DISSERTATION

THE SYSTEMS ENGINEERING

CASUALTY ANALYSIS SIMULATION (SE-CAS)

Submitted by

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ABSTRACT

THE SYSTEMS ENGINEERING
CASUALTY ANALYSIS SIMULATION (SE-CAS)

In this dissertation, we illustrate the use of the systems engineering casualty analysis simulation (SE-CAS). SE-CAS, inspired by the Army's need to detect, identify and operate in areas contaminated by Chemical Warfare Agent (CWA), is a framework for creating chemical warfare simulations. As opposed to existing simulations which emulate simple cause-and-effect relationships, SE-CAS is developed using a systems thinking approach to dynamically represent interconnected elements during weaponized release of CWA. Through use of monte-carlo simulation methods, integrated dynamic analytic models, and NASA WorldWind® global display, SE-CAS provides the capability to visualize areas of chemical warfare agent dispersion, symptomology and exposure effects, and prescription of optimal survival factors within a common constructive environment.

Supported by Colorado State University's Walter Scott Jr. School of Engineering and industry affiliates, SE-CAS is part of a larger research & development effort to expand industry modeling, simulation and analysis capabilities within Chemical, Biological, Radiological, Nuclear and Explosives (CBRN-E) discipline. SE-CAS is an open, parameterized simulation allowing the user to set initial conditions, simulation mode, parameters, and randomized inputs through a scenario editor. Inputs are passed through the simulation components and service layers. This includes: processor logic,

simulation management, visualization and observer services. Data output is handled within the simulation display, as well as in text format for easy back-end analysis.

The contributions of this dissertation: advanced the state of the systems engineering practice in modeling, simulation and analysis of chemical warfare agents during simulated military operations, created a robust systems engineering framework for creating chemical warfare simulations that is modular and customizable, developed a practical software solution to fill gaps in CBRN-E M&S tool offerings, integration of newly created dynamic models compatible with CBRN-E platforms, and formulated a roadmap for the application of Live, Virtual and Constructive training and operational planning for joint warfare integrated systems assessments.

ACKNOWLEDGEMENTS

"Don't let someone else's opinion of you become your reality."

Les Brown

A snot-nosed immigrant with majestic imagination overlooked and overshadowed told time and again, "you're not supposed to be here." This was my reality. I am forever indebted to those who contributed immensely to the culmination of this body of work, and others providing support and reassurance, which helped me weather the storm.

To my mother, Peturia, for instilling values and a moral compass that has helped me become a productive member of society, and for teaching me how to use my individual gifts to further contribute to the advancement of our culture and people. For my grandmother, Hyacinth, for long standing support to her daughter, allowing her an opportunity to make better of her circumstances as a young single mother.

The ideas presented here exist as a result of the trailblazing vision and persistence of my advisor, Dr. Ron Sega. Unconditional intellectual support provided by Dr. Peter Young, Dr. Thomas Bradley, and Dr. Brad Reisfeld.

I am grateful for the support from colleagues who have helped take my vision, from its most fundamental state, into the simulation framework it is today. Specifically, Mashfique Hassan from Northrop Grumman Mission Systems who served as a catalyst for the acceptance of SE-CAS amongst practitioners. This research has also received visibility, notoriety, and acceptance from: The Military Operations Research Society (MORS), Casualty Estimation and Force Health Protection Working Group 15, and

Northrop Grumman Mission Systems. Special thanks to Dulce Castro for thoroughly reviewing this manuscript, and those listed in Appendix L for additional levels of support.

DEDICATION

This dissertation is dedicated to my mother and grandmother,
Peturia and Hyacinth.

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MOE metric used to quantify the performance of a system, product or process in terms that describe a measure to what degree the real objective is achieved.

Requirement statement that identifies a system, product or process' characteristic or constraint, which is unambiguous, can be verified, and is deemed necessary for stakeholder acceptability.

System a combination of interacting elements organized to achieve one or more stated purposes.

Stakeholder a party having a right, share or claim in a system or in its possession of characteristics that meet that party's needs and expectations.

System the evolution with time of a system-of-interest from conception Lifecycle through to retirement.

Tradeoffs decision-making actions that select from various requirements and alternative solutions on the basis of net benefit to the stakeholders.

Validation confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled.

Verification confirmation, through the provision of objective evidence, that specified requirements have been fulfilled.

AFSIM® government war-gaming simulation framework developed in C++.

BRAWLER® tactical simulator of air-to-air combat between multiple flights of aircraft in both the visual and beyond-visual-range (BVR) arenas.

SUPPRESSOR® mission-level simulation system representing some-vs-some.

JANUS® software of tactical combined arms simulation for engagement level modeling.

OneSAF® entity-level simulation that supports both Computer Generated Forces and Semi-Automated Forces applications.

SIMNET® wide area network with vehicle simulators and displays for real-time distributed combat simulation: tanks, helicopters and airplanes in a virtual battlefield.

ADST® advance technology in distributed-simulation-related to support the U.S Navy next generation of 21st century simulation systems.

CCTT® trainer that integrates all facets of combat vehicle operations to immerse warfighters in the scenarios they will face on the battlefield.

AVCATT® designed to support the full mission spectrum of attack, reconnaissance, utility and cargo helicopter operations. Affordably supports proficiency at the individual through brigade unit levels, including individual aviation company, task force or other warfighting unit, coordinated with higher-level staff training.

DMO® distributed combat training exercises, testing and experimentation. Integrates virtual and constructive simulations across various networks to support a synthetic battlespace that models weapons and Command, Control, Intelligence, Surveillance and Reconnaissance systems.

JCIDS® is the formal United States Department of Defense (DOD) process, which defines acquisition requirements and evaluation criteria for future defense programs

DOE systematic method to determine the relationship between factors affecting a process and the output of that process. This used to find cause-and-effect relationships to manage process inputs in order to optimize the output.

IMP is an event-based, top-level plan consisting of a hierarchy of program events where top-level events are decomposed into specific accomplishments and each specific accomplishment is decomposed into specific criteria.

IMS network of tasks linked from program start through program finish, reflecting the interdependencies between tasks and milestones, and is the foundation of the performance measurement baseline (PMB) used to track progress, forecasts, and changes throughout program execution.

MOPP varying levels of protective gear (level 0-4) based on employment of chemical and biological attacks. Level 0 - base gear on hand. Level 1 – chemical agent present troop don garments. Level 2 – attack preparation and recovery, garments and boot fitted. Level 3 – gas mask, hood, and boot covers in place due to high vapor release. Level 4 – all garments, gas masks and hoods, gloves, and boot covers to be worn, as a chemical or biological threat is present in the area.

Chapter 1

1. Introduction

1.1 Motivation for a Systems Engineering Casualty Analysis Simulation

Many governments recognize the industrial and economic potential of advanced chemical and biological technology as an offensive advantage to adversaries who decide to employ them. Today, at least 25 countries now possess, or are in the process of acquiring and developing capabilities to inflict mass casualties and destruction (Richardt & et al., 2014). As nations are able to export a wide array of chemical products and controlled pathogens, the inability to detect and identify chemical warfare agent (CWA) sooner, limits operational preparedness and threat response. Despite advances in medium and short range detectors and sensor technologies (DOD, 2008), threat response planning remains a key driver in areas contaminated by CWA.

In CWA threat response planning, modeling and simulation (M&S) is commonly used to assess steering strategies specific to releases of hazardous gas (Patryl & et al., 2016). This is accomplished through use of physics-based models emulating hazardous gas release. Physics-based models are physical, mathematical, or otherwise logical representation of systems, entities, phenomenon or processes— expressed as analytical models. Analytical models consist of sets of solvable equations (i.e. a system of math functions representing cause and effect). These types of models are compiled within a computing framework, to support analysis through trade studies, as part of a comprehensive approach to inform decision-makers.

Within the Department of Defense (DOD) parlance, are three distinct types of simulations or levels of simulation: *Live*, *Virtual*, and *Constructive* (LVC). *Live* simulations involve use of real systems and people in real environments “i.e.” radar prototype being tested in the field against real targets. *Virtual* simulations are simulated representations of real systems “i.e.” flight simulator emulating flight controls and flight control surfaces of a real aircraft. Last, are *Constructive* simulations, like SE-CAS, constructive simulations simulate passage of inputs for compilation within a common framework (Madachy, et al., 2017). Because maintaining the physiological and psychological health of military forces, is a basic requirement for combat effectiveness. The U.S. Army (Commander-In-Chief/Joint Requirements Oversight Council—CINC/JROC), has established objectives or priorities for use of analytical models to include (DAU, 2014):

i. Detection, collection & identification of CWA by type.
ii. Early warning of CWAs.
iii. Identification of CWAs by type out to 2 km [kilometer] day or night force-wide.
iv. Transmittal of information into a force wide warning and reporting database.
v. Identification of source information within threat environment before, during, and after CWA release.
vi. Support decision tools for effective threat response strategy.

These objectives help our Services train jointly, develop doctrines, tactics, techniques and procedures (TTPs). This supports technology assessments, system development and full-scale prototyping, and development of operational plans and strategies in varied warfighting situations. Use of analytical models, covering a broad range of military organizations, support operations, acquisition and training at each level, or hierarchy of analytical modeling.

Chapter 2

2. Objective and Research Questions

To aid in advancing the state of the systems engineering practice in modeling, simulation and analysis of chemical warfare agents during simulated military operations, this thesis demonstrates the use of a systems thinking approach to chemical warfare response planning through use of the SE-CAS capability.

The objective of the work performed in completion of the proposed dissertation is to:

Provide a robust systems engineering framework for creating chemical warfare simulations that is modular and customizable.

2.1 Research Questions 1

During weaponized release of chemical warfare agents, what steering factors will cause improved survival rates?

This thesis is devoted to use of this proposed capability to visualize areas of chemical warfare agent dispersion, symptomology and exposure effects, and prescription of optimal survival factors. Because SE-CAS is a practical software solution that integrates newly created dynamic models compatible with CBRN-E platforms, through analysis of simulation results, steering factors influencing troop survival rates can be determined.

2.2 Research Questions 2

What route provides minimal exposure during weaponized release of CWA?

SE-CAS models the prescribed Forcible Entry/Civil Support engagement scenario based on identified mission tasks in accordance with military tactics, techniques and procedures (TTPs). We demonstrate use of SE-CAS during simulated dispersion of Sulfur Mustard (HD) chemical warfare agent, with post-processing of simulation results used to determine optimal routes of travel.

These optimal routes of travel are determined to be areas of reduced exposure to HD, ensuring successful completion of mission objectives with little to no noticeable human exposure effects.

Chapter 3

3. Application of Systems Engineering (SE)

3.1 What is Systems Engineering?

Systems engineering is defined as an iterative approach by which engineers transform customer needs into a validated system solution, evolving and maturing the system to achieve a system solution that balances cost, schedule, and technical performance (INCOSE, 2015). An evolving multi-disciplinary discipline that covering technical and technical management processes across complex systems in military, industrial, commercial and civil applications, and fundamental to predictable performance on programs. Systems engineering teams focus on understanding customer mission objectives while leveraging industry standard processes and tools to reduce complex problems into manageable components, mitigate risks, and ensure a balanced and executable technical baseline that meets customer mission requirements on-cost and on-schedule.

