| | Total | 45 units |

**Breadth Requirements.** Breadth courses are viewed as being an extension to the student's undergraduate breadth education. Breadth courses also are intended to benefit the student beyond the scope of his or her specialty or emphasis area coursework. The courses in mathematics, cost, and lethality meet these criteria.

**Emphasis Area Requirements.** Emphasis area requirements are the core of the program. They are intended to provide the student with the minimum educational skills and behavior capabilities needed to be successful in a given professional area of endeavor. The emphasis area courses for the model missile system design engineering program address the differences between the missions of airplanes and missiles, and the particular needs of the missile community.

The missile aerodynamics course addresses aerodynamic predictive methods throughout a wide speed range, from subsonic to hypersonic velocities. It also addresses fin-body interference, non-linear aerodynamics, skid-to-turn maneuvering, sidewash issues, extensive low-aspect ratio fin aerodynamics, launch constraints, and design related trade studies.
The course in warhead design will better enable the student to appreciate the missile mission, and better incorporate warhead issues such as size and weight into the missile design process than would otherwise be the case. The course also addresses a basic level of lethality concepts and issues.

The tactical missile propulsion course addresses a wide range of supersonic and hypersonic power plants. Extensive coverage is given to both liquid and solid rocket propulsive subsystems and plume characteristics. Such issues typically do not receive much, if any, attention in the typical airplane oriented curriculum.

The missile flight analysis or trajectory analysis course addresses the many issues associated with the coupling of dynamic stability and (often) constant maneuvering flight. Missile trajectory analysis is primarily concerned with the relationship between the target and the missile flight path. Guidance and control are the primary concerns of this course.

**Missile design** is the centerpiece of this model curriculum. Aerospace engineering departments have long struggled with the proper length of their vehicle design courses. The tradeoffs in length generally are associated with the concept of design (i.e., conceptual, preliminary, or final), the number of units allotted to the engineering program, and the importance of design versus analysis. For a master's level program, the author experience suggests that the design effort must be limited to conceptual design. Thus, in this paper, missile design refers only to conceptual missile design.

For a number of years, California State Polytechnic University, Pomona had a one-quarter undergraduate missile design course [11] in addition to their two-quarter aircraft and spacecraft design courses. The Naval Postgraduate School has a one-quarter missile design course as part of their four-course missile track [12]. The Georgia Institute of Technology has a two-semester missile design course sequence as part of their systems engineering missile track [13].

A two-quarter missile design course sequence is considered to be the minimum length of any missile system engineering design activity. A three-quarter design course would be better. However, in this model curriculum, the author believes that, for a master's level program, the tradeoffs limit the design course length to a two quarter sequence.

***Design and judgment are the essence of engineering; they are the primary factors that differentiate engineering from science.*** However, good engineering design brings science, economics (cost and financing), production, material selection, ascetics, form, function, human factors, logistics, operations, deployment, disposal, and every other facet of the project to an acceptable need solution. Acceptable solutions are usually sought because optimal solutions often cost more than they are worth – although optimal solutions tend to satisfy the "scientific" sense of order. Optimum is often the expensive enemy of acceptable or good enough. Expending resources to achieve design solutions beyond what is acceptable is often a waste of such resources. Engineers who concentrate only on the technological aspects of the solution do themselves and their clients a disservice. The missile methodology coursework preceding and concurrent with the missile design course sequence is intended to prepare the student for a comprehensive ***engineering*** design experience.

The design aspect of this missile program features small integrated (six-to-ten member) product and process design teams (IPPDTs) working to produce an acceptable solution to a specified set of missile requirements. Within an academic setting, design teams with more than ten members sometimes have internal organizational problems. The design solution will be documented by a 100 page report (conciseness is one aspect of good engineering) and a live team (everyone involved) oral presentation (forty minute presentation with ten additional minutes for questions by the review panel – again, conciseness is a key factor) to a review panel of missile design professionals from industry and government. There are some critics who will say that this approach yields nothing but a "paper" design. However, to the author's knowledge, almost every known (hardware) missile has started life as a "paper" design.

In this missile model curriculum, the missile design courses are taught as laboratory courses with six contact hours per week (two-quarter credit hours). Lectures are typically few in number and limited to issues that have not been considered in the preceding or concurrent course work. The laboratory environment of the design sequence permits maximum interaction among the students and the faculty mentor(s)/advisor(s)/instructor(s). The design faculty member(s) is expected to serve primarily as a consulting engineer, suggesting trade studies, alternative solutions, and perhaps different technologies, as needed; generally being a mentor and devil's advocate.

**Electives.** A group of six electives are available in this model missile system engineering design program. Specific courses in mathematics, structures, hypersonic aerodynamics, aerodynamic heating, and guidance and control are proposed. The hypersonic aerodynamics course supplements the introductory hypersonic work provided in the missile aerodynamics course. Aerodynamic heating is an issue only at Mach numbers exceeding three or four and for "long" flight times. The missile guidance and control course supplements the material provided in the required missile flight analysis course. Variational mathematics should be useful for improving trade study decision making. Most engineering students are likely to have a fundamental background in structures; thus, the material in AERO 530 is considered to be useful elective material, but not mandatory. Sensor integration into the missile system can be the difference between a good missile system and a great missile system.

**Degree Candidacy.** Advancement to candidacy is not an automatic process or event. The student is advanced to candidacy only upon the recommendation of the graduate program faculty. Advancement to candidacy means that the graduate faculty believes that the student is capable of either making a satisfactory score on the comprehensive examination or completing a research or design thesis in a satisfactory manner.

In implementing this missile system design engineering model graduate program, each university may have additional requirements for admission to candidacy. There may be special program admission requirements to be satisfied. A graduate writing examination may be required by some universities.

Most universities will require a minimum grade point average for courses taken in the program. Typically, the minimum grade point average is 3.0 (4.0 point system) for such courses.

If the missile program is taught in a typical university setting, the student may be encouraged to write a design or research thesis. If the curriculum is taught as an external degree program, corporate sponsors may place more value on coursework and encourage additional electives and the comprehensive examination, rather than the individual study associated with a design or research thesis [2, 3].

## Graduate Degree Course Matrix

Table I shows the one version of the missile system design engineering model curriculum for a typical university environment. The matrix has been constructed for the student who has been away from the classroom for several years and may feel the need for some review work prior to plunging headfirst into the new graduate material.

Review courses are shown in mathematics, heat transfer, aerovehicle performance, and gas dynamics. A review course in structural mechanics might also be required (but is not shown in the matrix). It is, of course, possible that a given student might need fewer than the four indicated review courses, or none at all. No graduate course credit is given for any needed (or requested) review course work. However, undergraduate course credit is given for review or refresher course work – in terms of accreditation or other assessment issues, this might be useful to the student with a non-aerospace engineering background.

