2017

# An SoS Conceptual Model, LVC Simulation Framework, and a Prototypical Implementation of Unmanned System Interventions for Nuclear Power Plant Disaster Preparedness, Response, and Mitigation

Matthew Davis
*University of Central Florida*

# AN SOS CONCEPTUAL MODEL, LVC SIMULATION FRAMEWORK, AND A PROTOTYPICAL IMPLEMENTATION OF UNMANNED SYSTEM INTERVENTIONS FOR NUCLEAR POWER PLANT DISASTER PREPAREDNESS, RESPONSE, AND MITIGATION

by

MATTHEW T. DAVIS
B.S. Southwest Baptist University, 2001
M.S. Air Force Institute of Technology, 2009

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Industrial Engineering and Management Systems
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Summer Term
2017

Major Professor: Michael D. Proctor

## ABSTRACT

Nuclear power plant disasters can have severe and far-reaching consequences, thus emergency managers and first responders from utility owners to the DoD must be prepared to respond to and mitigate effects protecting the public and environment from further damage. Rapidly emerging unmanned systems promise significant improvement in response and mitigation of nuclear disasters. Models and simulations (M&S) may play a significant role in improving readiness and reducing risks through its use in planning, analysis, preparation training, and mitigation rehearsal for a wide spectrum of derivate scenarios. Legacy nuclear reactor M&S lack interoperability between themselves and avatar or agent-based simulations of emergent unmanned systems. Bridging the gap between past and the evolving future, we propose a conceptual model (CM) using a System of System (SoS) approach, a simulation federation framework capable of supporting concurrent and interoperating live, virtual and constructive simulation (LVC), and demonstrate a prototypical implementation of an unmanned system intervention for nuclear power plant disaster using the constructive simulation component. The SoS CM, LVC simulation framework, and prototypical implementation are generalizable to other preparedness, response, and mitigation scenarios. The SoS CM broadens the current stovepipe reactor-based simulations to a system-of-system perspective. The framework enables distributed interoperating simulations with a network of legacy and emergent avatar and agent simulations. The unmanned system implementation demonstrates feasibility of the SoS CM and LVC framework through replication of selective Fukushima events.

Further, the system-of-systems approach advances life cycle stages including concept exploration, system design, engineering, training, and mission rehearsal. Live, virtual, and constructive component subsystems of the CM are described along with an explanation of input/output requirements. Finally, applications to analysis and training, an evaluation of the SoS CM based on recently proposed criteria found in the literature, and suggestions for future research are discussed.

# TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

# CHAPTER ONE: INTRODUCTION

With over 500 reactors either operating or under construction worldwide (WNA, 2015), nuclear power is a major component of the future of energy for the planet. Further, with 28 new reactors under construction in the United States and many more filing for extensions to operate up to 60 years, the nuclear power presence in the US stands to grow by nearly 30% over the next several years (NRC, 2015b). While nuclear power is relatively clean and efficient when compared with fossil fuel energy production, it is a complex and dangerous endeavor. The relatively short history of nuclear power is peppered with incidents and accidents (DOE, 2015; NRC, 2014a, 2014b; OPA, 2013a, 2013b; TEPCO, 2013). Those involved with nuclear power production understand the danger and have taken extensive measures in the form of monitoring and safety systems as well as personnel training. However, despite these preparatory efforts, an event may quickly grow beyond the capacity of on-site personnel to contain. Additional response efforts then fall to the utility company, local, state, and federal government agencies, or military organizations like the Joint Task Force Civil Support (JTF-CS) (JTF-CS, 2015b).

The most recent of these incidents occurred March 11, 2011 when an unprecedented earthquake struck off the east coast of Japan. One of the Tokyo Electric Power Company's (TEPCO) nuclear power plants known as Fukushima Dai-ichi was located on the coast near the epicenter. The plant's design and safety operations left the heart of the power plant, the nuclear reactors, undamaged from the quake, despite its magnitude being well beyond the

design basis of the plant. The quake damaged offsite power delivery systems causing the plant to transfer over to diesel generator back up power. This meant that monitor and cooling systems for the reactors continued without interruption. However, when the tsunami struck 50 minutes later and overtopped the seawall, the generators and backup batteries were flooded and failed. Figure 1 illustrates the magnitude of the tsunami compared with the defenses and backup systems of the plant.

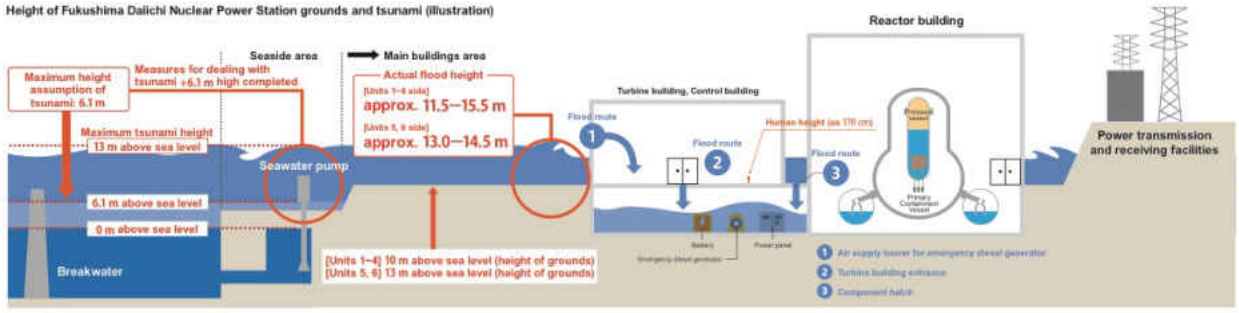



**Figure 1: Fukushima NPS and tsunami**
**Source: TEPCO (2013)**

The resultant power failure meant plant operators were unable to monitor and maintain cooling in the reactors. Without power supplied to coolant injection pumps, the coolant within the pressure vessels of the reactors began to heat up and eventually boil despite its high pressure. As coolant continued to boil off the fuel rods became exposed to the superheated steam building at the top of the reactor. The fuel began to swell as its temperature rose creating cracks in the zirconium cladding of the fuel rods thus releasing radioactive material into the coolant within the pressure vessel. The zirconium cladding also began to react with the high temperature steam to produce hydrogen gas. Eventually, the pressure inside the pressure

vessels became so great that emergency relief valves opened automatically venting radioactive materials and hydrogen gas to the suppression pools and eventually into the containment building. Eventually the core fuel heated up enough that it melted, forming a superheated mass at the bottom of the pressure vessel. It melted through the bottom of the pressure vessel into the primary containment vessel. This scenario played out in essentially the same way in units 1, 2, and 3 (TEPCO, 2013).

The hydrogen vented into the suppression pools in units 1-3 eventually made its way into the containment buildings where it began to build in concentration. Additionally, the ventilation systems of units 3 and 4 were connected and hydrogen from unit 3 made its way into unit 4's containment building as well (TEPCO, 2013). The buildup of hydrogen gas in units 1, 3, and 4 led to explosions that destroyed the tops of their respective containment buildings in the days immediately following the earthquake, tsunami, and site-wide power loss (TEPCO, 2013).

Unit 4 was shut down for maintenance and refueling at the time of the earthquake (TEPCO, 2013). This meant that an unusually large amount of fuel was in the spent fuel pool at the time including a full load of 548 spent fuel assemblies removed from the reactor in November 2010 (WNA, 2012). Including 204 fresh fuel assemblies, Unit 4's Spent Fuel Pool (SFP) contained 1,535 fuel assemblies at the time of the accident (G. o. Japan, 2011). This was very near it maximum capacity of 1,590 assemblies. This amount of total and recently active

fuel in the SFP created a significant heat load within the pool with estimates ranging from 2.26 to approximately 3 MW thermal (G. o. Japan, 2011; WNA, 2012).

Emergency managers considered fuel exposure from evaporative loss to be a relatively low threat immediately following the accident as estimates put the exposure point in late March (TEPCO, 2013). Consequently, emergency managers focused their attention and efforts on other aspects of the disaster. This calculus changed after the explosions in 1,3, and 4 introduced the possibility of damage to fuel assemblies from falling debris; damage to the pool itself potentially creating a drain down of coolant; or both. A rapid loss of coolant from a pool containing damaged and leaking fuel assemblies in a containment building where only portions of the superstructure remained became an urgent problem as a massive release of radioactive material directly into the atmosphere and surrounding environment became a very real possibility.

"…[O]ne of the lessons learned from the events is that the progression of the accident at one unit had a big impact on restoration work at the other units" (TEPCO, 2013). The events at Fukushima illustrate how the complex nature of nuclear power systems coupled with the unpredictability of natural events can have synergistic effects and quickly turn minor incidents into major catastrophes with global impact. Nuclear contaminants from Fukushima spread not only through the air over a large area of Japan (UNSCEAR, 2014), but because of its proximity to the sea were dispersed by currents in the Pacific ocean reaching measurable levels in the western United States (EPA, 2011). Similarly, earlier notable accidents like Three Mile Island

and Chernobyl illustrate the synergistic effects of complex systems design and human behavior resulting in severe accidents with long term global effects (OPA, 2013a, 2013b). Contaminants from Chernobyl spread across Europe affecting millions of people. To date, 6000 cases of child and adolescent thyroid cancer have been linked to radiation from Chernobyl (OPA, 2013a) and more are likely as many of the 600,000 workers tasked with various response and clean up duties after the accident and millions of affected residents of contaminated areas begin to age and die.

Response to such severe situations requires the most effective and efficient tools available. Historically, incident managers have employed a wide range of tools when responding to nuclear disasters (G. o. Japan, 2011; T. Johnson, 2006). Often those tools are employed in an ad hoc fashion as managers work feverishly to mitigate further damage.

One such tool, helicopters have often been a popular choice during response and mitigation efforts. Helicopters were used at Three Mile Island to sample atmospheric radioactivity above the plant shortly after the event began (OPA, 2013b). At Chernobyl helicopters were used to deliver a sand and boron mixture directly onto the fire, molten core, and contaminated reactor debris (OPA, 2013a). This was done using both slung loaded buckets and by the crew hand dumping bags from the cabin of the aircraft. At Fukushima Dai-ichi, in an effort to prevent fuel meltdown, helicopters attempted to dump fresh water into spent fuel rod cooling pools (NRC, 2012).

The use of manned helicopters in these environments put aircrews at substantial risk of radiation exposure. The crew of the helicopter used at Three Mile Island was tasked with sampling radiation levels that were as yet completely unknown. Helicopter crews at Chernobyl were tasked with operating directly within the highly radioactive plume of super-heated gas rising from the burning rubble where the reactor had been. The exposure of these crews to massive amounts of radiation led to many deaths (T. Johnson, 2006). In addition to the dangers of the radiological environment helicopters may be tasked to operate within, there are significant dangers associated with operating near the structures and super structures commonly found at nuclear reactor sites. Illustrative of this danger is the crash that occurred at Chernobyl when one of the helicopters struck crane cables near the reactor and fell from the sky killing the entire crew (Pripyat.com, 2006). Finally, at Fukushima emergency managers were extremely concerned with the potential for aircrew radiation exposure. Crew areas of the Japan Defence Force helicopters were lined with lead prior to flying missions over Fukushima. Further, operational and flight profiles were severly limited to protect crews and as a result mission capability was impacted so much that attempts to deliver sea water via helicopter to the cooling pools were quickly abandoned (JDF, 2011).

The preceding examples serve a dual purpose. First they demonstrate the long standing recognition within the nuclear disaster response community that air assets, and specifically helicopters are capability multipliers and have undeniable utility across multiple phases of the

response and mitigation effort. Secondly, they demonstrate the real, known, mission impacting risks associated with employing manned aircraft in response to a nuclear disaster.

While not part of the initial response to the disasters, unmanned systems were used at both Chernobyl and Fukushima Dai-ichi to aid in the recovery phase of emergency management. At Chernobyl remotely operated vehicles cleared highly radioactive debris from a rooftop (T. Johnson, 2006). At Fukushima Dai-ichi, TEPCO is currently using a variety of ground and submersible systems to assist in recovery within the reactor buildings (Oikawa, 2015).

Unmanned Aerial Vehicles (UAVs) "are used for missions that are 'dull, dirty, and dangerous'" presenting "a high risk factor for pilots" (van Blyenburgh, 2000). UAVs are rapidly being adopted by disaster response agencies even while the research and literature in this area is still limited (Tomaszewski, Judex, Szarzynski, Radestock, & Wirkus, 2015). Advances in unmanned system technology now allow missions previously assigned to manned helicopters to be accomplished using Rotary-wing Unmanned Aerial Systems (RUAS) (Alexis, Nikolakopoulos, Tzes, & Dritsas, 2009; Bernard, Kondak, & Hommel, 2008; Marconi et al., 2012; Mase, 2013; McGonigle et al., 2008; PB Farradyne, 2005; Saggiani & Teodorani, 2004; UTM, 2007). Beyond unmanned aerial systems, unmanned systems technologies are rapidly developing in other domains and now include submersible unmanned systems (Oikawa, 2015), maritime Unmanned Surface Vehicle (USV) systems (Campbell, Abu-Tair, & Naeem, 2014; Sharma, Sutton, Motwani, & Annamalai, 2014; Svec, Thakur, Raboin, Shah, & Gupta, 2014), and ground based systems

with the ability to "walk" like a person or animal (Hsu, 11/2014; Oikawa, 2015). Given the proximity of many nuclear reactor sites to large bodies of water, the implementation of USVs in disaster response planning is a natural fit. Notionally the employment of new technologies such as RUAS as well as other aerial, ground, and maritime unmanned systems offer potential new opportunities to not just recover from a nuclear event but respond, mitigate and protect by containing the scale and scope of a nuclear reactor disaster. Remote technology insertion drastically reduces human exposure risk and therefore reduces mission planning and execution constraints allowing more freedom of maneuver and expanding the operational envelope of the response. For example, an RUAS can operate at lower altitudes and closer proximities to the site because there is no aircrew on board in danger of radiation exposure.

NRC and FEMA are responsible for overseeing power company, agency and department EP from all levels of government. Response to a nuclear disaster is a large, complex and time critical endeavor (T. Johnson, 2006; JTF-CS, 2015a; TEPCO, 2013), yet planning for effective mitigation requires long lead times to address life cycle concerns such as resourcing, development, test and evaluation of potential material solutions, and training and mission rehearsal with solutions once fielded. Further, recent changes to the policies and regulations regarding EP made by NRC (NRC, 2011) and the establishment of a new regulatory body in Japan (N. D. o. Japan, 2012) highlight the level of effort required to properly prepare for emergency response. For nuclear disasters that breach site defenses, unmanned systems solutions promise significant planning advantages over past expedient, high-risk, and marginally

effective solutions. NRC also tests the validity of such plans through exercises and training on a regular basis (NRC, 2014c). The scenario actually experienced at Fukushima Dai-ichi provides a fertile case study for exploring the integration of unmanned systems into disaster response. More specifically, exploring the use of RUAS for SFP cooling through a system-of-systems approach applicable to the entire spectrum of unmanned systems both present and in the future is a large step forward in improving disaster planning and response training.

One potential alternative for improving disaster planning and response is the use of modeling and simulation. M. Davis and Proctor (2016) substantiate the need for live, virtual, and constructive (LVC) simulations modeling and simulation to more fully assess the consequences of SFP cooling system compromises that are beyond design specification. M. Davis, Proctor, and Shageer (2016) propose a conceptual model for establishing simulation interoperability encompassing live, virtual, and constructive simulations. In terms of disaster response, the inherent extensibility of a simulation conceptual model, like other modeling and simulation approaches to incident management, offers several advantages including, but not limited to:

- Projecting incident impact
- Testing emergency response plans
- Training response personnel
- Cost savings over live exercises
- Strategy exploration / war-gaming
- Long range resource planning
- Force lay-down evaluation (Jain & McLean, 2006)

Additionally, constructing a framework from a conceptual model using the system-of-systems approach that encompasses live, virtual, and constructive simulations meets the requirements for application of simulation to incident management proposed by McLean, Jain, Lee, and Shao (2007):

- Appropriate representation of the selected scenario
- Heterogeneous simulation integration
- Time synchronization
- Run-time execution control
- Support for large multi-agency exercises
- Heterogeneous data server access
- Reusability

This dissertation proposes to assess the suitability of one component of an instance of the conceptual framework M. Davis et al. (2016) propose by replicating aspects of the Fukushima NPS disaster. This base case will model events and mitigation attempts at Fukushima. In addition, this dissertation proposes to assess the suitability of one mitigation strategy, SFP water replenishment by UAV. While an SFP water replenishment by UAV may be mathematically modeled as an optimization problem, the ultimate benefit of this dissertation will be exploration of a potential M&S framework that incorporates live, virtual, and constructive simulation. Additional benefit includes reporting on framework capabilities and limitations for improving the planning and training for and response to SFP coolant loss. Notionally, a viable framework encompassing live, virtual, and constructive simulations will provide a generalized capability to evaluate the suitability of several unmanned systems

(current and proposed) to accomplish makeup water delivery missions to an exposed SFP during long term station black out (SBO). Since conducting such evaluations in the real world is both dangerous and cost prohibitive, a simulation approach is preferred. A simulation framework approach capable of supporting live, virtual, and constructive simulations also affords the opportunity to enhance the state of the art in the simulation domain since no linkage exists between the current simulation tools for nuclear power analysis and training, disaster management planning, and unmanned systems testing and training.

Chapter two provides context for the role of modeling and simulation in planning for and responding to nuclear disasters. It then provides a brief description, based on the work of M. Davis et al. (2016), of the conceptual model for constructing a System of Systems (SoS) framework for distributed simulation as applied to nuclear disaster response planning, training, and mission rehearsal. Chapter three further specifies the use case for demonstrating the validity of this approach to nuclear disaster response planning, training, and mission rehearsal. It then gives a specific methodology for evaluating the use case and by extension, the overarching conceptual SoS framework. Chapter four reports the results of the evaluation performed as specified in Chapter three. Finally, Chapter five provides concluding remarks and provides some direction for future research.

# CHAPTER TWO: LITERATURE REVIEW

## 2.1 Nuclear Disaster Modeling and Simulation

Nuclear scientists and disaster response planners leverage modeling and simulation to enhance their understanding of nuclear reactor behaviors during beyond design basis events. The NRC in partnership with Sandia National Laboratory maintains several dispersion, dosing, and severe accident reactor models. These models are all specialized to produce high fidelity predictions of very specific components of fuel and reactor behavior, accident progression, radionuclide transport, and dosing (NRC, 2015a). Further, research using these models is extensive: Leticia Fernandez-Moguel (2015); L. Fernandez-Moguel and Birchley (2015); Sanders (2013); Sevón (2015); J. Wang, Corradini, et al. (2015); J. Wang, Zhang, et al. (2015); T.-C. Wang, Wang, and Teng (2005); and WSC (2012) are a few recent examples. Other agencies outside of NRC have also developed extensive and widely used models for analyzing various aspects of nuclear reactor and power station behavior (Leticia Fernandez-Moguel, 2015; L. Fernandez-Moguel & Birchley, 2015; Kataoka, 2013; T.-C. Wang et al., 2005). Despite the large number of simulations available for both reactor thermohydraulics modeling (J. Wang, Zhang, et al., 2015; T.-C. Wang et al., 2005) and material dispersion modeling, very few are capable of operating in the near real-time required for training environments. And while some attempts have been made to create training tools with these models (K.-R. Kim, Park, Song, & Ahn, 2010; K. R. Kim, Jeong, Ha, & Jung, 2002; Po, 2010) including establishing the foundations of distributed

training (K. D. Kim & Rizwan, 2007), their scope has been limited to interacting only with the reactor systems modeled by the simulation codes.

Likewise, DoD has a long history pioneering advanced modeling and simulation techniques (Hollenbach & Alexander, 1997). Further, DoD assets and manpower are organized under the JTF-CS to support local, state, and federal authorities responding to Chemical, Biological, Radiological, Nuclear (CBRN) disasters (JTF-CS, 2015b). Heffelfinger, Tuckett, and Ryan (2013) provide a thorough treatment of the military role in domestic CBRN incident response. "Bringing together the myriad of capabilities of the military forces in a seamless response is a daunting task." Realistic training is integral to successful CBRN response and modeling and simulation plays a key role in this training (Heffelfinger et al., 2013).

DoD's longstanding employment of modeling and simulation for training stands in contrast to the more recent focus within the nuclear community to use existing analysis models in a training role. Further, distributed and large audience training has been a focus of DoD's simulation and training community for many years (P. K. Davis, 1995). Live, virtual, and constructive simulations are widely used by the military for such training (Hodson & Hill, 2014) using several different interoperability protocols to facilitate data transfer and communications between models, systems, and trainees. These protocols include: Distributed Interactive Simulation (DIS), High Level Architecture (HLA), and Test and Training Enabling Architecture (TENA). In addition to training and mission rehearsal, the resultant simulation "federations" formed by these disparate simulations, systems, and trainee interfaces are employed across

system life cycle phases to support and conduct concept development, analysis, test and evaluation, and system development.

One such federation that closely parallels wide-area nuclear disaster scenarios faced by the nuclear community is the Chemical-Biological Simulation Suite. "The Chemical-Biological Simulation Suite (CBSS) is a set of distributed simulation software tools designed to represent all aspects of CB defense on the tactical battlefield, including applications to analyze strategies, and to provide cost-effective test programs and training of U.S. and allied soldiers" (Baker, 2012).

The CBSS is used to:

- Develop effective CB defense materiel
- Evaluate tactics, techniques, and procedures (TTP)
- Provide constructive testing over a wide range of terrain, weather, and delivery conditions
- Provide broad scenario-based training
- Support live sensor testing at Dugway (Baker, 2012)

The CBSS computes transport and dispersion using high fidelity vapor, terrain, and weather models and delivers output to other federates via its Chemical/Biological Synthetic Natural Environment (Baker, 2012).

There are several other DoD-focused, CBRN environment models. One example is the Hazard Prediction and Assessment Capability (HPAC), a widely used tool (Chang, Hanna, Boybeyi, & Franzese, 2005; S. Hanna & Chang, 2015; Platt, Kimball, & Urban, 2014; Singh et al., 2015) licensed by the Defense Threat Reduction Agency. HPAC "assists in emergency response

to hazardous agent releases. Its fast running, physics-based algorithms enable users to model and predict hazard areas and human collateral effects in minutes. HPAC provides the capability to accurately predict the effects of HAZMAT releases into the atmosphere and their impact on civilian and military populations" (DoD, 2013). Another example recently produced by several organizations within DoD headed by NAWCTSD is a simulation called the Live Virtual Constructive Chemical Biological Radiological Nuclear Explosive Tactical Training System. This tool focuses on tracking individuals and maintaining situational awareness of ground forces within a CBRNE environment (NAWCTSD, 2014). There are also several other dispersion models at various levels of fidelity and interoperability (Hill, 2003). Of note here is that these DoD tools focus on the modeling of nuclear material dispersion and training responders and emergency managers how to deal with the radiation environment they will be forced to operate in during a nuclear disaster.

None of the civilian models or simulations provide an encompassing framework to enable large training audiences with disparate missions and resources to train together in an integrated response scenario. Additionally, while some of the DoD resources, like CBSS, provide broader coverage of environmental factors and mission areas, they are focused mainly on simulating military operations in CBRN environments. M. Davis et al. (2016) illustrate in Figure 2 the current lack of interoperability between the modeling and simulation tools required to construct a robust federation capable of providing meaningful, immersive training to emergency managers and responders during a nuclear disaster.

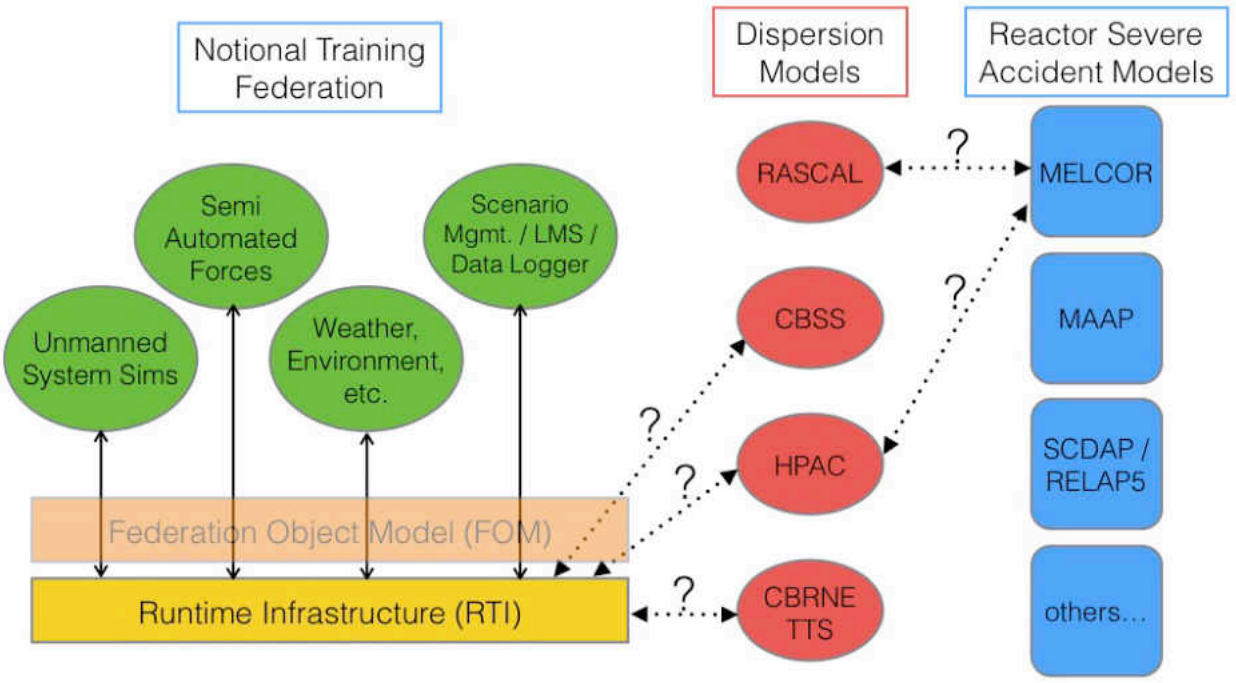



**Figure 2: Current level of interoperability**
**Source:** M. Davis et al. (2016)

## 2.2 General Research Approach

Given this current state, a new conceptual model (CM) and simulation framework or federation suitable for interoperating and training an entire response management team is needed. M. Davis et al. (2016) propose a CM of this framework, illustrated by Figure 3. Developing a fully functioning federation containing all the aspects of their proposed architectural framework is beyond the scope of this research, but several components of the framework will be necessarily developed and included. This will enable generation of reliable results as well as demonstrate the utility of their framework for evaluating systems' capabilities to efficiently and safely accomplish required tasks during a nuclear disaster scenario. Further,

the limited development proposed will demonstrate the extensibility of their architectural framework to training and mission rehearsal applications. Choosing simulation software designed for scenario development and training will enable this extensibility.