While there are several different perspectives representing the broad application of the principles of systems engineering, to include variants offered up by professional organizations like, International Council of Systems Engineers (INCOSE), notable practitioners: Simon Ramo, George Freidman, Andrew Sage, Ben Blanchard and Wolter Fabrycky, *et al.* referenced in Table 1, when executed well, systems engineering confirms proposals are technically sound, requirements and system inter-dependencies are understood, designs are robust and producible, and the system solution can be effectively verified and validated (Kossiakoff & et al., 2011). This results in fewer problems discovered throughout the development of systems, thereby reducing cost and shortening schedules.

Table 1. Alternate Definitions of Systems Engineering (INCOSE, 2015).

Source	Definition
Simon Ramo (Jackson 2002)	A discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect.
George Freidman (Jackson 2002)	That engineering discipline governing the design, evaluation, and management of a complex set of interacting components to achieve a given purpose.
Andrew Sage (Sage 1992)	Involves the application of a general set of guidelines and methods useful for assisting clients in the resolution of issues and problems often large in scale and scope. Three fundamental steps may be distinguished (a) problem or issue formulation, (b) problem or issue analysis, (c) interpretation of analysis results.
Blanchard and Fabrycky (Blanchard and Fabrycky 1998)	The application of efforts necessary to (1) transform an operational need into a description of system performance, (2) integrate technical parameters and assure compatibility of all physical, functional and program interfaces in a manner that optimizes the total system definition and design, and (3) integrate performance, producibility, reliability, maintainability, manability, supportability and other specialties into the total engineering effort.
INCOSE (2003)	An interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.
Howard Eisner (INCOSE 2003)	An iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system.

3.1.1 What is the Value of Systems Engineering?

Over the past few decades, the complexity of systems has overwhelmed previous technical and management processes. This complexity has resulted in developmental failures, cost overruns, schedule slippage, customer dissatisfaction and environmental disasters demanding systems engineering and a multi-disciplinary approach. Because there have been multiple industry studies showing a high correlation between high quality systems engineering and program success, the value of implementing sound systems engineering continues to gain further momentum, particularly on DOD programs (Jamshidi, 2008).

Systems engineering considers both the business and technical needs of customers, then integrates all the necessary disciplines and specialty groups into a team effort to define and balance system performance, lifecycle cost, schedule, risk, and system security from concept to production, through operation, as well as across individual systems, a combination of interacting elements organized to achieve one or more stated purposes, and programs. Consideration of both business and technical needs alongside management and technical processes is formalized in the systems engineering lifecycle model. This is detailed ahead to include summary of each of the systems engineering lifecycle sub-processes, enabling processes & tools, competencies, roles, responsibilities & authority, and work products most applicable to typical DOD programs. This along with best practices, as derived and shared by practitioners, provides the basis for developing a strong and robust systems engineering culture across varying domains, customer-base and programs.

3.2 Application of Systems Engineering in the Defense Industry

The Defense industry, offers several variations of what constitutes a system. In the DOD parlance, a system is defined as an integrated composite of people, products, and processes that provide a capability to satisfy a stated need or objective. Similarly, partners like NASA and professional organizations like INCOSE offer a simplistic variant—a set of interrelated components which interact with one another in an organized fashion toward a common purpose, or according to INCOSE, any collection of objects perceived by humans to be a system. From this as described in Table 2, systems are classified as: natural, human-made, physical and conceptual, static and dynamic, or closed and open. As an example, a rock can be viewed as a natural system, consisting of crystalline structured formed of various chemical compound. Each chemical compound is formed of chemical elements. Chemical elements are composed of protons, neutrons, and electrons. Conversely, a rock could be part of a larger system i.e. riverbed, geological environment making it a sub-system (Kossiakiff & et al, 2011).

Table 2. Classification of Systems.

Type	Examples
Natural and Human-Made	Solar system, trees, dams, rocks, etc.
Conceptual	Ideas, plans, hypothesis, poems, novels, the constitution, etc.
Closed	Chemical reaction in combustion engines, power-plants, etc.
Open	Plants, teams, business organizations, etc.
Static	Bridge, highways, roads, etc.
Dynamic	Jet engine, reactor, etc.

Fundamental to systems depicted in Figure 1, are segments, elements, sub-systems, units and components, parts, attributes and relationships. *Segments* represent grouping of elements that are closely related and which often physically interfaced. It may consist of elements produced by several organizations and integrated by one.

Next, within the hierarchy, are *Element*s, or integrated set of sub-systems capable of accomplishing an operational role or function. *Sub-systems* are next in sequence, which is a level intermediate between the system (top level) and the bottom level (components), which performs separated functions. *Components* are functional units viewed as an entity for purpose of analysis, manufacturing, testing, or record keeping. Components are the parts that make up a system (INCOSE, 2015).

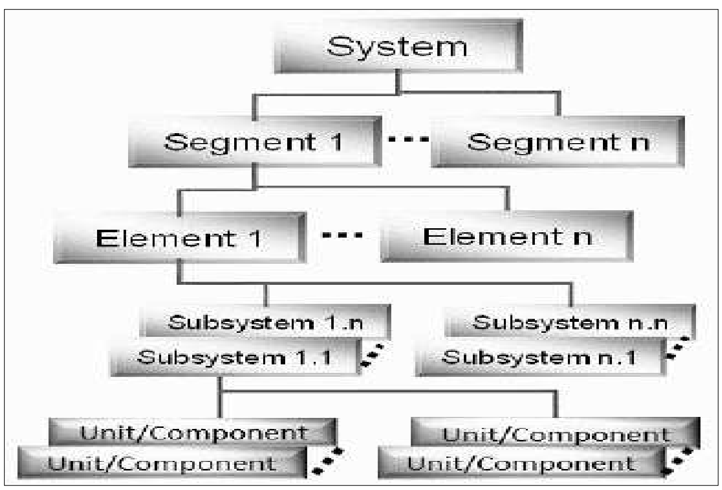


Figure 1. Systems Hierarchy. International Council of Systems Engineering (2015). *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities.*

These parts may be atoms or molecules, or larger bodies of matter like sand grains, raindrops, plants, animals, etc. Comprised of multiple piece parts or routines. These *Parts* represent the lowest level of separately identifiable items in the hierarchy of a system. Further defining systems are *Attributes*. Attributes are properties of the components that may be perceived and measured. These attributes characterize the system i.e. quantity, size, color, volume, temperature, and mass (Kossiakoff, et al., 2011). Last, are *Relationships.* Relationships are the links or associations that occur between components and attributes. These associations provide system properties beyond those of parts, and are what gives the system value. Systems are also displayed as hierarchical and are an essential element in describing a system. One of many system physical architectures, the system hierarchy has been found over the years to be the most useful view for depicting a system and integrating this view into technical and management processes described ahead (Jamshidi, 2008).

3.2.1 Systems Engineering Lifecycle Model

The systems lifecycle model is a collection of multidisciplinary activities focused on developing and sustaining a product that supports the customer's missions. Activities are coordinated through a set of well-defined processes and work products. Each process within the lifecycle transforms user needs and requirements into a verified system with identified maintenance and sustainment requirements. Along the way, the processes generate work products for stakeholders and other decisions makers. The systems engineering lifecycle is used across programs and supports program capture activities, as defined in the DOD's Business Acquisition Process (BAP).

The systems engineering lifecycle model or commonly termed ‘V-model’, shown in Figure 2, represents the technical and management processes from customer needs through definition, maturation and retirement of a system. Each box represents a phase with distinguishable inputs, outputs, constraints, enablers and controls (Jamshidi, 2008).

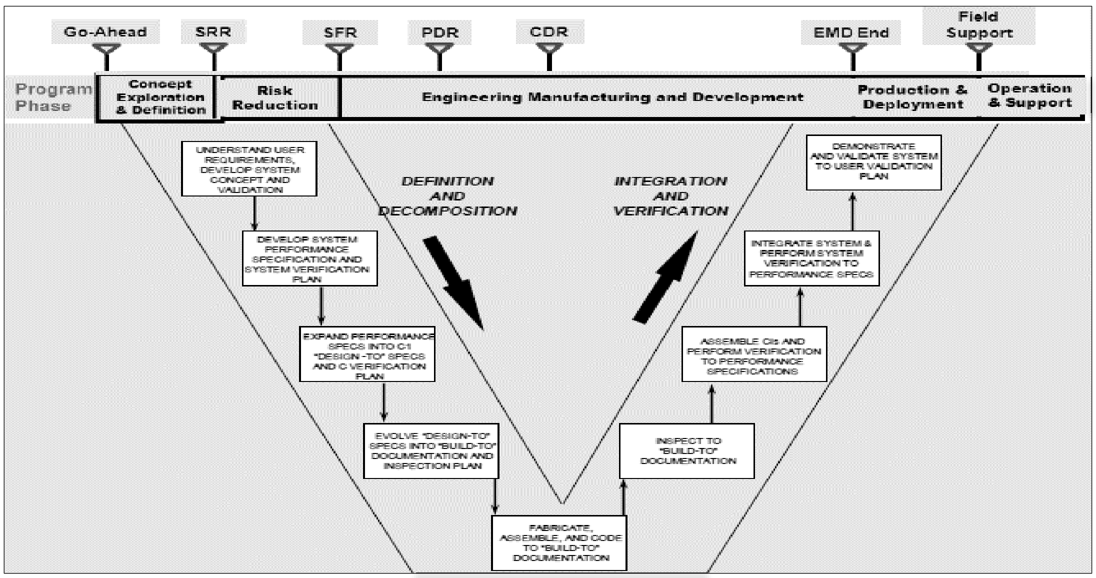


Figure 2. V-Lifecycle Model. International Council of Systems Engineering (2015). *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities.*

Processes at each phase are designed to efficiently support the activities within the phase by allowing tailoring to meet the needs of a customer while maintaining the rigor necessary to produce quality products. The V-model supports both traditional and modern model-based object oriented systems engineering methodologies, including others such as, waterfall-model or agile software development methodologies and techniques.