The model missile engineering program is shown as a five quarter program. A review quarter, three quarters of graduate courses in missile system design engineering, including two elective courses, and a fifth quarter consisting only of the preparation for and the successful completion of a comprehensive examination. The program suggested by this matrix is appropriate for a typical full-time university student.

A slightly different matrix would be required for part-time students who have a full-time industrial or agency technical or management position. Historically such students will take only one or two classes a quarter. Due to the fact that their students are working full-time, external degree programs typically only offer two or three courses each quarter, but offer classes four quarters during the year. Such students can complete the program in just a little over two years. Completion time also depends upon course scheduling by the oversight or sponsoring university – students are often consulted when class schedules are being prepared. Thus, there are a wide variety of matrices that could be shown for an external degree program matching that shown in Table I. In any case, it is expected that any of the possible external degree program matrices would be similar to Table I in the sense that they would work their way through Table I – top to bottom – but be only one or two columns wide [2, 3].

**Table I**

| Model Missile System Design Engineering Graduate Curriculum<br>Course Matrix<br>(Including Possible Necessary Review Courses) | | | | |
|---|---|---|---|---|
| Quarter | Course 1 | Course 2 | Course 3 | Course 4 |
| 1 | AERO 305<br>Engineering<br>Math Review<br>(4-0) | AERO 310<br>Heat Transfer<br>Review<br>(4-0) | AERO 315<br>Aero Perform-<br>ance Review<br>(4-0) | AERO 320<br>Gas Dynamics<br>Review<br>(4-0) |
| 2 | AERO 536<br>Missile<br>Lethality<br>(4-0) | AERO 500<br>Methods of<br>Engr Analysis<br>(4-0) | AERO 510<br>Missile<br>Aerodynamics<br>(4-0) | AERO 517<br>Tactical Missile<br>Propulsion<br>(4-0) |
| 3 | AERO 503<br>Engr Tensor<br>Analysis<br>(4-0) | AERO 520<br>Missile Flight<br>Analysis<br>(4-0) | AERO 548<br>Missile Cost<br>Analysis<br>(4-0) | AERO 524L<br>Missile<br>Design I<br>(0-2) |
| 4 | AERO 516<br>Warhead<br>Design<br>(4-0) | Elective<br>(4-0) | Elective<br>(4-0) | AERO 624L<br>Missile<br>Design II<br>(0-2) |
| 5 | AERO 698<br>Directed Study<br>Examination<br>(1-0) | (Lecture Units - Laboratory Units)<br>*Review courses do not receive graduate credit* | | |

It will be noted that, with the exception of the design and exam preparation courses, all of the courses represent four quarter credit hours or units of study. Each of the four-quarter unit lecture courses consists of four student contact hours. Each design course is a two-quarter unit laboratory course consisting of six student contact hours weekly (students will often spend many more hours than this on a design project). The directed study course leading to the comprehensive examination, is represented as a one-quarter unit lecture course, signifying one student contact hour per week

Table I would be slightly modified in quarters four and five (and possibly three) for students pursuing a thesis. It is expected that one-to- three cells in the matrix would be required for thesis activity.

## Certificate Program Course Matrix

External missile system design engineering program needs may not require a complete degree curriculum. In some geographical areas, with some portions of the missile industry, or, perhaps as an introduction to a complete degree curriculum, a shorter certificate curriculum may be appropriate. Such a certificate program is illustrated in Table II.

A short five-course missile system design engineering certificate program course matrix is shown in Table II. The five graduate level courses are shown to be preceded by three undergraduate level review courses, which, as in the case of the master's degree curriculum

**Table II**

| Model Missile System Design Engineering Certificate Program Curriculum Course Matrix (Including Possible Necessary Review Courses) | | | | |
|---|---|---|---|---|
| Quarter | Course 1 | Course 2 | Course 3 | Course 4 |
| 1 | AERO 305 Engineering Math Review (4-0) | AERO 315 Aero Perform-ance Review (4-0) | AERO 320 Gas Dynamics Review (4-0) | AERO 536 Missile Lethality (4-0) |
| 2 | AERO 500 Methods of Engr Analysis (4-0) | AERO 510 Missile Aerodynamics (4-0) | AERO 517 Tactical Missile Propulsion (4-0) | AERO 520 Missile Flight Analysis (4-0) |
| *Review courses do not receive graduate credit* | | | | |

discussed above, may or may not be needed. Also, as with the master's degree curriculum, it is also possible that different review courses may be required for a given individual student.

The certificate program itself consists of single courses in mathematics, missile aerodynamics, lethality, tactical missile propulsion, and missile flight analysis. Again, as with the degree program, the review courses are offered (or not) primarily to prepare the individual student for graduate work. No graduate course credit is given for the review course work. As in the case of the degree program, undergraduate course credit is given for the review or refresher work. A Certificate is given to the student who successfully completes the five- course graduate program.

It will be noted that the certificate program is representative of the front end of the degree program shown in Table I. Historically, certificate programs tend to consist of four and five courses – about half (or less) the length of a degree program. Design is not included for two reasons. First, the certificate program matrix shown in Table II could include design only at the expense of two needed background courses in missile aerodynamics, propulsion, flight analysis, or lethality. Minus these background courses, the student would not be properly prepared to perform missile design work. Secondly, there is not sufficient room in a certificate program for both the necessary preparatory course work and a ***minimum*** two-quarter design course sequence. Obviously, these two reasons are not mutually exclusive.

If a student successfully completes the certificate program (or any part thereof) and later has access to the complete model missile system design engineering master's degree program, the certificate course work can be transferred to the degree program.

## Curriculum Assessment

Curriculum assessment is first and foremost done to determine whether or not an educational program is meeting its objectives. An educational program that is not meeting its objectives should be changed to meet the program objectives, have the objectives changed to coincide with the program, or possibly be terminated. The program sponsor will probably insist upon an assessment of the program in order to justify further sponsorship and/or funding. Accreditation is another reason for performing program assessment.

**Educational Objectives**

Educational objectives can be identified at three levels. The first level and most abstract level of educational objectives deal with long term goals. Educational objectives of the second level are derived from the objectives of the first level, represent subsets of the first level objectives, provide less abstraction than those of the first level, and tend to describe objectives for a prescribed course of study. Educational objectives of the third level tend to be quite specific; are derived from second level objectives; are subsets of second level objectives; and state the student performance desired, the conditions under which the performance is to be given, and the criteria for acceptable performance [6, 7, 14].

**First Level Objectives.** With regard to the present discussion, one can identify several first level educational objectives: (1) missile engineers should possess the intellectual skills and abilities to successfully engage in the practice of missile development, (2) missile engineers should be able to appreciate the consequences of their design decisions, and (3) missile engineers should be able to appreciate the non-technological aspects of missile system development, deployment, and operation.