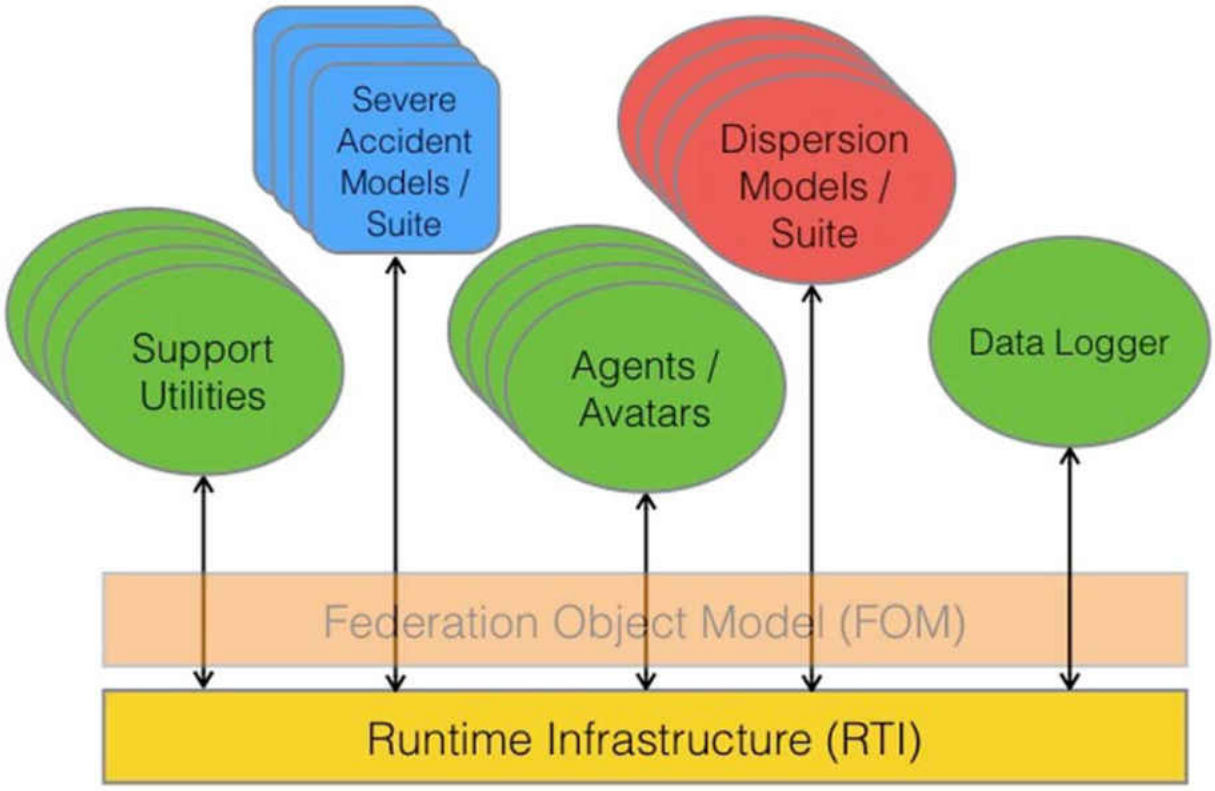



**Figure 3: Notional Conceptual Model**
**Source:** M. Davis et al. (2016)

The CM proposed by M. Davis et al. (2016) for integrating unmanned systems embraces a system-of-systems approach in nuclear disaster and mitigation modeling. Simulation architectural frameworks thus composed may be useful to the community because of its potential enhancement of nuclear power plant EP plans as well its alignment with DoD interest in unmanned systems and the JTF-CS tasking to support civil authorities responding to CBRN

incidents. The model's structure accommodates additional system integration. These new CMs are tailorable to various simulation federations and communication structures thus meeting the various organizational needs of utility operators, local and state governments, the NRC, and FEMA requirements to conduct evaluated exercises every two years (NRC, 2011). The flexibility offered by this approach is especially pertinent given the findings of Adalja, Sell, Ravi, Minton, and Morhard (2015), who report incident managers find current exercises "unrealistic" or "antiquated".

A generalized framework for simulation based analysis of UAS (Perhinschi, Napolitano, & Tamayo, 2010) and analysis of unmanned systems in a similar fashion (Flint, Fernandez, & Kelton, 2009; Liu, Guan, Song, & Chen, 2014) exist. Independent literature on operations research, nuclear power plants, nuclear reactor accidents and simulation is vast but disconnected with (Ai-Omari, Jaradat, & Jarrah, 2013; Alexis et al., 2009; Alver, Ozdogan, & Yucesan, 2012; Bernard et al., 2008; Chaimatanan, Delahaye, & Mongeau, 2013; Flint et al., 2009; Girault, Bosland, & Dienstbier, 2010; Holden & Dickerson, 2013; Hu et al., 2015; Ianovsky & Kreimer, 2011; Liu et al., 2014; MacFarlane et al., 2014; Marconi et al., 2012; Mase, 2013, 2015; McGonigle et al., 2008; Ouyang, Zhuang, Lin, & Liu, 2014; PB Farradyne, 2005; Peräjärvi, Lehtinen, Pöllänen, & Toivonen, 2008; Saggiani & Teodorani, 2004; Sheng et al., 2015; Towler, Krawiec, & Kochersberger, 2012; J. Wang, Zhang, et al., 2015) being but a few examples. Many of these works utilize simulation techniques, due in part to the complex nature of UAS and their

environmental interactions and the difficulty in analytically evaluating real-world systems (Law & Kelton, 2000).

Michael D. Proctor, Shageer, and Davis (2015) use the Fukushima disaster to shape the evolving role of modeling and simulation in planning DoD responses to nuclear accidents. But in contrast to many other disciplines covered by the literature cited above, a CM for interoperability and life cycle analysis of unmanned systems to nuclear disaster emergency planning, response, mitigation and recovery is lacking. As a result, replicating the Fukushima Dai-ichi scenario using existing high fidelity models and simulations of the various systems would involve extensive and time consuming hand coding to achieve interoperation. Yet, as in past system developments, modeling and simulation will be key to successful integration of unmanned systems into nuclear disaster response plans (INNG, 2015).

What M. Davis et al. (2016) propose is first to view the larger crisis, including all the components of human interaction, as a SoS, then to improve management, planning, response, and mitigation by the application of modeling and simulation in a fashion similar to other recent approaches (Liang, Lam Nina, Qin, & Ju, 2015; Stephens, Jafari, Boyles, Ford Jessica, & Zhu, 2015). As noted by Hodson and Hill (2014), "[Conceptual modeling] is almost certainly the most important aspect of a simulation project" and is widely discussed in the literature (Çelik, Gökdoğan, Öztürk, & Sarikaya, 2013; Gaffney & Vincent, 2011; Graniela & Proctor, 2012; Hamilton, 2006; Hodson, Esken, Gutman, & Hill, 2014; Morris, Grimaila, Hodson, McLaughlin, &

Jacques, 2014; Özhan, Oğuztüzün, & Evrensel, 2008; S. Robinson, 2008a, 2008b; Stewart Robinson, 2010; Sokolowski, Banks, & Morrow, 2012; Ünal & Topçu, 2014).

M. Davis et al. (2016) use the M. C. Jones (2015) process for CM development within a SoS. The creation of a SoS CM begins with first defining the experimental frame (M. C. Jones, 2015). Unmanned systems are part of a broad spectrum of alternative technologies that may be applied in future nuclear disasters. Defining the experimental frame for this research means limiting this scope. One way this is done is by defining a use case and the recent disaster at the Fukushima Dai-ichi Nuclear Power Plant (NPP) is a good choice. Further limiting the scope, this research will focus on the intended helicopter mission of delivering water to spent fuel pools. While other tasks may exist in the general case, the Fukushima Dai-ichi helicopter tasking evolved from efforts to avoid a major source term release and possible nuclear meltdown by maintaining sufficient water levels in the spent fuel pools (SFP). A thorough treatment of the timeline and situation evolution is available from several sources (ANS, 2012; Miller et al., 2011; TEPCO, 2013; WNA, 2012). As a representative case for interoperable modeling and simulation, the task was to deliver helicopter slung load water from above to the exposed SFP. Before a simulation of this task can be constructed the components of importance and their relationships to each other must be identified in a CM (M. C. Jones, 2015).

Complexity not only of the number of components and their interactions, but also the complex behaviors within each component driving its interactions with the other components makes a SoS approach to a nuclear disaster simulation appropriate. This view is derived from

Maier's conditions for classification as an SoS: (1) Components have valid, fulfillable purposes independent of the larger system, and (2) components are managed in view of their own objectives rather than the objectives of the larger system (Maier, 1998). M. C. Jones (2015) further supports this in their description of SoS: "SoS are distinguished from other systems by formation from independently operated and managed components."

Framing the real-world problem as a SoS where many subsystems interoperate within the larger system leads naturally to a conceptualization of the problem in simulation as a composition of models, each of which simulates the behavior of smaller subsystems of the overarching system. The ideas of composability and interoperability have remained foundational to M&S research over the last 15 years (Paul K. Davis & Anderson, 2004; Kasputis & Ng, 2000; Yilmaz, 2004). Paul K. Davis and Tolk (2007) provide a concise discussion of how the two ideas differ and offer a simple summary: "it is convenient to refer to the interoperability of simulations and to the composability of models." Interoperability is critical to proper SoS function (M. C. Jones, 2015), both in the real world and in simulation. But as described by Tolk and Muguira (2003) and Tolk, Diallo, and Turnitsa (2007) in the Levels of Conceptual Interoperability Model (LCIM), interoperability is a spectrum and enhanced SoS performance comes as the degree of interoperability between the sub-systems increases. Several standards are widely used by the modeling and simulation community to ensure a minimum degree of interoperability between simulation systems. DIS, HLA, and TENA are three

such standards, and detailed descriptions of each are available from several sources (2010, 2012; M. C. Jones, 2015; TRMC, 2015).

The enhanced simulation interoperability offered by a SoS view of the problem additionally elicits aggregate system behavior known as emergence (Fisher, 2006). And while M. C. Jones (2015) conclude emergent behavior may have beneficial or detrimental effects on both the SoS and its subsystems, in this case observing the emergent behaviors are a primary objective enabling a clearer understanding of the true utility of unmanned systems within nuclear disaster response.

## 2.3 Components of the SoS

This section highlights some of the relevant characteristics of the components of a nuclear disaster simulation SoS highlighted in Figure 3 and is taken largely from (M. Davis et al., 2016). SoS components and referent sub-systems include:

- The reactor and SFP thermohydraulics
- The RUAS or unmanned system of interest within a chosen scenario
- Agents including the ground control station and maintenance/refuel site for the RUAS including the fresh water source
- Radionuclide dispersion to the environment
- Atmospherics—weather, wind, etc. at and around the reactor site

In addition to these real-world systems that interact in the SoS, there are additional sub-systems that should be accounted for in the simulated SoS:

- A communication control module—interoperability standard ensuring module-to-module communication (DIS protocol, HLA RTI, TENA, etc.)
- A scenario management module
- A data logging module

Following the development process developed by Zeigler, Kim, and Praehofer (2000) and outlined by M. C. Jones (2015), the SoS CM below can be used to develop a software specific instance of a simulation model. Each of these is represented in an expanded view of the CM in Figure 4 and explained in detail in the following paragraphs.

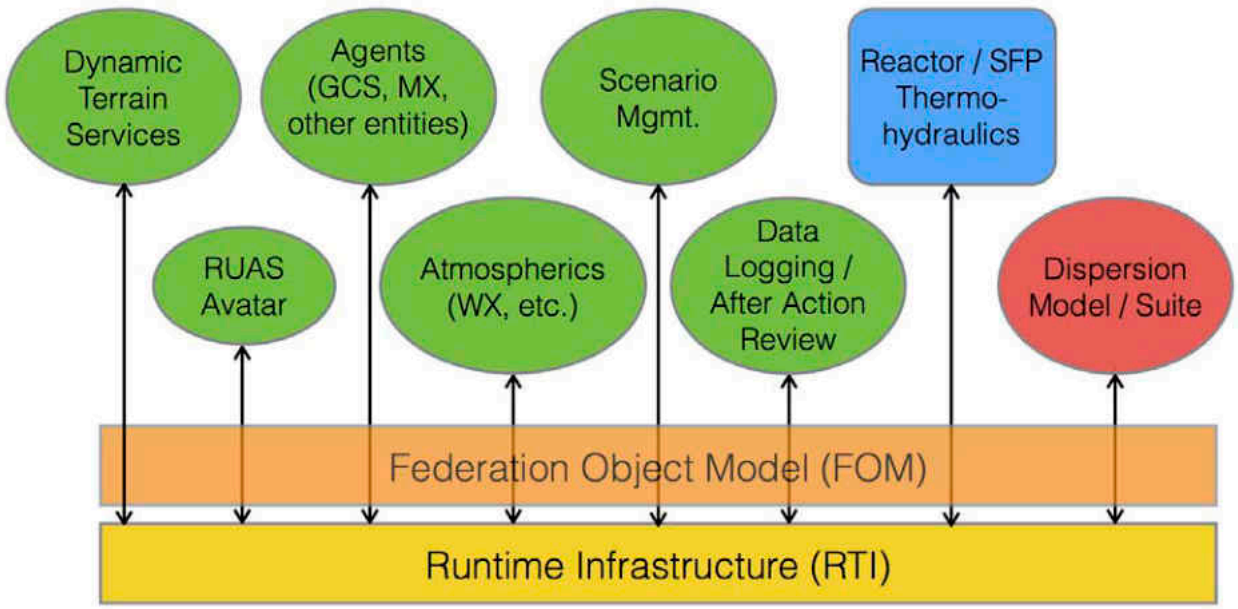



**Figure 4: Expanded Conceptual Model**

**Dynamic Terrain Services –** Within the modeling and simulation context, terrain is traditionally a static environment through which other agents move. Recent advances in

computing capability and representation techniques have created various terrain representations that actively influence agents and avatar ability to more realistically navigate and progress across different terrains (Graniela & Proctor, 2012). These technological advancements also enable real time physically-based modeling and simulation of dynamic terrain (Rami & Proctor, 2007) and implementations of these techniques in large scale exercises (Ellis, Babenko, & Goldiez, 2010). Active and dynamic terrain services would enable modeling ground vehicle movement inhibitors such as facility flooding (i.e. Fukushima tsunami overtopping), terrain and surface roadway erosion or rupturing, bridge collapse, and obstacles and debris from collapsed buildings, etcetera. The disruption of movement of ground vehicles justifies an independent representation within the illustrated CM as seen in Figure 4. This ensures hardware and I/O requirements for supporting dynamic terrain are not overlooked during scoping and development efforts.

**RUAS Avatar—** RUAS may avoid issues such as flooding, roadway or bridge collapse, and obstacles that confront ground vehicles. RUAS may be represented in a simulation as a pre-scripted agent or as a human operated avatar. Michael D. Proctor and Paulo (1996) established as far back as 1996 that agent representation in synthetic environments often operate significantly different than live operators in the real environments. Avatars facilitate live humans remotely operating unmanned systems in a simulation thus avoiding many anomalies generated by pre-scripted agents. Avatars require a human interface comparable to the real-world interface. Further, in RUAS avatar scenarios expected research and training challenges of

interest also include team situational awareness (Michael D. Proctor, Panko, & Donovan, 2004), field of view of individual pilot/co-pilot (Covelli, Rolland, Proctor, Kincaid, & Hancock, 2010), and unique to this research, flight crew controlling slings, lifts, cranes, and scoops. A real-world RUAS would also be exposed to unusual levels of radiation and heat and would be specially equipped to operate in unique environment associated with nuclear disaster response. Thus, the model of such an aircraft would need to include simulated shielding of electronics and sensors from radiation and heat. Accurately representing the RUAS would require several input data streams including environmental (weather, radiation levels, etc.), external load information, maintenance activity data, and radiation exposure. System health and status data must also be output with high frequency.

**Agents —**Most entities, while important, may not be central to the focus of a scenario and can therefore be represented by agents with varying levels of artificial intelligence. A single module within the CM can represent the implementation of perhaps many models of these various agents. Notionally, a model within the RUAS scenario could represent the RUAS's Ground Control Station and its operators as well as the maintenance and refuel facilities and personnel. All the other personnel and activities involved in the response and mitigation efforts are represented here as well. Additionally, once RUAS behaviors are established through avatar play, the capability to convert the RUAS avatar into an agent would contribute to experimentation. If an RUAS agent is to be created, consideration should be given not only to the obvious need for accuracy of the internal logic of the agent, but "correlated" sensor models

that "evolve with ... radiant energy, environmental effects, and sensor technology" across the electromagnetic spectrum with a simulation federation (M. D. Proctor & Connors, 2000).

**Atmospherics—**Atmospherics is a key component in determining radionuclide dispersion, thus a separate module is dedicated to handling its accurate representation (S. Hanna & Chang, 2015; Platt et al., 2014; Singh et al., 2015). Input to this module consists of date/time data for the scenario and the reactor location. Atmospherics, particularly turbulence, may adversely impact helicopter pilot performance with increased weight with respect to the velocity and altitude parameters of the helicopter (Michael D. Proctor, Bauer, & Lucario, 2007). Robust analytical and training capability necessitates this module offer users various weather generation techniques, so user definition of weather is another input stream. Output from this module includes a full complement of weather parameters to provide complete data for the dispersion, RUAS, and SAF modules.

**Scenario Management—**For analysis or training to occur, initial conditions must be set, operating parameters established, and an end state identified. These parameters are notionally bounded by the experimental frame and derived from the experimental design in the case of analysis and from the training objectives in the case of training. While these parameters are initially expressed in data formats oriented to human understanding (tables, figures, plain text), they must be delivered to the simulated SoS in a machine digestible format (Holden & Dickerson, 2013; Ünal & Topçu, 2014). This is the first task of the scenario management

module. Further, this module monitors the simulation during execution to ensure all participating sub-systems, or federates, are abiding by the established operating parameters.

**Data Logging—**To achieve the end goal of optimizing RUAS implementation or evaluating trainee performance, system behavior must be tracked and logged for post-scenario evaluation. This is the task of the data-logging module. This module is similar to After Action Review tools present in many DoD training simulations (Green, Leibrecht, & Fite, 2011; Meliza, Goldberg, & Lampton, 2007; Sawyer & Deering, 2013) and such a tool could notionally be applied to an implementation of our CM to accomplish this task. Input streams to this module are all output from every other module. This facilitates circumspect analysis and effective post-training debrief. Output from this module is a formatted version of the data it collected as input during scenario execution. That format will vary depending on the current purpose for the data.

**Reactor and SFP Thermohydraulics—**This module is representative of a high-fidelity model of the nuclear physics and thermodynamics taking place in and around the reactor and the SFP. The actual nuclear reactions as well as the heat transfer processes taking place in many areas near the reactor including within the SFP where our scenario is focused are highly complex and critical to accurate analysis of unmanned systems capability to mitigate source term release. Therefore, a model specifically built for predicting severe accident behavior is highly desirable. This module will require dynamic input of control signals from scenario scripts or human participants. It should also accept new mass (coolant, fuel assemblies, etc.) and

properly adjust calculated results accordingly. It will output parametric data regarding the current state of the reactor related systems to include current source term mass estimates and coolant levels, temperatures, and pressures. Several alternatives exist to include MELCOR, SCDAP/RELAP5, and MAAP (Polo-Labarrios & Espinosa-Paredes, 2015; T.-C. Wang et al., 2005).

**Dispersion—**The dispersion of radionuclides to the surrounding environment is the primary concern with any nuclear disaster. As such, a high-fidelity representation of this behavior is highly desirable. Most dispersion models focus on computing the dynamics of particle dispersion and therefore input to this module consists of source term information, specifically the total mass and its material qualities. Additionally, atmospheric conditions are integral to dispersion so that data should also be part of the input stream to this module. Output from this module would be total radionuclide density throughout the Synthetic Natural Environment (SNE). This should include effective dose rates for personnel operating within affected areas as well as radionuclide deposit on structures and vehicles traveling through affected areas. Several alternatives exist to include HPAC, RASCAL, ALOHA, AUSTOX, AUSPLUME, and CBSS (Baker, 2012; Hill, 2003; NRC, 2015a).

## 2.4 Simulation Framework and Prototypical Instance of the Conceptual Model

To conduct an evaluation of the ability of an RUAS to successfully replenish the water lost due to evaporation from an exposed SFP during long term station blackout, specific simulation framework must be implemented to provide input data streams for each of sub-systems depicted in Figure 4.

The Presagis Modeling & Simulation Suite (Presagis, 2015b) is "an open-standard simulation development framework designed to support a full range of simulation applications across the air, land, sea, and public safety market segments." This suite of tools includes a terrain database generation tool, a high-fidelity model building and editing application, a simulation development and management environment, high fidelity fixed and rotary wing flight dynamic simulations, high fidelity sensor models (radar, infrared), a high-quality 3D visualization tool, and a human machine interface (HMI) tool for creating realistic methods for human operators to interact with simulated systems within a scenario. This one suite of fully integrated tools is designed to provide an end-to-end solution for creating, managing, executing, and evaluating simulation training scenarios. As such, it is an ideal choice for many of the sub-systems identified in Figure 4. Presagis tools will handle the Dynamic Terrain Services, RUAS Avatar, Agents, Atmospherics, Scenario Management, Data Logging, and finally the underlying communication infrastructure.

High fidelity modeling of reactor thermohydraulics is a key component of accurately simulating reactor behavior before, during, and after any given disaster scenario. As mentioned earlier, several alternatives exist for handling this portion of the simulation. For this use case, since the mission success / failure parameters are based solely on the water level in the SFP, this is the only data needed from a reactor model. While several of the models mentioned above can provide accurate estimates of the SFP water level, they are not the best choice for this implementation for several reasons. First, very few if any of them have the capability to

provide water level updates in real time. Second, as computing SFP coolant levels are not their primary objective, massaging the model to provide this data may prove difficult. Finally, as depicted in Figure 2 and discussed earlier, these models are not designed to work in a multi-model distributed simulation environment. As such, considerable development would be necessary to create an interface for reliably passing data to and from these existing models.

M. Davis and Proctor (2016) offer a promising alternative. They base their work on that of Hugo (2015); Hugo and Kinsel (2014); and Hugo and Omberg (2015) who proposed a novel approach to computing evaporative loss of SFP water at high water temperatures. Their model accounts for evaporative loss from mass transfer (diffusion) processes in contrast to prior models that based their predictions on empirical data or heat transfer. Further, the Hugo et al. model includes velocity of air over the water surface, as occurred after destruction of the containment structure at Fukushima NPP. This is a key factor in more accurately predicting observed evaporative loss and SFP temperatures than other, previously proposed methods (Shah, 2014; D. A. Wang et al., 2012).

The Hugo model employed by (M. Davis & Proctor, 2016) is a straightforward mathematical computation using several inputs readily available from standard weather observations and either measure or predicted water temperatures within the SFP. The model from (Hugo & Omberg, 2015):

$$E = 9.24(1 + 2v^{1.35})^{0.67} \frac{T}{273K} \ln \frac{P - \phi P_{\text{sat, a}}}{P - P_{\text{sat, w}}} \quad (1)$$

where,

$E =$ mass flux, $\mathrm{kg/m^2hr}$

$v =$ air velocity, m/sec

$T =$ water temperature, K

$P =$ atmospheric pressure, Pa

$P_{\mathrm{sat,a}} =$ saturation pressure of water at the ambient air temperature, Pa

$P_{\mathrm{sat},w} =$ saturation pressure of water at the pool water temperature, Pa

$\phi =$ relative humidity, dimensionless

Integrating such a mathematical model in the context of a larger simulation framework is a relatively straightforward task. This is especially true when the model's output is directly and highly correlated to the mission success parameters set forth in the research objectives. Required inputs for the model are all potential design factors with varying impacts on the evaporation rate. These and other design factors will be discussed in further detail in Chapter Three. The relatively simple nature of the calculation maintains the computational speed required for real-time simulation. Further, integrating a mathematical model of this type into the Presagis scenario management tool, STAGE, is a relatively straightforward task.

The final portion of the overall simulation framework called out in Figure 4 is Dispersion Modeling. While dispersion of radioactive material and its effects is critical component of the

larger problem, its impact is beyond the scope of this research and it will therefore be disregarded.

## 2.5 Experimental Design

While several methods for enhancing and evaluating UAV effectiveness for particular mission sets have been proposed in the literature (Saggiani & Teodorani, 2004; van Blyenburgh, 2000) including the use of simulation (Bernabei, Sassanelli, Corallo, & Lazoi, 2014; Hodicky, 2014; Zittel, 2001), distributed, live, virtual, constructive (LVC) simulations "have been primarily an exercise and demonstration technology to date" (Hodson & Hill, 2014).

Statistical experimental design or Design of Experiments (DOE) is most simply a "planned approach for determining cause and effect relationships" (Anderson & Whitcomb, 2007). And while DOE has a long history in agriculture and process engineering, there is very little if any overlap between DOE and distributed, training focused simulations like those discussed above (Hodson & Hill, 2014).

Before detailing the specifics of the experimental design for this research it is prudent to define the language of experimental design used throughout the remainder of the present work. The parameter of interest is called the response variable. The parameters that may affect the value of the response variable are called factors. Each of these factors is assigned a value from within a range of interest or feasibility for each run of the experiment. The combination of parameter values for a specific run is called a treatment. These terms as well as

others related to formation, execution, and analysis of the experimental design are drawn from Montgomery (2013), a well-known reference text on experimental design and analysis.

Haase, Hill, and Hodson (2014) provide an overview of Coleman and Montgomery (1993)'s designed industrial experiment planning process and suggest a similar approach for LVC-experimental design. While the proposed research is only one component of LVC, the suggested planning and execution process is still applicable. It consists of seven steps:

1. Recognition and statement of the problem
2. Selection of the response variable
3. Choice of factors, levels, and range
4. Choice of experimental design
5. Performing the experiment
6. Statistical analysis of the data
7. Conclusions and recommendations

Minor regrouping of these steps fits them to the standard dissertation model. Step 1 aligns with Chapters 1 and 2 where the problem of interest is identified and motivated with background information. Steps 2-4 are typical of Chapter 3 where methodology is detailed. Step 5 is the self-explanatory. Steps 6 and 7 are Chapters 4 and 5 respectively.

In addition to guidelines offered by Coleman and Montgomery (1993), Haase et al. (2014) offer some additional considerations for designing an experiment in an LVC simulation environment. They warn simulation experimenters to scope their experiments carefully. Because of vast capabilities available in simulation tools, there is tendency to build large, complex environments much more complicated than required. One of the major benefits of

using large real-time simulation for designed experiments is large number of potential design factors within the experimenter's control (Haase et al., 2014). While many of these individual potential design factors (environmental parameters, agent behavior, agent interaction outcomes, etc.) may have very little influence on the response variable, when taken over time and in combination with the large number of other potential design factors over the length of the simulation run they can have synergistic effects that have large impacts on the response variable. This is an example of the desired emergent behavior mentioned above. However, too much increased complexity can ruin meaningful analytical insights (Haase et al., 2014). Further, they warn against the dangers of oversized experimental designs. Because of the broad capability of LVC simulations, designers are often tempted to employ large designs that will answer many questions about the system of interest in one experiment. Haase et al. (2014) also caution experimenters about the need for improved test discipline when conducting tests in a simulation environment. The flexibility offered by simulation tempts designers to "tweak" the simulation based on early results. This effectively taints all the collected data making a once good design poor which "no amount of statistical analysis can save" (Haase et al., 2014). They warn against the use of qualitative objectives contending LVC experiments' primary uses: SoS performance, joint task performance, and joint mission effectiveness are often nebulous and difficult to define and measure. They suggest innovative thinking by experiment designers is required to construct a simulation environment to gather data in support of qualitative assessments of system performance. Alternatively, developing a quantitative measure of the

response variable seems a more effective approach. Haase et al. (2014) discuss a few of the pitfalls associated with the large number of potential factors within simulation based experiments. Mixed-level factors (those where at least one factor has a different number of levels than the others) often occur in complex environments and require larger sample sizes. Simulation based experiments often have several high-order interactions that impact the response variable. This is somewhat unique to simulation experiments as most DOE analysis texts suggest that experimenters can often ignore high-order interactions due to their negligible impact on the response variable (Montgomery, 2013). Haase et al. (2014) suggest the confounding of high-order interactions and main effects can be overcome with careful planning and design selection. Finally, noisy test environments result from the large number of factors and the frequent inclusion of humans in LVC simulation experiments. Hodson and Hill (2014) echo the idea of noisy human action obscuring test results suggesting designers explicitly plan these kinds of hard to control factors, but at the same time warning that LVC simulations present a more complicated planning process than those of typical industrial or system experimental designs. While the research proposed here doesn't include human interaction, the noise of many factors once again points toward the emergent behavior of the System of Systems and is thus less likely to be explicitly controlled in the current research.

Hodson and Hill (2014) identify several sources of literature on experimental design: (Cortes, Duff, & Bergstrom, 2011; R. T. Johnson, Hutto, Simpson, & Montgomery, 2012; Steinberg & Hunter, 1984), but found none included "LVC simulation as a context for

experimentation." They go on to discuss experimental design for LVC simulations at a conceptual level but stop short of identifying designs or analysis techniques the practitioner may find useful. This gap in the literature leads back to (Haase et al., 2014) who offer thoughts on particular experimental designs well suited to LVC simulation testing in view of the unique test environment provided in simulation. Orthogonal and nearly orthogonal arrays, optimal designs, and split-plot designs are all suggested as well suited formats for LVC simulation experiments.

Orthogonal arrays (OA) are mathematical constructions with applications to many fields of study (Hedayat, Sloane, & Stufken, 1999). "An orthogonal design…is an $n \times m$ matrix with entries from a set of $q$ levels such that the $m$ columns are pairwise orthogonal. The columns and rows can be identified with factors and experimental runs, respectively" (Georgiou, Stylianou, Drosou, & Koukouvinos, 2014). The definition above limits the strength of an OA to two, meaning only two factors must appear in each of their combinations of levels. This strength measurement can be increased by simply increasing the number of factors that must appear in each of their level combinations (Hedayat et al., 1999). Full factorial experimental designs are OAs, but as the notation for such designs indicates ($q^m$) the size of the experiment increases geometrically as the number of factors increases even for just 2 levels of each (Anderson & Whitcomb, 2007). OAs are a popular topic in the literature and many construction methods and use cases now exist. Their ability to identify main effects and two factor interaction influence on response variables in a relatively small number of runs makes them a

popular choice for factor screening experiments (Haase, 2011; Haase et al., 2014; Hedayat et al., 1999).

