Repurposing of a Nuclear Integrated System Test Facility for Engineering Education

Dr. Hector E. Medina, Liberty University

Dr. Medina is a Professor of Mechanical Engineering at Liberty University (Lynchburg, Va.). He obtained a B.Sc. in Engineering from the Colorado School of Mines, and both an M.Sc. and Ph.D. in Mechanical and Nuclear Engineering from the Virginia Commonwealth University. Prior to graduate school, he worked in the oil industry and 7-12 education, in his native Venezuela and Aruba. Since 2012, he has published and presented about forty articles in peer-review journals and conference proceedings. Journals include Applied Mechanics Reviews, Polymer, and International Journal of Solids and Structures. He has also presented at both national and international podiums and won several awards. He recently was recognized as a co-winner of the Department of energy's FAST Prize for developing a novel Pump Storage Hydro System.

Jonathan Tristan Polk, Liberty University

Tristan is a student at Liberty University in Lynchburg, VA graduating with a bachelor's degree in Mechanical Engineering. He has worked as a Co-op for Framatome in Lynchburg, VA for the past two years gaining practical experience in the nuclear industry. Being from Lynchburg, VA, he was able to attend school and his Co-op throughout school. After graduation, he will be moving to New Jersey to work at Lockheed Martin as a Combat Systems Engineer Associate.

Re-purposing of a Nuclear Integrated System Test Facility for Engineering Education

Abstract

Nuclear energy (NE) represents more than 60% of the clean energy in the United States. Due to the great advantage that NE offers, it is important that more education that includes practical experience be made available to both undergraduate as well as graduate students. Furthermore, with the arrival of Small Modular Reactors (SMR) as a commercially available product, it is imperative that educational programs provide hands-on experience that include operations of those complex systems. However, the insurmountable costs and lengthy regulating processes render the aforementioned type of projects unfeasible.

In this paper, we discuss the potential to engineering education of re-purposing of a $40M Integrated System Test (IST) facility with a 1.7 MWt capacity, which was originally developed for the m-Power SMR design by BWXT Technologies, Inc. (a.k.a. BWXT), and it is currently located at Liberty University's Center for Engineering Research and Education, in Forest, Virginia. The aforementioned thermal-hydraulic loop could be used for complementing teaching on areas such as: controls, thermal-hydraulics, modularity in energy systems, cyber-physical systems, and many others. It will be used to contribute to existing courses such as Fluid Dynamics, Thermal-Fluids Design Lab, Mechatronics, Machine Learning, as well as nuclear engineering courses that will be developed.

Furthermore, the paper provides a rationale for the need to integrate the use of the IST as part of the experiential-learning approach of our engineering curriculum. The rationale is threefold: (1) the nature of our hands-on teaching philosophy, (2) the advent and relevance of SMRs and need of trained workforce, and (3) the ongoing need of engineering programs to be submerged in active interactions with local industry as well as provide our engineering students with real-world experience.

Introduction

According to the Virginia Nuclear Energy Consortium, nuclear energy from commercial Pressurized and Boiling Water Reactors (PWRs and BWRs, respectively) constitutes about 39% of Virginia’s electrical grid, more than 99% of Virginia’s emission free energy. Given nuclear’s clean energy advantages of high power density, reliability, and low land-use, it is imperative that more research be carried out, and that more practical academic experiences be made available to both undergraduate and graduate students. In addition, the entrance of (Light Water Reactor) LWR-based Small Modular Reactors (SMRs) has created a need for more facilities that can provide testing and validation services for this reactor design. However, the cost and regulations involved with setting up nuclear test facilities—for academic purposes—make the foregoing difficult, only accomplished by a limited number of universities in the nation.

BWXT is a provider of critical components and services to the United States government and commercial customers. They primarily work with nuclear technologies. BWXT developed an Integrated System Test (IST) facility. Integrated System Test facilities are designed to model nuclear reactors for the purposes of testing and validation. The BWXT IST facility is a 1:1 elevation scale thermal hydraulic test loop for the mPower SMR [1], which retains broad similarity with commercial PWRs [2]. Due to this and its fully integrated primary and secondary plants with a full feedwater and steam system on the secondary side, it is a one-of-a-kind IST. It is located at the Center for Engineering Research and Education (CERE) owned by Liberty University. This building is home to several companies and serves as a location in which engineering students can collaborate with industry on current research. There are several different labs at CERE including capabilities for advanced 3D printing, Electron Microscopy, and Non-Destructive testing. The element that stands out the most at CERE is the over 100-foot-tall tower which contains the IST facility whose construction finished in 2012 at a cost of $40 million. The IST is a fully equipped pilot-scale thermal hydraulic test loop and a unique learning and training environment for students focused on the energy sector. This IST is also a rare and valuable environment for cyber-physical system research. A team currently using the IST extensively for this purpose is the International Critical Infrastructure Security Institute (ICISI) headquartered at the CERE.