The generality of these first level objectives can be seen in their lack of specificity. For example, what are the intellectual skills and abilities that allow one to engage in the successful practice of missile engineering? What are the non-technological aspects of missile system development, deployment, and operation? Such objectives, in and of themselves, while extremely important as goals, are not truly measurable.

**Second Level Objectives.** Second level educational objectives, *derived from first level objectives,* are often viewed as program objectives. Some second level educational objectives, for the model missile system design engineering graduate curriculum discussed herein, can be taken directly from EC 2000 Criterion 3; attributes (a) through (k) [4].

For example (and slightly restated), (1) a graduate of the missile system design engineering model curriculum must demonstrate the ability to function as a member of a multi-disciplinary missile system design team, and (2) a graduate of the missile system design engineering design model curriculum must demonstrate the ability to design a missile system, component, or process to meet specified requirements. The other nine ABET attributes will not be restated here due to space limitations, and because they should be well known to engineering educators. However, innumerable other second level objectives can be generated for any missile engineering degree program; such objectives are not limited to the ABET criteria.

With regard to the missile system engineering curriculum discussed herein, a number of non-ABET inspired program objectives can be defined. For example, missile system engineers should be able to appreciate the economic consequences of their design decisions. Also, missile system engineers should be able to appreciate the intuitive aspects of missile configuration design. With regard to design decisions, missile system engineers should also be able to distinguish between better and good enough.

In and of themselves, one has difficulty in assessing both first level and second level educational objectives, since the conditions under which the student performance is to be made generally have not been specified, nor has a criteria been given for performance acceptance. These two levels of educational objectives are too general to be measurable. This difficulty creates the need for third level educational objectives.

**Third Level Objectives.** Third level educational objectives describe the specific performance required of the student, any conditions that influence the specific student behavior, and the criteria for acceptable student performance. Third level educational objectives are also known as behavioral or instructional objectives. They can be grouped, or organized, into three learning domains: cognitive [6, 8], affective [6, 9], and psychomotor [6, 10]. Taxonomies exist for each of the three learning domains. Each of the three taxonomies is hierarchical in form – starting with simple learning behaviors and ranging to the most complex learning behaviors. Each major subdivision of each taxonomy is further subdivided as needed [6]. A number of books have been written about the methodology of writing third level instructional objectives [7, 11, 12, 13, 14]. Since third level objectives are derived from second level objectives, and since third level objectives can be measured or assessed, they can be used to assess both second level and first level objectives.

Instructional objectives in the **cognitive domain** are related to the student's recall of specific bits of knowledge or to the development of specific individual intellectual skills and abilities. The major principle of classification is the degree of complexity of the cognitive process implied or described by the objective. The six major divisions of this taxonomy consist of knowledge (lowest level of cognitive behavior), comprehension, application, analysis, synthesis, and evaluation (most complex level of cognitive behavior) [6, 8]. Good design work requires all six divisions of cognitive processes – individually and in the several possible permutations and combinations with each other.

The **affective domain** is concerned with instructional objectives that are related to a student's emotions and his/her acceptance of some particular ideal or concept – like the concept of becoming a great missile system design engineer. This domain is concerned with the internal processes we use in our approach to all of the activities of our daily lives. It certainly is concerned with the internal processes one uses when given the task of developing a missile system engineering process. As the student progresses through the missile system design engineering curriculum, she/he needs to feel that the knowledge they are acquiring will enable them to be a successful missile design engineer. The five major categories of this domain consist of (in ascending order) receiving (attending), responding, valuing, organization, and characterization of a value or value complex [6, 9]. Again, good design work requires all five divisions of affective processes – individually and in the several possible permutations and combinations with each other.

Instructional objectives in the **psychomotor domain** are concerned with the student's ability to perform motor skills or acts involving neuromuscular coordination. Hand sketching with a pencil or pen, keyboard entry, software manipulation, mechanical skills associated with hardware construction, presentation gestures, and writing code are examples of the psychomotor skills needed to become a successful missile system design engineer [6, 9].

The psychomotor learning domain is less well developed than the cognitive and affective learning domains. As opposed to the educational community consensus regarding the divisions of the cognitive and affective taxonomies, there are at least two taxonomies for the psychomotor learning domain. Simpson developed a seven category classification scheme in the 1960s [6, 15,16]. Harrow developed an alternative psychomotor taxonomy in the early 1970s. The Harrow taxonomy is used herein. There are six major divisions in the Harrow psychomotor learning domain (in ascending order): reflex movements, basic-fundamental movements, perceptual abilities, physical abilities, skilled movements, and non-discursive communications [10]. As with the other two taxonomies, all six psychomotor division skills – individually and in their several possible permutations and combinations are needed to become a successful missile system design engineer.

Several examples of third level behavioral or instructional educational objectives, two for each missile systems engineering course, are given in Appendix B. Unless otherwise noted, the student will be able to satisfy each objective 100 percent of the time – the criteria of acceptance of student performance. For some objectives in Appendix B, the learning domain and the domain level of complexity is indicated. Whether stated or not, third level educational objectives are at the core of good teaching. Third level objectives are measurable and repeatable. They provide the basis for course, and program, and curriculum assessment.

Third level educational objectives are measurable. Third level objectives define student outcomes. They are useful, if not of paramount importance, in determining what should be taught in any curriculum. Since they are measurable, they form the foundation of any program assessment. They should be used as the basis for course projects and course examinations.

In the typical four credit hour quarter-long engineering course, it is not unusual to have some 150 or more third level behavioral objectives describing student outcomes for the course. While this may seem like an unreasonably large number of objectives for one course, such a course will typically have some forty-plus hours of instruction. Consider a different perspective. If four instructional (behavioral) objectives are addressed in each lecture hour, it is possible to cover some 160 behavioral objectives. Not all instructional objectives need to be comprehensive in character. These objectives will probably address student behaviors from all three learning domains and across all divisions of complexity. However, it is likely that most of the objectives will be in the cognitive domain.

As a result of the missile system design engineering model curriculum discussed herein, the student will be able to do a number of specific things. These specific program outcomes are defined as behavioral or instructional objectives. Appendix B provides two behavioral objectives for each course. The learning domains and the division of complexity are given some of the instructional objectives presented in Appendix B. Anyone implementing this model missile engineering curriculum can tailor any remaining objectives to the specific goals of the specific missile community.

## Program Assessment

Program assessment is required; if one is to be certain that an educational curriculum is achieving its intended purpose. The first level objectives define the goals of a given curriculum. Second level objectives are derived from the first level objectives, and third level objectives are derived from the second level objectives. First and second level objectives are difficult to assess. However, third level objectives are written in such a manner that they can be assessed by a number of methods, including written objective examinations, reports, papers, oral presentations, and demonstrations. If the third level learning objectives are being met, it follows that the second level and first level learning objectives likely are being met. It is likely that the above mentioned assessment tools are sufficient to evaluate the cognitive, and in many cases the psychomotor, aspect of any given set of learning objectives. Assessment of the affective learning objectives can be more difficult.