Nearly orthogonal arrays are better known in experimental design as fractional factorial designs. These designs have the same basic characteristics as full factorial designs except that only some subset of the factors, or columns, are orthogonal (Hedayat et al., 1999). Fractional factorial designs are widely used by experimenters (Montgomery, 2013) and are "especially good for 'screening' many factors in search of a vital few" (Anderson & Whitcomb, 2007). They are also popular because of the cost/benefit ratio they enjoy compared to full factorial designs. As the number of factors increases, the disparity of required runs between full and fractional factorial designs grows quite large. Despite the relatively small sample sizes collected from fractional factorial experiments, properly designed and executed experiments can be very powerful and effective tools for evaluating main effects and two-factor interactions (Montgomery, 2013).

Optimal Designs are those that use model parameter variance reduction techniques to determine the design of the experiment. (Montgomery, 2013) discusses three types: D-, G-, and I-optimal designs. D-optimal designs minimize regression model coefficient variances and thus produce more accurate regression models from the collected data. G-optimal designs minimize the maximum prediction variance across the design region. Finally, I-optimal designs minimize the average prediction variance over the design space. The reader is referred to Section 6.7 of (Montgomery, 2013) for a more detailed discussion of each of these designs. It is

worth noting that general factorial $2^k$designs are in fact also optimal designs satisfying the criteria for each of the above design types.

The final design type suggested as useful for simulation experiments is the Split Plot Design. Split Plot design analysis techniques are growing in popularity as more and more experimental analyses are being re-examined and found to have been either labelled as split plot then analyzed as if completely randomized or labelled as randomized yet displayed split plot structure (B. Jones & Nachtsheim, 2009). B. Jones and Nachtsheim (2009) describes split plot designs as, "a blocked experiment, where the blocks themselves serve as experimental units for a subset of the factors." Such designs are used when complete randomization of the runs is difficult or impossible due to restrictions (e.g. geography, logistics, economics) of one or more of the factors (Haase et al., 2014). Dividing the experiment into smaller experiments called whole plots introduces additional error terms for each of the whole plots that result from the levels of the factor causing the randomization issue (Montgomery, 2013). While split plot designs offer a viable solution for experiments with difficult to change factors or other randomization issues, Haase et al. (2014); B. Jones and Nachtsheim (2009); and Montgomery (2013) all agree that extreme care must be taken during the analysis to ensure the additional error and complex models are handled correctly.

As Haase et al. (2014) indicates, these are just a few of the design options available to experimenters who must consider the unique characteristics of not only their particular

problem of interest but also the simulation environment within which the experiment will occur in order to select the most appropriate design.

# CHAPTER THREE: METHODOLOGY

Before developing a specific methodology for testing the broad objectives described in Chapter Two, it is appropriate to specifically define the use case including specific mission objectives and parameters; the desired end state of the SoS; and the real-world situation to be simulated.

## 3.1 The Use Case

Based on the Fukushima nuclear power plant disaster, the focus of this dissertation is on representation and analysis of the general SFP mission use case within the constructive simulation component of the previously discussed SoS CM and LVC simulation framework. The scope of the SFP task for this research is to replenish and then maintain water level and temperature within the SFP above and below (respectively) some given thresholds. As mentioned in Chapter 1 and in part demonstrated in Chapter 2, while an SFP water replenishment by UAV may be mathematically modeled as an optimization problem, the ultimate benefit of this dissertation will be exploration of a potential simulation framework that incorporates concurrent and interoperating live, virtual, and constructive simulation based on a modeling architecture that is composed modularly using a System-of System approach. Additional benefit includes reporting on framework capabilities and limitations for improving the planning and training for and response to SFP coolant loss. Notionally, a viable SoS-based CM with simulation framework encompassing live, virtual, and constructive simulations will

provide a generalized capability to compose, simulate, and evaluate the suitability of several unmanned systems (current and proposed) to accomplish many possible missions including makeup water delivery missions to an exposed SFP during long term station black out (SBO). Since conducting such evaluations in the real world is both dangerous and cost prohibitive, a simulation approach is preferred. A simulation framework approach capable of supporting live, virtual, and constructive simulations also affords the opportunity to enhance the state of the art in the simulation domain since no linkage exists between the current simulation tools for nuclear power analysis and training, disaster management planning, and unmanned systems testing and training.

SFP safety thresholds relate to the depth of the water above the top of the fuel rods housed in the SFP and the water temperature's associated evaporation/boil rate. Water temperature in the SFP directly affects evaporation rate. According to D. A. Wang et al. (2012), the initial water temperature of the SFP at Fukushima at the time of power loss was 27 C. It then took approximately 3 days for the SFP to approach thermal equilibrium at around 84-90 C. Delivery operations via RUAS are thus assumed to begin once the pool has achieved thermal equilibrium at between 90 and 98 C which would likely occur 3-5 days after power is lost based on the empirical evidence collected at Fukushima. The mission success/failure parameters are: Mission success occurs when the water level and temperature in the SFP are within the operating parameters of normal operations 72 hours after water delivery operations begin. If the SFP can be maintained in a normal operating state with regard to water level and

temperature over a three-day period, it is assumed this state could be maintained indefinitely. Mission failure occurs when water level drops to within three feet of the top of the fuel rods. This is the level used in NUREG-1738: "The end state … was an SFP water level 3 feet above the top of the fuel. This simplified end state was used because recovery below this level, given failure to recover before reaching this level, was judged to be unlikely given the significant radiation field in and around the SFP at lowered water levels" (Collins & Hubbard, 2001).

Using the model from Equation (1) to compute evaporative loss rate from the SFP and measuring the RUAS's ability to counter this loss provides a direct, quantitative measure of effectiveness for one of the major objectives of the study. Equation (1) also addresses one of the major considerations identified by Haase et al. (2014) when conducting designed experiments for analysis in training focused simulation identified.

The real-world situation upon which the simulation scenario is based has a major impact on the outcome. This research will focus the nuclear power plant at St. Lucie, FL and the surrounding area. A slight modification will be made to the design of the power plant in that the containment buildings from Fukushima Dai-ichi will be used in place of the existing containment structures found at the St. Lucie plant. Because of the accident at Fukushima, data on plant layout, containment structure construction, timeline of the accident, and response efforts are readily available. In contrast, specific data for operating nuclear facilities within the United States is difficult to obtain. Even if specific data on the St. Lucie plant could be obtained, it is highly likely that use of such data would severely limit the distribution of the

results of this research. As alluded to by Michael D. Proctor et al. (2015), such limitations are contrary to advancing the body of knowledge and in this case promoting public safety.

## 3.2 Specific Instance Description

Figure 5 below is adapted from Figure 4 and shows the specific models types, tools, and techniques that will be used to execute the experimental design.

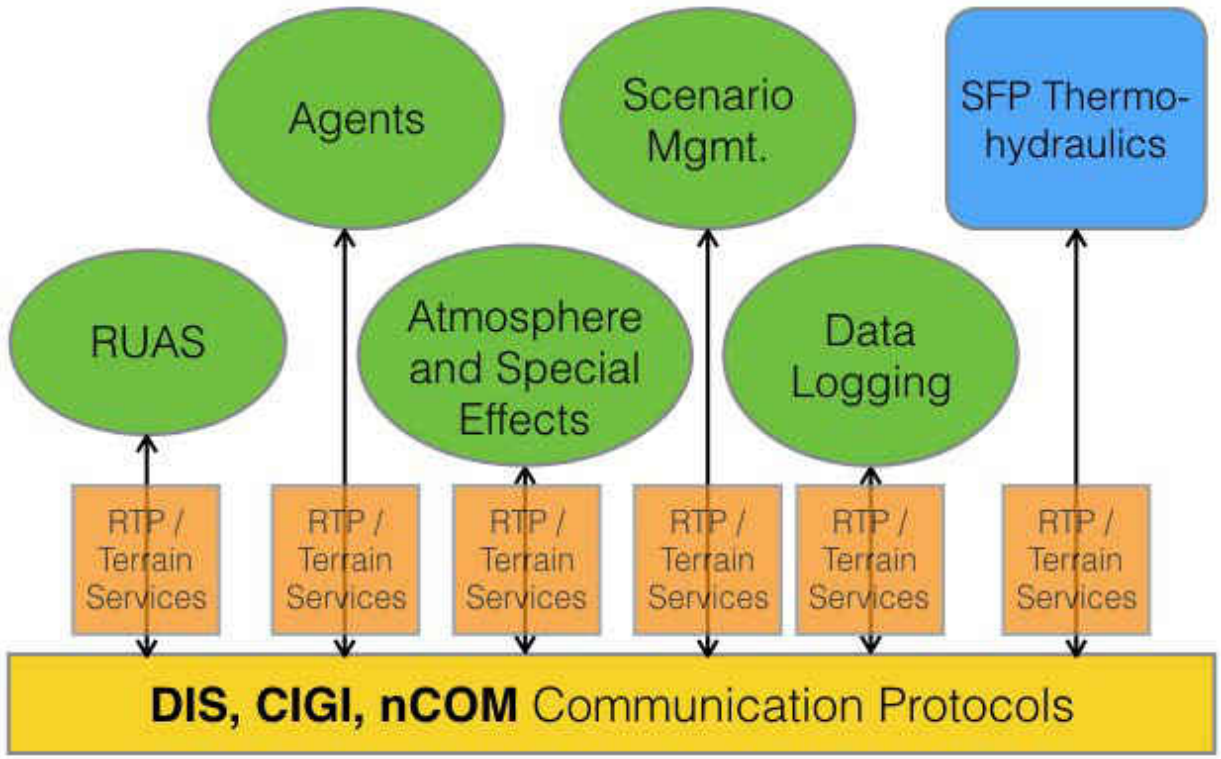



**Figure 5: Conceptual view of the Overall Simulation**

The paragraphs below describe Figure 5 from the bottom most common elements up, and the "lollipops" from left to right.

The shared foundation of any distributed simulation is communication. Communication protocols go beyond hardware interfaces necessary to transmit and receive data. The meaning, context, and timeliness of data is important. The protocol language used to communicate this content is critical to success. In this case, three well established simulation communication protocols will be used. First, Distributed Interactive Simulation (DIS) protocol will be used to transmit entity state data between the simulations. DIS is a widely-used standard for simulation data transmission. (P. K. Davis, 1995) provides a historical view of the potential growth of DIS and detail on its specifics are available in the IEEE standard (IEEE, 2012). Secondly, Common Image Generator Interface (CIGI) "is an open standards interface designed to promote a common method of communication between a host device and an image generator (IG)" (Presagis, 2016b). CIGI will be used to transmit entity and environmental data to the IG's of the RUAS and Scenario Management station. Finally, "nCOM is a communications layer that resides on top of standard protocols…" allowing individual Presagis tools to exchange data efficiently (Presagis, 2016a). This protocol will be used to publish, display, and log the state data of the SFP and the RUAS during runtime.

Above the shared communication backbone in Figure 5 but below each bubble is a box labeled RTP / Terrain Services. RTP / Terrain Services represent the source and management of terrain data for the simulation and is commonly known as part of the Synthetic Natural Environment (SNE). Traditionally, terrain represented static portions of the SNE necessary to support a scenario that took place on it. Generally, parts of the SNE that did not change,

respond, or interact with the agents or avatars within a given scenario would be part of the terrain. Anything in the scenario that needed to dynamically respond or interact with the entities would be represented as an entity/agent or as a special effect within constructive simulation code or within the virtual simulation image generator. Historically, real-time virtual simulations were developed to train aircrews operating at altitudes and speeds that precluded the need for dynamic interaction with the ground or most things on it. A representative static SNE format developed to meet the needs of these users is the original version of OpenFlight. OpenFlight is now ubiquitous within the LVC simulation community and has overlays that attribute the terrain for agent navigation and may also support dynamic terrain. As LVC simulation expanded to training audiences that are on or near the ground, the need for dynamic interaction with the terrain and objects on the terrain increased. Additionally, as event training audiences grew and became geographically distributed the need for a common "ground truth" database of the terrain arose. The Common Database (CDB) format developed to meet the needs of a portion of this growing and evolving user community. CDB differs from OpenFlight in that it consists of multiple layers of data that are correlated by a common georeferencing system. Further, CDB is designed to reside on a single server that provides environmental data to and manages changes for all the user systems within a distributed simulation. These enhanced capabilities of CBD make it an appealing choice for SNE management during this research.

The Presagis Run Time Publisher (RTP) manages and publishes CDB terrain data to subscribing models. The RTP is a backend process specifically designed to manage dataflow out of the CDB either from a local source or a terrain server. It formats the data in specific ways to optimize it for the model making the request. It operates similarly to an RTI within an HLA federation except that it focuses solely on terrain data. An instance of the RTP is needed on each computer running Presagis software in the experiment. Due to network throughput limitations within the laboratory discovered during initial research efforts, the client / server structure that is one of the most appealing features of the CDB architecture will not be used. Further, the current version of the CDB standard has proven extremely difficult to work with and a functional CDB terrain database for the use case of this research does not currently exist. As such, an OpenFlight version of the SNE will be used for the current research while looking to continued development of the CDB standard to support a more robust SNE for future research efforts.

Moving through the "lollipops" from left to right, the first participating model is responsible for simulating the RUAS during the exercise. The Presagis HeliSIM tool contains several preconfigured high-fidelity helicopter models, provides suitable real system representation, and is fully integrated with the rest of the Presagis Suite. Further, STAGE, acting as the overall simulation control interface, can call the virtual simulation HeliSIM during execution to "fly" a constructive helicopter entity. With the dual capability of virtual and constructive helicopter representation, the high-fidelity models available as part of HeliSIM can

be implemented without a human operator allowing the integration of highly accurate representations of helicopter operations into larger, fully constructive simulations. Implementing HeliSIM in this way is not only convenient for our immediate research purposes, but also serves to support the extensibility of the SoS CM and LVC simulation framework proposed in Ch. 2 since HeliSIM is a proven and widely used virtual simulation (Presagis, 2015a).

The Northrup Grumman MQ-8C Fire Scout unmanned helicopter is an excellent candidate for the water delivery mission under study and is based on the Bell 407 airframe(Northrup Grumman, 2015). The Bell 407 is an updated version of the Bell 406. The enhancements integrated into the 407 were based on modifications Bell made to the 406 to create a suitable airframe for the US Army's OH-58D Kiowa Warrior(Deagel, 2015). Thus, the MQ-8C and the OH-58D are based on the same airframe and powerplant and will therefore have very similar flight profiles and performance characteristics. Coincidentally, one of the default models delivered with HeliSIM is representative of the US Army OH-58 Kiowa Warrior. Due to the similarities between the two aircraft, the OH-58 model delivered as part of HeliSIM will be slightly modified to more closely resemble the MQ-8C and used as the test platform for the water delivery mission.

Choosing the OH-58 model as an initial test airframe is not only useful for the current research, but also feeds back once again to the extensibility of the SoS CM and LVC simulation framework through modularity. The HeliSIM module enables extensibility to many helicopter models that are being added to HeliSIM regularly as new helicopter platforms, UAV

reconfigured helicopters, and new, UAV specific, airframes as they emerge on the market. Further, FlightSim may replace the HeliSIM module in Figure 5 thus extending the SoS CM and the LVC simulation framework to fixed wing aircraft and UAV's contained within the FlightSim module. Using an aircraft built on a well-established and widely used airframe like the Bell 407 or any other potentially valid models in FlightSim or HeliSIM aids future research efforts tremendously.

The next sub-system in Figure 5 is called Agents. Agents in this context include all the other entities active within the scenario thus further demonstrating extensibility of the SoS CM and LVC simulation framework. Agents exhibit some level of artificial intelligence (AI) within a given simulation to add realism to the scenario. The sophistication of this AI varies from scenario to scenario as well as from entity to entity within any given scenario. Generally, the level of AI sophistication rises as the amount of interaction the training audience is expected to have with an entity rises. In this case where there is no human training audience, the epicenter of AI sophistication will be the system under test, the RUAS. The agents needed for this research are: the SFP, the fresh water source, the SFP at the NPP, and RUAS staging and maintenance facilities and personnel. These entities move beyond the background clutter of the scenario because of the RUAS's need to meaningfully interact with them. The RUAS must be able to exchange water with both the SFP and the fresh water source. Further, the RUAS must interact with staging and maintenance entities to create realistic sortie generation variability.

Atmosphere and Special Effects is the next sub-system in the figure. Weather is a critical component of modeling the larger nuclear disaster scenario because atmospheric transport is the major contributor to radioactive material proliferation after an accident (S. Hanna & Chang, 2015; S. R. Hanna, 2009; Plante, 2002; Platt et al., 2014; Singh et al., 2015). Further, radiation levels in the area immediately surrounding the disaster site are impacted by weather effects. While radiation can have rapid and drastic effects on electronics equipment (T. Johnson, 2006), the impact of such effects are beyond the scope of this research and will thus be ignored. This does not mean that weather can be ignored. The evaporation model presented in Equation (1) is based almost completely on weather related parameters. Further, the ability of the RUAS to operate effectively is directly impacted by its weather environment. Since this research is not concerned with particle dispersion, advanced dispersion models won't be used. Instead all that is needed are the weather parameters of interest to be made available to HeliSIM and the SFP evaporation model. STAGE has a capability to provide these weather parameters to other participants during the simulation runtime and will be used to do so.

Scenario Management and Data Logging are the next areas to be described. The primary purpose of STAGE is scenario creation and runtime management, so it will be used here. Data logging is important for maximizing the value of any simulation, but is crucial for any simulation for analysis effort. STAGE also offers a logging capability and will be responsible for capturing data generated during simulation runs for post-test analysis.

As noted in Chapter 2, the radiation dispersion model is peripheral to the focus of the current research and is therefore not included in Figure 5.

## 3.3 Experimental Design

The problem defined in Section 3.1 The Use Case identifies SFP water level as the parameter that determines success or failure of any mitigation efforts. Thus, SFP water level ($WL$) will be the response variable.

The factors affecting $WL$ in the real world are myriad. A small subset of those are represented within the simulation, and a small subset of those will be examined to determine their influence on mission success. Factors can be grouped in several ways throughout the experimentation process, but during the identification process it is most helpful to group them based on which area or model within the simulation they come from. The table below identifies the design factors for this study. Their common name, followed by a symbol to be used during analysis computations, and finally the model or component of the overall simulation from which they came is given for each. For a complete list of potential design factors, the reader is referred to Appendix A.

**Table 1: Design Factors for Initial Study**

| Factor Common Name | Mathematical Symbol | Component of Origin |
|---|---|---|
| Cruise Speed | $V$ | RUAS |
| Sling Load Capacity | $C$ | RUAS |
| Sortie Length | $S$ | RUAS |
| Number of Aircraft | $A$ | RUAS |
| Wind Velocity | $v$ | Weather |
| Atmospheric Pressure | $P$ | Weather |
| Relative Humidity | $\phi$ | Weather |
| Water Temperature | $T$ | SFP Thermohydraulics |
| Air flow reduction ratio | $r$ | SFP Thermohydraulics |

The focus of this research and the defined problem statement are exploratory in nature and as such it is not yet clear which, if any, of the factors in Table 1 have significant impact on the water level response as main effects or in interactions with one another. This lack of knowledge about how the system works and which subsystems are most closely related means that a factor screening design is a good choice for the initial experiment. As noted in Chapter 2, orthogonal arrays are a popular choice for factor screening experiments. While full factorial experiments are orthogonal, the run budget grows rapidly even when testing factors at only two levels (Anderson & Whitcomb, 2007). Fortunately, the wide study of OA construction has

led to several software implementations including in popular experimental design tools. One such tool, JMP®, is readily available and is useful for generating many types of experimental designs as well as analyzing results.

For the 9-factor screening experiment JMP recommends a 16 run orthogonal array. The disadvantage of this orthogonal array design is it only estimates main effects and aliases all two factor and higher interactions. This is not desirable in this case given the known relationship of several of the factors by way of the Hugo evaporation model.

JMP offers alternatives to the orthogonal design in the form of fractional factorial designs. These designs offer the advantage of increased resolution, or the ability to estimate higher order interaction effects not available in minimal run orthogonal arrays, but with a smaller run budget than full factorial experiments. Fractional factorial designs are widely used in product and process design and are an extremely popular choice for screening experiments (Montgomery, 2013). The details of a JMP recommended fractional factorial design are given below.

Using the JMP software to create a Screening Design, the first step is to identify the response variable, whether it is to be maximized or minimized and what its upper and lower limits are. $WL$ was early identified as the response variable. It should be maximized with an upper limit of 7 meters and a lower limit of 1 meter. These values are based on the dimensions of the SFP and the fuel assemblies. WNA (2012) lists the depth of the SFP at Fukushima unit 4 as 12 meters and the fuel assemblies as 5 meters tall. This means that 7 meters of water cover

the fuel during normal operations, thus this is the goal water depth. The minimum value of 1 meter is established from Collins and Hubbard (2001), who concluded that SFP water levels below 1 meter above the fuel assemblies made recovery unlikely due to the significantly increased radiation level in and around the pool area.

The next step is to input the factors of interest. The nine factors from Table 1 are given high and low values and assigned a type in Table 2 below.

**Table 2: High and Low Factor Treatments**

| Factor | High Value | Low Value | Type |
|---|---|---|---|
| Cruise Speed ($V$) | 40 m/s | 25 m/s | Continuous |
| Sling Load Capacity ($C$) | 1200 kg | 450 kg | Continuous |
| Sortie Length ($S$) | 360 min | 120 min | Continuous |
| Number of Aircraft ($A$) | 4 | 1 | Discrete Numeric |
| Wind Velocity ($v$) | 15 m/s | 3 m/s | Continuous |
| Atm. Pressure ($P$) | 103000 Pa | 100000 Pa | Continuous |
| Relative Humidity ($\phi$) | 90% | 55% | Continuous |
| Water Temp. ($T$) | 98 C | 90 C[1] | Continuous |
| Reduction Ratio ($r$) | 0.3 | 0.1 | Continuous |

1 According to D. A. Wang et al. (2012), the initial water temperature of the SFP at Fukushima at the time of power loss was 27 C. It then took approximately 3 days for the SFP to approach thermal equilibrium at around 84-90 C. Delivery operations via RUAS are thus assumed to begin once the pool has achieved thermal equilibrium at between 90 and 98 C which would likely occur 3-5 days after power is lost based on the empirical evidence collected at Fukushima.

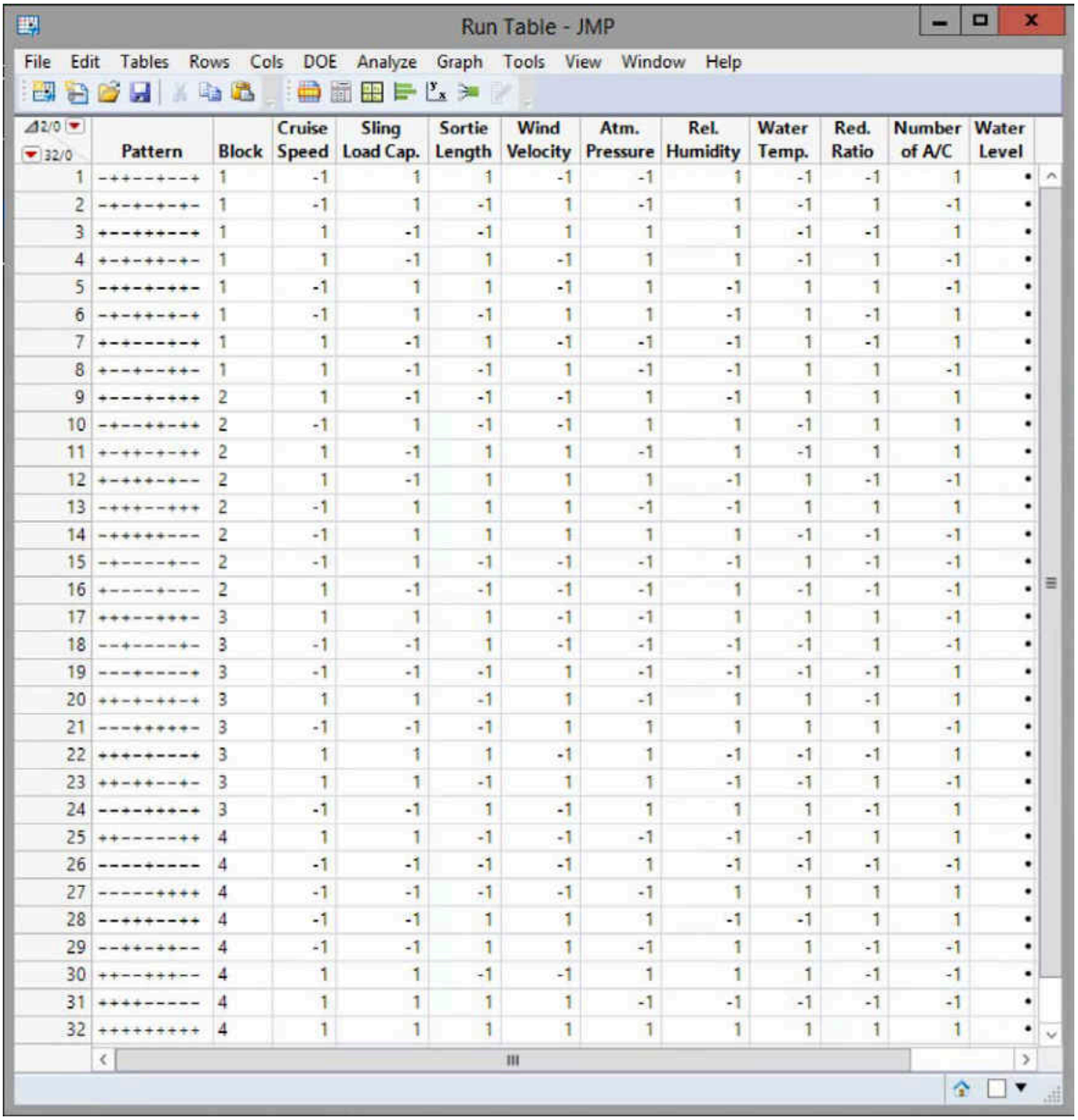
The factors and values from Table 2 were input into JMP. JMP then offers several fractional factorial screening designs of varying size and resolution. Design resolution refers to the ability to estimate main and interaction effects in the post analysis model. Details on these designs are available in Montgomery (2013), but they are essentially as follows:

- **Resolution III** designs do not have any main effects aliased with each other, but two-way interactions are aliased with main effects and other two-way interactions.
- **Resolution IV** designs have main effects clear of aliasing with each other or two-way interactions, but two-way interactions may be aliased with each other.
- **Resolution V** designs are those in which main effects and two-way interactions are not aliased with other main effects or two-way interactions, but the two-way interactions may be aliased with three-way interactions.

JMP suggests fractional factorial designs of resolution III, IV, and V with variations in run size generally increasing as the resolution increases. Given the known interactions of some of the factors, a Res. IV design accounts for some of these interactions. Most importantly, a design of this type does exactly what it is intended to do; identifies the main effects that are unimportant during this initial screening experiment. Several res IV designs are suggested each with run sizes of either 32 or 64. Doubling the size of the experimental data collection does not help to predict more effects, only to decrease the variance surrounding the main effects and two-way interactions that are not confounded. However, blocking the design, even the smaller design, is a valuable noise reduction technique (Montgomery, 2013) and can be used to remove the effects of nuisance factors while keeping the experiment size under control. Further, the use of a well-designed smaller fractional factorial experiment provides the opportunity for

sequencing of additional experiments. Sequencing refers to the use of a smaller fractional factorial design that can be run, have data analysis conducted, then use the results to generate a follow-on fractional factorial design based on the results of the first (Montgomery, 2013). Given these advantages, a 32 run, res IV, randomized 4 block design will provide good screening capability with limited two-factor to two-factor aliasing while allowing for the mitigation of the noise associated with an additional nuisance factor.