3.2.2 Systems Engineering Technical and Management Processes

Systems engineering processes provide an integrated lifecycle, within which the solution can be defined, built, tested, and sustained. During the development of the solution, a balance is sought between cost, risk, schedule, and technical approach (4-sides of the box). Furthermore, systems engineering ensures all requirements are well understood, the solution is robust under all required environments, and testing is effective. Foundational to the technical process, is the systems engineering approach. This, a type of problem-solving paradigm, considers attributes of the entire system to achieve the objective of the system, and allows designers to manage, encapsulate, and anticipate complex behaviors, coined '*Systems Thinking*,' is a logical extension to the application of systems engineering technical processes, applies to all types of systems already discussed (INCOSE, 2015). Fundamentals of the systems approach entail:

i. *Defining the Systems Purpose*: excavating the true problem or the need of the system. The purpose is explicitly defined and understood making it possible to establish how well the system must perform.

ii. *Identifying the Boundaries of the System Solution Space*: an essential step in the systems definition. Further delineating the system from its environment, the boundary of the solution space represents the surface across which internal-to-external interaction or system interfaces takes place.

iii. *Defining the System's Environment*: because most types of systems will in fact interact with their environment, whether natural or synthetic (in the case of constructive modeling and simulation), exchange information, energy, materials, etc. with said environments. These environments— easily physical, cultural, economic, social, and political enable interaction and is defined early in the system conception, design, synthesis and operations.

iv. *Identifying System Functions*: as the name implies, the identification of the purposeful action of the system is its function. Each function is divided into lower level functions (again, in a hierarchy view), which can be grouped or partitioned with functional interfaces communicated down to the elemental level i.e. every function has an element or elements which perform the function or functions.

v. *Identifying the Elements of the System*: the system of interest will interact with other systems to varying degrees both horizontally and vertically, akin to a system-of-systems perspective. Here, elements may be hardware, software, humans, processes, conceptual ideas or any combination for system like: development system, training system, test system, production system, operational system, etc.

vi. *Decomposition of System Elements into Smaller Elements*: as part of the hierarchical view and systems approach, this reduces complication and complexity by allowing complexity to the contained, encapsulated and concealed.

vii. *Aggregation & Partitioning of the Functions & Elements*: this introduces the concept of subordinate systems or sub-systems and is also core to the hierarchical approach of the system approach. Sub-systems form at the level of the problem being solved, of which is identified by its core functions.

viii. *Identifying the Interactions Amongst Elements*: because every system contains interacting elements, its identification becomes integral to designing in relationship or flows as the element level.

ix. *Synthesis of the System*: synthesis is the construction of the entire system and allows for choices of alternatives at each level. This is where use of modeling & simulation is key with respect to (w.r.t) system trades utilizing iterations and refinements to arrive at the most effectiveness.

x. *Proving the System*: this establishes that the system performs with optimum effectiveness in its operational environment while interacting with other systems, in short, proves that the system solves its problem. This is commonly coined Verification & Validation (V&V). Verification establishes that the system has been correctly created to meet its specification (test, analysis, etc.). Validation determines whether system meets its stakeholder need, which is ideally performed in real environment with real users and a physical instance of the system. Relative to modeling & simulation, use of a synthetic environment is appropriate to simulate the real environment.

xi. *Identifying the Emergent Characteristics of the System*: last is an approach to identify excitement features or characteristics not attributable to individual components while the system interacts in the real environment. Typically involves iterations or adjusting parts and their interactions to achieve desired emergent properties.

Up to this point, we have defined systems engineering, the purpose and value of its application on DOD programs, and identified the overall systems approach. Next, we detail each phase of the V-Lifecycle Model—working from left to right—their purpose, and key activities within each phase (Kossiakoff, et al., 2011).

The first phase of the V-Lifecycle Model begins with Mission & Requirements Definition.

3.2.2.1 Mission & Requirements Definition

The activities in the Mission & Requirements Definition phase define the goals, objectives, and requirements for the system to meet the needs of stakeholders in a defined environment. Stakeholder requirements are mapped to capabilities of the system and key performance metrics are identified. During the Mission & Requirements Definition phase, technical teams consisting primarily of systems engineers, meet with the appropriate stakeholders to understand their needs, expectations, and desires and develop a concept of operation document to communicate the stakeholder intent in a scenario-vignette style called (Mission CONOPS). These systems engineers transform user and mission operational needs or statement(s) of deficiency into system requirements and their associated verification methods. This set of requirements describes the system's interaction with the operational environment and is typically the reference against which each operational capability is validated (GUIDEX, 2006).

Systems engineers understand the objective system mission set, customers, how users interact with the system, as well as how the objective system integrates across system boundaries to meet mission objectives. They often works closely with stakeholders on needs and mission analysis to ensure that their needs and expectations are adequately captured. While system-level requirements are defined during this phase, the requirements definition activities continue at each level of the system hierarchy throughout the left side of the V-model. The Mission & Requirements Definition phase may begin long before contract award, therefore, this phase defines not only the technical aspects of the system but also allows the capture and business development teams the ability to inform the acquisition agency on the range of potential solutions. The Mission & Requirements Definition phase produces work products or artifacts depicted below. While some artifacts listed are typically provided as part of the Request for Proposal, some are not. This phase concludes with baseline set of system requirements and typically a technical gate review, such as the System Requirements Review (SRR).

Mission & Requirements Definition work products and artifacts are:

i. *Systems Engineering Management Plan (SEMP):* describes the overall systems engineering management approach.

ii. *Concept of Operations*: provides thorough graphics and/or words that depict how the system will be used to accomplish its mission.

iii. *Capability Development Document*: captures the capabilities, key performance parameters, key system attributes system, and others the system must meet upon acceptance.

iv. *Systems Requirements*: A requirement set that captures the set of desired capabilities of the system.

v. *Mission Operational Model*: a collection of artifacts, views and scenarios that provide the basis for requirements definition and functional decomposition.

vi. *Measures of Effectiveness* (MOE): specific metrics that assess the performance of the system in the context of how it is to be used.

vii. *System Level Verification Methods*: an indication of how each requirement will be verified.

3.2.2.2 Modeling, Simulation & Analysis

The purpose of the Modeling, Simulation & Analysis phase is to generate system solution alternatives (logical architectures) that frame stakeholder concerns and meet system requirements. Operational modeling transforms the stakeholder's requirement-driven view of desired capabilities into a logical architecture that is able to deliver those capabilities. Collaboration occurs with customers to ensure modeling is compatible and in alignment with customer needs, often comparing results against customer models. This phase also generates the operational context that focuses on the interactions and data flow between the system and external systems required to meet the customer requirements (GUIDEX, 2016).

During this phase, stakeholder needs and requirements are translated into many types of system requirements. Functional requirements are developed that define what activities the system must perform. Performance requirements are derived from mission requirements using modeling, simulation, and analysis. The functional and performance requirements are supplemented with design constraints i.e. size, weight, and power, and restrictions called out in the contract and specialty engineering requirements i.e. reliability, maintainability, and security (Madachy, et al., 2017). Requirements are also developed to capture how the system interacts with internal elements and external systems *i.e.*, interface requirements, including the environment in which the system will operate.

The Mission CONOPS developed in the previous phase is decomposed into mission threads and use cases. Use cases are mapped into the functional architecture using activity and sequence diagrams. M&S results are typically expressed in the form of descriptive system models i.e. SysML® diagrams and DODAF® viewpoints (Holt, et al., 2013). The architectural elements are linked with the requirements that are stored in requirements database, most notably—DOORS®. Performance modeling assists in making key decisions, such as how the system is decomposed. The architecture synthesized in this phase is not solution or technology specific and is used as an input to the next phase, Architectural Design & Synthesis. This phase concludes development of functional and logical architecture baselines, approved through the Preliminary Design Review (PDR) gate review process, shown in Figure 2.

While the Modeling, Simulation & Analysis phase ends with a logical architecture, it is important to note that modeling and analysis activities continue throughout the systems engineering lifecycle at each level of decomposition (Madachy & et al., 2017). Modeling and analysis techniques are also often used to verify requirements that are not easily verified by other methods. Modeling, Simulation & Analysis work products and artifacts are:

i. *Use Case & Activity Diagrams*: captures how the system is used and the behavior of the system.

ii. *System Trade Studies*: used to choose the best value options for the technical decisions. Trade Studies compare multiple options against weighted criteria.

iii. *Detailed and Derived Requirements*: an elaboration of the system requirements, including, but not limited to functional, performance, specialty, and interface requirements.

iv. *Specification Tree*: a diagram that shows the specifications of the system and their relationship to one another.

v. *Requirements Allocation*: maps requirements to functions and logical elements.

vi. *Key System Functions*: describes behavior of the system: data origination and its manipulation and destination.

vii. *Preliminary Interface Definition*: defines behavior and performance of interfaces to internal and external elements.

viii. *Performance Assessment*: describes preliminary assessment of performance with margins against specification and MOEs, Measures of Performance (MOPs), Key Performance Parameters (KPPs) and Technical Performance Measures (TPMs).

ix. *Preliminary Verification Plan*: identifies the approach for verifying the system, and required assets to support test.

3.2.2.3 Architectural Design & Synthesis

The Architectural Design & Synthesis phase synthesizes the system physical architecture that meets the requirements of the logical architecture developed in the prior phase. The physical architecture is elaborated from the element level to the unit/component level (putting piece parts to the design). Product line architectures are used, whenever possible, to aid in the development of the physical architecture as a technique to minimize risk and cost. The physical architecture stands as the structure for the complete set of specifications (INCOSE, 2015). The Architectural Design & Synthesis phase conducts trade studies that explore feasible approaches to mapping logical elements to specific technologies. The systems engineering team uses a variety of analytic and simulation methods to understand the implications of performance, supportability, cost, etc. of various architectures. This may require further functional analysis and a revisiting of previously conducted trade studies based on new information.

Results of trade studies become inputs to the baseline physical architecture that forms the basis for how the system will be implemented. In parallel, the system requirements are progressively decomposed from logical architecture to the physical architecture elements, subsystems, and units/components. Synthesis and Modeling, Simulation & Analysis phases are typically performed iteratively, since development of a physical architecture may require further functional analysis and a revisiting of previously conducted trade studies based on new information. The output of this phase is a system architectural design that captures both the logical and physical architecture down to the unit/component level (GUIDEX, 2006). The system architecture is typically captured in a set of architectural diagrams or views from the system model, along with documented justification for design chosen. The allocated baseline provides an implementable set of unit/component descriptions, whereas the system model provides traceability of the design to the system requirements and program plans i.e. integration, verification and validation, etc. This phase is complete with the Critical Design Review (CDR) gate review. Architectural Design & Synthesis products and artifacts are:

i. *Requirements Allocation*: elaboration of requirements to the physical design from system to the unit/component level. Each requirement accompanied by defined V&V approach at every level.

ii. *Interface Definition*: describes the behavior & details of interfaces within system and external interfaces.

iii. *Architecture Trade Studies*: used to choose the best options against weighted criteria for the system architecture.

iv. *System Architectural Design*: description of all system elements mapped to their system functions across physical units/components.

v. *Updated Verification Plans*: updates to the V&V approach for system verification, and identifies required test assets based on the physical architecture.

3.2.2.4 Development & Implementation

The Development & Implementation phase turns requirements, architecture, and design, into a system implementation. This phase begins with planning the development of the units/components identified in the allocated baseline and concludes with the verification of units/components and subsystems for delivery to the next phase, System Integration (INCOSE, 2015). Each configuration item is verified as it is integrated into the next higher-level assembly. The hardware, software, and firmware engineers perform many of the activities in this phase, using integrated product teams (IPT) with systems engineering representation.

Systems engineering activities in this phase include participating in regular IPT meetings and reviews to ensure requirements are being met and to resolve conflicts as risks are identified. Systems engineering ensures that the unit/components of the system are implemented consistently with the functional and physical architecture. Because the systems engineering team is responsible for the overall system performance, the team continually evaluates the anticipated end performance based on the development of the system components and updates margins to TPMs and associated models and simulations as needed. Systems engineers review intermediate artifacts, such as analyses and reports, and attend change control board meetings to monitor the technical baseline, including working closely with manufacturing and suppliers to address issues as they arise. Systems Engineering Development & Implementation activities may also include the initial development of end-user products, such as training materials, training systems, operational procedures, and maintenance manuals (INCOSE, 2015). The primary outputs of the Development and Implementation process are subsystems and/or elements, fabricated and coded, with the associated verification results. Development & Implementation products and artifacts are:

i. *Updated Specifications & Design Documentation*: specifications and design documentation at the subsystem level and below, updated to reflect as-built/as-tested implementation.

ii. *Interface Control Document*: describe the details of the as-built interfaces in the system.

iii. *Technical Performance*: describes the technical performance and identify the systems and subsystems performance margins.

iv. *Test Results*: results from component and subsystem level testing.

v. *Preliminary User and Maintenance Manuals*: describe how the system is to be used and maintained.

vi. *System Integration Plan*: a plan that describes how the elements of the system will come together during System Integration.

vii. *Preliminary System Verification and Validation Plan*: describe how the system requirements are going to be verified and the system validated.