In an effort to evaluate professorial teaching performance, many universities require that students complete a course evaluation survey for each and every course at the end of each quarter or semester. What kind of questions appear on such survey evaluations? Was the professor prepared for class? Would you take another class from this professor? Did the professor use the class time effectively? Did the professor wander from the course syllabus? Were the examinations fair? Did the examinations reflect the course material covered by the professor? These questions and others like them are, in fact, eliciting answers to affective learning objectives that may or may not have been posed by the professor or the university administration. Positive or negative answers to these questions say volumes about the efficacy of the learning environment in any class. They provide one assessment measure of the way a given class is perceived by the students. Perhaps more often than we would like to think, perception is reality.

Similar surveys can be developed for completion by the employers of students graduating from a given program, and from corporate sponsors of external degree programs. Advisory councils consisting of first line (or higher) corporate or government agency supervisors and/or managers can provide university department chairpersons and faculty with assessments regarding the efficacy of individual course content within any university program. These survey instruments provide one method for assessing affective behavioral objectives

## Accreditation

Originally the term accreditation meant trustworthiness. Within the United States, the original purpose of accreditation was to assure colleges and universities that secondary school graduates had mastered a given body of knowledge. Currently, there is the additional requirement that accredited programs demonstrate continual self-improvement. Accordingly, assessment is used to demonstrate that these goals are being met.

**WASC.** One level of accreditation is provided by regional accreditation associations. In the United States there are six such associations. In the western region, for example, such accreditation is under the purview of the Western Association of Schools and Colleges (WASC). The basic WASC accreditation criteria address organization of student learning, curriculum and instruction, support for student personal and academic growth, and resource management and development. The WASC web-site is http://www.acswasc.org.

The WASC criteria for curriculum and instruction are concerned with what students learn, how students learn, and how assessment is used to demonstrate continuous self-improvement. All three levels of educational objectives discussed above, particularly the third level objectives, can be used effectively to develop a missile system design engineering program assessment (e.g., examinations, reports, presentations, etc.) program, and thereby demonstrate that WASC type criteria can be met.

**ABET.** The Engineering Accreditation Commission (EAC) of the Accreditation Board for Engineering and Technology (ABET) is responsible for accrediting engineering programs within the United States. ABET accreditation of university engineering programs can be attained at either the basic level or the advanced level [4]. Most engineering programs are accredited at the basic level.

There are a number of requirements for accreditation at the basic level; only those of concern to this discussion will be treated herein. For example, ABET requires that educational objectives be published for each accredited engineering program at a given institution. Furthermore, an assessment of program outcomes (Criterion 3, a through k) must be available for each accredited engineering program. For any given program, the professional component requires (1) one year of college level mathematics and basic sciences, (2) one and one-half years of engineering topics, and (3) a general education component that complements the technical content of the curriculum and *is consistent with the program objectives.* Again, all three levels of educational objectives discussed above can be effectively used to develop a missile system design engineering program assessment that will satisfy the assessment issues of the ABET criteria.

For individuals whose undergraduate work is not in aerospace engineering, the individual student's undergraduate work would require review to ascertain that the professional component quantity requirements for mathematics, basic science, and engineering topics can be met. The review courses may help an individual student in this regard: certainly the model missile system design engineering degree program satisfies the comprehensive design experience requirement.

For advance level accreditation an engineering program must satisfy the basic level criteria and (1) provide one year of study beyond the basic level requirements, and (2) require a report that demonstrates both mastery of the subject matter an a high level of communication skills. Certainly the model missile system design engineering course work described herein provides slightly more than one year beyond the basic level of engineering topics. Either the design project or the thesis required by the model missile system design engineering program can be made to meet the report requirement.

## Conclusions

There is a paucity of missile engineering educational programs within the United States. One reason for this paucity is that the missile community is small compared to the airplane and space communities of the aerospace industry. Missile engineering receives scant attention in most aerospace engineering curricula.

A viable model missile system design engineering graduate program has been presented for implementation as either a typical "on campus" university program or as an external degree program. The need for graduate missile programs is stated. The program is supported by three levels of educational objectives.

Representative (two) measurable instructional (behavioral) objectives are given for each course in the proposed model curriculum. The instructional objectives are grouped into three categories: cognitive, affective, and psychomotor. Each category has several hierarchical divisions of complexity – from simple to very involved compositeness.

Since the instructional objectives are measurable, they provide a basis for program assessment by both regional and professional organizations such as, respectively, WASC and ABET. A number of these accreditation issues are addressed.

For situations where a complete graduate degree program in missile system engineering is not required, a shorter Certificate program has been identified. Both programs are designed to meet the specific educational needs of the missile engineering community.

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**Biography**

Dr. Newberry is Professor Emeritus at the California State Polytechnic University, Pomona and at the Naval Postgraduate School (Monterey). AA (Pre-engineering), Independence (Kansas) Junior College, 1951; BEME (Aeronautical Sequence), University of Southern California, 1957; MSME (Fluids Option), California State University, Los Angeles, 1971; MAEd (Tests and Evaluation), 1974; D. Env. (meteorology, air pollution control), University of California, Los Angeles, 1985. P.E. (CA, KS, NC, TX); Certified (AAEE Diplomate) Air Pollution Control Engineer. Approximately 20 years with Dixon Aircraft, North American Aviation, Atlantic Research, Lockheed Aircraft Service, Celesco, Northrop Aircraft Company, and Rockwell International (Space Division) with assignments in manufacturing, aerodynamics, flight test, aerothermodynamics, ballistic entry, and propulsion. Two years with the US Environmental Protection Agency completing air quality modeling and air pollution control assignments. Research interests include air quality modeling and the use of exergy, quality function deployment and optimization methodologies to improve aircraft, missile, engine, and spacecraft design. Chairman of the ASEE Aerospace Engineering Division 1979-80; Chairman of the Ocean and Marine Engineering Division 1993-95; Chairman of PIC II 1995-97. Member: AIAA (Fellow), BIS (Fellow), ASEE, AHS, NSPE, SNAME, RAeS, USNI, SAE, AWMA, SAWE, The Planetary Society, AUVSI, NAEP, IES, EAA, ASME, and AMS. He is the author or co-author of over fifty papers, reports, and books concerned with engineering, environmental science, and education. He has served as the associate editor (for design) of the AIAA Journal of Aircraft, a member of the ASNE Journal Committee, and a member of the Editorial Advisory Board of The International Journal of Engineering Education. His awards include the John Leland Atwood Award (1986), the Fred Merryfield Design Award (1997), and the US Navy Meritorious Civilian Service Award (2002).