Figure 6 below shows the coded run table in its randomized within block order. The -1 and 1 codes correspond to the low and high values for each factor shown in Table 2.




| | Pattern | Block | Cruise Speed | Sling Load Cap. | Sortie Length | Wind Velocity | Atm. Pressure | Rel. Humidity | Water Temp. | Red. Ratio | Number of A/C | Water Level |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | --++++--+ | 1 | -1 | 1 | 1 | -1 | -1 | 1 | -1 | -1 | 1 | • |
| 2 | --++++++- | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | • |
| 3 | +++++++++ | 1 | 1 | -1 | -1 | 1 | 1 | 1 | -1 | -1 | 1 | • |
| 4 | +-+-++++- | 1 | 1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | -1 | • |
| 5 | -++++++-- | 1 | -1 | 1 | 1 | -1 | 1 | -1 | 1 | 1 | -1 | • |
| 6 | --+++++++ | 1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | -1 | 1 | • |
| 7 | +++++++++ | 1 | 1 | -1 | 1 | -1 | -1 | -1 | 1 | -1 | 1 | • |
| 8 | +--++++-- | 1 | 1 | -1 | -1 | 1 | -1 | -1 | 1 | 1 | -1 | • |
| 9 | +++++++++ | 2 | 1 | -1 | -1 | -1 | 1 | -1 | 1 | 1 | 1 | • |
| 10 | -+++++++- | 2 | -1 | 1 | -1 | -1 | 1 | 1 | -1 | 1 | 1 | • |
| 11 | +-++++++- | 2 | 1 | -1 | 1 | 1 | -1 | 1 | -1 | 1 | 1 | • |
| 12 | +-++++--- | 2 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | -1 | -1 | • |
| 13 | -++++++- | 2 | -1 | 1 | 1 | 1 | -1 | -1 | 1 | 1 | 1 | • |
| 14 | -++++--- | 2 | -1 | 1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 | • |
| 15 | -+-++--- | 2 | -1 | 1 | -1 | -1 | -1 | -1 | 1 | -1 | -1 | • |
| 16 | +---+--- | 2 | 1 | -1 | -1 | -1 | -1 | 1 | -1 | -1 | -1 | • |
| 17 | +++++++- | 3 | 1 | 1 | 1 | -1 | -1 | 1 | 1 | 1 | -1 | • |
| 18 | --+---+- | 3 | -1 | -1 | 1 | -1 | -1 | -1 | -1 | 1 | -1 | • |
| 19 | ---++++- | 3 | -1 | -1 | -1 | 1 | -1 | -1 | -1 | -1 | 1 | • |
| 20 | ++-+++-+ | 3 | 1 | 1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | • |
| 21 | ---++++- | 3 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | 1 | -1 | • |
| 22 | +++++++- | 3 | 1 | 1 | 1 | -1 | 1 | -1 | -1 | -1 | 1 | • |
| 23 | ++-++--+- | 3 | 1 | 1 | -1 | 1 | 1 | -1 | -1 | 1 | -1 | • |
| 24 | ---++++- | 3 | -1 | -1 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | • |
| 25 | ++++++++ | 4 | 1 | 1 | -1 | -1 | -1 | -1 | -1 | 1 | 1 | • |
| 26 | ---++++- | 4 | -1 | -1 | -1 | -1 | 1 | -1 | -1 | -1 | -1 | • |
| 27 | ---++++ | 4 | -1 | -1 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | • |
| 28 | ---++++ | 4 | -1 | -1 | 1 | 1 | 1 | -1 | -1 | 1 | 1 | • |
| 29 | --++++-- | 4 | -1 | -1 | 1 | 1 | -1 | 1 | 1 | -1 | -1 | • |
| 30 | ++--++-- | 4 | 1 | 1 | -1 | -1 | 1 | 1 | 1 | -1 | -1 | • |
| 31 | ++++---- | 4 | 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 | -1 | • |
| 32 | +++++++++ | 4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | • |

**Figure 6: JMP created experiment run table**

Figure 7 below shows the aliasing scheme for the two-factor interactions for those aliased with other two-factor interactions and those aliased with blocks.

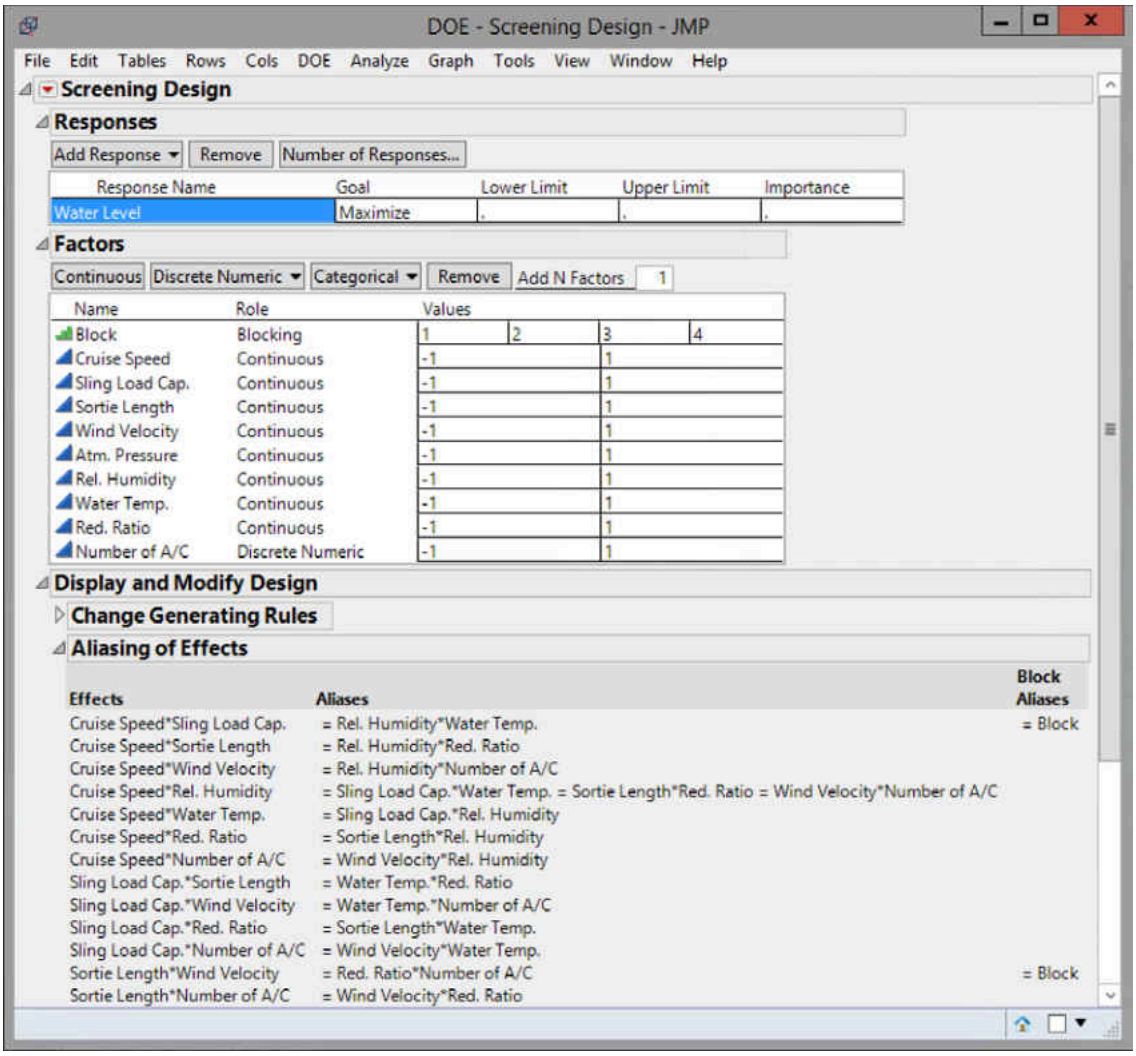



**Figure 7: Aliased effects in the experimental design**

There are several factors in the Table A-1 in Appendix A that are good candidates for noise mitigation via blocking. However, one of them presents the classic case for blocking by its potential for introducing noise with no other mitigation alternatives. There are several computers available for this research with matching hardware and software configurations. And

while these machines have the same specifications, each may perform differently during a simulation run. There is no way to isolate run-to-run variability between machines to either factor changes or the machine unless the experiment is blocked by machine. Further, blocking on computers allows multiple runs to execute simultaneously and reduce the overall time required to complete the data collection phase of the experiment.

There are also several factors listed in Table A-1 Appendix A that are closely related to mission execution, but won't be explicitly tested during this research. Despite their potential impact on the real-world outcome of this type of mission, these factors will be controlled during the simulation experiment to better observe the impacts of the factors under test.

First, RUAS Reliability and Sortie Regen Time are closely related to the maintenance facilities and personnel agents mentioned above. Variability in decontamination, maintenance, and refueling activities certain to impact real-world operations will be simulated in this research by introduction of pseudo-normally distributed noise variables. After each sortie a random variable is selected from a uniform distribution. The value of this variable is used to select one of 13 bins each with preassigned a z-scores. The selected z-score is multiplied by the sortie length factor and the computed estimate of average maintenance man hour ratio (1.1) for the Bell 407 (Bell Helicopter, 2010). This creates a pseudo-normally distributed random maintenance time for each sortie. This maintenance time is then multiplied by a 1.5 to account for the extended time required for maintenance personnel to complete tasks in MOPP 4 gear (E. G. W. Davis, Charles H. ; Salvi, Lucia ; Kash, Howard M., 1990). Finally, a static 45 minutes of

decontamination time is added to the maintenance period to account for radiological decontamination of the aircraft (TRADOC, 2000).

Secondly, Water Drop Height, Bucket Fill Efficiency, and Delivery Efficiency will also be held constant. While each of these are related, and have an impact on the total volume of water delivered over the course of a sortie, they are not only beyond the abilities of the selected simulations to model, they are also beyond the scope of this initial evaluation of general effectiveness of a particular class of platforms. Therefore, all three will be rolled up into a single reduction factor applied to the maximum slung load capacity of the platform. This maximum lift capability translates to a maximum volume of water per trip. The process of filling the bucket and transporting it from the fresh water source to the SFP will be assumed to result in 90% of the maximum bucket volume of water making it to the drop point. This is the controlled value of Bucket Fill Efficiency. Water Drop Height, weather conditions, physical and chemical properties of the fresh water, size and shape of the bucket emptying apparatus, and several other factors all play a role in how the water falls from the bucket toward the SFP. How much of that water makes it into the SFP is further affected by things like the size and shape of the SFP, the approach heading and velocity of the aircraft, the residual super structure or lack thereof above and around the SFP, etc. Once again, these factors are beyond the capability of the simulation to accurately model and are beyond the scope of the current research. Thus, the combined effect of all these will be assumed to result in only 80% of the water dropped entering the SFP. The overall effectiveness or volume of water delivered to the SFP with each

trip is then the product of the Sling Load Capacity, the fill and transit efficiency, and the drop efficiency:

$$\text{Sling Load Capacity} \times 0.9 \times 0.8 = \text{Total Volume Delivered} \quad (2)$$

Third, there are some SFP characteristics that could affect the outcome of the experiment. SFP Depth over Fuel, SFP Surface Area, and SFP Water Volume all contribute directly to the overall Water Level response variable. However, each of these are unique to NPPs and in some cases individual reactors at the NPP site. Varying these factors to evaluate the effectiveness of an RUAS platform to mitigate evaporative loss for a wide variety of SFPs is an excellent topic for future research and will be discussed further in Ch. 5. As noted in Ch. 2, this research will use the dimensions of the Fukushima Daiichi Unit 4 reactor SFP because of the availability of data associated with this plant and reactor. Thus, SFP Depth over Fuel, SFP Surface Area, and SFP Water Volume will all be held constant.

Fourth, Daily Precipitation and Fresh Water Temperature will be held constant. Daily Precipitation will be held at zero to avoid effects of rainfall on the SFP directly as well as the effects on the evaporation model in Eq. ( 1 ) created by precipitation. Even though data collected from Fukushima showed that injecting cold seawater into the SFP had an effect on overall SFP temperature (M. Davis & Proctor, 2016; G. o. Japan, 2011), ignoring the effects of

cold fresh water additions to the SFP will maintain higher computed evaporation rates and build buffer into the estimate of effectiveness in the post simulation analysis.

Finally, two factors in the list are geographical in nature and each has large potential impact to the outcome of the experiment. The locations of both a fresh water source and the staging area for the RUAS have the potential for major impact on the mission profile of the RUAS during the experiment. Each of these is severely limited by the actual geography of the area surrounding the NPP, thus they are difficult to arbitrarily change. To avoid these impacts and difficulties, both will be fixed for the duration of the experimental runs.

## 3.4 Execution and Data Collection

Table A-2 in Appendix A shows the run-by-run settings for each of the factors under test. They are grouped by block and then their order randomized within each block. Each run will begin with each of the factors set to levels specified in the table.

There are several other initial conditions that won't be tested, but should be specified to enable recreation of the results. The RUAS will begin each run on the ground at the maintenance point ready to begin its first sortie. The SFP will begin each run with its water level at its normal operating full state seven meters above the assemblies. Each run will continue for 72 hours of simulation time.

Due to the dynamic nature of the real-time simulation, events of interest may occur at intermediate points during a simulation run. To capture this information, data logs of each run will be collected so that detailed post-run analysis can be performed if necessary. For instance,

if the water level drops below one meter above the fuel assemblies the time of this failure will be important to know when that mission failure occurs. Alternatively, if the pool level reaches the seven-meter level before the end of the simulation, it may be of interest to know when and how often during the run this occurred.

# CHAPTER FOUR: DATA AND ANALYSIS

The data from the experimental methodology described in Chapter 3 are detailed in this chapter along with analysis and interpretation of the results. This chapter describes the complete data collection and analysis process. It begins with a description of the data collection and cleaning techniques followed by a summary of the raw results with some initial analysis of the results in tabular and plot form. Finally, a statistical analysis is performed and the results interpreted.

## 4.1 Data Collection and Preparation

There are multiple accessory windows available within the STAGE environment both during design and runtime. Figure 8 below shows a screen capture of several of these windows during runtime.

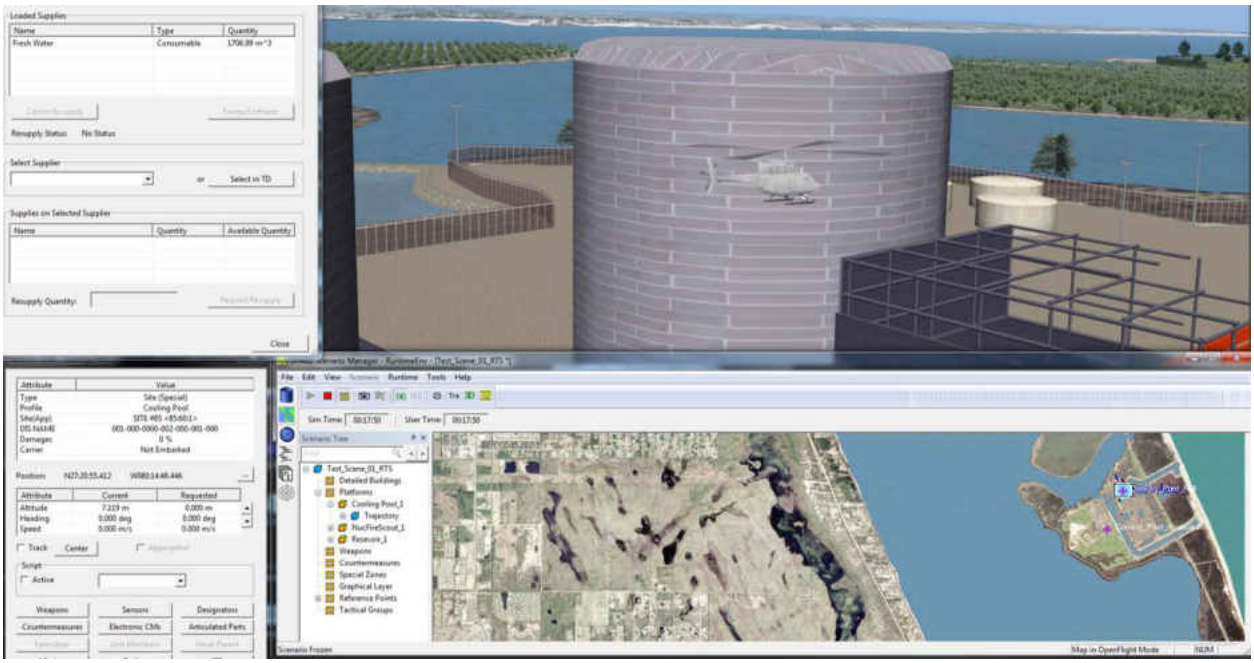


**Figure 8: STAGE windows during runtime**

One of the available windows is called Mission History and is shown in Figure 9. This window displays a log of all the mission calls and actions performed by the entities within the current simulation. This log contains the SFP water levels reported at approximately 1 minute intervals for the entire simulation run. It should be noted that the baseline STAGE install does not produce this SFP data. The STAGE IDE (Integrated Development Environment) was used to extend STAGE's underlying database and a plugin was written to modify its baseline capabilities to collect and report the SFP water levels. Details about the STAGE setup and modification can be found in Appendix C.

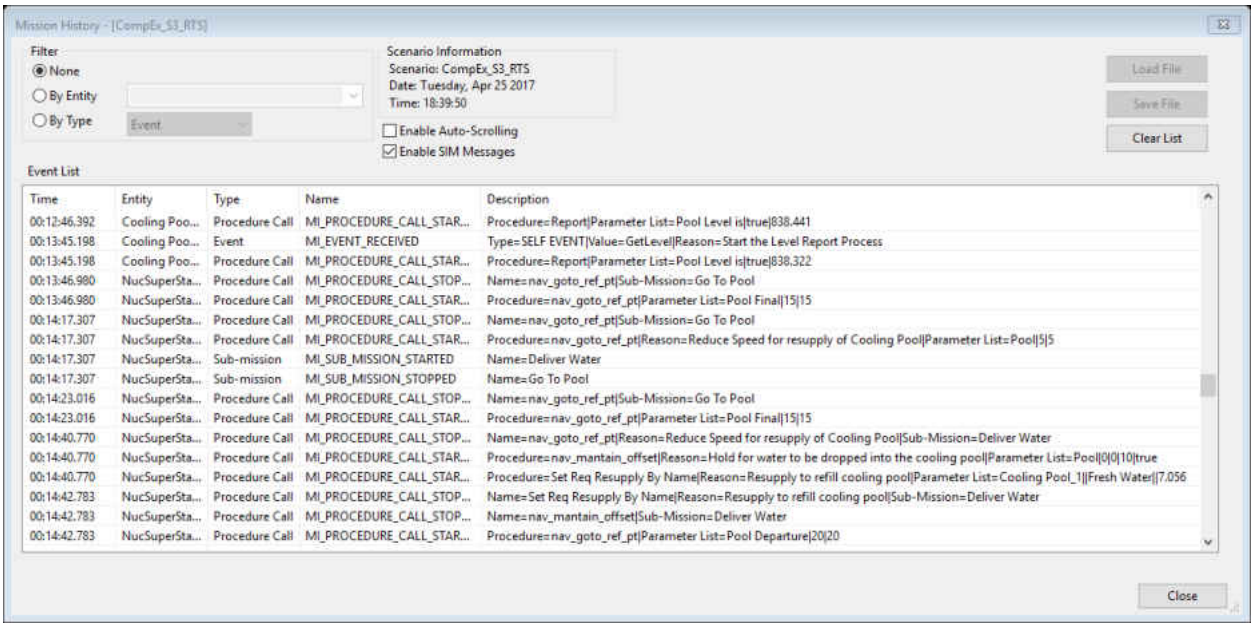



**Figure 9: STAGE Mission History log**

At the conclusion of each run, the mission history log file was saved as a raw text file. The only data pertinent to the current research is the water level data which is intermingled with thousands of lines of other data, so scrubbing of these raw text files was necessary. Several techniques and software packages are available for this type of data scrubbing including MS Excel, JMP, and R studio. Since 32 runs were completed each generating a log file over 30,000 lines long, an efficient method to scrub these files in batch form was developed using R studio. The script not only scrubbed the data, but also produced plots of the water level over time and captured the end-of-simulation water level for each run and wrote these all into a single file for easy import to JMP for statistical analysis of the overall experiment. The R studio files are provided in Appendix D.

Once scrubbed, the raw results of the 32 runs were contained in 33 separate files, one for each run and another containing the SFP water level reported at the end of each run. These data are available in electronic from the author upon request, but are not included here or in appendices due to their size.

## 4.2 Raw results and preliminary analysis

Table 3 reports raw results of the 32-run experiment. The table includes the treatment level for each of the 9 factors along with the end of run water volume. The last column (Mission Fail Time) reports the simulation time when the six runs (runs 2, 8, 13, 21, 29, 32) that reached critical low-water levels classified as safety failures reported SFP water levels at 1 meter above the fuel assemblies. M. Davis, Proctor, and Shageer (2017) make several observations about the treatment levels common to these failures:

> "Common to the runs 2, 8, 21, and 29… [were] high wind speeds and only one Fire Scout RUAS. Runs 13 and 32… had high wind speeds and four Fire Scout RUAS as well as a 360-minute sortie length and high water temperature in common. Based only on observed safety failures, from a reliability perspective emergency managers should plan on four Fire Scout RUAS with maintenance equipment, spare parts, and crew of sufficient size to reduce between-sortie maintenance time to the minimum."

**Table 3: Summary of Treatments and Results**

| Run | Pattern | Block | Cruise Speed (m/s) | Sling Load Cap. (kg) | Sortie Length | Wind Vel. (m/s) | Atm. Pressure (Pa) | Rel. Hum. | Water Temp. (C) | Red. Ratio | Number of A/C | End of Run Water Volume | Mission Fail Time (hours) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | −++−−+−−+ | 1 | 25 | 1200 | 360 min | 3 | 100000 | 0.9 | 90 | 0.1 | 4 | 839.882 | NA |
| 2 | −+−+−+−+− | 1 | 25 | 1200 | 120 min | 15 | 100000 | 0.9 | 90 | 0.3 | 1 | 111.523 | 71.247 |
| 3 | +−−+++−−+ | 1 | 40 | 450 | 120 min | 15 | 103000 | 0.9 | 90 | 0.1 | 4 | 718.313 | NA |
| 4 | +−+−++−+− | 1 | 40 | 450 | 360 min | 3 | 103000 | 0.9 | 90 | 0.3 | 1 | 696.69 | NA |
| 5 | −++−+−++− | 1 | 25 | 1200 | 360 min | 3 | 103000 | 0.55 | 98 | 0.3 | 1 | 477.836 | NA |
| 6 | −+−++−+−+ | 1 | 25 | 1200 | 120 min | 15 | 103000 | 0.55 | 98 | 0.1 | 4 | 433.407 | NA |
| 7 | +−+−−−+−+ | 1 | 40 | 450 | 360 min | 3 | 100000 | 0.55 | 98 | 0.1 | 4 | 809.647 | NA |
| 8 | +−−+−−++− | 1 | 40 | 450 | 120 min | 15 | 100000 | 0.55 | 98 | 0.3 | 1 | 0 | 26.485 |
| 9 | +−−−+−+++ | 2 | 40 | 450 | 120 min | 3 | 103000 | 0.55 | 98 | 0.3 | 4 | 520.788 | NA |
| 10 | −+−−++−++ | 2 | 25 | 1200 | 120 min | 3 | 103000 | 0.9 | 90 | 0.3 | 4 | 839.459 | NA |
| 11 | +−++−+−++ | 2 | 40 | 450 | 360 min | 15 | 100000 | 0.9 | 90 | 0.3 | 4 | 366.218 | NA |
| 12 | +−+++−+−− | 2 | 40 | 450 | 360 min | 15 | 103000 | 0.55 | 98 | 0.1 | 1 | 197.392 | NA |
| 13 | −+++−−+++ | 2 | 25 | 1200 | 360 min | 15 | 100000 | 0.55 | 98 | 0.3 | 4 | 0 | 34.964 |
| 14 | −+++++−−− | 2 | 25 | 1200 | 360 min | 15 | 103000 | 0.9 | 90 | 0.1 | 1 | 655.95 | NA |
| 15 | −+−−−−+−− | 2 | 25 | 1200 | 120 min | 3 | 100000 | 0.55 | 98 | 0.1 | 1 | 542.717 | NA |
| 16 | +−−−−+−−− | 2 | 40 | 450 | 120 min | 3 | 100000 | 0.9 | 90 | 0.1 | 1 | 735.265 | NA |
| 17 | +++−−+++− | 3 | 40 | 1200 | 360 min | 3 | 100000 | 0.9 | 98 | 0.3 | 1 | 473.966 | NA |
| 18 | −−+−−−+− | 3 | 25 | 450 | 360 min | 3 | 100000 | 0.55 | 90 | 0.3 | 1 | 652.545 | NA |
| 19 | −−−+−−−+ | 3 | 25 | 450 | 120 min | 15 | 100000 | 0.55 | 90 | 0.1 | 4 | 614.354 | NA |
| 20 | ++−+−++−+ | 3 | 40 | 1200 | 120 min | 15 | 100000 | 0.9 | 98 | 0.1 | 4 | 734.44 | NA |
| 21 | −−−+++++− | 3 | 25 | 450 | 120 min | 15 | 103000 | 0.9 | 98 | 0.3 | 1 | 0 | 30.665 |
| 22 | +++−+−−−+ | 3 | 40 | 1200 | 360 min | 3 | 103000 | 0.55 | 90 | 0.1 | 4 | 839.882 | NA |
| 23 | ++−++−−+− | 3 | 40 | 1200 | 120 min | 15 | 103000 | 0.55 | 90 | 0.3 | 1 | 204.37 | NA |
| 24 | −−+−+++−+ | 3 | 25 | 450 | 360 min | 3 | 103000 | 0.9 | 98 | 0.1 | 4 | 747.735 | NA |
| 25 | ++−−−−++ | 4 | 40 | 1200 | 120 min | 3 | 100000 | 0.55 | 90 | 0.3 | 4 | 839.994 | NA |
| 26 | −−−−+−−− | 4 | 25 | 450 | 120 min | 3 | 103000 | 0.55 | 90 | 0.1 | 1 | 726.889 | NA |
| 27 | −−−−−++++ | 4 | 25 | 450 | 120 min | 3 | 100000 | 0.9 | 98 | 0.3 | 4 | 375.833 | NA |
| 28 | −−+++−−++ | 4 | 25 | 450 | 360 min | 15 | 103000 | 0.55 | 90 | 0.3 | 4 | 270.459 | NA |
| 29 | −−+−++−− | 4 | 25 | 450 | 360 min | 15 | 100000 | 0.9 | 98 | 0.1 | 1 | 51.1627 | 65.780 |
| 30 | ++−−+++−− | 4 | 40 | 1200 | 120 min | 3 | 103000 | 0.9 | 98 | 0.1 | 1 | 645.779 | NA |
| 31 | ++++−−−−− | 4 | 40 | 1200 | 360 min | 15 | 100000 | 0.55 | 90 | 0.1 | 1 | 720.925 | NA |
| 32 | +++++++++ | 4 | 40 | 1200 | 360min | 15 | 103000 | 0.9 | 98 | 0.3 | 4 | 25.4982 | 63.722 |

The exploratory nature of this work meant that there was much uncertainty about the effectiveness of the water delivery mission especially with so many factors influencing both RUAS operations and evaporation rates from the SFP. Figure 10 below contains a sampling of the output of from the R script mentioned in 4.1. The selected plots are representative of the behavior shown throughout the experiment and water volume plotted against elapsed time for 4 representative runs: 1-8, 2-4, 3-4, and 4-1. Graphical analysis of these time series water volume data for each run reveals further evidence that at least some of these factors have significant impact on water volume and that results vary widely as conditions are varied.

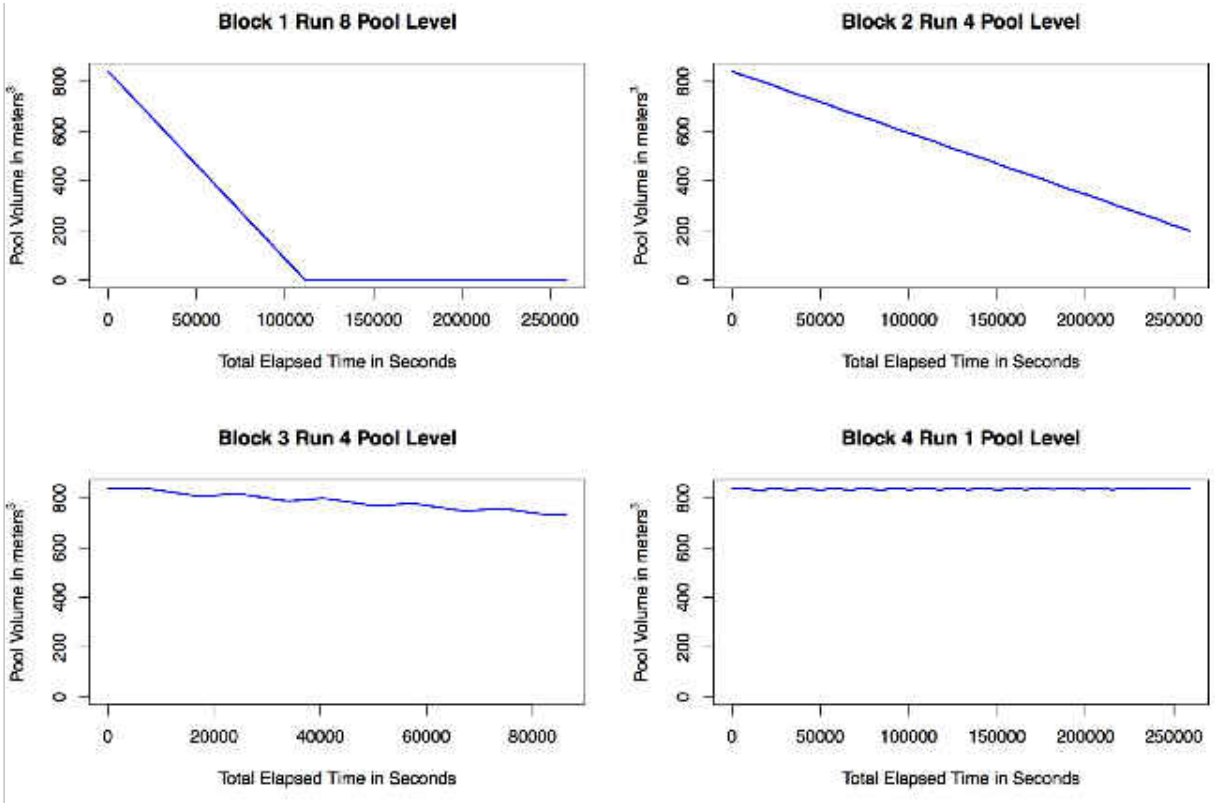



**Figure 10: Plots of water volume over time**

## 4.3 Statistical analysis and interpretation

Developing an effects model capable of predicting performance from a limited set of inputs is the goal, but the first step is determining which factors influence outcome most. The half normal quantile plot in Figure 11 indicates Wind Velocity, Reduction Ratio, Water Temperature, Number of Aircraft, and the Wind Velocity crossed with Reduction Ratio interaction term all have significant impact on end state water volume.