3.2.2.5 System Integration

The System Integration phase is focused on the assembly of the system from the software, firmware, and hardware developed during the previous phase. System Integration is conducted using an iterative process of integrating elements, verifying them, and then integrating more elements until a completed system result is achieved. A critical aspect of this is the management and verification of interfaces as more elements are added (INCOSE, 2015). Building up a system in this manner ensures that the system is functioning and performing correctly before formal, customer-demonstration testing occurs. Throughout System Integration, defects in the requirements, design, or implementation are found. Defects are documented, adjudicated and prioritized, and then fixed as appropriate. System documentation is also updated to reflect any changes made.

In industry, DOD contractors typically possess a number of large and strategic integration facilities and assets, which allow Systems Integration to occur with lower risk and cost. As an example, this could include collections of antenna integration facilities, satellite payload integration facilities, propulsion systems integration labs, etc. These facilities allow systems engineers to test the full gamut of capabilities without waiting for approvals and certifications from agencies i.e. Federal Communications Commission (FCC). Another example are hangers with large fleets of test aircraft that can be used to resolve discrepancies only seen in flight prior to formal acceptance at customer sites. This phase typically concludes with the Test Readiness Review (TRR), where concurrence is obtained from stakeholders that the system is ready for verification. System Integration products and artifacts are:

i. *Updated Specification and ICDs*: updates to the requirements and interfaces description to represent as-built conditions.

ii. *Updated Verification and Validation Plans and Procedures*: describes how the system requirements are going to be verified and the system validated.

iii. *Updated Technical Performance*: describes the technical performance and identify the systems and subsystems performance margins.

iv. *Updated Technical Baseline*: an update to the technical baseline to reflect as-built system implementation.

3.2.2.6 Verification & Validation

The Verification & Validation phase confirms that all specified system requirements are met and the system meets the customer needs. Verification addresses the question, "*Is the system right?"* by ensuring that all system requirements are fulfilled and the system has been built to specifications. Verification also ensures that the system elements are free from defects and are acceptable for operation. Validation addresses the question, "*Is this the right system?"* by demonstrating the requirements provide the needed capabilities to the stakeholder(s) in the intended operational environment (INCOSE, 2015).

The verification strategy determines the schedule, verification methods: inspection, analysis, test, and demonstration, verification levels, and conditions of the verification activities based on many factors, including cost, schedule, and customer requirements. Requirements are verified at the lowest level possible, prior to system verification, in order to avoid re-verifying at the system level. The verification strategy also identifies the plans and procedures needed for the verification methods, as well as any necessary facilities, test equipment, simulators, and other verification resources that are required. The planning portion of the Verification & Validation phase begins earlier in the lifecycle, usually during the Mission & Requirements Definition phase. As an example, verification methods are determined as requirements are identified. Requirements are initially validated against stakeholder needs as they are written.

Often, for the validation activities of this phase, stakeholders (such as end users and benefactors) are involved and often leading the effort. Operational threads form the basis of the Validation Plan, with additional inputs from the Verification Cross Reference Matrix (VCRM), validation criteria, Mission CONOPS, analytical mission model, and stakeholder requirements. Performing validation includes developing scenarios that demonstrate performance over all operating conditions and the behavior of the system is what the stakeholders expect. IT is important to note that Validation can be run in concert with Verification, and may have overlapping methods and results.

Verification & Validation products and artifacts are:

i. *Verification Plan*: updates to the Verification Plan based on lessons learned during integration.

ii. *Verification Procedures*: final detailed description of how to run each test in the Verification Plan.

iii. *Validation Plan*: updates to the Validation Plan based on lesson learned during integration.

iv. *Validation Procedures*: final detailed description of how to run each demonstration in the Validation Plan.

v. *Systems Verification Reports/Final Acceptance Reports*: provides verification results from this phase documenting that the system meets the requirements specified.

vi. *Final System Technical Baseline Documentation*: provides the customer with the final documentation to be used for maintenance, sustainment, and future enhancements.

vii. *Verified and Validated System*: the completed system meeting stakeholder's needs, ready to be delivered to the customer.

viii. *Transition Plan*: describes the plan of the delivery and installation of the system.

ix. *Logistics and Supportability Plans*: in preparation for the next phase, describes activities necessary for sustaining the system once transitioned, including roles and responsibilities.

x. *System Certifications*: certifications required for the system to operate in its intended environment.

3.2.2.7 Operations, Maintenance & Sustainment

Of the phases described to this point within the V-Lifecycle Model, the final phase is Operations, Maintenance, & Sustainment. The Operations, Maintenance & Sustainment phase deploys the system into the operational environment, specified by stakeholders, to provide the required capabilities for the benefit of the system's users. Prior to fielding the system, a transition plan is created that includes delivery and installation planning, transition milestones and decision points, rollback strategies, transition procedure development, and transition resources. The Transition Plan is accompanied by a Logistics and Supportability Plan that includes (but is not limited to) operator and maintainer training, maintenance planning, manpower and personnel requirements for sustainment, problem identification and resolution processes, operator and maintainer security clearances or access requirements, facilities requirements, and lifecycle costs (INCOSE, 2015).

DOD contractors typically employ an extensive staff of field services support who are deployed to sites all across the world. Field Services plays a key role during this phase by supplying personnel to operate the system and monitor for problems. While in Operations, Maintenance, & Sustainment, the system is calibrated and characterized in the operational environment, may it be at sea, airborne, or in in space. Any operational problems are resolved via the logistics support or mission operations organization, including updating the system configuration documentation and documenting any actions taken. Integrated Logistics Support ensures that all maintenance, supplies, and resources are managed and available as needed while supporting mission operations. Operations, Maintenance & Sustainment provides engineering solutions to maintenance and logistics challenges, operational enhancements, and data analysis of predicted versus actual performance data.

Often, while the system is operational, the customer, users, or even field services devise novel ways to make use of the new system solution. New feature requests are returned to program management as features outside scope of the contractual terms. If approved, the system solution returns to the V-Lifecycle Model as a new iteration. The addition of features and fixes can be incorporated as Engineering Change Proposals or satisfaction of trouble tickets under what is known as a sustainment contract. Either of these alternatives generally requires various customer configuration change board approval and associated funding. Operations, Maintenance, & Sustainment end once the system is retired. This typically occurs when the cost of sustaining and upgrading the system is greater than developing a replacement or a new mission need has made the current system obsolete (obsolescence), something that is inevitable of all systems. Operations, Maintenance & Sustainment products and artifacts are:

i. *Updated Logistics and Supportability Plan*: updates made as lessons learned and system enhancements are made.
ii. *Operations Report*: system performance reports and system trouble/anomaly reports.
iii. *Updated User Manuals and Training Materials*: changes to manuals and training materials based on lessons learned and system enhancements.
iv. *Planned Product Improvement*: proposed changes to the system based on observed problems and/or technology updates.
v. *Analyses & Drawing Changes*: identifies and mitigates potential obsolescence impacts from diminishing manufacturing sources and material shortages.
vi. *System Certifications*: updates and maintenance of system certifications required operating in the intended environment.

3.2.3 SE in Modeling, Simulation, Analysis & Experimentation

Having sufficiently described use of systems engineering on DOD programs, and its application in the development of products—by way of the SE approach and V-Lifecycle Model, we turn our attention to how such methods are exclusively applied to modeling, simulation, analysis & experimentation (MSA&E) Events. As the name suggests, the MSA&E V-Lifecycle Model in Figure 3 incorporates Mission CONOPS, Mission Decomposition Functional Allocation, Functional Analysis, Design Build Simulation capability, Design Synthesis and ultimately concluding with Analysis and Demonstrations of system capabilities.

In very similar fashion, the MSA&E V-Lifecycle Model focuses on the subordinate steps or actions necessary to identify capabilities of interest, formulate analysis problem sets, determine best approaches to explore said problem sets, build the capability in meaningful ways, and demonstrate utility in representative environments—albeit synthetic, virtual or live (GUIDEX, 2006).

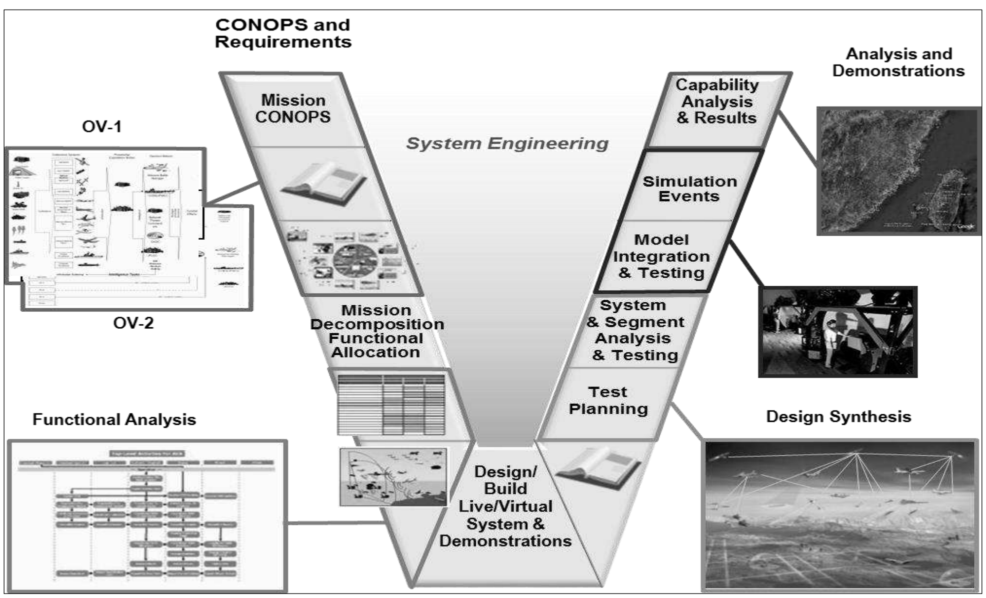


Figure 3. MSA&E V-Lifecycle Model. Guide for Understanding and Implementing Defense Experiments (GUIDEX, 2006).

In subsequent sections, we will continue to detail the relevant activities to execute MSA&E Events, in the context of the Modeling, Simulation, Analysis & Experimentation Process. First, it is important to understand the difference in levels of simulations and analytical models.

3.2.3.1 Hierarchy of Simulations

MSA&E Events are generally affinitized into one of three approaches: *Constructive* (analytic wargame) simulation, *Virtual* (hardware or human-in the-loop) simulation, and *Live* (real systems and platforms with real capabilities used in the field). Constructive simulations are those in which no human intervention occurs in the play after modelers set initial parameters and run (start) and finish the simulation compilation. Constructive simulations are a mainstay of military analytical agencies. They allow repeated replay of the same battle under identical conditions, while systematically varying parameters–the insertion of a new weapon or sensor characteristic, behavioral logic, flight profiles, kinetic or non-kinetic effects, etc. the employment of a different resource or tactic, or the encounter of a different threat. MSA&E Events using constructive simulations with multiple runs or monte-carlo methods are ideal to detect change and to isolate its cause. Because modeling complex events requires many assumptions, including those of variable human behavior, the applicability of constructive simulation results toward operational situations is restrictive and of lower-fidelity. Tools used for Constructive simulation include Analytic Framework for Simulation Integration & Modeling (AFSIM®), BRAWLER®, SUPPRESSOR®, OneSAF®, and others (GUIDEX, 2006).