## Appendix A

## Missile System Design Engineering Course Descriptions

AERO 305    Engineering Mathematics    (4-0)

Review of college algebra, trigonometry, solid geometry, and analytic geometry. Differentials. Differentiation: algebraic functions, transcendental functions, numerical methods, applications. Integration: techniques, definite integrals, indefinite integrals, numerical methods, applications. Limits. Infinite series: Taylor's series. Analytical geometry: two-dimensions, three-dimensions; direction cosines, surfaces of revolution, coordinate systems. Partial differentiation: directional derivatives, implicit functions. Double integrals; applications. Triple integrals; applications. Envelopes. Ordinary differential equations. Partial differential equations. Prerequisite: Graduation from an ABET accredited engineering program or equivalent.

AERO 310    Heat Transfer    (4-0)

Basic modes of heat transfer: conduction, convection, and radiation. Dimensions and units. Material properties: thermal conductivity, specific heats, thermal diffusivity, and fluid viscosity. Heat conduction: one-dimensional, multi-dimensional. Free convection. Forced convection: equations of motion, laminar flow, turbulent flow. Boundary layers: displacement, momentum, and energy thicknesses. Reynolds' analogies. Working formulas, correlations. Radiation: black body radiation, gray surfaces. Heat exchangers: parallel flow, counter flow. Prerequisite: Graduation from an ABET accredited undergraduate engineering program or equivalent.

AERO 315    Gas Dynamics    (4-0)

Thermodynamic concepts: control mass, control volume analysis. Compressible flow: sonic velocity, critical velocity, Mach number, h-s and T-s process diagrams. Variable area adiabatic flow: nozzle operation, nozzle performance. Normal shockwaves. Oblique shockwaves: internal, external, optimal two-dimensional inlet ramp sizing. Prandtl-Meyer flow: expansion, compression. Conical flow: Taylor-Maccoll theory. Fanno flow: friction choking. Rayleigh flow: thermal choking. Reaction propulsion systems: Otto cycle (exception), Brayton cycle, propulsion engines, thrust, power, efficiencies. Supersonic diffusers. Rockets: fuels, oxidizers. Prerequisite: Graduation form an ABET accredited engineering program or equivalent.

AERO 320    Aircraft Aerodynamics and Performance    (4-0)

Atmospheres: standard, hot, cold, tropical, polar. Aerodynamic concepts and nomenclature: laminar flow, turbulent flow. Aerodynamic shapes: airfoils, wings. Aerodynamic coefficients: lift, drag, axial force, normal force, moment. Drag: form, skin friction, induced. Lift distributions: subsonic, supersonic; elliptical, non-elliptic. Aircraft performance: equations of motion, thrust (power) required, thrust (power) available, rate of climb, time to climb, ceilings, range, endurance, turning flight, energy methods. Static stability: longitudinal, directional, lateral. Prerequisite: Graduation from an ABET accredited engineering program or equivalent.

AERO 325 Strength of Materials (4-0)

Method of sections: free body diagrams. Stress: normal, shear, bearing. Axial loads. Strain: stress-strain diagrams, Hooke's Law, Poisson's ratio. Torsion: formulas, circular members, angle of twist, thin-walled hollow members. Axial force shear and bending moment: loading conventions. Beam bending: flexure formula; shear, bending moment, rotation, and deflection diagrams. Compound stresses. Analysis of plane stress and strain. Pressure vessels. Statically indeterminate structures. Columns: buckling. Connections. Energy methods. Prerequisite: Graduation from an ABET accredited engineering program or equivalent.

AERO 500 Methods of Engineering Analysis (4-0)

Matrix algebra: definitions, determinants, inverses, simultaneous equations, eigenvalue problems, transformations. Complex analytic functions: conformal mapping, integrals, sequences, and series. Numerical methods: differentiation, integration. Probability and statistics: mean, variance, distributions, sampling, confidence intervals, quality control, regression analysis. 4 Lectures. Prerequisite: Mathematics equivalent to that contained in an ABET-accredited undergraduate curricula.

AERO 503 Tensor Analysis for Engineers (4-0)

Summation convention. Transformations: linear, curvilinear coordinates. Vectors and tensors: contravariant, covariant, mixed, Kronecker Delta, outer multiplication, inner multiplication, properties. Metric tensor: base vectors, direction cosines. Geodesics and the Christoffel symbols, Riemannian coordinates. Inertia tensors. Differentiation of vectors and tensors: covariant, intrinsic (absolute), conjugate. Ricci's Theorem. The Contravariant derivative. Components of tensors, relative tensors, and Cartesian tensors. Permutation symbols. Vector quantities in tensor form. 4 Lectures. Prerequisite: Mathematics equivalent to that contained in an ABET Accredited undergraduate curricula.

AERO 506 Variational Methods in Engineering (4-0)

Necessary and sufficient conditions for an extremum; variations and Hamilton's Principle; the nonparametric problem of Bolza; parametric problems; direct methods; measure, integrals, and derivatives; variational theory in terms of Lebesgue integrals; nonclassical problems; and the Hamilton-Jacobi theory. Approximate methods. Applications to aerodynamics, propulsion, structures, dynamics, and heat transfer. Application to missile system design trade studies. 4 Lectures. Prerequisite: Mathematics equivalent to that contained in an ABET accredited curricula.

AERO 510 Missile Aerodynamics (4-0)

Atmospheric properties. Differences between aircraft and missile aerodynamics. Aerodynamic coefficients. Subsonic pressure theories. Shock-expansion, Ackeret, Busemann second- and third-order pressure theories. Newtonian flow. Fin planform effects: aspect ratio, sweep, and taper ratio. Fin thickness effects. Fin linear and nonlinear forces and moments. Body linear and nonlinear forces and moments. Configuration and component interference effects; downwash, sidewash. Configuration force and moment distributions. Aerodynamic control: wing, tail, canard. Static stability: aerodynamic center, neutral point, center-of-pressure and static margin. Maneuvering flight; vertical pull-up, rate damping, bank-to-turn, skid-to-turn. Trade between stability and maneuverability. Launch constraints: AAM, SAM. Design considerations. 4 Lectures. Prerequisites: ABET accredited engineering undergraduate aerodynamics and gas dynamics courses, or equivalent.

AERO 513 Tactical Missile Propulsion (4-0)

Types of power plant: turbojet, fan jet, ram jet, scramjet, rocket, hybrid propellant rocket, air turbo rocket. Air breathing inlet design (two-dimensional, conical). Liquid rocket design: propellant selection criteria, injectors, reaction kinetics, nozzle configuration, combustion instabilities, and motor performance. Solid rocket design: propellant selection criteria, grain design, service life analysis, nozzle configuration, combustion instabilities, and motor performance. Application of motor performance and grain design codes (e.g., PEP, and NASA SP 233). Insensitive munitions. Rocket plume signature characteristics: NATO/AGARD performance and plume classification methodology. Thrust vector control. Insensitive munitions solid rockets. Design trade studies. 4 Lectures. Prerequisite: ABET Accredited undergraduate gas dynamics course or equivalent.