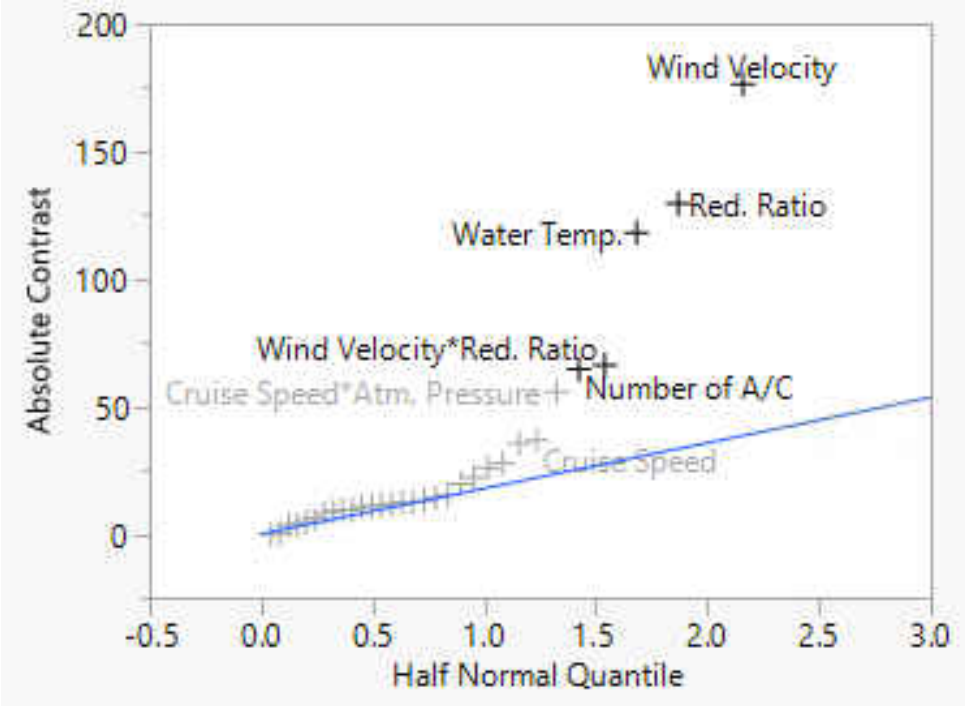



**Figure 11: Half Normal Quantile Plot of Effects**

ANOVA confirms these factors importance as shown in Figure 12. Each of the factors listed above shows an F-statistic that is significant at the 0.95 level. Note that while the Wind Velocity crossed with Reduction Ratio isn't shown in the ANOVA table, Figure 7 shows that it is aliased with the Sortie Length crossed with Number of Aircraft term that does have a significant

F-stat. Recall that this aliasing structure means when two (or more) factors are aliased with each other the indicated significance of one of the factors may come from its significance or from any one of its aliased factors. Thus, in this case it is assumed that the indicated significance of Sortie Length crossed with Number of Aircraft is attributable to Wind Velocity crossed with Reduction Ratio since both those main effects display significance in both the half-normal plot and the ANOVA. The ANOVA also indicates significance for Cruise Speed crossed with Atmospheric Pressure. Including this term in a predictive model would mean also including the contributing main effects (Cruise Speed and Atmospheric Pressure). However, since neither of these main effects indicates significance on their own and since this initial effort is intended to screen for factors important to overall mission, they will not be included in the final model.

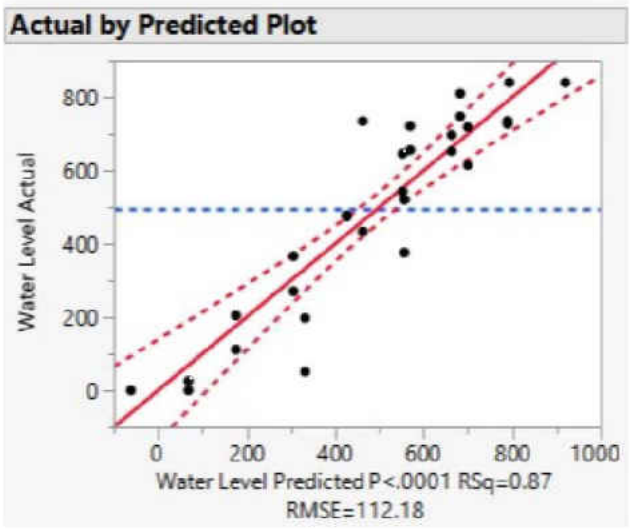
| Source | Nparm | DF | Sum of Squares | F Ratio | Prob > F |
|---|---|---|---|---|---|
| Cruise Speed | 1 | 1 | 44209.7 | 4.9823 | 0.1118 |
| Sling Load Cap. | 1 | 1 | 25444.2 | 2.8675 | 0.1890 |
| Sortie Length | 1 | 1 | 1476.2 | 0.1664 | 0.7107 |
| Wind Velocity | 1 | 1 | 1001429.2 | 112.8587 | 0.0018* |
| Atm. Pressure | 1 | 1 | 544.3 | 0.0613 | 0.8204 |
| Rel. Humidity | 1 | 1 | 866.4 | 0.0976 | 0.7751 |
| Water Temp. | 1 | 1 | 450423.2 | 50.7616 | 0.0057* |
| Red. Ratio | 1 | 1 | 540425.8 | 60.9047 | 0.0044* |
| Number of A/C | 1 | 1 | 135577.2 | 15.2792 | 0.0297* |
| Cruise Speed*Sortie Length | 1 | 1 | 3202.4 | 0.3609 | 0.5904 |
| Cruise Speed*Wind Velocity | 1 | 1 | 6938.0 | 0.7819 | 0.4417 |
| Cruise Speed*Atm. Pressure | 1 | 1 | 100740.0 | 11.3532 | 0.0434* |
| Cruise Speed*Rel. Humidity | 1 | 1 | 4046.3 | 0.4560 | 0.5479 |
| Cruise Speed*Water Temp. | 1 | 1 | 4237.1 | 0.4775 | 0.5392 |
| Cruise Speed*Red. Ratio | 1 | 1 | 4745.3 | 0.5348 | 0.5175 |
| Cruise Speed*Number of A/C | 1 | 1 | 2413.2 | 0.2720 | 0.6381 |
| Sling Load Cap.*Sortie Length | 1 | 1 | 5464.2 | 0.6158 | 0.4899 |
| Sling Load Cap.*Wind Velocity | 1 | 1 | 5888.6 | 0.6636 | 0.4749 |
| Sling Load Cap.*Atm. Pressure | 1 | 1 | 5369.3 | 0.6051 | 0.4933 |
| Sling Load Cap.*Red. Ratio | 1 | 1 | 16295.1 | 1.8364 | 0.2684 |
| Sling Load Cap.*Number of A/C | 1 | 1 | 12956.8 | 1.4602 | 0.3135 |
| Sortie Length*Atm. Pressure | 1 | 1 | 593.3 | 0.0669 | 0.8127 |
| Sortie Length*Number of A/C | 1 | 1 | 142737.0 | 16.0861 | 0.0278* |
| Wind Velocity*Atm. Pressure | 1 | 1 | 3168.9 | 0.3571 | 0.5922 |
| Atm. Pressure*Rel. Humidity | 1 | 1 | 41349.2 | 4.6600 | 0.1197 |
| Atm. Pressure*Water Temp. | 1 | 1 | 3.5 | 0.0004 | 0.9853 |
| Atm. Pressure*Red. Ratio | 1 | 1 | 2776.4 | 0.3129 | 0.6150 |
| Atm. Pressure*Number of A/C | 1 | 1 | 7863.5 | 0.8862 | 0.4160 |

**Figure 12: ANOVA of Effects**

The significant factors were then used to produce a reduced factor least squares model. M. Davis et al. (2017) provide the following analysis which briefly summarizes the validity of the resultant model:

> "Analysis of Variance of the selected prediction model in Figure 4(c) shows it has maintained its significance after complexity reduction. The Actual by Predicted plot in Figure 4(a) visualizes fit while an adjusted $R^2$ of .849 shown in Figure 4(b) indicates the

prediction model has maintained good predictive power with a reduced set of inputs. The identified factors maintained significance in Figure 4(d) after model effects reduction. Despite the somewhat scattered nature of the results shown in Figure 4(a), the additional statistical analysis indicates this prediction model has relatively good predictive power. However, because this was a factor screening experiment the indications of significance for the selected effects that are maintained after reducing the prediction model complexity are the most important outcome of this analysis."




(a)

**Summary of Fit**

| | |
|---|---|
| RSquare | 0.874043 |
| RSquare Adj | 0.849821 |
| Root Mean Square Error | 112.1832 |
| Mean of Response | 495.9037 |
| Observations (or Sum Wgts) | 32 |

(b)

**Analysis of Variance**

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 5 | 22705923 | 454118 | 36.0839 |
| Error | 26 | 327211.6 | 12585 | Prob > F |
| C. Total | 31 | 25978039 | | <.0001* |

(c)

**Effect Tests**

| Source | Nparm | DF | Sum of Squares | F Ratio | Prob > F |
|---|---|---|---|---|---|
| Wind Velocity | 1 | 1 | 1001429.2 | 79.5728 | <.0001* |
| Red. Ratio | 1 | 1 | 540425.8 | 42.9418 | <.0001* |
| Water Temp. | 1 | 1 | 450423.2 | 35.7903 | <.0001* |
| Number of A/C | 1 | 1 | 135577.2 | 10.7729 | 0.0029* |
| Wind Velocity*Red. Ratio | 1 | 1 | 142737.0 | 11.3418 | 0.0024* |

(d)

**Figure 13: Effects Model Analysis**

## 4.4 Sequenced experiment to extend the LVC Framework

As mentioned in 3.3, a thoughtful design and execution of the initial experiment creates the opportunity for a sequenced follow-on experiment. The analysis of the first experiment indicated four factors were significant to the final SFP water level after 72 hours of intervention.

As reminder and noted in Chapter 3, delivery operations were assumed to start 3-5 days after power loss at the plant since this is the timeframe observed at Fukushima. During this timeframe the SFPs were heating up from normal operating temperatures to thermal equilibrium between 84 and 90 C (D. A. Wang et al., 2012). The 3-5 day lag in beginning external delivery operations to replace powered SFP cooling also correlates well with the lag time between incident, understanding the need for external support, request for external response, and finally response by DoD resources, which currently "deploys within 24 hours of notification" (JTF-CS, 2015a).

The factors that are indicated as significant by the ANOVA can be further divided into two basic categories: those beyond the control of responders and those within the control of responders. Wind Velocity is beyond the control of responders. Reduction Ratio is an arbitrary adjustment parameter established to correct the fit of the Hugo model by accounting for reduced wind velocity across the surface of the pool caused by obstructions (remaining superstructure, pool deck height above the water surface, etc.) that slow down the air moving over the surface compared to observed wind speed at nearby weather data collection points. Thus, Reduction Ratio is adjustable but is based on circumstances beyond responder's control. Water temperature within the SFP is the result of complex thermohydraulic interactions between the spent fuel, coolant water, pool walls and floor, and the air directly above the pool. While D. A. Wang et al. (2012) showed that massive injections of cool water had a significant effect on the overall SFP temperature and thus on evaporative loss, water temperature is

largely beyond the control of responders. Unlike the other significant effects, number of aircraft is completely within emergency managers' control.

Given this categorization, Number of Aircraft was a likely candidate for further examination in a follow-on experiment. Further, the dominant significance of Wind Velocity meant that it must also be further explored while all others from the initial screening experiment were held constant. In addition to Number of Aircraft and Wind Velocity, the follow-on experiment included Aircraft Type as a categorical factor. This follow-on experiment was a comparative analysis of different airframes' utility in meeting mission requirements. Three airframes were compared at three different numbers of aircraft used and in three different wind velocities. The experimental objective of this comparison experiment was to determine which lift capability (light, medium, or heavy) using representative airframes could produce consistent successful mission accomplishment in a variety of stronger than average, but not extreme wind velocities. The broader research objective of this experiment was to demonstrate the adaptability, extensibility, and utility of the LVC framework over a variety of experimental objectives and use cases.

Following the screening experiment, an I-optimal 20-run design was selected for this second experiment. I-optimal designs seek to minimize prediction variance of the response (Montgomery, 2013). This is a desirable attribute for the follow-on experiment since it reduces the uncertainty of the expected performance from a given platform under certain conditions.

Given the objective of this experiment was to more closely evaluate performance variability resulting from a limited number of factors, many other factors and sources of

variability from the first experiment were fixed for this second effort. Cruise speed was fixed at 40 m/s for all aircraft since it was within the operating capability of each airframe and very near the recommended max velocity of the water bucket (SEI Industries, 2013). Sortie Length was fixed at 120 minutes since this was near the operating limits of the two larger aircraft (NAVAIR, 2000; US Army, 2003). The following parameters were fixed at the average observed values in the Port St. Lucie area for 2016: Atmospheric Pressure, Relative Humidity, and Air Temperature. SFP water temperature was fixed at 98 C and Reduction Ratio set to 0.3 to provide conservative prediction of water loss from the Hugo evaporation model.

Each airframe was assigned a different max water volume based on their published slung load capabilities. The MQ-8C Firescout was assigned a bucket with a maximum capacity of 1000 kg of water, which after the assumed losses during pickup, transit, and delivery resulted in a delivered volume of 0.72 $m^3$ of water per drop. The CH-47D Chinook was assigned a bucket with a max capacity of 5000 kg of water, which resulted in 3.6 $m^3$ of water per drop. Finally, the CH-53E Super Stallion was assigned a bucket with a max capacity of 9800 kg of water, which resulted in 7.056 $m^3$ of water per drop.

Further, while the computation methods for maintenance wait times did not change from the first experiment, each airframe was assigned individual mean maintenance times to base wait time on for each run. Mean maintenance times took into account both the published maintenance-man-hour/ flight-hour (MMH/FH) ratios and standard maintenance crew sizes for each aircraft. Table B-2 in Appendix B provides details regarding MMH/FH ratios, crew sizes, resultant aggregated maintenance hour/flight hour ratios and sources for these data.

Table 4 below shows the run by run treatments and responses for the comparison experiment. The full table of setup values for this experiment is given in Appendix B. Visual analysis of the results in Table 4 show that only four failures occurred during the 20-run experiment and each of the failures occurred when the MQ-8C Firescout was employed during either medium (7.5 m/s) or high (10 m/s) winds.

**Table 4: Summary of Follow-on Experiment Treatments and Results**

| Run | Number of A/C | Aircraft Type | Wind Vel. (m/s) | End of Run Water Volume | Mission Fail Time (hours) |
|---|---|---|---|---|---|
| 1 | 1 | MQ-8C | 10 | 0 | 42:57:55 |
| 2 | 3 | MQ-8C | 7.5 | 81.1749 | 69:17:46 |
| 3 | 3 | CH-53E | 5 | 838.97 | |
| 4 | 1 | CH-47D | 10 | 255.365 | |
| 5 | 5 | CH-53E | 7.5 | 838.848 | |
| 6 | 5 | CH-47D | 10 | 838.651 | |
| 7 | 1 | MQ-8C | 5 | 166.521 | |
| 8 | 5 | CH-47D | 5 | 839.185 | |
| 9 | 1 | CH-47D | 5 | 772.421 | |
| 10 | 3 | CH-53E | 10 | 608.98 | |
| 11 | 5 | CH-53E | 7.5 | 838.859 | |
| 12 | 1 | CH-53E | 7.5 | 394.554 | |
| 13 | 5 | MQ-8C | 5 | 518.96 | |
| 14 | 3 | CH-47D | 7.5 | 839.343 | |
| 15 | 3 | CH-53E | 10 | 623.087 | |
| 16 | 5 | MQ-8C | 10 | 5.81369 | 61:45:00 |
| 17 | 3 | CH-53E | 5 | 839.651 | |
| 18 | 3 | CH-47D | 7.5 | 838.258 | |
| 19 | 3 | MQ-8C | 7.5 | 80.4351 | 69:00:12 |
| 20 | 1 | CH-53E | 7.5 | 394.634 | |

Statistical analysis of these results, found in Appendix B indicates that a main effects only model is a good predictor of water level with an adjusted $R^2$ of 0.869. A plot of the residual by predicted water level does not show any structure of note and Analysis of Variance of the model further confirms is validity with an F-stat <0.0001. Individual effects testing shows Type of Aircraft is the most powerful effect in the model with an F-stat < 0.0001.

As indicated above, the Type of Aircraft factor was a complex input into the simulation since not only did the available volume of deliverable water change from airframe to airframe but the computation of maintenance time varied between airframes. JMP's Prediction Profiler graphically depicts the effect that each combination of treatment levels has on the response while simultaneously indicating the desirability of each combination. This output is shown in Figure 14 and indicates the CH-47D is the best choice among the three aircraft under test. Even under "worst case" conditions of the other two factors with winds at 10 m/s and only 1 aircraft

in use, the model predicts approximately 3.6 meters of water over the top of the fuel assemblies at the end of the 72-hour simulation.

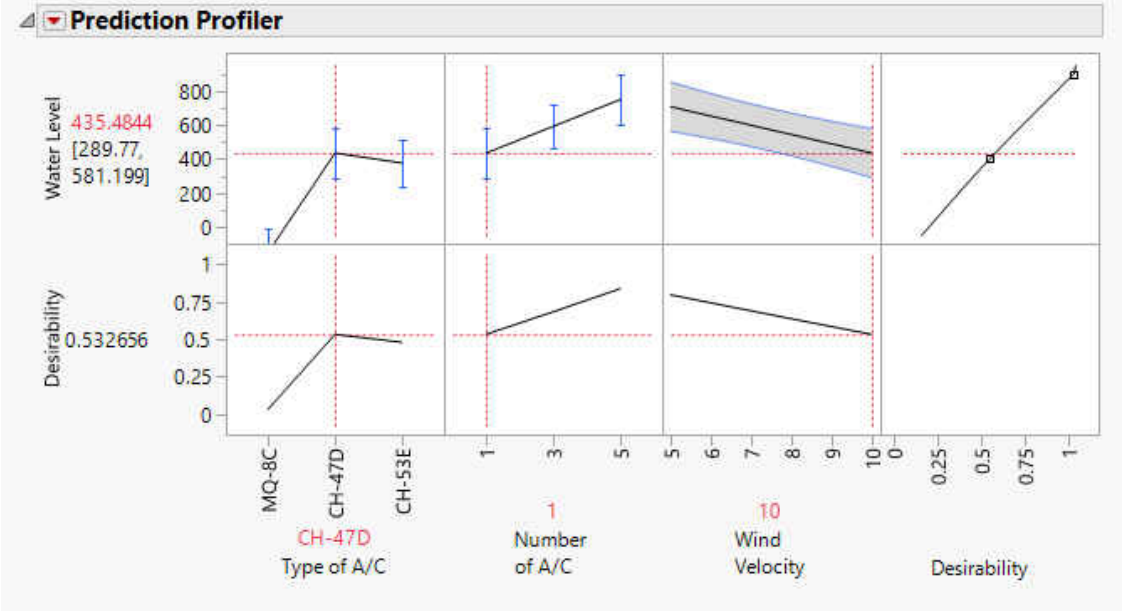



**Figure 14: Prediction of single CH-47D performance at 'high' wind velocity level**

While this analysis is insightful, it is likely inadequate for making a decision about which airframe is best suited for response to a potential nuclear power plant disaster. As indicated above, the real value of this particular experiment and subsequent analysis is in its use as an example of the flexibility of the LVC simulation framework. The constructed framework was quickly and easily adapted from its initial use for factor screening to a more specific evaluation of particular platforms under a variety of conditions.

# CHAPTER FIVE: CONCLUSIONS, LESSONS LEARNED, LIMITATIONS, AND FUTURE RESEARCH

## 5.1 Conclusions

As seen at Chernobyl and Fukushima, nuclear disasters have severe, far-reaching consequences in both near- and long-term time horizons. Disaster response teams at all levels must be ready to protect both citizens and the environment from these consequences. The inability to train in a live radiation environment increases the need for modeling and simulation to fill the voids in system life cycles to include system development, planning, and training for such disasters. Challenges facing addressing these voids include: (1) stove-pipe designs of existing reactor models that do not interoperate with more integrated M&S tools for training and evaluation of new system integration; (2) lack of representation of a reactor model in a LVC simulation framework; (3) lack of techniques to reduce factor complexity inherent to a LVC simulation framework; and (4) demonstration of use of the LVC simulation framework for systems analysis.

This research, as documented in M. Davis et al. (2016), took a first step toward filling this gap in capability with the development of a conceptual model for integrating a LVC simulation framework using a SoS approach. Nuclear power station safety and reliability systems are extensive systems of systems susceptible to catastrophic chain of events ripple-effect failures. These situations are too complex, costly, and risky to assess by other means, so M&S tools are once again well suited for the task. An LVC framework was proposed to evaluate an unmanned system's effectiveness for SFP replenishment.

Secondly this research, as documented in M. Davis and Proctor (2016), created a suitable SFP model in the LVC simulation framework capable of replicating the SFP disaster at Fukushima. The work proposed a technique for predicting evaporative loss under forced air flow. The work is based on that of Hugo and Omberg (2015), but rather than focusing in cooling effects, Davis and Proctor apply their model to worst-case conditions to predict water loss rates. These rates were compared to published throughput capabilities of several alternative sources of SFP replenishment and although analytic comparison suggested excess capacity from several mitigation techniques, empirical evidence from Fukushima indicated significant inefficiencies since the selected techniques struggled to meet demand at several points during the response and recovery efforts. This work is foundational to the experiments presented above and future experiments involving SFP disaster response. Specifically, the resultant evaporation model became the loss portion of the overall water level computation in designed experiments.

Thirdly, this research, as demonstrated in M. Davis et al. (2017), conceived and demonstrated an approach to reduce factor complexity inherent to an integrated LVC framework through the use of a screening experiment. The screening factor design evaluated the significance of a large number of factors that may impact the ability of an RUAS to successfully maintain the water level within a nuclear power plant SFP over the course of a 72-hour simulation. The use of a screening experiment was shown an effective technique for identifying significant factors affecting SFP water level within the simulation. Analysis of the first experiment indicated that Wind Velocity, Reduction Ratio, Water Temperature, Number of

Aircraft, and the Wind Velocity crossed with Reduction Ratio were all significant to the outcome of the simulation.

Finally, this research, as discussed in Chapter 4 and expected to be submitted for possible future publication, demonstrated system analysis of competing UAS platforms. This was but one of many possible applications of the overall theoretical approach discussed in this dissertation and to be included in a forthcoming article. Specifically, a second experiment, detailed in Section 4.4 was conducted based on the outcomes of the screening experiment which determined factors significant to end state SFP water level. This experiment compared 3 different aircraft for their suitability for use as an RUAS in the water delivery scenario. Setup of the second experiment was based on the results of the first, and Wind Velocity, Number of Aircraft, and Aircraft Type were selected as the factors under test. Analysis of the second experiment's results showed the CH-47D Chinook was the best choice of aircraft over the range of Wind Velocity and Number of Aircraft tested. Interestingly, this result suggested that system selection for this mission is not simply about carrying the most water. Rather, airframe reliability and maintainability are critical factors that must be considered and given careful analysis during the system selection phase of the systems engineering process for this problem. Further, the airframe comparison research shows that the LVC simulation framework is not only adaptable to a variety of system evaluation tasks but is also sensitive to a wide variety of system characteristics.

Overall this work showed that the LVC framework provides a "generalized capability to compose, simulate, and evaluate from multiple perspectives the suitability of various systems

and conceptual models to accomplish a broad range of emergency response missions" (M. Davis et al., 2017). While these results are both interesting and insightful to nuclear power plant operators, disaster management planners, and first responders, the most important outcome of both experiments are not their individual results but rather their part in demonstration of the effectiveness and flexibility of the overall approach. This approach starts with SoS Conceptual Modeling and leads to LVC Simulation framework design. LVC simulation framework design identified simulation gaps, which in this case involved the gap in radiation model modeling. Through a unique approach in SFP modeling, this research partially bridged the radiation modeling gap in LVC simulation. The subsequent screening experiment and follow on designed experiment demonstrate that the complexity of the simulation is scalable to fit available data and models and the LVC framework is adaptable to a wide variety of research questions.

## 5.2 Lessons Learned

There are several "Lessons Learned" to be taken away from this research effort. Researchers hoping to repeat or improve on this work would benefit from taking into account decisions made during this effort, both good and bad.

The first lesson learned applies to all resource constrained research efforts, but is especially true for those employing LVC modeling and simulation tools. Limiting the scope of research questions and supporting simulations is vital to success. Well defined and limited questions lead to well defined answers, especially when employing simulation as a research vehicle. Further, as Haase et al. (2014) advise, experiments conducted in LVC environments can

easily become unwieldy because of the ease with which LVC frameworks enable complex environments and interactions between systems. Thus, it is critical for researchers either recreating or building upon this work to limit the scope of both their inquiries and their constructed simulations.

Second, researchers conducting this or similar research should remember that simulation provides opportunities to simulate and aggregate. Depending on the questions of interest, many of the peripheral system interactions and behaviors can be simulated or aggregated together. This research leveraged this attribute at several points. For instance, STAGE entities do have the inherent capability to act as both suppliers and consumers of a given supply. Thus, the RUAS entities were not able to take on water from the fresh water source (consumer) and then deliver water to the SFP (supplier). While STAGE does allow for modification of entity behavior, such an effort was beyond the scope and capabilities of the available researchers. Thus, the loading of fresh water into the bucket was simulated by a variable RUAS wait time near the fresh water source and by exploiting the STAGE entity characteristic that allowed the RUAS to begin the simulation with what was effectively an infinite supply of water available to be delivered to the SFP. This ability to reduce the complexity and suspend the limitations of the real world made the process of developing a method to answer the question of interest an achievable task. This ability to reduce interaction complexity where possible was critical to the successful completion of this research and should be kept in mind by future researchers.

Third, a rather extensive knowledge of how the individual software components and models function and communicate with one another was critical to developing a functional simulation. In order to create useful and reasonable behaviors from the entities within the scenario, a great deal of STAGE Mission Editor expertise was required. Thus, in order to replicate this work or create any new simulations using STAGE, a deep understanding of how all the components of STAGE and the other Presagis tools work and work together is required. For instance, this research required the development of a pseudo normal sampling distribution using the STAGE mission editor and its only available sampling distribution (Uniform). Further, in order to obtain the SFP's water level, the underlying database for STAGE functionality was modified. This effort took several weeks and eventually a great deal of assistance from Presagis customer support. The lesson for future researchers here is to ensure your chosen simulations' baseline configurations provide the data you need, or the time and resources are available to make the necessary modifications to that configuration.

Finally, transformations can be critical to success. The chosen case study for this research focuses on SFP water levels. Nuclear power station operators and researchers often view SFPs and nuclear reactors and heat management problems. The transformation of the SFP heat management problem to its brute force correlate, the water evaporation problem, meant that the response of concern was no longer the total heat output from the fuel in the SFP but much more simply the water level of the pool. If water deliveries outpaced loss from evaporation, then the total heat output from the fuel in the SFP was effectively dealt with no

matter how much or little there was. Thus, the exploitation of data transformations is lesson to keep in mind as future simulation research is undertaken.