To address some of the shortfalls with constructive simulations handling of operational scenarios, tools like AFSIM® have incorporated decision course of action by way of state machines and quantum processors where dynamic changes are injected based on apriori decision points, given changes in outcomes (simulation attempts to learn next course of action to take). Conversely, there is still major limitation in the inability to isolate true cause and effect given a coupling of the decision space (simulation unable to take the right course of action as the amount of possible outcomes increases)—given these real limitations, integration of different layers of simulation capability is frequently used to provide added level of fidelity across the solution space.

Next, are Virtual simulations representing a broad category of real-time simulations with which humans interact with pieces of hardware. In these types of simulation events, military subjects receive real-time inputs from the simulation, make real-time decisions, and direct simulated forces or platforms against simulated threat forces. The use of actual military operators and staffs allows this type of event to reflect warfighting decision making better than event using purely constructive simulation. However, when humans make decisions, variability increases, and changes are more difficult to detect and consequently to attribute to the cause. Virtual simulations are a type of "virtual reality," akin to flight simulators emulating inputs of flight control surfaces. Virtual simulations incorporate an important layer, distributed interactive simulation (DIS). DIS represents a type of protocol for simulations communicating with each other remotely real-time across multiple platforms and host computers. A capability that has enhanced the reach of wargame exercises across the customer space. Example tools include: Simulation Network (SIMNET®), Advance Distributed Simulation Technology (ASDT®), Close Combat Tactical Trainer (CCTT®), Aviation Combined Arms Tactical Trainer (AVCATT®), Distributive Mission Operations (DMO®), AFSIM®, and others.

Last, are Live Simulations. Live Simulation is a misnomer, there is nothing simulated here, Live Simulations are Live MSA&E Events. Live MSA&E Events encompass real systems (actual military units and equipment and with operational prototypes) with real capabilities (as a matter of safety, in few cases only weapon effects are simulated) in actual environments. The results of MSA&E Events in these environments are highly applicable to real situations, and are the closest thing to real military operations. A dominant consideration however, is the difficulty in isolating the true cause of any detected change since live events also include much of the same uncertainty, variability, and challenges of actual operations, but are seldom replicated due to costs. Live simulations involve crew in real vehicles moving on instrumented ranges. These events of simulation may all interoperate in a single exercise, or multiple exercises, simultaneously across networks. By interfacing this type of event with DIS, there is greater value placed on these types of wargame exercises, especially considering the time and money spent (GUIDEX, 2006).

3.2.3.2 Hierarchy of Analytical Models

Similar to levels of simulations, there are hierarchies to analytical models. The term model represents two distinct flavors, descriptive and analytical models. While descriptive models incorporate some mathematical relationship by way of association and higher-order functions, descriptive models are generally thought of as, non-physics-based models. Instead, descriptive models emulate physical attributes of systems that are numerically constrained or parameterized by factors like: size, weight, power, range, etc. Analytical models on the other hand, derive outputs solely based on mathematical relationships and governing physical principles—simply put, analytical models consist of several meta-models, in the case of platforms with motion or movers, representing foundational equations of motions and Newtonian dynamics, and other physical principles.

Analytical models are classified based on four groups: *Engineering, Engagement, Mission* and *Campaign*. Engineering-level models are used to measure the impact of changes in performance. An X-[lbs.] decrease in weight for System A results in a Y-[knot] increase in maximum speed and a z-nautical mile increase in maximum range for Aircraft B. Next, are *Engagement-level models.* Engagement model are used to reflect the direct outcomes of those changes: a y-[knot] increase in maximum speed results in a 0.67% increase in survivability per shot by SAM-X against Aircraft B or a Z-[nmi.] increase in maximum range results in a 150-[nmi.] increase in effective combat radius for Aircraft B in an air-to-ground configuration (GUIDEX, 2006). As represented in Figure 4, the analytical model hierarchy reflects the *Mission-level model* used to gauge the contextual effects of those outcomes. For example: a 0.67% increase in survivability for Aircraft B per shot by SAM-X results in an 0.05% decrease in Aircraft B attrition in the air-to-ground role against area targets in an integrated low-medium altitude air defense environment or a 150-nm increase in effective combat radius results in the potential utility of Aircraft B for air-to-ground missions other than Close Air Support (CAS) in a theater with an operational depth of 700-nm (DOD, 2006).

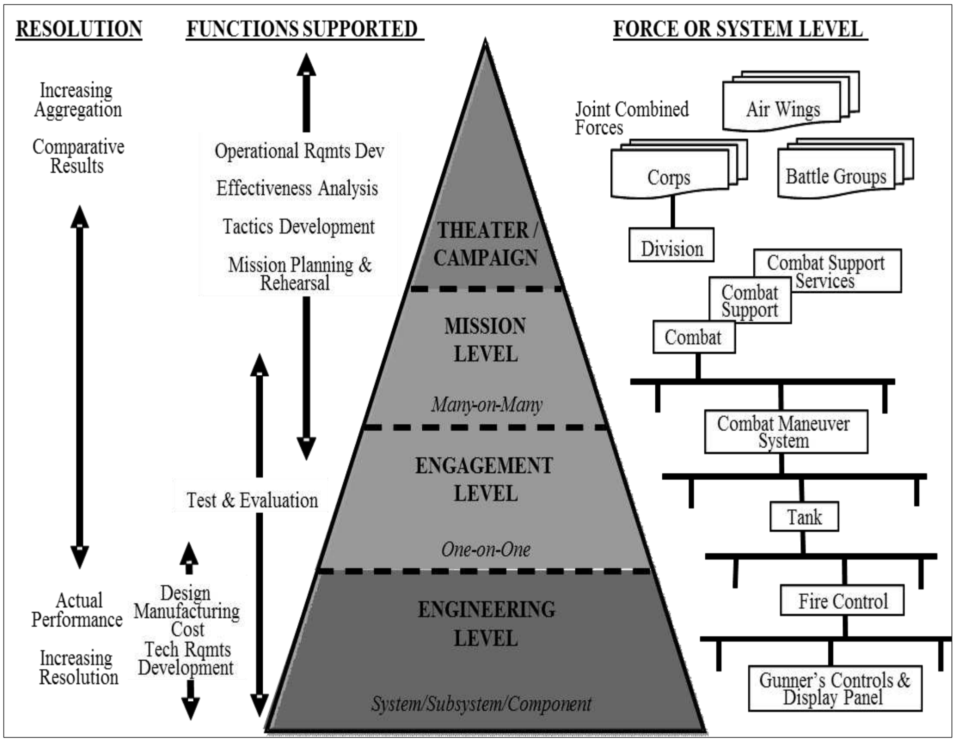


Figure 4. Analytical Model Hierarchy. Guide for Understanding and Implementing Defense Experiments (GUIDEX, 2006).

Last are *Campaign-level models.* Campaign models are used to understand the compounding impact of those effects. Over 90 days of combat, the improved survivability of a faster Aircraft B in the air-to-ground role against area targets in an integrated low-medium altitude SAM environment could result in: an increase in the number of Aircraft B available over time. A corresponding increase in percentage of total sorties flown by Aircraft B, an x% increase in targets attacked, and a y% increase in munitions expended. Over 90 days of combat, an extended-range Aircraft B for non-CAS air-to-ground missions (SEAD, strike, and interdiction) could result in: a potential decrease in the number of Aircraft B available for the CAS mission and a corresponding increase in the number of days required to reach a "Halt Phase" in ground operations a potential increase in the overall attrition of Aircraft B if non-CAS missions involve transiting a SAM environment with a higher lethality against

Aircraft B. A lower sortie rate for extended-range Aircraft B owing to deeper targets and longer missions.

Nonetheless, because decision-makers at varying levels and branches of the Defense community require fundamentally different information and insights, each type of analytical model serves its unique purpose for the Defense community. Notwithstanding the clear hierarchical relationships that exist between the levels of M&S, it is probably more accurate to think of a continuum of tools. The capabilities of a given model or simulation frequently extend beyond the boundaries usually ascribed to a type of tool and specific models and simulations within a given type may differ in what they address and how they address it. The figures below describe each of the major levels of the hierarchy and provide a sense of the potential calibrating relationship between different types of models across the continuum (GUIDEX, 2006).

3.2.3.3 Modeling, Simulation, Analysis & Experimentation Process

In the Defense domain, the Modeling, Simulation, Analysis & Experimentation Process represents use of an experiment-based approach to the solution of complex defense capability development problems across the full spectrum of conflicts. This includes warfighting, peace enforcement, and humanitarian relief and peace-keeping, of which and generally assessed across a range of analytical techniques and MSA&E Events within a vast field of simulations and models of varying scope, complexity, fidelity and accuracy. For the purpose of optimizing effectiveness of its joint force to achieve its vision of the future, use of MSA&E as an integrated approach allows the problem set to be approached in a coordinated, manageable manner with a variety of analytical techniques and allows a degree of iteration and synthesis between activities that help ensure that the overall problem set is sufficiently addressed. Because problem sets are typically ill defined, this integrated approach allows the problem set to be refined in succession or spiral. Analytically, there are multitudes of reasons to employ an integrated approach to executing MSA&E Events to include (GUIDEX, 2006):

i. *Problem Set Complexity*: military capability development problems are generally complex and coercive. The socio-technical nature of the system and the interaction between the components and the environment characterize the system as complex. The importance of an opposing force, itself a sociotechnical system, means the system is coercive. Many problem set that might be explored through constructive means, are simply too complex and required integration with combination of virtual or live simulations.

ii. *Increased Accuracy & Fidelity:* an integrated event allows a gradual buildup of the knowledge surrounding the problem set or issue under investigation, leading to a more refined and robust concept. This increases confidence that the findings are valid and creates a systematic body of knowledge to inform and investigate capability development.

iii. *Operational & Analytical Synthesis:* integrating different techniques provides improved opportunity for analytical and military skills to be applied to the problem.

iv. *Controlled Environments:* when the strategic environment is uncertain and unprecedented, and the impact of technology unknown, the experience base is usually too narrow to conduct the problem formulation confidently. Within an integrated approach, there is the opportunity to build a synthetic experience base and the process of scientific inquiry dynamically.

v. *Integration of Analytical Methods:* integration of a range of methods: observations, empirical evidence, deductive reasoning or other into a coherent package that addresses a complex capability development problem.

vi. *Iterative Methods:* effective problem formulation is fundamental to the success of any analyses, and more significant through simulation integration approaches due to ill-defined, complex and adversarial dimensions. Flexibility is key dealing with early uncertainty during problem formulation, though it slows the process of executing MSA&E Events, the flexibility to balance the physical and psychological aspects of the problem set by using warfighters as the players while adjudicating their actions using models or rule sets, allows the right inferences to be drawn backed by an overall in techniques to perform required analyses. It is only when all activities are brought together in a coherent manner and the insights synthesized, that the overall problem under investigation is advanced as a whole.

While these represents some of the motivating factors to employing an integrated MSA&E approach for complicated and complex military scenarios, what are practical steps to execute on such efforts? The following sections will detail each phase of the MSAE&E Process and corroborating activities to drive execution.