AERO 516 Warhead Design (4-0)

Introduction to tactical warheads: classification of warhead types, mechanics of warhead types. Explosives: materials, performance, effects, and predictive techniques. Material characterization for warhead computation. Velocity of explosively driven liners: symmetric geometries, asymmetric geometries. Warhead simulation: governing equations, numerical solution techniques. Mechanics of shaped charges: configurations, jet formation, jet particulation. Explosively formed projectiles: mechanics, configuration, aerodynamics. Fragmentation warheads: natural, controlled, kill mechanisms. Target interaction. Special topics. Design trade studies. 4 Lectures. Prerequisite: AERO 510.

AERO 520 Missile Flight Analysis (4-0)

Static and dynamic stability and control of missiles: longitudinal, lateral, and directional. Nonlinear dynamics. Stability derivatives. Transient modes: phugoid, short period. Lyapunov stability principles. Subsonic, transonic, supersonic, and hypersonic force and moment data for performance calculations. Missile performance: cruise, climb, turns, acceleration, ceiling, range, specific excess power, agility, and maneuvering flight. Load factors. Controllability and pole placement: time domain, frequency domain, yaw dampers. Missile-target trajectory simulations. Circular probable error (CPE). Introduction to autopilot design. Atmospheric turbulence: sharp edged gust, one-minus-cosine gust, random processes. Design trade studies. 4 Lectures. Prerequisite: AERO 510.

AERO 524L Missile Design I (0-2)

Student integrated product and process design teams (IPPDTs) are formed to produce, in consultation with the design professor, a systemic solution to a customer need (including a mission profile) defined by Request-For-Proposal (RFP). The student teams are comprised of some six-to-ten individuals; team integrity and leadership is maintained over the two-quarter design sequence. Each member of the design team is responsible for at least one design discipline (e.g., aerodynamics, propulsion, structures, cost, quality, guidance, effectiveness). The design methodology draws upon the total life experience of each individual student. Tradeoffs among the engineering, production, acquisition, and deployment related requirements are performed to support design decisions. A minimum of three possible solutions (and configurations) will be evaluated prior to the down-selection of the baseline solution that will be further refined in the second quarter of the design sequence. Lectures will be given only to address topics new to the student design teams. 4 Lecture credits are allocated to this laboratory course. Prerequisites: completion of AERO 500, AERO 510, AERO 513, and AERO 548.

AERO 530 Missile Structures (4-0)

Aerodynamic loads: subsonic, transonic, supersonic, hypersonic. Inertia loads. Separation loads. Shear, bending moment, torsional moment, deflection diagrams for both the body and fins. Material properties: aluminum, titanium, steel, composites. Strength-to-weight considerations: optimum fin configuration. Load path analysis. Combined stresses. Factors of safety, margins of safety: maximum working stress levels. Temperature effects. Missile component weight estimation. Fabrication issues. Design trade studies. 4 Lectures. Prerequisite: ABET accredited undergraduate engineering mechanics, strength of materials, and structural mechanics courses, or equivalent

AERO 533 Hypersonic Aerodynamics (4-0)

Definitions. Shock-expansion theory. Newtonian theory. Two-dimensional flow: airfoils, thickness effects, normal and chord forces, similarity laws. Three-dimensional flow: bodies of revolution, normal and axial forces, center-of-pressure, non-linear effects. Minimum drag bodies. Hypersonic small-disturbance theory. Slender body theory. Hypersonic flow over blunt bodies. Complete configurations: nose, afterbody, wings (fins). Stability and control: static longitudinal stability, control surfaces, lateral control power, stability derivatives. Reentry. Real gas effects. Design trade studies. 4 Lectures. Prerequisite: Upper-division undergraduate course in gas dynamics or supersonic aerodynamics, or equivalent.

AERO 536 Missile Lethality (4-0)

Surface-to-air, surface-to-surface, air-to-surface, and air-to-air missile system effectiveness. Target detection, identification, and tracking. Propagator trajectories. Target signatures for visual, infra-red, and radar directed missile systems. Types of fuzes and warheads used by guided missile propagators. Target susceptibility and vulnerability. Assessment of target vulnerability due to damage mechanisms such as penetrators, fragments, incendiary particles, and blast. Damage processes associated with damage mechanisms. Estimation of total missile system lethality expressed in terms of the probability of a kill for a given encounter. Countermeasures used to reduce missile system lethality. Design trade studies. 4 Lectures. Prerequisite: AERO 510, AERO 513, and AERO 516.

AERO 539 Missile Guidance & Control (4-0)

Missile guidance fundamentals: proportional navigation, linearization, simulation, closed form solutions, zero effort miss distance. Method of adjoints and the homing loop: single time constant guidance system, adjoints for deterministic systems, closed form solutions. Noise analysis: white noise, shaping filters, fading memory filters, random processes, stochastic adjoint. Proportional navigation and miss distance: design relationships, evasive maneuvers, thrust vector control. Advanced guidance laws. Kalman filters and the homing loop. Other guidance subsystems: proportional navigation homing guidance, proportional navigation command guidance, beam rider guidance, command to line-of-sight guidance, and Lambert guidance. Missile zones: velocity, drag, acceleration, gravity, strategic considerations. Missile guidance software. Design trade studies. 4 Lectures. Prerequisite: AERO 520.

AERO 542 Aerodynamic Heating (4-0)

Basic concepts: skin friction, velocity boundary layer, thermal boundary layer. Fundamental equations for conduction, convection, radiation, and mass transfer. Molecular velocity approximations. Incompressible and compressible flow laminar and turbulent boundary layer properties: heat transfer, pressure gradient effects, Reynolds Analogy. Laminar and turbulent skin friction: theoretical and approximate formulations. Recovery temperature. Reference enthalpy method for fluid properties: laminar flow, turbulent flow. Stagnation point heat transfer: incompressible flow, compressible flow. Flat plate heat transfer: laminar flow, turbulent flow. Calculation of missile skin temperatures. Mass transfer cooling. Slip flow. Free molecule flow. Design trade studies. 4 Lectures. Prerequisite: ABET accredited upper-division undergraduate engineering course in heat transfer, or equivalent.

AERO 548 Missile Cost Analysis (4-0)

Cost estimates for airframe, warhead, guidance subsystem, structural, and propulsion subsystems. Development of cost estimates for unique components. Use of historical cost data. Use of the Consumer Price Index and deflation factors to provide cost estimates for any given year. Cost models: RAND, Price. Model calibration. Learning curve analysis. Life -cycle cost: research & development, flight testing, production, operations, support, acquisition, spares, disposal, and indirect. Total ownership costs. Design trade studies. 4 Lectures. Prerequisite: AERO 506.