## 5.3 Limitations

This research effort was an exploratory proof of concept and therefore was limited in scope on many fronts. Further, since this work was unfunded research tools were limited to those readily available in the Synthetic Environments Learning Laboratory and to the UCF student body at large.

Although the LVC simulation framework was developed to readily integrate existing and future high fidelity nuclear reactor and power plant models, none of the current and available models were designed to integrate using existing LVC standards and protocols. Time and resource limitations prohibited undertaking the development of a middleware capable of bridging the communication gap between these models and the existing LVC framework. Thus, the study was limited to the use of the Hugo et al evaporation model. Further, the baseline STAGE configuration does not include a complex and variable consumption rate. While the Hugo model take into account several environmental variables, the representation of evaporation in STAGE does not. Therefore, the evaporation rate for each run was precomputed based on the environmental inputs for that run and the SFP's consumption rate was then assigned that constant value for the entire run. With regard to environmental variables, STAGE does not enable variability of environmental variables over time. As an example, if the selected wind speed for a run was 5 m/s, that value remained constant for the entire 72-hour run even though this is highly unlikely to occur in the real world.

The RUAS behavior was also limited in terms of its complexity. First, each aircraft was assigned a rudimentary mission that consisted of flying to predetermined points near the staging area, fresh water source, and power plant. Despite many runs including multiple aircraft, collision avoidance was not an included behavior, thus aircraft were routinely super-positioned in the airspace. Further, as mentioned above their rudimentary behavior did not include supply transfer from the fresh water source to the helicopter. This meant that water pickup was limited to a simple delay with uniform variability. No unplanned failures were simulated, so the sortie behavior of the RUASs was limited to the scheduled times for each run. Variability was created with a pseudo-Normal sampling of predicted maintenance time, but between sortie times were otherwise based solely on an aggregation of mean times for various tasks found in the literature.

Avoiding radiation exposure is one of the major motivating factors for use of unmanned systems in nuclear disaster response. Electronic systems are not immune to radiation effects, but this research was limited in that no consideration was given to radiation or its effects on the RUAS except that a decontamination time was added to the between sortie maintenance times.

Finally, the scope of this research was limited to solely constructive simulations. One of the major advantages of the LVC framework is the ability to readily integrate live and virtual components into a constructive simulation. Since this research sought ultimately to evaluate the suitability of the LVC framework to evaluate the integration of new systems into complex systems of systems, the initial proof of concept case study limited the scope of the LVC framework to constructive simulations only.

## 5.4 Future Research

The LVC framework developed here is only a first step and proof of concept. A great deal of work is needed to increase its fidelity to a level suitable for producing decision-quality results. Despite the foundational nature of the current LVC framework, the success of this research leads to a vast array of future research opportunities and unanswered questions.

One of the major benefits of developing a systems of systems evaluation technique with an LVC framework is that framework's extensibility beyond system evaluation applications. Further development of the LVC framework, including integration of new higher fidelity models for each of the components detailed in Figure 4 will enable expanded use of the framework to the system selection portion of the systems engineering life cycle. One such fidelity enhancement worthy of consideration is the inclusion of water temperature modeling within the SFP. As noted elsewhere, SFP water temperature is affected by cold water injections (D. A. Wang et al., 2012) and SFP evaporation is affected by overall SFP water temperature (Hugo & Omberg, 2015), thus a variable temperature SFP model is an important aspect of overall fidelity enhancement of the LVC framework for this particular use case.

LVC simulation is already widely used as a training tool both for individuals and teams of nuclear disaster first responders (INNG, 2015). Developing and utilizing an LVC framework for system of systems development and evaluation creates a foundation for integrating these new systems into the LVC training of the response teams. Integrated training allows response teams to adapt to sharing their operational space with unmanned systems in a low threat environment. The LVC framework also allows planners and responders to evaluate the impact

of a gradual increase in available resources over multiple days of response as will likely occur during an actual crisis. Further, large scale, fully integrated training scenarios give planners and leaders the opportunity to observe the emergent behaviors of the new system of systems that will occur when a new tool is introduced.

The effects of radiation on electronic systems are ignored in the current LVC framework. However, these effects are well documented (AP, 2017) and must be a major consideration in any nuclear response strategy. As such, research is already underway to integrate radiation into the LVC framework and assess its effects on RUAS (Shageer, Proctor, Davis, & Schreiber, IN REVIEW).

Further, accurate measurement of radiation levels in and around the immediate vicinity of a nuclear power plant experiencing a disaster is a major concern of emergency managers and disaster responders. Small UAS are a promising and growing area of capability for such a mission set. The demonstrated adaptability of the LVC framework makes it an ideal environment for exploring the suitability of small UAS for a variety of tasks within the nuclear disaster environment. Thus, future research efforts should explore this application of the LVC framework.

This research focused on the replenishment of water from a small set of RUAS to a single SFP modeled after those found at Fukushima. Future research is needed to determine whether RUAS or some other system, unmanned or otherwise, provides the most robust capability to provide fresh water to an SFP experiencing long-term blackout. Additionally, future efforts should investigate the integration of RUAS and other unmanned systems to

support the needs of other aspects of NPPs in crisis. For example, the delivery of equipment like portable generators, water cannons, and hydrogen recombiners is a task RUAS are well suited for. Further, SFPs exist in a wide variety of designs and configurations. It is likely that the replenishment solution is not "one size fits all" but rather certain systems will provide the most efficient replenishment to certain SFP sizes and configurations while other systems will be better suited to other SFP types. The mapping of replenishment systems to SFPs and the trade space between efficiency and robustness of response capability is an area that must be explored before response plans can be solidified.

Finally, the LVC framework may be expanded to include human system integration (HSI) models and simulations. HSI is already possible using HeliSIM or FlightSim as a virtual simulation rather than a constructive simulation. Further human interface designs within HeliSIM or FlightSim may be modified using the Presagis VAPS-XT software. Developing enhanced human systems interfaces may improve human-system performance in more complex environments while maintaining or increasing operator situational awareness as well as decreasing the likelihood of information overload.

In conclusion, this research effort successfully developed and implemented an SoS conceptual model and LVC framework to evaluate the suitability of an RUAS to respond to a nuclear power plant disaster. The results indicate designed experiments can successfully be used within an LVC simulation to achieve this end. Based on these promising results, further future research is warranted.

# APPENDIX A: SCREENING EXPERIMENT DATA

The STAGE setup files and collected raw data files from this experiment are too large to include with this document. All data is available upon request from the author.

**Table A-1: Potential Design Factors**

| Factor | Type | Component of Origin | Category |
|---|---|---|---|
| Cruise Speed | Continuous | RUAS | Tested |
| Sling Load Capacity | Continuous | RUAS | Tested |
| Sortie Length | Continuous | RUAS | Tested |
| Number of A/C | Discrete Numeric | RUAS | Tested |
| RUAS Reliability | Continuous | RUAS | Controlled |
| RUAS Sortie Regen Time | Continuous | RUAS | Controlled |
| Water Drop Height | Continuous | RUAS | Controlled |
| Bucket Fill Efficiency | Continuous | RUAS | Controlled |
| Delivery Efficiency | Continuous | RUAS | Controlled |
| Wind Velocity | Continuous | Weather | Tested |
| Atmospheric Pressure | Continuous | Weather | Tested |
| Relative Humidity | Continuous | Weather | Tested |
| Ambient Temperature | Continuous | Weather | Tested |

| | | | |
|---|---|---|---|
| Daily Precipitation | Continuous | Weather | Controlled |
| Water Temperature | Continuous | SFP Thermohydraulics | Tested |
| Air Flow Reduction Ratio | Continuous | SFP Thermohydraulics | Tested |
| SFP Depth over Fuel | Continuous | SFP Thermohydraulics | Controlled |
| SFP Surface Area | Continuous | SFP Thermohydraulics | Controlled |
| SFP Water Volume | Continuous | SFP Thermohydraulics | Controlled |
| Fresh Water Temperature | Continuous | Terrain Services | Controlled |
| Fresh Water to SFP Distance | Continuous | Terrain Services | Controlled |
| Staging to SFP Distance | Continuous | Terrain Services | Controlled |
| Computer used for Simulation | Categorical | N/A | Blocked |

**Table A-2: Screening Experiment Data Collection Table**

| Run | Pattern | Block | Cruise Speed | Sling Load Cap. | Sortie Length | Wind Vel. | Atm. Pressure | Rel. Hum. | Water Temp. | Red. Ratio | Number of A/C | Water Level | Start Date | End Date | Computer | O/S Version | Software Version |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | −++−−+−−+ | 1 | 25 m/s | 1200 kg | 360 min | 3 m/s | 100000 Pa | 0.9 | 90 C | 0.1 | 4 | | | | | | |
| 2 | −+−+−+−+− | 1 | 25 m/s | 1200 kg | 120 min | 20 m/s | 100000 Pa | 0.9 | 90 C | 0.3 | 1 | | | | | | |
| 3 | +−−+++−−+ | 1 | 50 m/s | 450 kg | 120 min | 20 m/s | 103000 Pa | 0.9 | 90 C | 0.1 | 4 | | | | | | |
| 4 | +−+−++−+− | 1 | 50 m/s | 450 kg | 360 min | 3 m/s | 103000 Pa | 0.9 | 90 C | 0.3 | 1 | | | | | | |
| 5 | −++−+−++− | 1 | 25 m/s | 1200 kg | 360 min | 3 m/s | 103000 Pa | 0.55 | 98 C | 0.3 | 1 | | | | | | |
| 6 | −+−++−+−+ | 1 | 25 m/s | 1200 kg | 120 min | 20 m/s | 103000 Pa | 0.55 | 98 C | 0.1 | 4 | | | | | | |
| 7 | +−+−−−+−+ | 1 | 50 m/s | 450 kg | 360 min | 3 m/s | 100000 Pa | 0.55 | 98 C | 0.1 | 4 | | | | | | |
| 8 | +−−+−−++− | 1 | 50 m/s | 450 kg | 120 min | 20 m/s | 100000 Pa | 0.55 | 98 C | 0.3 | 1 | | | | | | |
| 9 | +−−−+−+++ | 2 | 50 m/s | 450 kg | 120 min | 3 m/s | 103000 Pa | 0.55 | 98 C | 0.3 | 4 | | | | | | |
| 10 | −+−−++−++ | 2 | 25 m/s | 1200 kg | 120 min | 3 m/s | 103000 Pa | 0.9 | 90 C | 0.3 | 4 | | | | | | |
| 11 | +−++−+−++ | 2 | 50 m/s | 450 kg | 360 min | 20 m/s | 100000 Pa | 0.9 | 90 C | 0.3 | 4 | | | | | | |
| 12 | +−+++−+−− | 2 | 50 m/s | 450 kg | 360 min | 20 m/s | 103000 Pa | 0.55 | 98 C | 0.1 | 1 | | | | | | |
| 13 | −+++−−+++ | 2 | 25 m/s | 1200 kg | 360 min | 20 m/s | 100000 Pa | 0.55 | 98 C | 0.3 | 4 | | | | | | |
| 14 | −+++++−−− | 2 | 25 m/s | 1200 kg | 360 min | 20 m/s | 103000 Pa | 0.9 | 90 C | 0.1 | 1 | | | | | | |
| 15 | −+−−−+−−− | 2 | 25 m/s | 1200 kg | 120 min | 3 m/s | 100000 Pa | 0.55 | 98 C | 0.1 | 1 | | | | | | |
| 16 | +−−−+−−− | 2 | 50 m/s | 450 kg | 120 min | 3 m/s | 100000 Pa | 0.9 | 90 C | 0.1 | 1 | | | | | | |
| 17 | +++−−+++− | 3 | 50 m/s | 1200 kg | 360 min | 3 m/s | 100000 Pa | 0.9 | 98 C | 0.3 | 1 | | | | | | |
| 18 | −−+−−−+− | 3 | 25 m/s | 450 kg | 360 min | 3 m/s | 100000 Pa | 0.55 | 90 C | 0.3 | 1 | | | | | | |
| 19 | −−−+−−−+ | 3 | 25 m/s | 450 kg | 120 min | 20 m/s | 100000 Pa | 0.55 | 90 C | 0.1 | 4 | | | | | | |
| 20 | ++−+−++−+ | 3 | 50 m/s | 1200 kg | 120 min | 20 m/s | 100000 Pa | 0.9 | 98 C | 0.1 | 4 | | | | | | |
| 21 | −−−+++++− | 3 | 25 m/s | 450 kg | 120 min | 20 m/s | 103000 Pa | 0.9 | 98 C | 0.3 | 1 | | | | | | |
| 22 | +++−+−−−+ | 3 | 50 m/s | 1200 kg | 360 min | 3 m/s | 103000 Pa | 0.55 | 90 C | 0.1 | 4 | | | | | | |
| 23 | ++−++−−+− | 3 | 50 m/s | 1200 kg | 120 min | 20 m/s | 103000 Pa | 0.55 | 90 C | 0.3 | 1 | | | | | | |
| 24 | −−+−+++−+ | 3 | 25 m/s | 450 kg | 360 min | 3 m/s | 103000 Pa | 0.9 | 98 C | 0.1 | 4 | | | | | | |
| 25 | ++−−−−−++ | 4 | 50 m/s | 1200 kg | 120 min | 3 m/s | 100000 Pa | 0.55 | 90 C | 0.3 | 4 | | | | | | |
| 26 | −−−−+−−−− | 4 | 25 m/s | 450 kg | 120 min | 3 m/s | 103000 Pa | 0.55 | 90 C | 0.1 | 1 | | | | | | |
| 27 | −−−−−++++ | 4 | 25 m/s | 450 kg | 120 min | 3 m/s | 100000 Pa | 0.9 | 98 C | 0.3 | 4 | | | | | | |
| 28 | −−+++−−++ | 4 | 25 m/s | 450 kg | 360 min | 20 m/s | 103000 Pa | 0.55 | 90 C | 0.3 | 4 | | | | | | |
| 29 | −−++−++−− | 4 | 25 m/s | 450 kg | 360 min | 20 m/s | 100000 Pa | 0.9 | 98 C | 0.1 | 1 | | | | | | |
| 30 | ++−−+++−− | 4 | 50 m/s | 1200 kg | 120 min | 3 m/s | 103000 Pa | 0.9 | 98 C | 0.1 | 1 | | | | | | |
| 31 | ++++−−−−− | 4 | 50 m/s | 1200 kg | 360 min | 20 m/s | 100000 Pa | 0.55 | 90 C | 0.1 | 1 | | | | | | |
| 32 | +++++++++ | 4 | 50 m/s | 1200 kg | 360 min | 20 m/s | 103000 Pa | 0.9 | 98 C | 0.3 | 4 | | | | | | |

# APPENDIX B: COMPARISON EXPERIMENT DATA

The STAGE setup files and collected raw data files from this experiment are too large to include with this document.

All data is available upon request from the author.

**Table B-1: Comparison Experiment Data Collection Table**

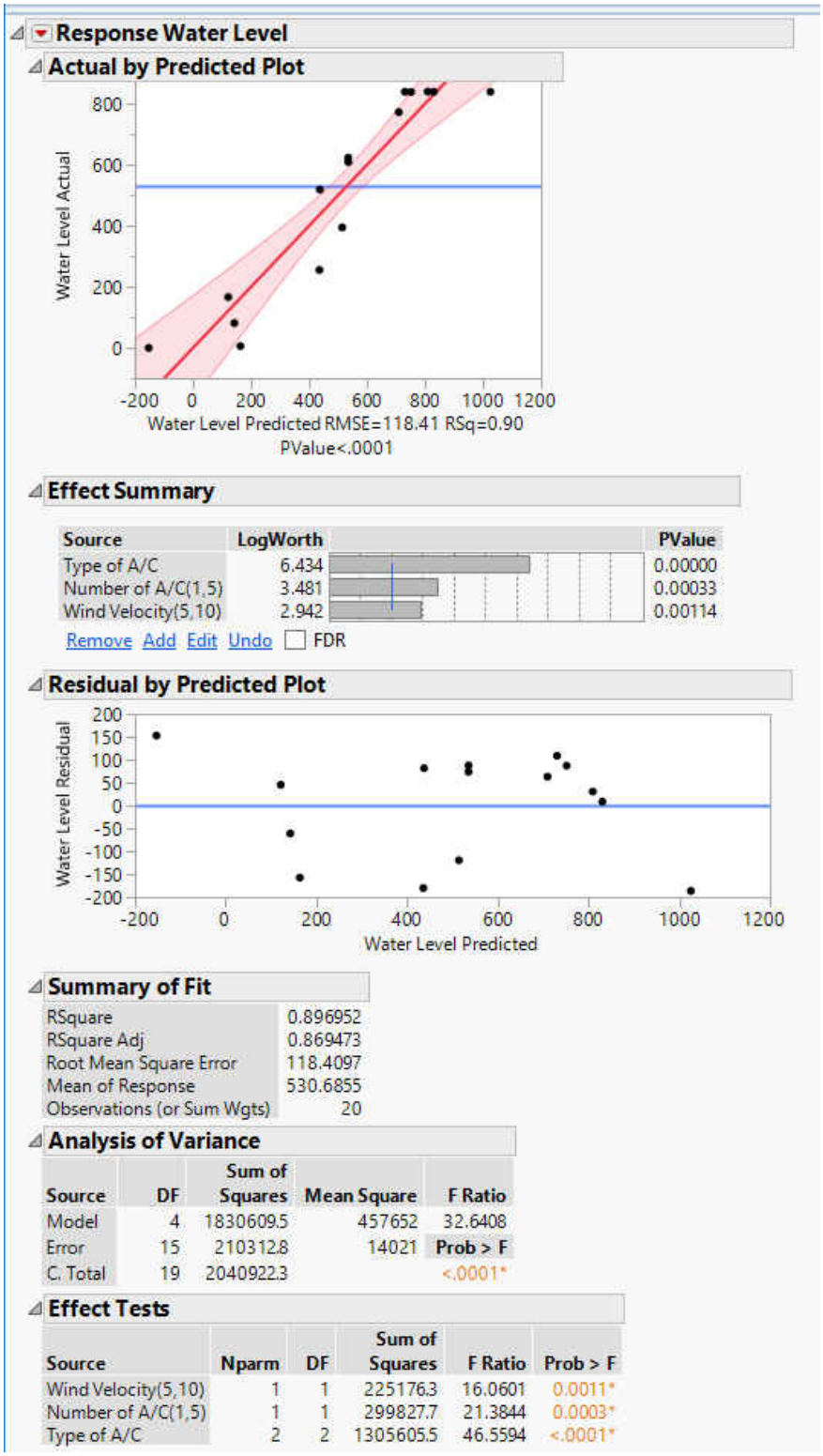
| Run | Pattern | STAGE Database | Number of A/C | Aircraft Type | Wind Vel. (m/s) | Atm. Pressure (Pa) | Rel. Hum. | Water Temp. (C) | Red. Ratio | Air Temp | P sat, w | P sat, a | Consumption Rate (kg/m^2*hr) | Total Pool Consumption Rate (m^3/hr) | Delivered Volume (m^3) | End of Run Water Volume | Mission Fail Time (hours) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | CompEx_F1_10 | 1 | MQ-8C | 10 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 150.8209471 | 18.09851365 | 0.72 | | |
| 2 | | CompEx_F3_75 | 3 | MQ-8C | 7.5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 120.0042367 | 14.40050841 | 0.72 | | |
| 3 | | CompEx_S3_5 | 3 | CH-53E | 5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 88.88510798 | 10.66621296 | 7.056 | | |
| 4 | | CompEx_C1_10 | 1 | CH-47D | 10 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 150.8209471 | 18.09851365 | 3.6 | | |
| 5 | | CompEx_S5_75 | 5 | CH-53E | 7.5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 120.0042367 | 14.40050841 | 7.056 | | |
| 6 | | CompEx_C5_10 | 5 | CH-47D | 10 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 150.8209471 | 18.09851365 | 3.6 | | |
| 7 | | CompEx_F1_5 | 1 | MQ-8C | 5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 88.88510798 | 10.66621296 | 0.72 | | |
| 8 | | CompEx_C5_5 | 5 | CH-47D | 5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 88.88510798 | 10.66621296 | 3.6 | | |
| 9 | | CompEx_C1_5 | 1 | CH-47D | 5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 88.88510798 | 10.66621296 | 3.6 | | |
| 10 | | CompEx_S3_10 | 3 | CH-53E | 10 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 150.8209471 | 18.09851365 | 7.056 | | |
| 11 | | CompEx_S5_75 | 5 | CH-53E | 7.5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 120.0042367 | 14.40050841 | 7.056 | | |
| 12 | | CompEx_S1_75 | 1 | CH-53E | 7.5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 120.0042367 | 14.40050841 | 7.056 | | |
| 13 | | CompEx_F5_5 | 5 | MQ-8C | 5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 88.88510798 | 10.66621296 | 0.72 | | |
| 14 | | CompEx_C3_75 | 3 | CH-47D | 7.5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 120.0042367 | 14.40050841 | 3.6 | | |
| 15 | | CompEx_S3_10 | 3 | CH-53E | 10 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 150.8209471 | 18.09851365 | 7.056 | | |
| 16 | | CompEx_F5_10 | 5 | MQ-8C | 10 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 150.8209471 | 18.09851365 | 0.72 | | |
| 17 | | CompEx_S3_5 | 3 | CH-53E | 5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 88.88510798 | 10.66621296 | 7.056 | | |
| 18 | | CompEx_C3_75 | 3 | CH-47D | 7.5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 120.0042367 | 14.40050841 | 3.6 | | |
| 19 | | CompEx_F3_75 | 3 | MQ-8C | 7.5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 120.0042367 | 14.40050841 | 0.72 | | |
| 20 | | CompEx_S1_75 | 1 | CH-53E | 7.5 | 101777 | 0.76 | 98 | 0.3 | 24 | 94390 | 2985.8 | 120.0042367 | 14.40050841 | 7.056 | | |

To better evaluate the suitability of the airframes tested in the comparison experiment each one was assigned a MMH/FH ratio approximating the real world systems' MMH/FH ratio. These ratios were based on information gathered from the available literature. MMH/FH biasing was already integrated into the between sortie time computations in the screening experiment, so for the comparison experiment all that was needed was to update the biasing factor based on the currently selected airframe. The biasing factor was based on the available MMH/FH ratios and the standard size maintenance crew for each aircraft. The MMH/FH ratio was multiplied by the sortie length leaving the total MMH per sortie. This value was then divided by the number of crew members in a given aircraft's standard maintenance team. The result is now the total maintenance time per sortie. This value is a point estimate, so it was then used as such to create a randomized maintenance time for each sortie within each scenario. The table below contains the required values for each of the compared airframes.

**Table B-2: MMH/FH Data for Each Airframe of the Comparison Experiment**

| Aircraft | MMH/FH | Crew Size |
|---|---|---|
| MQ-8C Firescout | 1.1<br><br>Computed from data in (Bell Helicopter, 2010) | 1.25<br><br>Estimated to be the same size as FCS plan for MQ-8B (Raymer, 2009) |
| CH-47D Chinook | 2.71<br><br>(DAMIR, 2012) | 11<br><br>(US Army) |
| CH-53E Super Stallion | 40<br><br>(Head, 2017) | 11<br><br>(USMC, 1999) |

**Figure B-1: Statistical Analysis of Comparison Experiment Results**



# APPENDIX C: STAGE SETUP AND MODIFICATION

The STAGE databases, scenarios, and missions created for this research were rather extensive. Further, the run-to-run variability necessitated creating new database and scenario files for each run. The basic functionality of STAGE was also modified to enable collection of the data of interest from the SFP entity. While the entirety of the STAGE file library is too extensive to include here, it is available upon request from the author. Included below are the correspondence with Presagis support and the screen caps referenced in that correspondence. The result of this correspondence was a Visual Studio project that compiled into a .dll file. This file extended STAGE's baseline capability based on the modifications within the IDE as described in the screen caps. The overall result was a modified STAGE program that included the ability to query and report the current water supply value from the SFP.

**Subject:** Re: Case # 00103529: Recording Supply levels throughout a scenario [ ref:_00D708m0L._500391dt7gR:ref ]
**Date:** Wednesday, July 6, 2016 at 7:45:50 PM Eastern Daylight Time
**From:** Matthew Davis
**To:** Support Stage
**CC:** michael.proctor@ucf.edu, lamar.harrell@presagis.com
**Attachments:** Pool Level Report

Pascal,
SUCCESS!!! The attached mission history log shows pool level at ~1 min intervals which is the data I need to get this experiment going!

I took a look at your userTask.cpp file... I was on the right track but would have spent weeks trying to figure out the changes to those last bits of code. I can't thank you enough for your outstanding support!

One final question: What is the best way to port this new STAGE configuration to another machine? Can I just copy over the TaskLib.dll and the %stage_gen_dir%\lib directory that is updated by the IDE (cur_quantity) / Build / Generate process? Or is it more complicated than that?

Regards,
Matt

---

**From:** Support Stage <stage@presagis.com>
**Sent:** Wednesday, July 06, 2016 4:36:28 PM
**To:** Matthew Davis
**Cc:** michael.proctor@ucf.edu; lamar.harrell@presagis.com
**Subject:** Re: Case # 00103529: Recording Supply levels throughout a scenario [ ref:_00D708m0L._500391dt7gR:ref ]

Hi Matt,

I have created a small sample based on the screen shot of what you did in the IDE(Created an Entity Property cur_quantity)

As you noted in the 2nd screen shot, how you get the entity property is through code.

So I created a small snippet that would return the cur_quantity of the 1st supply installed on the entity.

I did this in the Suite15\STAGE\devel\mission sample

Here it is attached with the changes I made(userTask.cpp)

You should just be able to do the following to make it work:(assuming you have Visual Studio 2010)

Open a CMD prompt.

START→Run type CMD

enter

Browse to where you have STAGE installed(i.e cd C:\Presagis\Suite15\STAGE)

enter

type: setup.cmd

enter

this sets your STAGE environment

browse to the devel directory: cd devel

enter

type: devel_setup.cmd

enter

this will set your development environment

Now you can just drag and drop the .sln file provided in the attachment(once all files were extracted) into the DOS CMD window(shell)

enter

Once the solution is opened just build the sample.

It will create a TaskLib.dll in the C:\Presagis\Suite15\STAGE\UserPlugins\sim directory if it was successful.

Now you will be able to access the current quantity of supply from the mission editor.

Please note this will only work on an entity with 1 supply as I am not looking for other supplies on the entity.

It is just to show you how it is done.

If more work is required I will have to suggest other resources to help you on this.

I hope this helped,

Let me know,

Pascal

Presagis Technical Support

---------- Original Message ----------
**From:** Matthew Davis [matt.davis@knights.ucf.edu]
**Sent:** 7/5/2016 4:38 PM
**To:** stage@presagis.com
**Cc:** michael.proctor@ucf.edu; lamar.harrell@presagis.com
**Subject:** Re: Case # 00103529: Recording Supply levels throughout a scenario, [ ref:_00D708m0L._500391dt7gR:re
[ ]

Pascal,
OK. I guess I don't really know what I'm reading in the help files because the impression I got was that the IDE created the all the needed code once generated and built.

I understand what you're code is doing when I look at it, but when you ask if I've tried it... I don't know where to put it. The last time I wrote code was MATLAB in 2009. Before that was my freshman computer science class in the spring of 1998. So when I look through the samples and all files that are related to them the calls to libraries and data structures look familiar, but it has been a long, long time.

Given that, can I add your code to any of the samples? If not, which do you recommend? Then, which file should be updated? I think it goes in a .cpp file, but in some samples there is more than one of those... which one does it go in? Does it matter?

I know I'm asking a lot of really basic questions and I apologize for what I'm sure is a conversation that is trying your patience, but I sincerely appreciate your help.

Regards,
Matt

---

**From:** Support Stage <stage@presagis.com>
**Sent:** Tuesday, July 05, 2016 4:10:58 PM
**To:** Matthew Davis
**Cc:** michael.proctor@ucf.edu; lamar.harrell@presagis.com
**Subject:** Re: Case # 00103529: Recording Supply levels throughout a scenario, [ ref:_00D708m0L._500391dt7gR:re ]

Hi Matt,

What I think you need to understand is that when you start making changes as you have in the IDE, you still need to add code to it as just making the changes to what you did is not enough.

Have you tried the sample code I sent you earlier?

Regards,

Pascal

Presagis Technical Support

---------- Original Message ----------
**From:** Matthew Davis [matt.davis@knights.ucf.edu]
**Sent:** 7/5/2016 1:38 PM
**To:** stage@presagis.com
**Cc:** michael.proctor@ucf.edu; lamar.harrell@presagis.com
**Subject:** Re: Case # 00103529: Recording Supply levels throughout a scenario, [ ]

Here are some pictures to help illustrate what I'm trying to do with the IDE tool. Like I said before, I can get my entity property name to show up as selectable from the Mission Editor, but its not returning any data as far as I can tell.