Background

Scaled-down thermal-hydraulic test loops are a common method in the nuclear industry for obtaining critical information for the design and operation of new fuel and reactor design types. When developing a reduced-scale testing facility such as this IST, it is important to choose for which characteristics similitude is desired. Since a full-scale model would be impractical and it is impossible to emulate all of the characteristics of a full-scale model in a scaled facility, it is important to prioritize which characteristics of the IST will be accurately comparable to the full-scale reactor. The scaling-basis of the IST originated from the method of Ishii and Kataoka and confirmed using the hierarchical two-tiered scaling (H2TS) method developed by Zuber [2-5]. The H2TS method is two-tiered because it uses both a top-down and a bottom-up hierarchy to approach the problem of organizing what components should be scaled and how they should be designed. The top-down hierarchy derives scaling groups and a methodology which is all-encompassing and is traceable. The bottom-up approach focuses on the specific processes involved in the IST being scaled. It ensures that the individual processes are controllable and return useful scaled data [5]. The top down hierarchy was used to show the characteristics involved with the mPower plant, different event scenarios, and process characteristics. The bottom-up method was used to assess problem variables that would be involved with the development of the IST [2]. The Phenomena Identification and Ranking Table (PIRT) process [6] was used to fulfill these two hierarchies and rate the importance of their contents—in that it was used to identify the more important phenomena that occur in one particular Design Basis Accident (DBA) and rank them according to the desired importance of accurately recreating that event. BWXT developed a PIRT around what they believed to be the maximum hypothetical accident for the mPower SMR, a Loss of Coolant Accident (LOCA). Characteristics of a LOCA include depressurization of the Reactor Coolant System (RCS), a Reactor Trip followed by the stabilization of pressure and recovery of coolant in the RCS by a passive Emergency Core Cooling System (ECCS). From the PIRT exercise, a list of events that were essential for the scaled-facility to recreate was developed. This included[2]:

- Loop thermal-hydraulics, natural circulation (NC), and entrainment
- Steam Generator primary/secondary heat transfer
- Pressurizer phasic heat and mass transfer
- Break flow (RCS mass and energy release)
- Containment pressurization
- Accumulator/RWST coolant injection
- Vessel and fuel stored energy
- Reactivity feedback
- Fission product decay heat

With the above priorities in mind, BWXT then conducted a scaling analysis to determine how this IST must be scaled to achieve the desired test conditions listed above. The goal of their scaling analysis was to preserve as much similitude as possible to support a broad suite of events important to safety, while prioritizing on the most severe (i.e., the LOCA). Once this analysis was completed and the guidelines for the construction of the IST were clear, these parameters were experimentally validated. The validation was done in two rounds. The first round of tests involved operational tests that supported the development of analytical models and simulation of this IST. The second round of tests involved executing tests emulating DBAs such as LOCAs.

The BWXT team completed the tests and provided the different aspects that were preserved in the scaled IST. The core region, heat transfer, flow patterns, and coolant inventory in the downcomer, core and the riser above the core were all kept in similitude with an actual reactor. The steam generator preserved the heat transfer and boiling effects and the condensation with and without non-condensable gases [2]. Outside of these, the design of the IST included features to support its adaptation for other design or research missions.

While testing in support of the mPower SMR ended in 2014, the facility has been maintained to support other projects. The facility is still in use by several companies and Liberty University for the purposes of furthering nuclear engineering research on multiple fronts.

Description of Thermal Hydraulic Test Loop

The BWXT IST is fully equipped for pilot-scale thermal-hydraulic testing. Fig. 1 presents a full 3D depiction of the IST as it currently appears at the CERE in Forest, VA. The IST has electrical heaters emulating nuclear fuel rods, a steam generator, pressurizer and an ECCS served by the coolant inventory of a large Refueling Water Storage Tank (RWST), a Reactor Coolant Inventory and Purification (RCIP) system, and balance of plant systems such as a full feed and steam system. This IST was scaled to be full height but 1/345 the area and volume of the actual systems (based on the original mPower SMR full power of 425 MWth).