3.2.3.3.1 MSA&E Process: Phase 0 – Capability Identification

Phase 0, Capability Identification is the starting point of the MSA&E Process. Here, the focus is to identify and prioritize the DOD customer's efforts, insights &

capabilities by initiating and maintaining customer relationships through engagement. One of the most important first steps, as it provides a list of capabilities deemed strategically appropriate and pursuable. Capability Identification helps prioritize capability needs with greater strategic or economic value, opposed to those to revisit downstream. Phase 0, *Capability Identification* in Figure 5 tasks include:

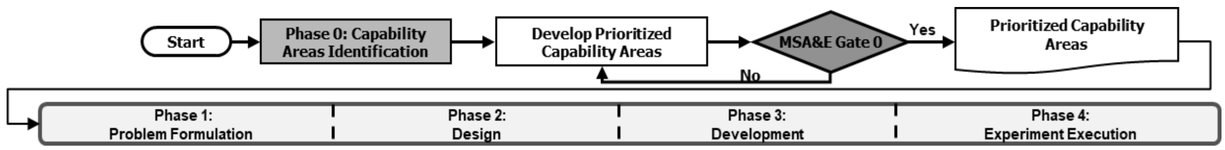


Figure 5. MSA&E Process: Phase 0, Capability Identification. Guide for Understanding and Implementing Defense Experiments (GUIDEX, 2006).

i. Identification and Prioritization of List of Capability Needs (several source of reference: JCIDS, DOD Quadrennial Reports, Strategy Assessments, lesson learned from prior engagements, etc.).
ii. Identification of customer needs, gaps, questions, interest, and capability development.
iii. Identification of Internal and External Customer contacts.
iv. Identification of general time frame related to need dates.
v. Development of study mission statement and top-level study proposal (planned study benefit).

3.2.3.3.2 MSA&E Process: Phase 1 – Problem Formulation

Phase 1, Problem Formulation begins the individual study process based on defined capability areas from the prior phase. As the study team is formalized, M&S objectives are determined, which are clearly defined goals of what is to be accomplished, high-level concepts and action plans: analysis, project, master schedules, and other artifacts. Phase 1, *Problem Formulation* in Figure 6 tasks include:

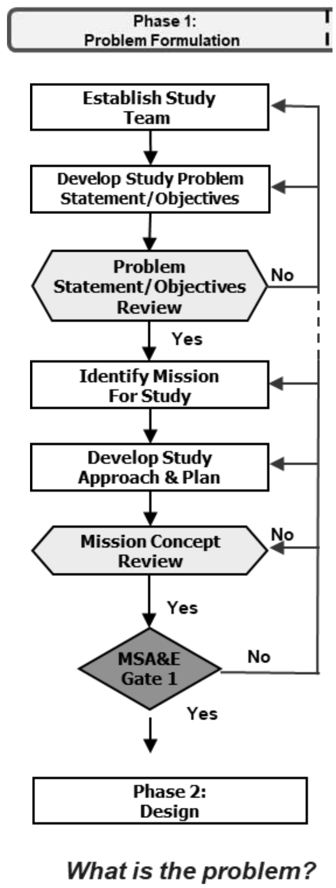


Figure 6. MSA&E Process: Phase 1, Problem Formulation. Guide for Understanding and Implementing Defense Experiments (GUIDEX, 2006).

i. Identification of M&S study teams with specific domain knowledge and skills relevant to Mission CONOPS subject area.

ii. Development of study problem statements & objectives. This represents proposed problem statements for evaluation as to which will be addressed in study outcomes.

iii. Decomposition of assigned Capability Area into specific problem statement(s). Some levels of iteration occur to explore and narrow Study domain (Capability

Area). Working with domain IPTs, this includes specific hypothesis to be analyzed.

iv. Identification of high-level desired MOE, which are ideal measure of high level benefits or effects- with respect to study objectives.

v. Consensus on content and maturity of problem statement(s) and study objectives.

vi. Identification of study mission(s), statements, tasks, and opportunities in relationship to the study and capability domain. This includes determining how key questions in the problem statement are related to the mission are to be obtained from the study.

vii. Selection of other measures: MOP, TPM, KPP with respect to the operational mission(s) portrayed in the scenario/vignette(s).

viii. Development of study approach & plan. An important step here is determining what specific aspect of the overarching study is better handled at the constructive, virtual or live levels, or both.

ix. Definition of analysis and study tool set as enabler to support MSA&E Event execution.

x. Definition of ground rules and core assumptions or constraints governing the study from inception through execution.

xi. Identification of hardware, software, infrastructure, networks, visualization, engagement technologies as enablers to execution of study objectives.

xii. Development of detailed study plans, schedule including systems engineering plans, analysis, Mission CONOPS, customer engagement, security, planning tasks, etc.

xiii. Completion of gate review consistent with approval authority from domain IPT, customer personnel representing development of all artifacts signoff for the next phase, design.

3.2.3.3.3 MSA&E Process: Phase 2 – Design

Phase 2, Design primarily encompasses completion of constructive M&S activities, including planning to execute other levels i.e. virtual simulation of the MSA&E Event. This requires mapping key functions of various models (motivated by customer Mission CONOPS) that will be represented in hardware and software systems. The Design phase triggers creation of key DODAF® operational and system views along with updated master plans i.e. resource, schedule, analysis, experimentation, etc. Phase 2 provides the foundation to develop required capabilities for operator-in-the-loop (OITL) / hardware-in-the-loop (HWIL) virtual simulation supported by predictive M&S outputs—per preliminary constructive analysis results—that informs the initial capability space relative to performance. Phase 2, *Design* in Figure 7 tasks include:

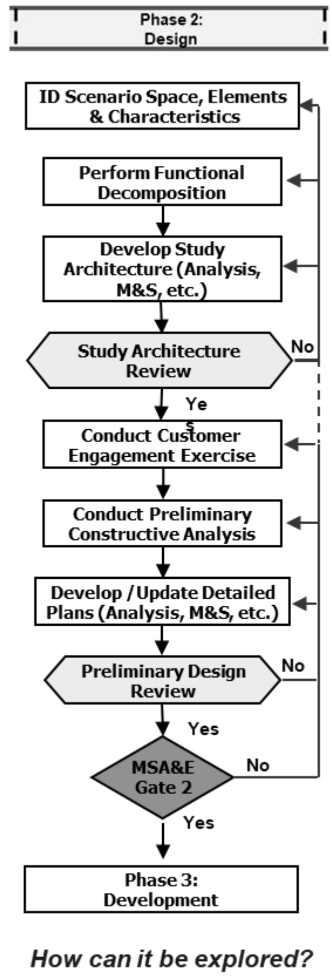


Figure 7. MSA&E Process: Phase 2, Design. Guide for Understanding and Implementing Defense Experiments (GUIDEX, 2006).

i. Identification and description of scenario features and elements, events / vignettes within scenario.

ii. Definition of solution to support analysis and study plan scenario features & elements include: systems, geography, weather, threats, rules of engagement, and other input or control variables, include characteristics of each element.

iii. Development of architecture including possible interactions between elements and the needs associated with those interactions.

iv. Development of operational views: (OV) 1 high level overview graphic including key players (OV4), roles, and OV 2, 3 communications.

v. Development of initial system view (SV) 1, 2 systems description / interface documentation as required.

vi. Development and documentation of concept of employment (CONEMP) relating to the problem statement and scenario space.

vii. Translation of MSA&E Event operational vignettes into DODAF artifacts.

viii. Completion of functional decomposition and allocation of operational tasks to systems / resources, documentation of timing and synchronization of tasks and information flow.

ix. Definition of constructive and virtual analysis trades based on capability needs, mission scenarios, CONEMPs, and design capability attributes like: operational architectures, employment variations, rules of engagement, threat courses of action, system allocation choices, system performance definitions, affordability.

x. Definition of analysis for preliminary constructive and virtual trades. Identification of MOE, MOP, and development of data collection plan: data generation, collection, transformations, storage, including schedule and costs.

xi. Development of requirements for M&S development for Analysis tools, data collection, data analysis, and OITL simulations.

xii. Define primary evaluation criteria for trades and design concepts, existing models and tools.

xiii. Compile customer engagements events to understand customer questions and to listen to customer needs and feedback: overview of the Event, objectives, questions being addressed, scope, assumptions, mission, scenario / vignettes, Mission CONOPS, Analyses and measures.

xiv. Development of test matrix based on design of experiments (DOE) methodology.

xv. Conduct preliminary constructive Analysis sanity checks.

xvi. Development & integration of analysis tools, and execution of constructive analysis and analyze results.

xvii. Execution of analysis tool development & integration. Develop & integrate Analysis tool development capabilities.

xviii. Collection of data from each case and perform data analysis of preliminary constructive analysis results to determine if there are useful solution sets to identify virtual test conditions and focus areas, if appropriate.

xix. Updated MSA&E Event plans based on updated information and preliminary constructive analysis results from Phase 2 steps. This includes preliminary constructive analysis, virtual analysis, and overall Event plans.

xx. Update based on updated information & preliminary constructive analysis results from Phase 2 step: IMP/IMS in addition to relevant info from phase 1 such as: Team / Supporting Personnel, High Level Plan / IMS.

xxi. Completion of gate review consistent with approval authority from domain IPT, customer personnel representing development of all artifacts signoff for the next phase, development.

3.2.3.3.4 MSA&E Process: Phase 3 – Development

Phase 3, Development synthesizes prior plans, architecture, preliminary constructive analysis results, and approach to drive development of proposed capability in the relevant environment. Moving toward capability maturation introduces combined efforts of M&S competencies and SCRUM software development approach, particularly with the integration of hardware and software components. Phase 3 culminates with development of virtual simulation capability and supporting analysis—informed by final constructive analysis runs and results.

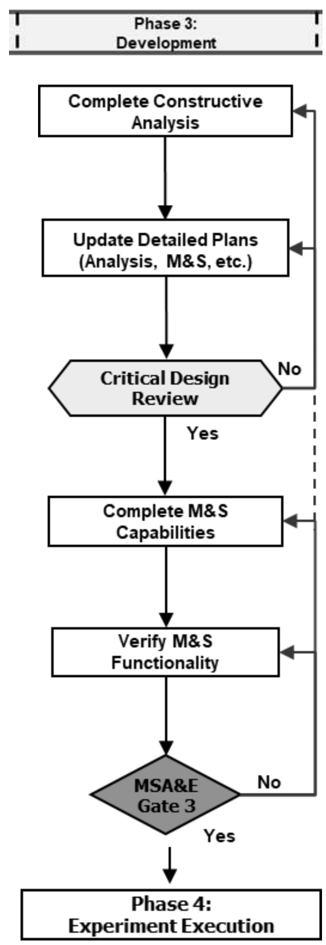


Figure 8. MSA&E Process: Phase 3, Development. Guide for Understanding and Implementing Defense Experiments (GUIDEX, 2006).

Phase 3, *Development* in Figure 8 tasks include:

i. Completion of development & integration analysis tools and constructive analysis results.

ii. Collection data needed to model and/or run tools

iii. Conduct final constructive analysis runs (trials) based on DOE test matrix.

iv. Complete analysis of results of final constructive analysis runs to determine if there are useful solution sets to identify Virtual assessment test conditions and focus areas, if appropriate.

v. Refine virtual analysis plan. Develop virtual analysis plan including data collection (generation, collection, transformations, and storage), analysis tool development, M&S development and V&V, data analysis methodologies.

vi. Update of MSA&E Event planning, integrate and de-conflict proposed schedules and cost estimates from M&A experimentation, and analysis details.

vii. Completion of development of models and simulation to support virtual simulation, execution of integration and tests for the virtual M&S environment.

viii. Completion of integration of models and simulation to support virtual simulation.

ix. Updated test models and simulation to support and verify M&S functionality based on virtual analysis plan, M&S plan including requirements and V&V criteria test / conduct V&V on models and simulation.

x. Completion of documentation of modifications needed to meet M&S requirements based on V&V needs, and modification to the M&S environment to meet V&V criteria. Preparation of briefing content based on final constructive analysis results.

xi. Completion of gate review consistent with approval authority from domain IPT, customer personnel representing development of all artifacts signoff for the next phase, execution.