AERO 555 Sensor Technology (4-0)

Properties of microwaves: propagation, circuity, characteristics of beams in space. Radar: pulse and continuous-wave beams, scanning considerations, subsystem components, tracking and fire control, radar range, reflecting areas of targets, discrimination and resolution of targets, design considerations. Infrared: physical laws (Stefan-Boltzmann, Wien, Planck, and Kirchhoff), emissive power, radiosity, irradiation, absorptivity, reflectivity, transmissivity, transmission effects, black bodies, non-black bodies, shape factors, detectors, detector materials, subsystem components, seekers (optics, scanning characteristics, range), design considerations. Inertial: displacement and rate gyros, design considerations. Unattended sensors. Design trade studies. Prerequisite: ABET accredited upper-division undergraduate engineering course in heat transfer, or equivalent.

AERO 624L Missile Design II (0-2)

Continuation and completion of the design problem started in ARO 524L. Lectures as required. Formal oral presentation of the final design solution (by all team members) to a review panel of government and industry missile designers. Preparation of a 100 page, including the table of contents and appendices, report (with signed contributions from all team members) describing the final design solution and demonstrating how the design solution meets the given RFP requirements. Prerequisite: AERO 524L.

AERO 698 Directed Study for the Comprehensive Examination (1-2)

Directed study, supplementing coursework in the student's emphasis area, proposed by the student, with the approval of the student's advisory committee, and supervised by the Chairman of the student's advisory committee. The study should address possible topic areas, within the emphasis area, to be covered by the examination. The course should be taken during, or in the first quarter following, the last disciplinary course taken in the student's graduate program. The study should conclude with a four-hour comprehensive examination supervised by the Chairman of the student's advisory committee. Prerequisite: Advancement to Candidacy.

AERO 699 Design or Research Thesis (0-8)

Up to eight quarter units (hours) may be spent in thesis research or design. These units may be acquired in one- or two-unit increments. Each two-unit increment is expected to be the equivalent of a four-unit or four-hour lecture course. Each student working on a thesis is expected to be enrolled in this class. With strict faculty advisor(s) quality control oversight, team design or team research projects may be accepted for the individual design or thesis experience. The thesis or design project must be of an unclassified, unlimited nature. Prerequisite: Advancement to Candidacy.

## Appendix B

### Model Missile System Design Engineering Curriculum
### Representative Course Objectives

AERO 305    Engineering Mathematics    (4-0)

(1) Given an interval over which a positive, single valued, continuous function exists; the number of equally spaced increments into which the interval is divided; and the value of the function at the end points of each increment, the student will be able to compute the value of the integral over the interval by using both Simpson's Rule and Gaussian Quadrature.

(2) Given a polynomial having at least one real root, the student will be able to find all of the real roots by Newton's Method. [cognitive learning domain (application)]

AERO 310    Heat Transfer    (4-0)

(1) Given the surface temperatures on each side of a multi-layered wall, the thickness and thermal conductivity (assumed constant) of each layer, the student will be able to compute the steady state one-dimensional heat flux. [cognitive learning domain (synthesis)]

(2) For a black body radiating at a given temperature, the student will be able to compute the (a) wavelength at which the maximum monochromatic emissive power occurs; (b) the emissive power at that wavelength; (c) total emissive power; (d) fraction of the total emissive power that lies between two specified wavelengths.

AERO 315    Gas Dynamics    (4-0)

(1) Given the total pressure ratio between any two stations in an adiabatic, no-work, perfect gas, variable area flow; the upstream and downstream Mach numbers; and the upstream area; the student will be able to compute the downstream area.

(2) On an h-s diagram, the student will be able (from memory) to sketch a Rayleigh line; the corresponding subsonic and supersonic stagnation enthalpy curves; identify the sonic point of the flow; and the regions of subsonic and supersonic flow. [cognitive learning domain (knowledge); psychomotor learning domain (perceptual abilities - coordinated abilities)]

AERO 320    Aircraft Aerodynamics and Performance    (4-0)

(1) For a given airframe configuration, four specified vehicle weights, and one operating altitude, the student will be able to construct a thrust required versus free stream velocity (hardcopy or computer) graphic illustrating curves of constant weight and identify the maximum range velocity value for each weight. [cognitive learning domain (synthesis)]

(2) For a given boundary layer velocity distribution or profile, the student will be able to compute the boundary layer displacement thickness, momentum thickness, and energy thickness.

AERO 325 Strength of Materials (4-0)

(1) Given a continuous spanwise loading for a cantilever beam of specified length and constant flexural rigidity, the student will be able to compute the corresponding shear, bending moment, rotation (slope), and deflection distributions.

(2) Given the length of a column, pin-ended at both ends, and its flexural rigidity, the student will be able to compute the corresponding critical (Euler) load that can be applied axially.

AERO 500 Methods of Engineering Analysis (4-0)

(1) Given a non-singular, fourth order matrix, the student will be able to compute its inverse by the method of successive transformations using row operations. [cognitive learning domain (application), 100% performance implied]

(2) If all possible samples of a given size are drawn from a normally distributed population with a given mean and a given standard deviation, the student will be able to compute the range (ninety percent of the time) within which a given middle percentage of the sample means will fall. [cognitive learning domain (evaluation)]

AERO 503 Tensor Analysis for Engineers (4-0)

(1) Given the relationship $a_{ij}x_j$, the student will be able to expand the relation for i = 1,2,3 and j = 1,2,3,4. [cognitive learning domain (comprehension)]

(2) The student will be able to transform the vector relationship **A x (B x C)** into tensor form.

AERO 506 Variational Methods in Engineering (4-0)

(1) The student will be able to apply Hamilton's Principle to the motion of a particle of mass m on a frictionless x axis, the only force being directed toward the origin and with magnitude proportional to the displacement from the origin.

(2) The student will be able to apply Hamilton's Principle to the system of differential equations of motion, in terms of the angular (pendulum) displacements and time, of the ideal (classic) two-degree of freedom double pendulum consisting of two given masses, two weightless inextensible cords, with different angular displacements (from the vertical) for each pendulum.

AERO 510 Missile Aerodynamics (4-0)

(1) Given the ratio of specific heats for a given gas and a Mach number, the student will be able to compute the coefficients $C_1$, $C_2$, $C_3$ and D used in Busemann's Third Order Theory.