There are 60 electrically heated rods emulating a nuclear core. It includes multiple thermocouples for measurements and a Monel alloy sheath to prevent corrosion or other forms of damage. The steam generator is a once-through 19 tube alloy 690 B&W design. The pressurizer resides near the inlet of the steam generator and is connected to the large tanks representative of the mPower SMR's RWST and containment. There are also intermediate pressure injection tanks which can inject water from pressures up to 1500 psia. The feed and steam system on the secondary side are able to control inlet water temperature to the steam generator. This control has precision from ambient to more than 400°F. The feed flow, feed preheater, and primary condenser fan are all controlled by variable frequency drives that can be fine-tuned and have algorithmic capabilities for a number of different design scenarios. The RCIP system has a high-pressure pump and a low-pressure pump. The high-pressure pump provides flow for letdown and make-up of the RCS while the low-pressure pump is designed for long-term cooling scenarios. The RCIP system also has two regenerative and three non-regenerative heat exchangers which control the temperature of the fluid from the RCS. The RCIP system also monitors the chemistry of the water continuously. These systems are all highly adaptable. This leads to a high research value for this IST due to the large range of merely physical tests that can be run using this IST.

The IST has two primary modular areas for further expansion of its research capabilities. The first is a 5-foot removable test section above the core heaters that can be replaced with several different components such as a sapphire windowed pipe for visual access to flow, a test heater can be put inside the 5-foot length, and a component to create a slip stream for research into a tertiary loop in order to lift cleanliness requirements. To assist with this, materials, dyes, and chemicals can be added to the tertiary loop.

The second modular section is a 5-inch diameter test port in a flange perpendicular to the RCS. This area has dynamic flow regimes during all modes of operation. The port has the option for the installation of advanced instruments similar to the 5-foot removable section.

The IST also has a full-scale control center that receives almost 1200 data points per second from over 500 different sensors on the IST. The IST provides an opportunity for research into all the systems, the data stream, and the human interactable elements that exist in a typical control room. This control center can be used to test computer code to ensure proper function in any scenario and test digital platforms to verify they can handle the necessary calculations and other such work that needs to occur on the thousands of data points coming in.

Previous Projects

Much research and testing has already been conducted using the IST at CERE. BWXT, ICISI, CAER, and Liberty University have all used the IST for multifarious forms of research and testing.