3.2.3.3.5 MSA&E Process: Phase 4 – Experiment Execution

Phase 4, Experiment Execution represents culmination of all study activities, modeling and simulation of capability, integration of hardware and software components, and pertinent support tolls. This phase “brings it all together” in the execution of the customer demonstration exercise to include execution of virtual OITL experimentation with external customers. Equally important is the MSA&E Event study briefing, which is development of packaged final analysis, both constructive and virtual OITL results and recommended path forward.

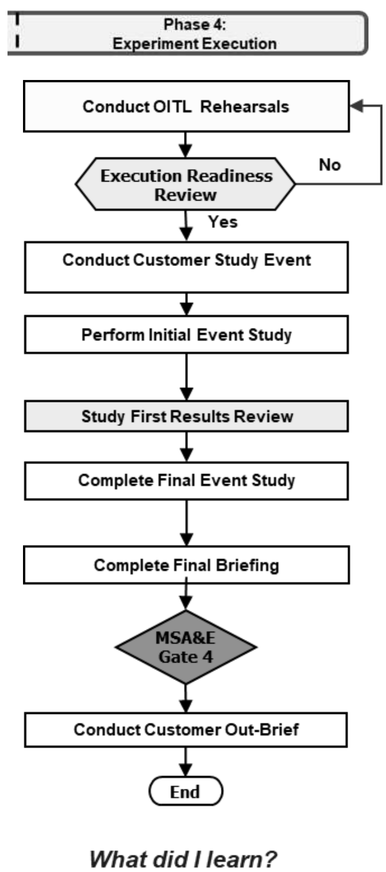


Figure 9. MSA&E Process: Phase 4, Experiment Execution. Guide for Understanding and Implementing Defense Experiments (GUIDEX, 2006).

Phase 4, *Experiment Execution* in Figure 9 tasks include:

i. Preparation for rehearsal activities including: generation of training material M&S planning documentation, post-execution analysis planning, operator training material and full event schedule, and updated customer engagement planning.
ii. Execution of training guidance relative to participants and their roles.
iii. Execution of virtual simulation OITL runs and trades, and interim analysis task of the virtual simulation plan including capturing/documenting results.
iv. Collection of data from each run and task to perform analysis, quantify analysis metrics based on results of the virtual simulation, observations, and customer feedback.
v. Analysis of post execution analysis results including lessons learned.
vi. Completion of in depth data analysis of data, observations, and feedback to produce results of MSA&E Events.
vii. Completion of customer review of findings to gain consensus on recommended path forward—agreement is reached with stakeholders on how to proceed given insights.
viii. Completion of final report for internal audience and for customer external audience. Develop summary briefing of results and summary analysis of overall results across virtual simulation tasks and documentation.

Having highlighted the process steps to move a capability through design, development and demonstration in the synthetic environments, including execution of constructive and virtual analysis trades to assess performance outcomes, there are similar approaches to determine an MSA&E Event's validity. Subsequent sections will detail requirements for quality MSA&E Event execution, along with types of measures and measurement factors for sound experiment execution.

3.2.3.4 Requirements of MSA&E Experiment Execution

So far, we have discussed the value of conducting MSA&E Events by way of experiment execution. MSA&E Events provide improved capabilities development and drive future warfighting effectiveness. Use of experimentation as a unique scientific method to establish the cause-and-effect relationship of hypothesized capabilities. Experiments are designed with fourteen [14] principles to ensure meeting experiment validity requirements. This, a microcosm of the larger MSA&E Process, represents the "develop–experiment–refine" approach to ensure that a rigorous methodology relates new capabilities to warfighting effectiveness. Fourteen [14] governing principles for successful MSA&E experiment execution are (GUIDEX, 2006):

i. *Principle 1*: experiments are uniquely suited to investigate the cause-and-effect relationships underlying capability development.
ii. *Principle 2*: effective experiments requires an understanding of the logic of experimentation.
iii. *Principle 3*: experiments should be designed to meet validity requirements.
iv. *Principle 4*: experiments should be integrated into a coherent campaign (multi-level integrated experiments) of activities to maximize their utility.
v. *Principle 5*: an iterative process of problem formulation, analysis and experimentation is critical to accumulate knowledge and validity within a campaign.

vi. *Principle 6:* campaigns should be designed to integrate all three scientific methods of knowledge generation (studies, observations and experiments).

vii. *Principle 7:* multiple methods are necessary within a campaign in order to accumulate validity.

viii. *Principle 8*: human variability in experimentation requires additional experiment design considerations.

ix. *Principle 9:* defense experiments conducted during collective training and operational test and evaluation require additional experiment design considerations.

x. *Principle 10:* appropriate exploitation of modeling and simulation is critical to successful experimentation.

xi. *Principle 11:* an effective experimentation control regime is essential to successful experimentation.

xii. *Principle 12:* a successful experiment depends upon a comprehensive data analysis and collection plan.

xiii. *Principle 13:* defense experiment design must consider relevant ethical, environmental, political, multinational, and security issues.

xiv. *Principle 14*: frequent communication with stakeholders is critical to successful experimentation.

While many of these principles are developed into the MSA&E process already discussed, one of the first requirements to valid MSA&E experiment execution is, the *Cause-and-Effect Relationship*.

3.2.3.4.1 Cause-and-Effect Relationship in Experiment Execution

The relationship of cause-and-effect, also known as hypothesis in the mathematical parlance, is to understand cause-and-effect relationships between capabilities and increased warfighting effectiveness. Presented in the form: Does Effect-A causes Result-B? An experimental capability or concept is examined in experimentation to determine if the proposed capability A causes the anticipated military effect B. It is an “If...then...” statement, with the proposed cause–innovative concept–identified by the-if clause, and the possible outcome–the problem resolution–identified by the then clause. Whether large, small, or multi-level integrated experimentation, field, laboratory, military or academic in nature, requires use of the cause-and-effect relationships. This is described by five [5] components of hypothesis:

i. The *treatment*, the possible cause A, is a capability or condition that may influence warfighting effectiveness.
ii. The *effect* B of the treatment is the result of the trial, an increase or decrease in some measure of warfighting effectiveness.
iii. The *experimental unit* 4 executes the possible cause and produces an effect.
iv. The *trial* is one observation of the *experimental unit* under treatment A or under the alternative ~A to see if effect B occurred, and includes all of the contextual conditions of the experiment.
v. The *analysis* phase of the experiment compares the results of one trial to those of another.

These five components are useful in understanding experiments. In cases where experiments are decomposed into several lower-level experiments, to be experimentally valid or useful, individual vignette experiments are configured as mini-experiments with its own subset of the five components already mentioned. Each initiative is a particular treatment with its own experimental unit, its own set of outcome measures, and its own set of trial conditions.

3.2.3.4.2 Validity in MSA&E Experiment Execution

Determining an experiment's validity typically draws more questions than answers. For many years, as computing capability increased, there is a general belief that greater fidelity, or accuracy, was always better. Many took the term "validity" to be synonymous with fidelity and detail. However, the modern view of validity is, "just enough." Because the central purpose of modeling and simulation is to rationalize the complexity of the real world by simplifying it, the experiment design should effectively define what levels of fidelity is not only adequate, but appropriate (GUIDEEX, 2006). Use of simple models that provide useful insights are often preferred. As such, sound experimentation should leverage analytical models that are simple as possible while remaining adequate for the task in hand (GUIDEX, 2006).

Experiments are required to support future capability development and the prototyping process advancing through early technology readiness levels. Not only are experiments used to examine capability redundancies and tradeoffs, reveal capability gaps, investigate the robustness of proposed solutions developed during refinement for possible future military operations, but also provide empirical refinement that substantiates and quantifies the extent proposed capabilities increases military effectiveness in specific scenarios. Achieving this, requires steps to achieve a valid experiment, and as such, experiments must satisfy the following requirements:

i. *Make use of new Capability*: bringing about new capabilities introduces a host of issues as complexity increases. Generally, hardware and software components and services coming together perfectly, including levels of responsiveness to operator inputs tend to not be fully realized when new capabilities are brought together in experiments. Because of this, the ability to realize the capability sought, as attributed to systems performing as intended, is first sign of a valid experiment.

ii. *Detect change in the Effect:* when the player unit correctly employs a new capability, does it result in any noticeable difference in the effect B during the experiment trial? This brings into question principles of reproducibility and repeatability. Experimental errors produce too much variability. Reduction of experiment variations, through data collection calibration, limited stimuli presentations, and a controlled external environment, mitigates experiment-induced error. In addition, since the computation of variability in statistics decreases as the number of repetitions increases, a larger sample size increases the validity of results. Analysts measure change in effectiveness by comparing the results of one experiment trial to those of another. Typically, different experiment trials represent different levels of applications of the same capability, alternative competing capabilities, or the same capability under different conditions.

iii. *Isolate reasons for change in the Effect:* as a noticeable effect is revealed from employment of the intended cause isolation of the true cause is at time difficult to reveal. In experimentation, outcomes with alternative explanations are eliminated using various techniques: counterbalancing the presentation of stimuli to the experimental unit, the use of placebos, the use of a control group, and random assignment of participants to treatment groups, and elimination or control of external influences. Either way, a valid experiment establishes clear distinguishable lines of rationale and explanation.

iv. *Relate results to Operations:* valid experiments offer the ability to generalize results beyond the experiment context providing experiment realism and robustness, in response to the effect *B* noticed by exciting the cause *A*. Experiment realism revolves around the representation of surrogate systems, the use of operational forces as the experimental unit, and the use of operational scenarios with a realistic reactive threat. Ensuring operational robustness, the experiment should examine multiple levels of threat capabilities under various operational conditions.

3.2.4 Data Collection & Analysis

Data analysis and collection is an essential part of an experiment. Data collection is designed to support the experiment analysis objectives that in turn rely on the underlying model in the experiment. Data analysis offers the opportunity to revisit this model to determine its cause-and-effect relationships. Interpreting this information into findings and combining them with already known information to obtain new insights tends to be challenging. Once it is determined what needs to be measured, a decision is required to identify the data necessary and to analyze it using appropriate statistical analysis techniques. This ensures appropriate and valid data are generated and that the key issues of the experiment are addressed. Determining the right analytical techniques to use depends on the expected variability amongst dependent variables (parameters or values traded against), and number of observations. Equally important, is sufficient observations for all objectives, MOP and MOE requiring analysis.

There are several collection methods explored in MSA&E i.e. surveys and observations. Surveys and observations are used in data collection because of the ability to gather numerous amounts of information quickly. Data gathered typically relates to topics surrounding systems and processes tested, view on teams or forces participating, strengths and weaknesses of the systems and processes, as well as recommended improvements (GUIDEX, 2006). There is also methods of data synchronization, during observations form disparate sources. Here, observers are utilized to provide a chronological narrative of the events that occurred during the experiment exercise. This provides documentation about what happened during the experiment and can be used to corroborate reasons for certain results occurring during the experiment.