(2) Given a delta wing planform with a 50 degree leading edge sweep angle, the student will be able to compute the wing normal force coefficient (based on the planform area), for free-stream



*Proceedings of the 2005 American Society for Engineering Education Annual Conference & Exposition*

Mach numbers of M = 1.5 and M = 4.0. [cognitive learning domain (evaluation), affective learning domain (responding)]

AERO 513 Tactical Missile Propulsion (4-0)

(1) Given the ratio of specific heats for a perfect gas flowing through a converging-diverging nozzle with a specified area ratio and a given off-design exit Mach number, the student will be able to compute the operating pressure ratio ninety percent of the time.

(2) The student will be able to provide a written description of five advantages and two disadvantages of gelled propellants. [cognitive learning domain (knowledge), psychomotor learning domain (perceptual abilities – coordinated abilities)]

AERO 516 Warhead Design (4-0)

(1) The student will be able to provide a written description of three advantages and two deficiencies of plastic-bonded explosives (PBXs).

(2) For a given explosive and charge to mass ratio, the student will be able to use the Gurney equation(s) to compute the initial velocity of symmetric sandwich, cylinder, and spherical warhead liner fragments.

AERO 520 Missile Flight Analysis (4-0)

(1) Given a missile free-stream altitude and velocity, instantaneous weight, and turn radius normal (lift) force coefficient, the student will be able to compute the rate of change of the missile flight path angle, during both pull-up and pitch-down maneuvers.

(2) Given the thrust available and the thrust required (drag) at a given free-stream velocity, together with the instantaneous missile weight, the student will be able to compute the missile rate of climb.

AERO Missile Design I (0-2)

(1) Given a Request-for-Proposal (RFPs), the student will be able to construct a missile design mission profile [computer/hardcopy graphic: altitude versus time (launch to terminus, with velocity or Mach number labels)]. [cognitive learning domain (evaluation), and psychomotor learning domain (perceptual abilities – coordinated abilities)]

(2) Given a Request-for-Proposal, the student will be able to construct a three-dimensional computer/hardcopy graphic [three-view: front, side, top] of one possible configuration of a missile with volume, lifting surface, and fineness ratio sufficient to meet the needs of the customer as specified in the RFP. [cognitive learning domain (evaluation), psychomotor learning domain (perceptual abilities – coordinated abilities)]

AERO 530 Missile Structures (4-0)

(1) Given a three-dimensional coordinate system, all of the missile weight components, and their respective centers-of-gravity (or mass) relative to that coordinate system (assuming that the component weights act at the component center-of-gravity); the student will be able to compute the three coordinates the overall missile center-of-gravity.

(2) Given a three-dimensional coordinate system, all of the missile weight components, and their centers-of-gravity (or mass) relative to that coordinate system (assuming that the component weights act at the component center-or-gravity); the student will compute the missile moments of inertia: $I_{xx}$, $I_{yy}$, $I_{zz}$, $I_{xy}$, $I_{xz}$, and $I_{yz}$.

AERO 533 Hypersonic Aerodynamics (4-0)

(1) Given the blunt body radius, the shock detachment distance, and the free-stream velocity, the student will be able to estimate (compute) the stagnation point velocity gradient for both a cylinder and a sphere in hypersonic flow.

(2) Given a free-stream Mach number, the ratio of specific heats for air, and the wing angle of attack, the student will be able to estimate (compute) the lift coefficient for the wing in hypersonic flow.

AERO 536 Missile Lethality (4-0)

(1) The student will be able to provide a written description of the terms lethality, vulnerability, susceptibility, and survivability. [cognitive learning domain (knowledge), psychomotor learning domain (perceptual abilities – coordinated abilities)]

(2) Given the probability of kill-given-a-detonation, a miss distance, a guidance standard deviation, a fuze cut-off distance, a reliability factor, and a fuze factor, the student will be able to estimate (compute) the single shot kill probability.

AERO 539 Missile Guidance & Control (4-0)

(1) Given a Mach number, altitude (standard day), and the requirement to generate a specified load factor at a specified angle of attack, the student will be able to compute the effective turning rate time constant.

(2) Assuming a nonmaneuvering straight-line target course, constant target and missile velocities, a fixed point of control, and target and missile operation in a two-dimensional plane, together with the initial launching angle of the missile, the constant target altitude, and the initial slope of the trajectory, the student will be able to compute the missile flight path from launch to terminus.



*Proceedings of the 2005 American Society for Engineering Education Annual Conference & Exposition*

AERO 542 Aerodynamic Heating (4-0)

(1) Given missile operation on a standard day, the altitude of the blunt-nosed axisymmetric missile, the missile Mach number, the temperature of the blunt-nosed missile skin surface, and the missile nose radius, the student will be able to compute the stagnation point heating rate to within an accuracy of ten percent.

(2) Given the static temperature of the free-airstream, the missile skin surface temperature, the free-stream Mach number, and the boundary layer recovery factor, the student will be able to compute the (Eckert) reference temperature for missile surface flows downstream from the missile nose.

AERO 548 Missile Cost Analysis (4-0)

(1) The student will be able to use both the Consumer Price Index and U. S. government (federal) price deflators to convert given costs for goods, services and equipment from one calendar year to a second calendar year (using extrapolation, if necessary). [cognitive learning domain (synthesis)]

(2) Given the airframe weight, design speed, number of units produced during the development, flight test, and production phases, both engineering and manufacturing labor rates, motor weight, motor diameter, motor case weight, nozzle weight, nozzle throat diameter, propellant weight, insulation volume, nozzle inlet radius, free-stream dynamic pressure, warhead weight, fuzing type factor (i.e., contact or proximity), and federal price deflators, the student will be able to estimate (compute) the development, flight test, and production costs of a solid rocket powered missile.

AERO 555 Sensor Technology (4-0)

(1) Given a pen and paper, the student will be able to provide a written description of the components of radar “jitter.” [cognitive learning domain (knowledge)]

(2) Given the transmittance and a calculator, the student will be able to compute the corresponding optical density without referring to a reference manual or book. [cognitive learning domain (knowledge), psychomotor learning domain (skilled movements)]

AERO 624L Missile Design II (0-2)

(1) Given an altitude, standard day operating conditions, a range of free-stream Mach numbers, a range of axisymmetric nose radii, and the missile nose surface temperature, the student will be able to construct a carpet plot showing the impact of varying nose radius and free-stream Mach number upon the stagnation point heating rate. [cognitive learning domain (synthesis), affective learning domain (conceptualization of a value), psychomotor learning domain (skilled movements)]

(2) Given an attribute of risk, a utility function, the risk attribute requirement (e.g., rate of climb, or unit cost), the probability distribution of attribute estimates, and the consequence of failure weight, the student will be able to estimate (compute) the risk of failure associated with the given risk attribute. [cognitive learning domain (evaluation), affective learning domain (characterization of a value or value complex), psychomotor learning domain (skilled movements, i.e., placement of the attribute estimate distribution function in relation to the utility function)]