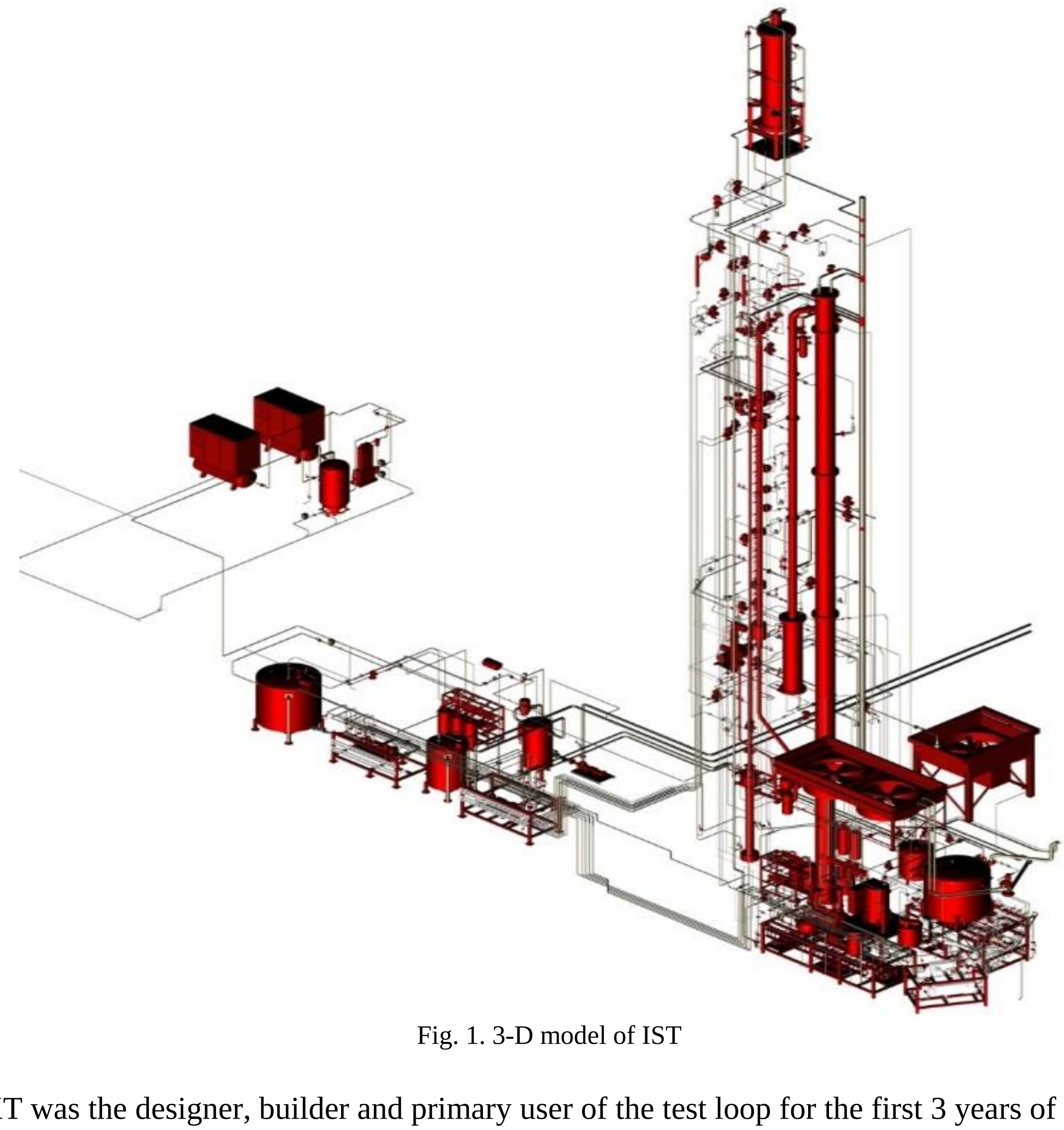

Fig. 1. 3-D model of IST

BWXT was the designer, builder and primary user of the test loop for the first 3 years of its life. These tests include LOCA events for the IST involving different break sizes, overheating and over cooling events as well as loss of flow transients. BWXT also tested and verified the steam generator, the

ECCS, and the natural circulation system. Further testing was done on various leak scenarios involving the primary and secondary systems. Most of this research went toward providing design verification for the mPower SMR design.

ICISI is "a research and workforce development organization that specializes in cybersecurity and the protection of critical infrastructure from cyber-based threats." This 501(c)(6) organization focuses on cyber security in research and in industry. ICISI's research at the IST involves highly invasive and disruptive cyber-physical tests to verify the resilience of important control systems in a real reactor to cyber-attacks. ICISI also tests new protection systems for ability to defend against cyber-attacks. Liberty University has conducted similar cyber-security testing under the lead of its center for cyber excellence. This research focused on protecting core-systems from being hacked and purposefully tampered with in a way to cause a reactor meltdown.

Implementation in the School of Engineering

In this section, rationale will be presented for the need to integrate the use of the IST as part of the experiential-learning approach of our engineering curriculum. With that, we seek to better prepare our graduates for the current challenges in the work place.

Rationale 1: *Hands-on teaching philosophy*. As a follow-up to the landmark Grinter Report [7], Froyd, Wankat, and Smith summarized "what has reshaped, or is currently reshaping, engineering education over the past 100 years." [8] The five shifts identified were the following:

1. A shift from hands-on and practical emphasis to engineering science and analytical emphasis;
2. A shift to outcomes-based education and accreditation, leading to the establishment of ABET and its predecessors;
3. A shift to emphasizing engineering design, especially in the capstone design course and first-year foundational design course, but not so much during the mid-years courses;
4. A shift to applying education, learning, and social-behavioral sciences research (i.e., "engineering education"); and
5. A shift to integrating information, computational, and communications technology in education.