Regards,
Matt

---

**From:** Support Stage <stage@presagis.com>
**Sent:** Monday, July 04, 2016 3:08:23 PM
**To:** Matthew Davis
**Cc:** michael.proctor@ucf.edu; lamar.harrell@presagis.com
**Subject:** Re: Case # 00103529: Recording Supply levels throughout a scenario, [ ]

Hi Matt,

Happy 4th of July, hope it was as good as our Holiday was.

To answer your questions…

The SIM plugin usually comes in the form of a .dll file. It is similar as to the final output once you compile\build our samples. The end result will depend of what you want it to do. When coded you can have the messages of % Supply remaining printed to the SIM Console(or other format).

As for what you did with the Call Definitions /Decision Calls, I think if I understood correctly(not sure ☺ ), you can try something like this:

When creating your entity property you get an "Entity_Data *a_pEnt" pointer as parameter and if you want the quantity of a specific supply then

```
int _SupplyIdx = sim_supply_get_supply_index_by_name(a_pEnt, "SupplyName");
float _Quantity = 0.0;
if ( _SupplyIdx >= 0 ) {
  Permanent_Supply_Data* _pSupply =
    &_pEnt->supplies->perm_data.supplies[_SupplyIdx];
  if ( NULL != _pSupply ) {
    _Quantity = (float)_pSupply->quantity;
  }
}
return _Quantity;
```

I hope this helps,

Pascal

Presagis Technical Support

---------- Original Message ----------
**From:** Matthew Davis [matt.davis@knights.ucf.edu]
**Sent:** 6/30/2016 8:11 PM
**To:** stage@presagis.com
**Cc:** michael.proctor@ucf.edu; lamar.harrell@presagis.com
**Subject:** Re: Case # 00103529: Recording Supply levels throughout a scenario, [ ]

Pascal,

One more to clutter up your in-container after a long weekend. [Inline image name : OutlookEmoji-.png]

I've spent the past couple hours digging through the help files and poking around in the IDE. In Call Definitions / Decision Calls there is a Decision named 'Actual Supply Quantity By Name'. This returns the value I need! However, that value is not listed in the Call Definitions / Entity Properties list where I need it to be available for assignment to a Report procedure.

I read how to create a new entity property, made one and generated and compiled the code. That part worked, I was able to see my new property and select it as the 'value' of my report procedure when I reopened the mission editor. But my property turned out to just be a name and didn't apparently link back to any data field from the entity because when I ran the scenario the SELF EVENT showed up in the log, but not the REPORT. Making that connection between a selectable entity property in the mission editor and actual data from the entity is missing from the help file. I tried using the same name (cur_quantity) that I found in an entity description .xml file, but that didn't work.

How can I find out what field the 'Actual Supply Quantity By Name' decision is referencing and then get my new entity property to reference the same field? Or get the entire "decision call" copied over to the "procedure call" side?

Thanks again for all your help.

Regards,
Matt

---

**From:** Support Stage <stage@presagis.com>
**Sent:** Thursday, June 30, 2016 3:40:12 PM
**To:** Matthew Davis
**Cc:** michael.proctor@ucf.edu; lamar.harrell@presagis.com
**Subject:** RE: Case # 00103529: Recording Supply levels throughout a scenario, [ ]

Hi Matt,

We tried to come up with different ways to come up with a solution for you, but in the end it all comes down to this being achievable only via a SIM plugin(coding).

Please note that our Canadian offices are closed tomorrow and I guess so are yours on Monday.

Happy 4th of July,

Pascal

Presagis Technical Support

---------- Original Message ----------
**From:** Matthew Davis [matt.davis@knights.ucf.edu]
**Sent:** 6/29/2016 3:37 PM
**To:** stage@presagis.com
**Cc:** lamar.harrell@presagis.com; michael.proctor@ucf.edu
**Subject:** Recording Supply levels throughout a scenario

Pascal,
Now that I have the missions/sub-missions controlling behavior correctly within the scenario I need to record the data of interest. The only data I need that I don't see in the mission history log is the supply level of an entity. Tracking how the supply level reacts to varying conditions within the scenario is the focus of my research, so I'm stuck until I figure a way to record it over the course of the scenario runs. There are two procedures that get very close to what I need ("Report" and "Return Event at Frequency") but don't have the option to return supply levels. "Return Event at Frequency" would be ideal since I could set it to report at a particular frequency for the entire scenario, but it won't allow me to select a supply level as the 'event'.

I've looked at the Monte Carlo sample Readme, but I'm not a coder so my attempts to follow the instructions and get batch testing going have been unsuccessful. Even if I could get that working, it looks to me like the output data only reports end-of-scenario values...not what I'm looking for.

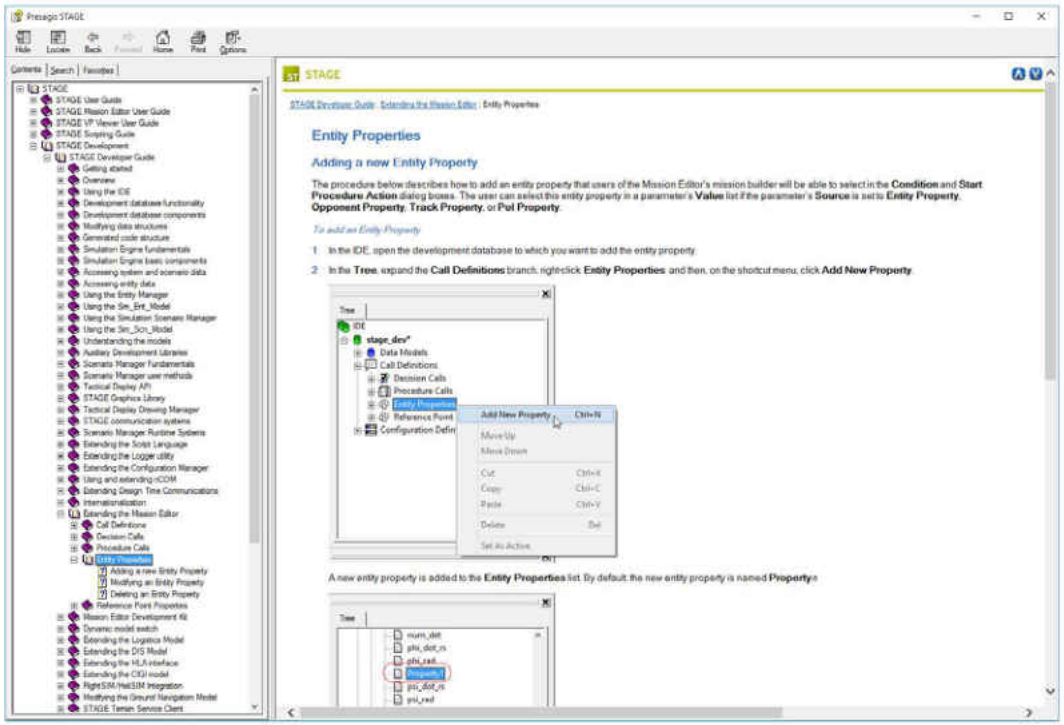
I've also look at the STAGE_nCOM EntityStats sample, but I've got no idea how to modify that code to send nCOM data to a third-party logging software.

If possible, I think modifying the "Return Event at Frequency" procedure would be ideal since that will generate a SIM message in the mission history log which I can save as a text file and use Excel to filter and analyze. At this point I'll take any solution you can offer, however.

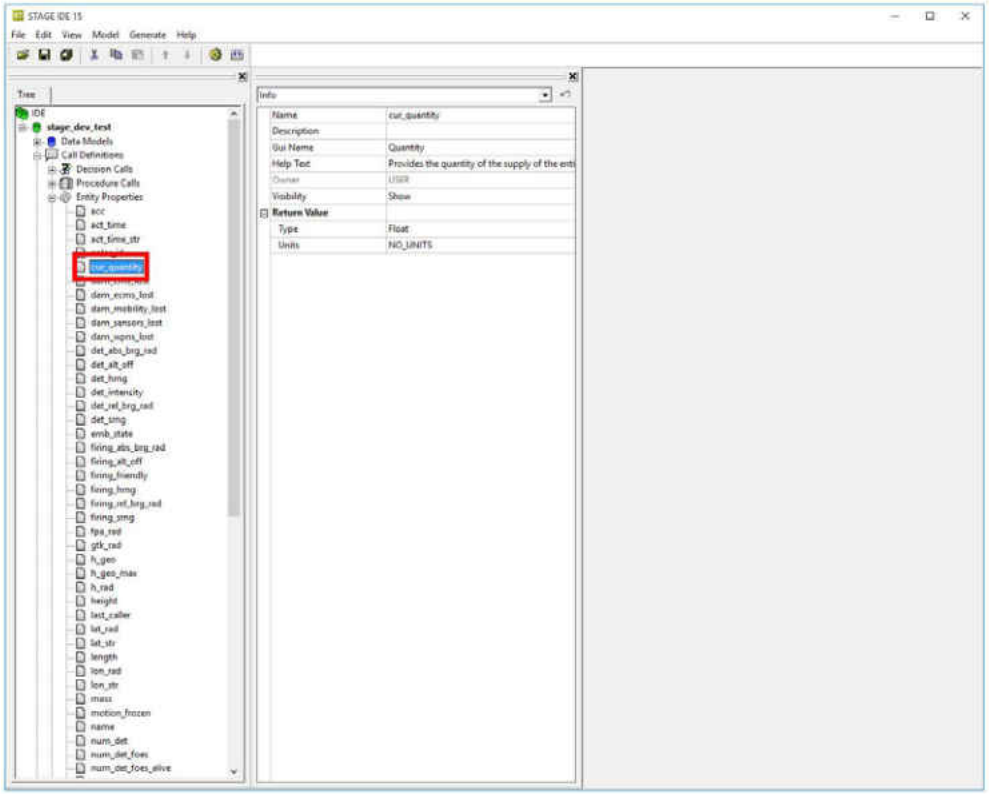
Look forward to hearing back from you soon.

Regards,
Matt

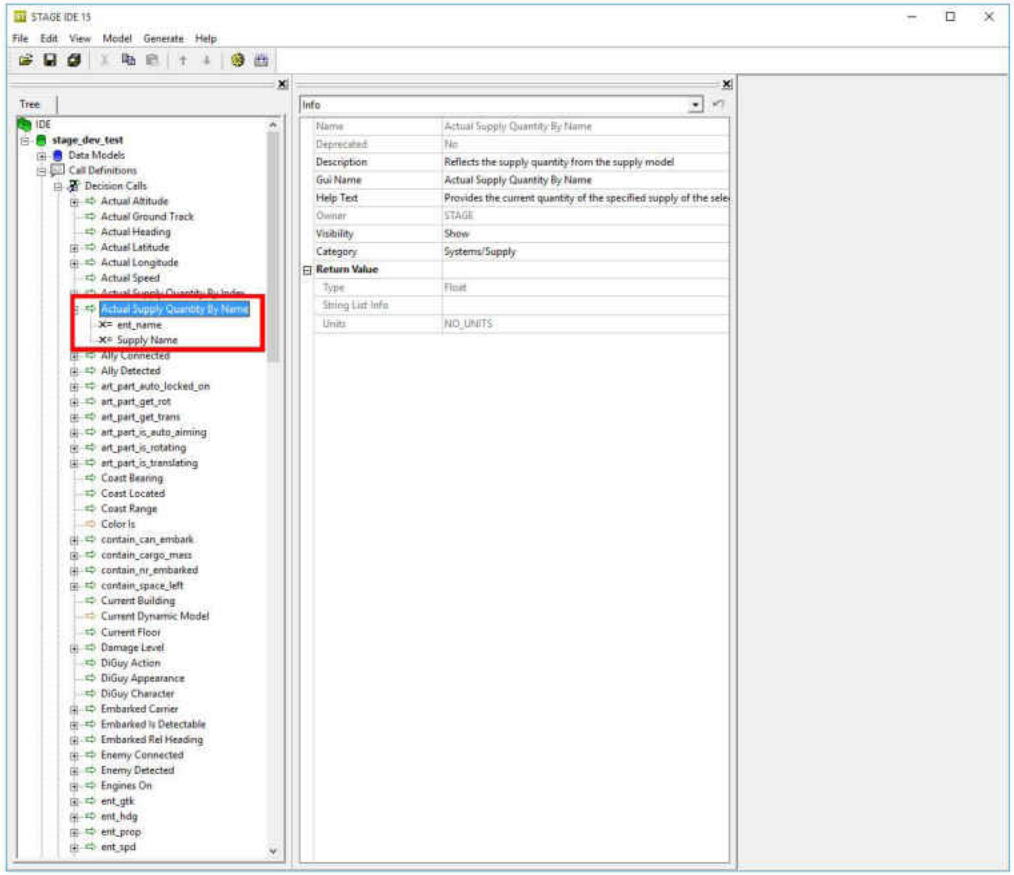
This page from the help file describes how to create a new entity property using the STAGE IDE, but doesn't describe how to point my new entity property at a data field within the entity's attribute array.



So I created this new 'Entity Property' called "cur_quantity" but don't know how to change where it gets its data from. In fact I can't tell where any of these entity properties are getting their data from. They are pointing to values within a entity's attribute array because they actually return values. How can I tell which location within that array they point to and then modify where it is pointing?



This Decision Call, “Actual Supply Quantity By Name” returns the Float value I want to ‘Report’. How do I get my entity property in the previous slide to return the same value being returned by this?



# APPENDIX D: R SCRIPT

Below is the text of the R script used to scrub, concatenate, and plot the raw water level data from each run of the screening experiment. The .R files are available from the author upon request.

```
#Import and Plot Loop
#A loop to import data from .csv and then plot pool levels

#Need to load packages:
#lubridate
#ggplot2
#gridExtra
#grid

#Initialize list of plots
P <- list()
P <- list(plots = P)

#Initialize vector for storing end-of-run water levels and
failure time matrix
water.level <- vector()
fail.vec <- data.frame()
```

```
     #Outer for loop moves through each of the 4 Blocks of the
experiment
     for(j in 1:4)
     {
         setwd(paste("~/OneDrive - University of Central Florida
- UCF/Dissertation/Data/Experiment 1/Block", j, sep = " "))

         #for loop completes the data manipulation and plots
pool level for each run of a Block
         for(i in 1:8)
         {
           #read in the data table from .csv
           run.table <- read.table(paste("B", j, "R", i,".txt",
sep = ""),
                                   header = FALSE,
                                   sep = "\t")

           #Add Column names
           colnames(run.table) <- c("Time", "Entity", "Type",
"Name",
                                    "Description", "Desc2",
"Reason",
```

```
                                    "Data", "D2", "D3", "D4")

            #convert reported times to numeric seconds
            run.table$Time <- hms(run.table$Time)
            run.table$Time <- period_to_seconds(run.table$Time)

            #attach run.times vector to the front of the data
table
            #run.table <- cbind(run.times, run.table)

            #filter for only rows containing pool level data
            run.sub <- subset(run.table, Reason == "TRUE" |
Reason == "true", c(Time, Data))

            #convert Data column to numeric values
            run.sub$Data <-
as.numeric(as.character(run.sub$Data))
            #run.sub$Data <- as.numeric(run.sub$Data) #nested
above

            #plot Pool Level vs Elapsed Time
            red.plot <-
```

```
            ggplot(run.sub, aes(x = Time, y = Data), ylim =
c(0,840)) +
                geom_point(color = "red", size = .1) +
                labs(title = paste("Block", j, "Run", i, "Pool
Level", sep = " ")) +
                xlab("Total Elapsed Time in Seconds") +
                ylab(expression("Pool Volume in meters"^3)) +
                scale_y_continuous(limits = c(0,840)) +
                theme(plot.title = element_text(size = 10)) +
                theme(axis.title = element_text(size = 5)) +
                theme(axis.text = element_text(size = 5))


          #Concatenate new plot into list P
          P$plots <- c(P$plots, list(red.plot))


                plot(run.sub$Time, run.sub$Data,
                type = "o",
                col = "blue",
                cex=.1,
                pch = 20,
                ylim = c(0,840),
```

```
                main = paste("Block", j, "Run", i, "Pool
Level", sep = " "),
                xlab = "Total Elapsed Time in Seconds",
                ylab = expression("Pool Volume in meters"^3)
                )


          #Save the ending pool level to a vector - water.level
          water.level <- c(water.level, tail(run.sub$Data, n =
1))

          #Save failure times for each run to a new vector
          fail.point <- min(which(run.sub$Data < 120))
          fail.time <- data.frame(Block = j, Run = i, Time =
run.sub[fail.point,"Time"], Data = run.sub[fail.point,"Data"])
          fail.vec <- rbind(fail.vec, fail.time[1,])

          #progess check
          print(c(j, i))

        } #End of run for loop (i)

    }  #End of block for loop (j)
```

```
    #Create single page plot of all 32 runs
    do.call(grid.arrange, c(P$plots, ncol = j))

    #Create a multipage plot of the runs ... easier to read
when they're bigger
    ggsave("mpage.pdf", marrangeGrob(P$plots, ncol = 2, nrow =
4))
```

## References


Adalja, A. A., Sell, T. K., Ravi, S. J., Minton, K., & Morhard, R. (2015). Emergency Preparedness in the 10-Mile Emergency Planning Zone Surrounding Nuclear Power Plants. *Journal of Homeland Security and Emergency Management, 12*(1), 81-100. doi:https://doi.org/10.1515/jhsem-2013-0106

Ai-Omari, M. A. R., Jaradat, M. A., & Jarrah, M. (2013, 9-11 April 2013). *Integrated Simulation Platform for Indoor Quadrotor Applications.* Paper presented at the 9th International Symposium on Mechatronics and its Applications (ISMA).

Alexis, K., Nikolakopoulos, G., Tzes, A., & Dritsas, L. (2009). *Coordination of Helicopter UAVs for Aerial Forest-Fire Surveillance*: Springer.

Alver, Y., Ozdogan, M., & Yucesan, E. (2012, 1/1/2012). *Assessing the Robustness of UAV Assignments.* Paper presented at the 2012 Winter Simulation Conference (WSC).

Anderson, M. J., & Whitcomb, P. J. (2007). *DOE Simplified : Practical Tools for Effective Experimentation* (2nd ed.). Boca Raton, FL: CRC Press Taylor and Francis Group.

ANS. (2012). Status of Spent Fuel in the Unit 1 Through 6 and Common Spent-Fuel Pools at the Fukushima Daiichi Nuclear Power Station *Fukushima Daiichi: ANS Committee Report* (pp. Appendix G): American Nuclear Society Special Committee on Fukushima.

AP. (2017). Robot probes show Japan reactor cleanup worse than expected [Press release]. Retrieved from http://www.cbsnews.com/news/bad-news-from-japans-wrecked-fukushima-nuclear-reactor/

Baker, J. (2012). *Capabilities Report 2012 West Desert Test Center*. Retrieved from http://oai.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADA559993: http://oai.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADA559993

Bell Helicopter. (2010). Bell 407 Product Specifications. In B. Helicopter (Ed.).

Bernabei, G., Sassanelli, C., Corallo, A., & Lazoi, M. (2014). *A PLM-Based Approach for Un-manned Air System Design: A Proposal*. Paper presented at the Modelling and Simulation for Autonomous Systems Workshop, Rome, Italy.

Bernard, M., Kondak, K., & Hommel, G. (2008). A Slung Load Transportation System Based on Small Size Helicopters *Autonomous Systems–Self-Organization, Management, and Control* (pp. 49-61): Springer.

Campbell, S., Abu-Tair, M., & Naeem, W. (2014). An Automatic COLREGS-Compliant Obstacle Avoidance System for an Unmanned Surface Vehicle. *Proceedings of the Institution of Mechanical Engineers Part M-Journal of Engineering for the Maritime Environment, 228*(2), 108-121. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000336266300002&site=eds-live&scope=site

Çelik, T., Gökdoğan, G. F., Öztürk, K., & Sarikaya, B. (2013). An HLA-Based Tactical Environment Application Framework. *The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology, 10*(3), 217-233. doi:10.1177/1548512912465993

Chaimatanan, S., Delahaye, D., & Mongeau, M. (2013, July 2013). *Strategic Deconfliction of Aircraft Trajectories.* Paper presented at the 2nd International Conference on Interdisciplinary Science for Innovative Air Traffic Management, Toulouse, France.

Chang, J. C., Hanna, S. R., Boybeyi, Z., & Franzese, P. (2005). Use of Salt Lake City URBAN 2000 Field Data to Evaluate the Urban Hazard Prediction Assessment Capability (HPAC) Dispersion Model. *Journal of Applied Meteorology, 44*(4), 485-501.

Coleman, D. E., & Montgomery, D. C. (1993). A Systematic Approach to Planning for a Designed Industrial Experiment. *Technometrics, 35*(1), 1-12. doi:10.2307/1269280

Collins, T. E., & Hubbard, G. (2001). *Technical study of spent fuel pool accident risk at decommissioning nuclear power plants NUREG-1738*. (0160616204). Washington, DC : Division of Systems Safety and Analysis, Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Commission : Supt. of Docs., U.S. G.P.O. [distributor], 2001. Retrieved from http://purl.access.gpo.gov/GPO/LPS14839.

Cortes, L. A., Duff, W., & Bergstrom, D. (2011). *A Primer on Design of Experiments for US Navy T&E Managers*. Retrieved from Naval Sea Systems Command:

Covelli, J. M., Rolland, J. P., Proctor, M., Kincaid, J. P., & Hancock, P. A. (2010). Field of View Effects on Pilot Performance in Flight. *The International Journal of Aviation Psychology, 20*(2), 197-219. doi:10.1080/10508411003617888

DAMIR. (2012). *Selected Aquisition Report CH-47F Improved Cargo Helicopter (CH-47F)*. Retrieved from

Davis, E. G. W., Charles H. ; Salvi, Lucia ; Kash, Howard M. (1990). *Soldier Performance of Military Operational Tasks Conducted While Wearing Chemical Individual Protective Equipment (IPE): Data Analysis in Support of the Revision of the U.S. Army Field Manual on NBC Protection (FM 3-4)* (BRL-TR-3155). Retrieved from http://www.dtic.mil/get-tr-doc/pdf?AD=ADA230157

Davis, M., & Proctor, M. (2016). The Viability of Extraordinary Methods to Mitigate Compromised SFP Cooling. *International Nuclear Safety Journal, 5*(2), 16-25. Retrieved from http://nuclearsafety.info/international-nuclear-safety-journal/index.php/INSJ/article/view/147

Davis, M., Proctor, M., & Shageer, B. (2016). A Systems-Of-Systems Conceptual Model and Live Virtual Constructive Simulation Framework for Improved Nuclear Disaster Emergency Preparedness, Response, and Mitigation. *Journal of Homeland Security and Emergency Management*. doi:https://doi.org/10.1515/jhsem-2015-0051

Davis, M., Proctor, M. D., & Shageer, B. (2017). Disaster Factor Screening using SoS Conceptual Modeling and an LVC simulation framework. *Reliability Engineering & System Safety*. doi:http://doi.org/10.1016/j.ress.2017.04.020

Davis, P. K. (1995). Distributed interactive simulation in the evolution of DoD warfare modeling and simulation. *Proceedings of the IEEE, 83*(8), 1138-1155. doi:10.1109/5.400454

Davis, P. K., & Anderson, R. H. (2004). Improving the Composability of DoD Models and Simulations. *Journal of Defense Modeling & Simulation, 1*(1), 5-17. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=53089736&site=eds-live&scope=site

Davis, P. K., & Tolk, A. (2007, 9-12 Dec. 2007). *Observations on New Developments in Composability and Multi-Resolution Modeling.* Paper presented at the Winter Simulation Conference.

Deagel. (2015). ARH-70A. Retrieved from http://www.deagel.com/Combat-Helicopters/ARH-70A_a000133004.aspx

DoD. (2013). DOD 3150.08-M "Nuclear Weapon Accident Response Procedures" (NARP) Internet Supplement. Retrieved from http://www.acq.osd.mil/ncbdp/narp/Radiation_Data/Specialized_Radiological.htm

DOE. (2015). Energy Technology Engineering Center Closure Project: The SRE Accident. Retrieved from http://etec.energy.gov/Operations/Major_Operations/SRE_Accident.html

Ellis, C., Babenko, P., & Goldiez, B. (2010). Dynamic Terrain for Multiuser Real-Time Environments. *IEEE Computer Graphics & Applications, 30*(1), 80-84. doi:10.1109/MCG.2010.5

EPA. (2011). Radiation Monitors Continue to Confirm That No Radiation Levels of Concern Have Reached the United States. Retrieved from http://yosemite.epa.gov/opa/admpress.nsf/d0cf6618525a9efb85257359003fb69d/3724de8571e1b03f8525785c00041a7a%21OpenDocument

Fernandez-Moguel, L. (2015). Comparative Assessment of PSI Air Oxidation Model Implementation in SCDAPSim3.5, MELCOR 1.8.6 and MELCOR 2.1. *Annals of Nuclear Energy, 81*, 134-142. doi:https://doi.org/10.1016/j.anucene.2015.03.015

Fernandez-Moguel, L., & Birchley, J. (2015). Analysis of the Accident in the Fukushima Daiichi Nuclear Power Station Unit 3 with MELCOR_2.1. *Annals of Nuclear Energy, 83*, 193-215. doi:10.1016/j.anucene.2015.04.021

Fisher, D. A. (2006). *An Emergent Perspective on Interoperation in Systems of Systems*. Retrieved from http://oai.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADA449020: https://login.ezproxy.net.ucf.edu/login?auth=shibb&url=http://search.ebscohost.com/login.aspx?direct=true&db=edsoai&AN=edsoai.831944695&site=eds-live&scope=site http://oai.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADA449020

Flint, M., Fernandez, E., & Kelton, W. D. (2009). Simulation Analysis for UAV Search Algorithm Design Using Approximate Dynamic Programming. *Military Operations Research, 14*(2), 41-50. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.136.1550&rep=rep1&type=pdf

Gaffney, H., & Vincent, A. (2011). Modeling Information Operations in a Tactical-level Stabilization Environment. *Journal of Defense Modeling & Simulation, 8*(2), 105. doi:10.1177/1548512910388199

Georgiou, S. D., Stylianou, S., Drosou, K., & Koukouvinos, C. (2014). Construction of orthogonal and nearly orthogonal designs for computer experiments. *Biometrika, 101*(3), 741-747. Retrieved from https://login.ezproxy.net.ucf.edu/login?auth=shibb&url=http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=97826079&site=eds-live&scope=site

Girault, N., Bosland, L., & Dienstbier, J. (2010). LWR Severe Accident Simulation Fission Product Behavior in FPT2 Experiment. *Nuclear Technology, 169*(3), 218-238. Retrieved from http://www.ans.org/pubs/journals/nt/a_9375

Graniela, B., & Proctor, M. D. (2012). A Network-Centric Terrain Database Regeneration Architecture. *The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology, 10*(3), 247-261. doi:10.1177/1548512912444178

Green, C., Leibrecht, B. C., & Fite, J. E. (2011). *After Action Review Guide for Trainers of Virtual Battlespace-2 Missions*. Retrieved from http://oai.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADA548308: http://oai.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADA548308

Haase, C. L. (2011). *Tailoring the Statistical Experimental Design Process for LVC Experiments.* (Master of Operations Research), 2011-03., Air Force Institute of Technology. Retrieved from http://oai.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADA544636

Haase, C. L., Hill, R. R., & Hodson, D. (2014). Planning for LVC Simulation Experiments. *Applied Mathematics, 5*(14), 2153. doi:https://doi.org/10.4236/am.2014.514209

Hamilton, J. A. (2006). A Conceptual Model for Interoperable Command and Control Acquisition. *Journal of Defense Modeling & Simulation, 3*(2), 125-138. doi:10.1177/875647930600300205

Hanna, S., & Chang, J. (2015). Skyscraper Rooftop Tracer Concentration Observations in Manhattan and Comparisons with Urban Dispersion Models. *Atmospheric Environment, 106*(2015), 215-222. doi:10.1016/j.atmosenv.2015.01.051

Hanna, S. R. (2009). *Urban HPAC/SCIPUFF and a simple urban dispersion model compared with the Madison Square Garden 2005 (MSG05) tracer observations in New York City.* Paper presented at the Eighth Symposium on the Urban Environment.

Head, E. (2017, January 24). Meet the King. *Vertical Magazine*.

Hedayat, A., Sloane, N. J. A., & Stufken, J. (1999). *Orthogonal arrays : theory and applications*: New York : Springer, c1999.

