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Improving Predictive Capabilities of Classical Cascade Theory for Nonproliferation Analysis

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To the Graduate Council:

I am submitting herewith a dissertation written by David Allen Vermillion entitled "Improving Predictive Capabilities of Classical Cascade Theory for Nonproliferation Analysis." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Nuclear Engineering.

Howard L. Hall, Major Professor

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Improving Predictive Capabilities of Classical Cascade Theory for Nonproliferation Analysis

A Dissertation Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

David Allen Vermillion

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DEDICATION

I dedicate my academic achievements to the family, friends, high school teachers, professional mentors, and complete strangers who chose to provide unwavering encouragement and support in my times of need. Very few have the courage and character to continually believe and invest in others after all motivations of self-interest have been removed. I have been extremely fortunate to have met and relied on so many altruistic individuals. You know who you are, and I sincerely thank you. Your collective selfless acts of kindness have defined who I am and who I will eventually become.

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I would also like to thank Bill Strunk, Len Phillips, Carolyn Andrews, Christopher Poe, and Mike Goss who always kept me on task and made sure that I never said anything I wasn't supposed to. A special thanks to Patrick D. Williams, whose conversations always got me thinking and questioning ideas and concepts that I thought I knew. Patrick has been a great friend and the best research partner a person could ask for, and I appreciate all the work you have done to help me make this research successful.

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ABSTRACT

Uranium enrichment finds a direct and indispensable function in both peaceful and nonpeaceful nuclear applications. Today, over 99% of enriched uranium is produced by gas centrifuge technology. With the international dissemination of the Zippe archetypal design in 1960 followed by the widespread illicit centrifuge trafficking efforts of the A.Q. Khan network, traditional barriers to enrichment technologies are no longer as effective as they once were. Consequently, gas centrifuge technology is now regarded as a high-priority nuclear proliferation threat, and the international nonproliferation community seeks new avenues to effectively and efficiently respond to this emergent threat.

Effective response first requires an accurate and dependable predictive capability. Modern scientific efforts have focused on predicting the hydrodynamics within a single centrifuge. Unfortunately, a single centrifuge alone is not a viable proliferation threat. An arrangement of hundreds or thousands of centrifuges operating in concert to produce meaningful quantities of enriched uranium, however, is. Such an arrangement is called a cascade, which represents the indivisible unit of the enrichment proliferation threat. Cascade theory was deemed a conquered science since before the advent of the gas centrifuge. It is suspected that the international nonproliferation community requires more robust developments in cascade theory rather than centrifuge hydrodynamics models.

Consequently, many of the traditional cascade analysis methodologies still heavily rely upon ideal cascade theory developed during the Manhattan Project and its modest improvements since. This study proposes a modern theory of cascade dynamics to compliment classical ideal cascade theory. This novel contribution includes the addition of time-dependent and non-ideal cascade analysis.

The benefits of employing cascade dynamics are demonstrated in this study using the NonProliferation Analysis of Centrifuge Cascade (NPACC) methodology. NPACC estimations are benchmarked to traditional ideal cascade analysis methods currently used by the nonproliferation community. It is discovered that traditional methods are unequipped to accurately estimate the performance of realistic centrifuge cascades as their physical design and feed rate result in deviations from ideal conditions. Implementation of cascade dynamics is expected to more accurately predict the performance of centrifuge cascades and therefore better meet the needs of the international nonproliferation community.

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VITA

David A. Vermillion graduated as valedictorian from Greenback High School in May 2003. David initially pursued a career with the United States Navy as a nuclear engineer submariner and was sworn into U.S. military service in September 2002 as a delayed-entry enlisted seaman. This career path was short-lived due to a motor vehicle accident in 2003 that resulted in a traumatic head injury and a honorable medical discharge from military service. Despite these injuries and complete lack of financial support, David enrolled at Roane State Community College from August 2003 – November 2004 to continue pursuit of a career as an engineer. He enrolled at The University of Tennessee in August 2005 to pursue an undergraduate degree with the Department of Nuclear Engineering.

As part of his undergraduate career, David participated in The University of Tennessee College of Engineering's Cooperative Education Program between May 2006 – August 2009. During this period, David was employed full-time by Southern Nuclear Company for five alternating semesters. The first two co-op semesters were spent at the Alvin W. Vogtle Electric Generating Plant located at Waynesboro, GA gaining invaluable hands-on experience as a nuclear reactor engineer. David was stationed at Southern Nuclear Company Headquarters in Birmingham, AL for the other three co-op semesters. During his time at Birmingham, David designed and analyzed six light water reactor cores located in the southeastern United States.

During his alternating academic semesters, David was heavily involved in professional societies and undergraduate research. He initially formed the University of Tennessee's Institute for Nuclear Material Management (INMM) student chapter and served as its founding president from 2008-2010. David also served as the vice president of the American Nuclear Society (ANS) student chapter between 2009-2010. David was recognized for his undergraduate research where he was awarded scholarships from U.S. Department of Energy (DOE) and the Nuclear Energy Institute's National Academy for Nuclear Training (NANT). David graduated with his Bachelor's of Science in Nuclear Engineering in May 2010.

In August 2009, David passed the Nuclear Engineering PhD qualifying exam as an undergraduate senior and was quickly accepted into graduate school at The University of Tennessee's Department of Nuclear Engineering. David's research interests transitioned away from commercial nuclear reactor operation and design to the nuclear security arena. In May 2010, David began working full-time under the auspices of Dr. Howard Hall at Oak Ridge National Laboratory (ORNL) to support nuclear nonproliferation and international safeguards activities that leveraged his previous background within the nuclear industry. In

May 2012, David earned his Master of Science by designing and simulating prototypes of ORNL's Radiological Signature Training Devices. The fabrication of these devices eventually matured into a highly successful ORNL program and have since been employed by several U.S. government agencies to bolster national security. David was inducted into The University of Tennessee's Honor Society of Phi Kappa Phi in Spring 2012.

From June 2012 – July 2013, David was recognized for his graduate research and was awarded the prestigious position of Nonproliferation Graduate Fellow with the National Nuclear Security Administration (NNSA) Office of Research & Development. During this one year sabbatical, David was stationed at DOE headquarters in Washington, D.C. where he assisted in the federal management of approximately $8M in appropriated funding to fundamental research directed at detecting foreign nuclear weapons development activities; to support nuclear arms control treaties verification and monitoring for compliance; and to support national nuclear security more broadly.

In July 2013, having been awarded a competitive, federally-funded fellowship to pursue a technical doctoral degree dedicated to nuclear nonproliferation as a NNSA Nuclear Nonproliferation & International Safeguards (NNIS) fellow, David returned to The University of Tennessee to complete his academic career. In light of the increasing number of clandestine established uranium enrichment programs between 1991-2010, David chose to pursue a dissertation topic that would advance U.S. technical capabilities to counter and safeguard against the misuse and clandestine establishment of uranium enrichment technologies.

At the time of graduation, David continues to work full-time at ORNL supporting U.S. government nuclear security needs.