Embracing both the spirit and the letter of the five major shifts in engineering education, the LU School of Engineering and Computational Sciences was established in 2007. Four engineering programs were initially offered with 44 incoming freshman. The first Electrical Engineering, Software Engineering, and Industrial & Systems Engineering graduates received their degrees in 2011, with the first Computer Engineering graduates following in 2012. Although the Software Engineering program was subsequently dropped, the Electrical and Industrial & Systems Engineering programs received initial ABET accreditation in 2012, followed by Computer Engineering in 2013. Mechanical Engineering began in 2014 and produced its first graduates in 2018, with ABET accreditation currently (as of January 2019) pending. The Electrical, Computer, and Industrial & Systems Engineering programs were all reaccredited by ABET in 2018. The Computer Science programs were transferred to the School of Business in the spring of 2018, resulting in the renaming of the Liberty University School of Engineering (LUSE). Civil Engineering will start in the 2019-20 school year, and Computational Engineering is planned for 2020-21. The number of declared engineering majors has grown steadily reaching a peak enrollment of 518 in the 2018-2019 school year.

The current LUSE approach to engineering education consists of a traditional lecture/laboratory residential-based program conducted at the campus of LU in Lynchburg, Virginia. Students in the program have the option of taking their general education courses through LU Online to help provide flexibility in their scheduling. Continuing with the LU founder's vision, LUSE is committed to an ethical based philosophy producing men and women with the values, knowledge, and skills necessary to impact tomorrow's technology-related disciplines. Students have access to modern facilities and technology and qualified faculty seek to know their students personally and to provide them with opportunities for education, research, and a professional career. One-on-one faculty interaction, combined with a value-center campus environment, helps prepare graduates for a lifetime of service. The LUSE degree programs encourage undergraduate research and the effective application of technology from holistic worldview, and LUSE faculty are proactive in their involvement in professional societies, professional certification programs, and engineering education research [9-12].

Rationale 2: Small modular reactors. Nuclear energy (NE) represents more than 60% of the clean energy in the United States. Due to the great advantage that NE offers, it is important that more education that includes practical experience be made available to both undergraduate as well as graduate students. Furthermore, with the arrival of Small Modular Reactors (SMR) as a commercially available product, it is imperative that educational programs provide hands-on experience that include operations of those complex systems. However, the insurmountable costs and lengthy regulating processes render the aforementioned type of projects unfeasible.

Rationale 3: Bridging the Valley of Death. The “Valley of Death” (VOD) is a metaphor for getting from basic research to successful application [13]. This VOD is characterized as the gap between the dynamics of “technology-push” and “market-pull” in which research leading to new technologies often fails to reach the market place. The technology-push concept is based on the perspective that a novel scientific discoveries will generate innovations ending with commercialization of a new technology or product. From this view, the users’ needs have a relatively minor role in determining the pace and direction of technological innovation. On the other hand, the industry-pull concept is based on the view that users’ needs are the key drivers of innovation, thereby suggesting that companies should pay more attention to the needs of users. In other words, established industries are reluctant to embrace new technology unless there is a demonstrated market based on user demand.

Based on the aforementioned arguments, it is imperative that our programs be submerged in active interactions with local industry as well as provide our engineering students with real-world experience. The IST provides some of that opportunity by allowing students with hands-on experience on topics such as: Autonomous systems; Cyber-physical systems; Cyber-security; Thermal-hydraulics; Energy generation; Sensors and actuators; Controls; etc. These topics are being embedded in some of our engineering courses: Mechatronics, Thermal-fluids lab, Fluid Mechanics, Thermodynamics II, Heat Transfer, Mechanics of Materials, Machine Learning, and Dynamic System Modeling. In addition, there are 12 more courses being developed as part of a list of concentrations, which include mechatronics and energy Systems.

Other Potential and Future Projects

Due to the high level of modularity of the repurposed IST and the variety of research opportunities that are possible, there is a wealth of knowledge to be obtained for both academia and industry from the

IST. Moving forward, BWXT in collaboration with the CERE is planning to use the IST to advance knowledge on the thermal hydraulics of novel LWR designs. There is also a plan to replace the current 5-foot removable test section above the heat region with a heat exchanger to support a tertiary loop in order to study thermal-hydraulic characteristics of molten salt as a coolant. The tests with the molten salt will not be focused around particular SMR designs but will be focused on the behavior of molten salt as a coolant generally, and its behavior in various scenarios.

ICISI will continue to utilize the IST for cyber-security testing for new technologies or verification of old ones. This includes protecting current technologies against cyber-attacks. It also includes verifying new control room technologies resilience to operating conditions. CERE will continue to seek out new opportunities for co-operative research with between companies and universities.