Heffelfinger, D. G., Tuckett, C. M., & Ryan, J. R. (2013). The Military's Response to Domestic CBRNE Incidents. *Journal of Homeland Security and Emergency Management, 10*(1), 57-75. doi:https://doi.org/10.1515/jhsem-2012-0013

Hill, A. (2003). *Using the Hazard Prediction and Assessment Capability (HPAC) Hazard Assessment Program for Radiological Scenarios Relevant to the Australian Defence Force*. Retrieved from http://oai.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADA416823: https://login.ezproxy.net.ucf.edu/login?auth=shibb&url=http://search.ebscohost.com/login.aspx?direct=true&db=edsoai&AN=edsoai.834255026&site=eds-live&scope=site
http://oai.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADA416823

Hodicky, J. (2014). HLA as an Experimental Backbone for Autonomous System Integration into Operational Field. *Modelling and Simulation for Autonomous Systems: First International Workshop, MESAS 2014, Rome, Italy, May 5-6, 2014, Revised Selected Papers, 8906*, 121. doi:https://doi.org/10.1007/978-3-319-13823-7_11

Hodson, D. D., Esken, B. L., Gutman, A. J., & Hill, R. R. (2014). Quantifying Radar Measurement Errors in a Live–Virtual–Constructive Environment to Determine System Viability: A Case Study. *Journal of Defense Modeling & Simulation, 11*(2), 115-124. doi:10.1177/1548512913503740

Hodson, D. D., & Hill, R. R. (2014). The Art and Science of Live, Virtual, and Constructive Simulation for Test and Analysis. *Journal of Defense Modeling & Simulation, 11*(2), 77-89. doi:https://doi.org/10.1177/1548512913506620

Holden, T., & Dickerson, C. (2013). A ROSETTA Framework for Live / Synthetic Aviation Tradeoffs: Preliminary Report. *Proceedings of the 2013 8th International Conference on System of Systems Engineering*, 218-223. doi:10.1109/SYSoSE.2013.6575270

Hollenbach, J. W., & Alexander, W. L. (1997). Executing the DoD Modeling and Simulation Strategy—Making Simulation Systems of Systems a Reality. *Proceedings of the 29th Winter Simulation Conference*, 948-954. doi:10.1145/268437.268690

Hsu, J. (11/2014). The Weight Of War. *Popular Science, 285*(5), 60-65. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=hxh&AN=99527262&site=eds-live&scope=site

Hu, L., Zhang, Y., Li, L., Su, G. H., Tian, W., & Qiu, S. (2015). Investigation of Severe Accident Scenario of PWR Response to LOCA Along with SBO. *Progress in Nuclear Energy, 83*(2015), 159-166. doi:https://doi.org/10.1016/j.pnucene.2015.03.014

Hugo, B. R. (2015). *Modeling Evaporation From Spent Nuclear Fuel Storage Pools: A Diffusion Approach.* (Doctor of Philosophy Dissertation), Washington State University.

Hugo, B. R., & Kinsel, W. C. (2014). Predicting evaporation rates from spent nuclear fuel storage pools. *International Nuclear Safety Journal, 3*(1), 50-56.

Hugo, B. R., & Omberg, R. P. (2015). Evaluation of the Fukushima Daiichi Unit 4 Spent Fuel Pool. *International Nuclear Safety Journal, 4*(2), 1-5. Retrieved from http://nuclearsafety.info/international-nuclear-safety-journal/index.php/INSJ/article/view/66

Ianovsky, E., & Kreimer, J. (2011). An Optimal Routing Policy for Unmanned Aerial Vehicles (Analytical and Cross-Entropy Simulation Approach). *Annals of Operations Research, 189*(1), 215-253. doi:https://doi.org/10.1007/s10479-009-0609-1

IEEE. (2010). IEEE Standard for Modeling and Simulation (M\&S) High Level Architecture (HLA)--Framework and Rules *IEEE Std 1516-2010 (Revision of IEEE Std 1516-2000)* (pp. 1-38).

IEEE. (2012). IEEE Standard for Distributed Interactive Simulation--Application Protocols *IEEE Std 1278.1-2012 (Revision of IEEE Std 1278.1-1995)* (pp. 1-747).

INNG. (2015). Vibrant Response Q and A [Press release]. Retrieved from http://www.atterburymuscatatuck.in.ng.mil/Portals/18/PageContents/Training/JE/Q_and_A.pdf

Jain, S., & McLean, C. R. (2006). An Integrating Framework for Modeling and Simulation for Incident Management. *Journal of Homeland Security and Emergency Management, 3*(1), 1-5. doi:10.2202/1547-7355.1194

Japan, G. o. (2011). *Additional Report of the Japanese Government to the IAEA (Second Report)*. Retrieved from https://www.iaea.org/newscenter/focus/fukushima/additional-japan-report

Act for Establishment of the Nuclear Regulation Authority, (2012).

JDF. (2011). *Special Feature: Response to the Great East Japan Earthquake*. Retrieved from JDF website: http://www.mod.go.jp/e/publ/w_paper/pdf/2011/04SpecialFeature.pdf

Johnson, R. T., Hutto, G. T., Simpson, J. R., & Montgomery, D. C. (2012). Designed Experiments for the Defense Community. *QUALITY ENGINEERING, 24*(1), 60-79. Retrieved from https://login.ezproxy.net.ucf.edu/login?auth=shibb&url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000299336500007&site=eds-live&scope=site

Johnson, T. (2006). The Battle of Chernobyl [Film]. http://icarusfilms.com/new2007/batt.html: Icarus FIlms.

Jones, B., & Nachtsheim, C. J. (2009). Split-Plot Designs: What, Why, and How. *JOURNAL OF QUALITY TECHNOLOGY, 41*(4), 340-361. Retrieved from https://login.ezproxy.net.ucf.edu/login?auth=shibb&url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000270320700002&site=eds-live&scope=site

Jones, M. C. (2015). Composability. In L. B. Rainey & A. Tolk (Eds.), *Modeling and Simulation Support for System of Systems Engineering Applications* (pp. 45-73). Hoboken, New Jersey: Wiley.

JTF-CS. (2015a). *JTF-CS 101 Brief v5.5*. http://www.jtfcs.northcom.mil/Documents/JTF-CS%20101%20Brief%20v5.5%20(28%20APR%202015).pdf: Joint Task Force Civil Support Retrieved from http://www.jtfcs.northcom.mil/Documents/JTF-CS%20101%20Brief%20v5.5%20(28%20APR%202015).pdf.

JTF-CS. (2015b). JTFCS Operational Focus. Retrieved from http://www.jtfcs.northcom.mil/OperationalFocus.aspx

Kasputis, S., & Ng, H. C. (2000). Composable Simulations. *Proceedings of the 2000 Winter Simulation Conference, 2*, 1577-1584. doi:10.1109/WSC.2000.899142

Kataoka, I. (2013). Review of thermal-hydraulic researches in severe accidents in light water reactors. *Journal of Nuclear Science and Technology, 50*(1), 1-14. Retrieved from https://login.ezproxy.net.ucf.edu/login?auth=shibb&url=http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000312592400001&site=eds-live&scope=site

Kim, K.-R., Park, S.-Y., Song, Y.-M., & Ahn, K.-I. (2010). Development of desktop severe accident training simulator. *Nuclear Engineering and Technology, 42*(2), 151-162. doi:https://doi.org/10.5516/NET.2010.42.2.151

Kim, K. D., & Rizwan, u. (2007). A web-based nuclear simulator using RELAP5 and LabVIEW. *Nuclear Engineering and Design, 237*(11), 1185-1194. doi:10.1016/j.nucengdes.2007.01.004

Kim, K. R., Jeong, K. S., Ha, J. J., & Jung, W. D. (2002). *Development of a severe accident training simulator using a MELCOR code*. Retrieved from Korea, Republic of:

Law, A. M., & Kelton, W. D. (2000). *Simulation Modeling and Analysis* (3rd ed.). Boston: McGraw-Hill.

Liang, W., Lam Nina, S. N., Qin, X., & Ju, W. (2015). A Two-Level Agent-Based Model for Hurricane Evacuation in New Orleans. *Journal of Homeland Security and Emergency Management, 12*(2), 407-435. doi:https://doi.org/10.1515/jhsem-2014-0057

Liu, X. F., Guan, Z. W., Song, Y. Q., & Chen, D. S. (2014). An Optimization Model of UAV Route Planning for Road Segment Surveillance. *Journal of Central South University, 21*(6), 2501-2510. doi:10.1007/s11771-014-2205-z

MacFarlane, J. W., Payton, O. D., Keatley, A. C., Scott, G. P. T., Pullin, H., Crane, R. A., . . . Scott, T. B. (2014). Lightweight Aerial Vehicles for Monitoring, Assessment and Mapping of Radiation Anomalies. *Journal of Environmental Radioactivity, 136*(2014), 127-130. doi:https://doi.org/10.1016/j.jenvrad.2014.05.008

Maier, M. W. (1998). Architecting Principles for Systems-of-Systems. *Systems Engineering, 1*(4), 267-284. doi:10.1002/(SICI)1520-6858(1998)1:4<267::AID-SYS3>3.0.CO;2-D

Marconi, L., Melchiorri, C., Beetz, M., Pangercic, D., Siegwart, R., Leutenegger, S., . . . Tomatis, N. (2012). The SHERPA Project: Smart Collaboration Between Humans and Ground-Aerial Robots for Improving Rescuing Activities in Alpine Environments. *2012 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, 1-4. doi:10.1109/SSRR.2012.6523905

Mase, K. (2013). Wide-Area Disaster Surveillance Using Electric Vehicles and Helicopters. *2013 IEEE 24th International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, 3466-3471. doi:10.1109/PIMRC.2013.6666748

Mase, K. (2015). Wide Area Surveillance Using Electric Vehicles and Limited-Flying-Time Helicopters. *Sensors & Transducers, 185*(2), 84-92. Retrieved from http://www.sensorsportal.com/HTML/DIGEST/P_2606.htm

McGonigle, A. J. S., Aiuppa, A., Giudice, G., Tamburello, G., Hodson, A. J., & Gurrieri, S. (2008). Unmanned Aerial Vehicle Measurements of Volcanic Carbon Dioxide Fluxes. *Geophysical Research Letters, 35*(6), 1-4. doi:10.1029/2007GL032508

McLean, C. R., Jain, S., Lee, Y. T., & Shao, G. (2007). *An Integrated Simulation Environment For Incident Management Training*. Retrieved from http://www.nist.gov/manuscript-publication-search.cfm?pub_id=822742:

Meliza, L. L., Goldberg, S. L., & Lampton, D. R. (2007). *After Action Review in Simulation-Based Training*. Retrieved from http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA474305: http://oai.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADA474305

Miller, C., Cubbage, A., Dorman, D., Grobe, J., Holahan, G., & Sanfilippo, N. (2011). *Recommendations for Enhancing Reactor Safety in the 21st Century*. Retrieved from http://pbadupws.nrc.gov/docs/ML1118/ML111861807.pdf: http://pbadupws.nrc.gov/docs/ML1118/ML111861807.pdf

Montgomery, D. C. (2013). *Design and Analysis of Experiments* (8th ed.). Hoboken, NJ: John Wiley & Sons, Inc.

Morris, J. D., Grimaila, M. R., Hodson, D. D., McLaughlin, C. V., & Jacques, D. R. (2014). Using the Discrete Event System Specification to Model Quantum Key Distribution System Components. *The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology, 12*(4), 457-480. doi:10.1177/1548512914554404

NAVAIR. (2000). NATOPS Flight Manual Navy Model MH-53E Helicopters: Naval Air Systems Command.

NAWCTSD. (2014). *NAWCTSD Research Project Summaries: Fiscal Years 2014-2015*. Retrieved from http://www.navair.navy.mil/nawctsd/Programs/Files/NAWCTSD-FY-14-15-Grey-Book.pdf:

Northrup Grumman. (2015, April 2015). MQ-8C Fire Scout Unmanned Air System. Retrieved from http://www.northropgrumman.com/Capabilities/FireScout/Documents/pageDocuments/MQ-8C_Fire_Scout_Data_Sheet.pdf

NRC. (2011). *Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants: Guidance for Protective Action Strategies*. Washington, DC : U.S. Nuclear Regulatory Commission, FEMA, [2011] Rev. 1, Supplement 3 Retrieved from http://purl.fdlp.gov/GPO/gpo54473.

NRC. (2012). *Order Modifying Licenses with Regard to Reliable Spent Fuel Pool Instrumentation*. Nuclear Regulatory Commission Retrieved from http://www.nrc.gov/docs/ML1205/ML12056A044.pdf.

NRC. (2014a). *2002 Davis-Besse Reactor Pressure Vessel Head Degradation Knowledge Management Digest* (NUREG/KM-0005). Retrieved from http://www.nrc.gov/docs/ML1403/ML14038A119.pdf:

NRC. (2014b). *The Browns Ferry Nuclear Plant Fire of 1975 Knowledge Management Digest* (NUREG/KM-0002, Rev. 1). Retrieved from http://www.nrc.gov/docs/ML1321/ML13210A179.pdf:

NRC. (2014c). *NUREG-1350*. Retrieved from http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1350/v26/sr1350v26.pdf: http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1350/v26/sr1350v26.pdf

NRC. (2015a). Computer Codes. Retrieved from http://www.nrc.gov/about-nrc/regulatory/research/safetycodes.html#sac

NRC. (2015b). Location of Projected New Nuclear Power Reactors. Retrieved from http://www.nrc.gov/reactors/new-reactors/col/new-reactor-map.html

Oikawa, K. (2015). Robot Technology for Nuclear Decommissioning of Fukushima Daiichi NPS. http://irid.or.jp/_pdf/20150421_1.pdf: International Research Institute for Nuclear Decommissioning (IRID).

OPA. (2013a). Chernobyl Nuclear Power Plant Accident. Retrieved from http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/chernobyl-bg.html

OPA. (2013b). Three Mile Island Accident. Retrieved from http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

Ouyang, J., Zhuang, Y., Lin, M., & Liu, J. (2014). Optimization of Beamforming and Path Planning for UAV-Assisted Wireless Relay Networks. *Chinese Journal of Aeronautics, 27*(2), 313-320. doi:10.1016/j.cja.2014.02.011

Özhan, G., Oğuztüzün, H., & Evrensel, P. (2008). Modeling of Field Artillery Tasks with Live Sequence Charts. *Journal of Defense Modeling & Simulation, 5*(4), 219-252. doi:10.1177/875647930800500402

PB Farradyne. (2005). *Use of Unmanned Aerial Vehicles in Traffic Surveillance and Traffic Management*. Retrieved from http://www.i95coalition.org/wp-content/uploads/2015/03/Report_TechMemo_UAV_FL.pdf

Peräjärvi, K., Lehtinen, J., Pöllänen, R., & Toivonen, H. (2008). Design of an Air Sampler for a Small Unmanned Aerial Vehicle. *Radiation Protection Dosimetry, 132*(3), 328-333. doi:10.1093/rpd/ncn304

Perhinschi, M. G., Napolitano, M. R., & Tamayo, S. (2010). Integrated Simulation Environment for Unmanned Autonomous Systems--Towards a Conceptual Framework. *Modelling & Simulation in Engineering, 2010*, 1-12. doi:https://doi.org/10.1155/2010/736201

Plante, D. E. (2002). *An Evaluation of the Hazard Prediction and Assessment Capability (HPAC) Software's Ability to Model the Chornobyl Accident.* (Master of Science), Air Force Institute of Technology, Wright Patterson Air Force Base, OH. Retrieved from

http://oai.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADA407725 Available from Oclc EBSCOhost OAIsteredsoai database.

Platt, N., Kimball, W. R., & Urban, J. T. (2014). The Use of Probabilistic Plume Predictions for the Consequence Assessment of Atmospheric Releases of Hazardous Materials. *International Journal of Environment and Pollution, 55*, 1-5. doi:10.1504/IJEP.2014.065899

Po, L.-c. C. (2010). PC-based simulator for education in advanced nuclear power plant construction. *International Journal of Nuclear Knowledge Management*(2). doi:https://doi.org/10.1504/IJNKM.2010.032309

Polo-Labarrios, M. A., & Espinosa-Paredes, G. (2015). Comparative Study of the Hydrogen Generation During Short Term Station Blackout (STSBO) in a BWR. *Annals of Nuclear Energy, 83*(2015), 274-282. doi:10.1016/j.anucene.2015.04.027

Presagis. (2015a). Helisim. Retrieved from http://www.presagis.com/products_services/products/modeling-simulation/simulation/helisim/

Presagis. (2015b). M&S Suite. Retrieved from http://www.presagis.com/products_services/products/modeling-simulation/

Presagis. (2016a). Interoperability. Retrieved from http://www.presagis.com/solutions/solutions_more/interoperability/

Presagis. (2016b). Networking and Open Standards. Retrieved from http://www.presagis.com/solutions/solutions_more/networking_and_open_standards/

Pripyat.com. (2006). Chernobyl Disaster: Helicopter crash near Nuclear Power Plant. Retrieved from https://youtu.be/8s40uKLCjcU

Proctor, M. D., Bauer, M., & Lucario, T. (2007). Helicopter Flight Training Through Serious Aviation Gaming. *Journal of Defense Modeling & Simulation, 4*(3), 277-294. doi:10.1177/154851290700400305

Proctor, M. D., & Connors, P. E. (2000). Data Representation for Sensor Models Within a Synthetic Natural Environment (SEDRIS). *Transactions of the Society for Computer Simulation International, 17*(2), 46-53. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000088857700001&site=eds-live&scope=site

Proctor, M. D., Panko, M., & Donovan, S. J. (2004). Considerations for Training Team Situation Awareness and Task Performance Through PC-Gamer Simulated Multiship Helicopter Operations. *International Journal of Aviation Psychology, 14*(2), 191-205. doi:10.1207/s15327108ijap1402_5

Proctor, M. D., & Paulo, G. (1996). Modeling in Support of Operational Testing. *Mathematical and Computer Modelling, 23*(1-2), 9-14. doi:https://doi.org/10.1016/0895-7177(95)00211-1

Proctor, M. D., Shageer, B. M., & Davis, M. T. (2015). Considering Modeling and Simulation of DOD Response to Accidental Nuclear Disaster. *Journal of Defense Management, 5*(2), 134. doi:https://doi.org/10.4172/2167-0374.1000134

Rami, N., & Proctor, M. D. (2007). Real Time Physically-Based Modeling and Simulation of Cratering and Fragmentation of Terrain. *Simulation-Transactions of the Society for Modeling and Simulation International, 83*(12), 830-842. doi:10.1177/0037549707086786

Raymer, M. K. (2009). *A COMPARATIVE ANALYSIS OF THE ARMY MQ-8B FIRE SCOUT VERTICAL TAKEOFF UNMANNED AERIAL VEHICLE (VTUAV) AND NAVY MQ-8B MANPOWER & TRAINING REQUIREMENTS.* (Master of Science in Management), Naval Post Graduate School.

Robinson, S. (2008a). Conceptual Modelling for Simulation Part I: Definition and Requirements. *Journal of the Operational Research Society, 59*(3), 278-290. doi:10.1057/palgrave.jors.2602368

Robinson, S. (2008b). Conceptual Modelling for Simulation Part II: A Framework for Conceptual Modelling. *Journal of the Operational Research Society, 59*(3), 291-304. doi:10.1057/palgrave.jors.2602369

Robinson, S. (2010). *Conceptual Modeling for Discrete-Event Simulation*. Boca Raton: CRC Press.

Saggiani, G. M., & Teodorani, B. (2004). Rotary Wing UAV Potential Applications: An Analytical Study Through a Matrix Method. *Aircraft Engineering and Aerospace Technology, 76*(1), 6-14. doi:https://doi.org/10.1108/00022660410514955

Sanders, R. P., Barney. (2013). *Integration of the THOR Models with the MELCOR Severe Accident Codes.* Paper presented at the 2013 PowerPlantSim Conference, Tampa, FL.

Sawyer, T. L., & Deering, S. (2013). Adaptation of the US Army's After-Action Review for Simulation Debriefing in Healthcare. *Simulation in Healthcare-Journal of the Society for Simulation in Healthcare, 8*(6), 388-397. doi:10.1097/SIH.0b013e31829ac85c

SEI Industries. (2013). Bambi Max Operations Manual (version g ed.): SEI.

Sevón, T. (2015). A MELCOR Model of Fukushima Daiichi Unit 1 Accident. *Annals of Nuclear Energy, 85*(2015), 1-11. doi:10.1016/j.anucene.2015.04.031

Shageer, B., Proctor, M., Davis, M., & Schreiber, L. (IN REVIEW). An LVC Simulation-based Operational Reliability Assessment Methodology. *Quality and Reliability Engineering International*.

Shah, M. M. (2014). Methods for calculation of evaporation from swimming pools and other water surfaces. *ASHRAE Transactions*(2), 3. Retrieved from https://login.ezproxy.net.ucf.edu/login?auth=shibb&url=http://search.ebscohost.com/login.aspx?direct=true&db=edsgao&AN=edsgcl.394346828&site=eds-live&scope=site

Sharma, S. K., Sutton, R., Motwani, A., & Annamalai, A. (2014). Non-Linear Control Algorithms for an Unmanned Surface Vehicle. *Proceedings of the Institution of Mechanical Engineers Part M-Journal of Engineering for the Maritime Environment, 228*(2), 146-155. doi:10.1177/1475090213503630

Sheng, L., Song, Z., Hu, J., Lü, K., Tong, H., Li, B., & Qiao, Q. (2015). The Comparison of Ensemble or Deterministic Dispersion Modeling on Global Dispersion During Fukushima Dai-ichi Nuclear Accident. *Science China Earth Sciences, 58*(3), 356-370. doi:10.1007/s11430-014-4872-x

Singh, A., Spak, S. N., Stone, E. A., Downard, J., Bullard, R. L., Pooley, M., . . . Stanier, C. O. (2015). Uncontrolled Combustion of Shredded Tires in a Landfill – Part 2: Population Exposure, Public Health Response, and an Air Quality Index for Urban Fires. *Atmospheric Environment, 104*(2015), 273-283. doi:10.1016/j.atmosenv.2015.01.002

Sokolowski, J. A., Banks, C. M., & Morrow, B. (2012). Using an Agent-Based Model to Explore Troop Surge Strategy. *Journal of Defense Modeling & Simulation, 9*(2), 173-186. doi:10.1177/1548512911401739

Steinberg, D. M., & Hunter, W. G. (1984). Experimental Design: Review and Comment. *Technometrics, 26*(2), 71. Retrieved from https://login.ezproxy.net.ucf.edu/login?auth=shibb&url=http://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=5987075&site=eds-live&scope=site

Stephens, K. K., Jafari, E., Boyles, S., Ford Jessica, L., & Zhu, Y. (2015). Increasing Evacuation Communication Through ICTs: An Agent-Based Model Demonstrating Evacuation Practices and the Resulting Traffic Congestion in the Rush to the Road. *Journal of Homeland Security and Emergency Management, 12*(3), 497–528. doi:https://doi.org/10.1515/jhsem-2014-0075

Svec, P., Thakur, A., Raboin, E., Shah, B. C., & Gupta, S. K. (2014). Target Following with Motion Prediction for Unmanned Surface Vehicle Operating in Cluttered Environments. *Autonomous Robots, 36*(4), 383-405. doi:https://doi.org/10.1007/s10514-013-9370-z

TEPCO. (2013). *The Development of and Lessons from the Fukushima Daiichi Nuclear Accident*. Retrieved from http://www.tepco.co.jp/en/decommision/accident/images/outline01.pdf

Tolk, A., Diallo, S., & Turnitsa, C. (2007). Applying the Levels of Conceptual Interoperability Model in Support of Integratability, Interoperability, and Composability for System-of-Systems Engineering. *Journal of Systemics, Cybernetics and Informatics, 5*(5), 65-74. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=edsdoj&AN=cb024d0dd875313da4caa464235060e0&site=eds-live&scope=site

Tolk, A., & Muguira, J. A. (2003). The Levels of Conceptual Interoperability Model. *Proceedings of the 2003 Fall Simulation Interoperability Workshop, 7*, 1-11.

Tomaszewski, B., Judex, M., Szarzynski, J., Radestock, C., & Wirkus, L. (2015). Geographic Information Systems for Disaster Response: A Review. *Journal of Homeland Security and Emergency Management, 12*(3), 571-602. doi:10.1515/jhsem-2014-0082

Towler, J., Krawiec, B., & Kochersberger, K. (2012). Radiation Mapping in Post-Disaster Environments Using an Autonomous Helicopter. *Remote Sensing, 4*(7), 1995-2015. doi:https://doi.org/10.3390/rs4071995

TRADOC. (2000). *FM 3-5 MCWP 3-37.3 NBC Decontamination*. Department of the Army.

TRMC. (2015). TENA Introductory Material. Retrieved from https://www.tena-sda.org/display/intro/Documentation

Ünal, Ö., & Topçu, O. (2014). Modelling Unmanned Surface Vehicle Patrol Mission with Coalition Battle Management Language (C-BML). *Journal of Defense Modeling & Simulation, 11*(3), 277-308. doi:10.1177/1548512912475107

UNSCEAR. (2014). *Levels and Effects of Radiation Exposure Due to the Nuclear Accident After the 2011 Great East-Japan Earthquake and Tsunami*. Retrieved from http://www.unscear.org/docs/publications/2013/UNSCEAR_2013_Report_Vol.I.pdf:

US Army. Heavy Helicopter Company. Retrieved from https://fas.org/man/dod-101/army/unit/toe/01447A000.htm

US Army. (2003). TECHNICAL MANUAL OPERATOR'S MANUAL FOR ARMY CH-47D HELICOPTER. In D. O. T. A. HEADQUARTERS (Ed.).

USMC. (1999). Table of Organization Marine Heavy Helicopter Squadron. Retrieved from http://www.globalsecurity.org/military/library/policy/usmc/to/aviation/8960.htm

UTM. (2007, 2 Feb 2007). Palm Bay, FL, Deploys Unmanned Air Vehicles. *The Urban Transportation Monitor,* p. 1. Retrieved from https://trid.trb.org/view.aspx?id=808168

van Blyenburgh, P. (2000). *UAVs - Current Situation and Considerations for the Way Forward*. Retrieved from http://oai.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADP010752: http://oai.dtic.mil/oai/oai?&verb=getRecord&metadataPrefix=html&identifier=ADP010752

Wang, D. A., Gauld, I. C., Yoder, G. L., Ott, L. J., Flanagan, G. F., Francis, M. W., . . . Gehin, J. C. (2012). Study Of Fukushima Daiichi Nuclear Power Station Unit 4 Spent-Fuel Pool. *Nuclear Technology, 180*(2), 205-215. Retrieved from http://www.ans.org/pubs/journals/nt/a_14634

Wang, J., Corradini, M. L., Fu, W., Haskin, T., Zhang, Y., Tian, W., . . . Qiu, S. (2015). Simulation of the PHEBUS FPT-1 Experiment Using MELCOR and Exploration of the Primary Core Degradation Mechanism. *Annals of Nuclear Energy, 85*(2015), 193-204. doi:10.1016/j.anucene.2015.05.015

Wang, J., Zhang, Y., Mao, K., Huang, Y., Tian, W., Su, G., & Qiu, S. (2015). MELCOR Simulation of Core Thermal Response During a Station Blackout Initiated Severe Accident in China Pressurized Reactor (CPR1000). *Progress in Nuclear Energy, 81*(2015), 6-15. doi:https://doi.org/10.1016/j.pnucene.2014.12.008

Wang, T.-C., Wang, S.-J., & Teng, J.-T. (2005). Comparison of Severe Accident Results Among SCDAP/RELAP5, MAAP, and MELCOR Codes. *Nuclear Technology, 150*(2), 145-152. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=edswsc&AN=000228655600003&site=eds-live&scope=site

WNA. (2012, Sep. 2012). Fukushima: Background on Fuel Pools. Retrieved from http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Appendices/Fukushima--Fuel-Ponds-Background/

WNA. (2015). Nuclear Database. Retrieved from http://www.world-nuclear.org/NuclearDatabase/rdResults.aspx?id=27569

WSC. (2012). WSC Brings Severe Accident Modeling to 3KEYMASTER With MELCOR [Press release]. Retrieved from https://www.ws-corp.com/wsc08/wsc14/LiveEditor/images/newsletter/2012/index.html

Yilmaz, L. (2004). On the Need for Contextualized Introspective Models to Improve Reuse and Composability of Defense Simulations. *Journal of Defense Modeling & Simulation, 1*(3), 141-151. doi:10.1177/875647930400100302

Zeigler, B. P., Kim, T. G., & Praehofer, H. (2000). *Theory of Modeling and Simulation: Integrating Discrete Event and Continuous Complex Dynamic Systems* (2nd ed.). San Diego, [Calif.] ; London: Academic Press.

Zittel, R. C. (2001). The Reality of Simulation-Based Acquisition -- And an Example of U.S. Military Implementation. *Acquisition Review Quarterly, 2001*(2), 121-132. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=edsgao&AN=edsgcl.81763216&site=eds-live&scope=site