Framatome has also expressed interest in utilizing the IST facilities. Framatome "designs, manufactures, and installs components, fuel and instrumentation and control systems for nuclear power plants and offers a full range of reactor services." Framatome's interest includes R&D into SMR. They are currently involved in developing fuel for the NuScale SMR. They also desire to focus on testing for the purpose of maintenance and repair research.

Conclusions

This paper has presented a discussion on the re-purposing of a $40M Integrated System Test (IST) facility with a 1.7 MWt capacity, which was originally developed for the m-Power SMR design by BWXT, and it is currently located at LU's CERE, in Forest, Virginia. The so-called "test loop" is equipped with a full-scale control center, which receives almost 1200 data points per second over 500 different sensors; it also has core heaters, a steam generator, pressurizer and emergency core cooling system, a reactor coolant inventory and purification system, full feed and steam systems, and other modular components as part of the balance of plant. The aforementioned thermal-hydraulic loop is being used for complementing teaching on areas such as: controls, thermal-hydraulics, modularity in energy systems, cyber-physical systems, and many others. It will be used to contribute to existing courses such as Fluid Dynamics, Thermal-Fluids Design Lab, Mechatronics, Machine Learning, as well as nuclear engineering courses that will be developed.

Liberty University will utilize the IST as a path to get students who are interested in the energy sector involved in real-world, cutting-edge research with industry leaders. Liberty University students will have access to the IST for broad cyber-physical systems research and development.

LU's CERE is open to welcoming other universities, research institutions, and companies to propose and carry out research and educational projects that involve the use of the IST.

References

1. Martin, R. P., Williams, E. S., & Williams, J. G., "Thermal-Hydraulic Design of the B&W mPower SMR," The 15th International Topical Meeting on Nuclear Reactor Thermal – Hydraulics (NURETH-15), Pisa, Italy, May 12-17, 2013.
2. Martin, R. P., Miller, J. K., & O'brien, J. E.. "A Scaling-based Applicability Assessment of the CAER Integrated Systems Test Facility." BWX Technologies Inc. and Idaho National Laboratory. (n.d.).
3. Ishii, M., Kataoka, I., "Scaling criteria for LWR's under single phase and two-phase natural circulation," Proceedings of the Joint NRC/ANS Meeting on Basic Thermal Hydraulic Mechanisms in LWR Analysis, NUREG/CP-0043, Bethesda, MD, (1982).

4. Ishii, M., Kataoka, I., “Similarity and scaling criteria for LWR’s under single-phase and two-phase natural circulation,” Argonne National Laboratory, ANL-83-32, NUREG/ CR-3267 (1983).
5. Zuber, N. “A Hierarchical, Two-tiered Scaling Analysis, an Integrated Structure and Scaling Methodology for Severe Accident Technical Issue Resolution.” US Nuclear Regulatory Commission. (1991).
6. Wilson, G. E., & Boyack, B. E.. “The Role of the PIRT Process in Experiments, Code Development and Code Applications Associated with Reactor Safety Analysis.” *Nuclear Engineering and Design, 186*, 23, (1998).
7. L. E. Grinter, “Summary of the report on the evaluation of engineering education,” Journal of Engineering Education, vol. 46, pp. 25-60, 1955.
8. J. Froyd, P. Wankat, and K. Smith, “Five major shifts in 100 years of engineering education,” Proceedings of the IEEE, vol. 100, pp. 1344-1360, 2012.
9. C. I. Pettiford, “3-Course Capstone Sequence,” Proceedings of the Capstone Design Conference, Columbus, OH, 2014.
10. C. I. Pettiford, “Enhancing visualization of magnetic fields in Electromagnetic Fields Course,” Proceedings of the ASEE Annual Conference, New Orleans, LA, 2017.
11. J. L. Long, and C. Ziebart, “First-Year Program Enhancements at Liberty University,” Proceedings of the FYEE Annual Conference, Daytona Beach, FL, 2017.
12. H. E. Medina and K. M. Ceffaratti, (2015, June), “Novel Visual Algorithm to Teach Benefit-cost Ratio Analysis,” Proceedings of the ASEE Annual Conference, Seattle, Washington, 2015.
13. D. Ford, and J. Dillard, “Crossing the Technology Valley of Death: The Case of the MDUSV”, Calhoun: The NPS Institutional Archive, 2018.