3.2.4.1 Metrics: Hard versus Soft: Answers versus Insights

Another area of consideration is use of metrics. Metrics are presented in two forms—hard metrics versus soft metrics. Measures of merit become more subjective as the scope and scale of a model increases, irrespective of level of modeling or level of simulation. These measures typically reflect the focus of the end-user. Engineering-level through Mission-level models denominates their output in scientifically quantifiable units i.e. [nmi] nautical miles, [lbs.] U.S pounds, etc. Conversely, Campaign-level models try to make decisions with implications for large-scale force applications across a range of scenarios. As a result, Campaign-level models ultimately measure outcomes in soft subjective terms, typically warfighting contexts such as “days to achieve air superiority” or “territory lost” prior to halting enemy advance (GUIDEX, 2006).

Predictive utility diminishes dramatically with increases in the number of implicit and explicit interactions reflecting both physical processes and human behavior. Engineering-level models employ quantitative data and are the most predictive. Values derived from physical properties and phenomena populate algorithms that express actual processes, resulting in change in an input value directly traced to a corresponding change in output value. This provides an ‘answer’ to a given question—a node with ‘X’ radar resource manager can handle no more than ‘Y’ packets before platforms being tracked are lost.

In contrasts, similar to cases above, Campaign-level models must contend with the compounding effects of increasing levels of abstraction i.e. aggregation vice single items, collective ideas vice individual performance, unaddressed and unknowable effects i.e. morale, fatigue, confusion, and accumulation of complex interactions following from seemingly simple actions i.e. implications of prosecuting a two-ship strike mission that requires in-flight processing of near real-time intelligence updates to acquire targets in attenuating environments (foggy, mountainous terrain, etc.) within an integrated air defense environment.

Given these considerations, results of Campaign-level models should be viewed as insights, and less as answers (GUIDEX, 2006). Insights, or learning attributed to events without clear cause and effects. Providing the necessary context, having detailed the application of systems engineering in modeling, simulation, analysis &

experimentation, the remaining sections shifts focus on the central theme of this dissertation.

Here, we begin exploration on the development of a simulation capability to support engineering trades exploring effects surrounding weaponized release of chemical warfare agents.

Chapter 4

4. Chemical Warfare: Weapons of Mass Destruction

Chemical weapons of mass destruction (WMD) have long been the centerpiece of U.S policy because of the potential for millions of casualties in the American homeland (Prockop, 2006). Dating back to World War I, at the start of the 20th century, the first large-scale employment of WMDs was in the form of a chemical weapon attack using chlorine gas in 1915 (Fitzgerald & et al., 2008). Here, members of the German Army filled 6000 steel cylinders with pressurized liquid chlorine 3 weeks prior. Upon confirmation that the area's prevailing wind patterns were optimal, soldiers opened the valves along their defensive perimeter, and within minutes roughly 160 tons of chlorine gas drifted over the opposing French troops, engulfing those downwind who were totally unprepared for this new type of weapon. The surprise use of chlorine gas allowed Germans to rupture the French line along a 3.5 mile front, causing terror and forcing a panicked and chaotic retreat. This slow moving wall of gas killed more than 1,000 French and Algerian soldiers, while wounding approximately 4,000 (Fitzgerald & et al., 2008). This marked a turning point in military warfare, as the first successful use of lethal chemical weapons on the battlefield.

Germany spearheaded the early development, production, and deployment of war gases. Use of chlorine, phosgene, and mustard created new and complex methods of enacting military intent. Overall, the deployment of chemical weapons was met with mixed results as the tactics, techniques and strategy, and military culture of membered forces struggled to adjust to this new weapon (O'Keefe, 2006). The ability to woundopposed-to-kill presented tactical advantages. Given the chemical agent in use, respiratory damages were most likely to occur, especially with chlorine and phosgene. Both chlorine and phosgene require extended periods of recuperation. Then, average number of days the typical gas victim spent recovering was on the order of 60 days for chlorine, and 45.5 days for phosgene (Fitzgerald & et al., 2008). The physical and psychological damage, and sheer exposure to large numbers of soldiers and civilians would result in over 1.3 million casualties and approximately 90,000 deaths by the time of cease-fire amongst nations. Germany continued efforts to remain technologically ad politically relevant, would lead to advances in the use of weaponized chemical munitions development with vastly more powerful chemical agents—mustard gas which was responsible for roughly 80% of gas-related deaths. Nations with competing interests, like the United States, would also look to make inroads, buttress by academic and industrial research increasingly servicing military needs. Germany on the other hand continued to widen the scale and scope of chemical weapons production. Private enterprise, universities, and government laboratories from warring nations labored at great cost to produce like-solution not only for traditional war materiel, but also for the new generation of weapons and munitions. Germany, then the world's leading chemical weapons manufacturer, would go on to produce more than 33 million pounds of gas shells by early 1920s. With Germany head-and-shoulders above others in production, it was not until the much later could scientists, engineers, and physicians predictably and consistently produce chemical weapons to inflict mass casualties. The French, British, and U.S. all made marginal gains in chemical weapons development using a variety of techniques of similar chemical constituents—most notably 72,904 shells in totality of phosgene across all three nations. With technological development of chemical WMDs continued on, several nations rejected chemical WMDs use through legislative protocols, while others focused on development of gas mask technologies and evolution of gas defense. This would lead to chemical weapon response planning to include, donning and tactical procedures, order of battle and development of military doctrine that later inform U.S nations alike dealing with challenges in the latter part of the 20thcentury (Fitzgerald & et al., 2008).

Moving beyond the Cold War to the modern era, the threat of chemical, warfare had come to the forefront for U.S military troops during preparation for the Persian Gulf War Operation Desert Storm in the early 1990s. Iraq was known to have a large stockpile of chemical weapons and had demonstrated during its conflict with Iran, that it would employ them at will. During that time, as disagreements intensified, nearly 100 Iranian soldiers with were found to have suffered from chemical wounds consistent with mustard gas release (Fitzgerald & et al., 2008). The public outcry to the continued use of these weapons was less than overwhelming, with Iraq continuing to employ this method. Leading up to the Persian Gulf War, several nations, like Libya developed over 30 tons of mustard laced chemical weapons, under the guise of fulfilling a pharmaceutical need. Similarly, the Soviet Union expanded to incorporate WMDs bringing airborne anthrax spores to the fray. In 1994, tyrannical attacks in Matsumoto, Japan introduced agents like sarin, which produced more than 200 casualties including 7 fatalities. In a second incident in a Tokyo subway system in March of 1995, 510 people were taken to medical facilities or sought medical assistance with 12 succumbing to their injuries. More of a concern at its organization is lack of sufficient training and understanding in the handling of casualties and general function within contaminated environments. Chemical and biological weapons combine maximum destructiveness and easy availability—with a study by the Office of Technology Assessment (OTA) concluding that an airplane delivering 100 [kg] of anthrax spores by aerosol on a clear, calm night over the Washington, D.C., area could kill between one million and three million people from toxins causing hemorrhaging in the body, managing the challenges comes with development of passive countermeasures for chemical and biological defense (pretreatments, therapies, timely detectors, effective protective equipment) and deployment of appropriate response strategies concerning military and civil defense (Francis & et al, 1918).

4.1 Chemical Weapons: Technology in the Modern Era

The employment of poisonous gases as a means of offensive warfare has made it imperative that troops have some knowledge of the action of the various gases that are likely to be met with and of rational lines of response and treatment. In the case of a chemical attack, developments within recent decades have shown that the immediate and reliable detection, identification, and monitoring of CWAs and its effects are increasingly a key technology in overall CBRN-E risk management (Wrigley & et al., 2004). State of the art technology has enabled advancements in some of the following areas:

i. *Source Information Sharing:* sensor information from multiple biosensor reading passed as inputs over time intermittently.
ii. *Threat Event Mapping:* biosensor track management enables threat visualization across given region.

iii. *Adaptable, Flexible Architecture:* model learning to direct focused sensor deployment based on changing vulnerabilities, and adaptable with various platforms for deployment i.e. land, sea, air ports, FOB, etc. (modularity).

iv. *Quick Turn Analysis*: real-time analysis given biosensor inputs of threat location and movement. This can include ambient conditions integrated into the casualty estimation processes.

v. *CBRN-E Casualty Estimation:* health monitoring and forecasting given threat event mapping processes.

vi. *Sensor-Agnostic Architecture*: adaptability and modularity across distributed (DIS) environments.

vii. *Operational Response Planning:* plan based on force on force assessment over large time/space.

viii. *Tactical Response Planning*: plan based on model versus model assessment over local time/space.

ix. *Predictive Modeling & Simulation Tools*: constructive simulations, engineering-level, engagement and mission modes providing monte-carlo style simulation capabilities across: sensor inputs, agent exposure, concentration, attenuation and environmental considerations, and other parameterized factors for the purpose of improving threat responsive strategy and avoidance effectiveness. Common tools include:

    a. *GASTAR® & ADMS®*, developed by Cambridge Environmental Research Consultants, is a dense gas dispersion model incorporating semi-empirical relations amongst clouds, wind pattern, obstacles, etc. in the modeling of accidents and emergency response scenarios.

b. *HEGA®/DEGADIS®*, widely used amongst government agencies, simulates aerosol jet release based on CWA plume-density inputs and evaporation rates.

c. *INPUFF®*, Environmental Protection Agency (EPA) developed based on the Gaussian puff diffusion model for dispersion downwind of the source.

d. *GPM,* the Gaussian CWA plume model, forms the basis of most regulatory EPA models. *AERMOD®*, *AERMET®*, *PRIME®*, *CALINE®*, *ALOHA®*, are several variants providing turbulent parameterization for handling flow with consideration to fluid flow in congested areas.

e. *HPAC®,* forward deployable and reach back model capability under auspices of the Defense Threat Reduction agency (DTRA), with similar hazard effects prediction capability

f. *JBREWS®,* Joint Biological Remote Early Warning System is comprised of an integrated suite of sensors consisting of a Short Range, Biological Standoff Detection System (SR-BSDS*®*) and a Deployable Unit Biological Detection System (DUBDS*®*) made up of Sample Identification Units (SIUs), the Sensor Network Command Post (SNCP), and the associated communications architecture. The JBREWS® ACTD contributes to Joint Vision 2020 by enhancing the survivability of Joint Forces in that it provides increased situational awareness and information superiority to supported headquarters and forces. By providing these elements with the real-time capability of detecting biological agent cloud arrival, JBREWS® contributes to full-dimensional protection to the force (JBREWS, 2018).

g. *JWARN®,* Joint Warning and Reporting Network provides Joint Forces with a capability to report, analyze and disseminate detection, identification, location and warning information to accelerate the warfighter's response to CBRN-E attack. JWARN® is a computer-based application integrating CBRN-E data and facilitates sensor information into Joint and service command and control systems for battlespace situational awareness. JWARN® replaces the manual processes of incident reporting, hazard plot generation and warning affected forces. JWARN® reduces the time from incident observation to warning to less than two minutes, enhances situational awareness throughout the area of operations and supports warfighter battle management tasks (JWARN, 2006).

h. *JBPDS®,* Joint Biological Point Detection System is a robust bio-detection instrument suite that is fully functional in any operational environment the user may encounter. JBPDS® provides automatic detection and identification of airborne biological agents at very low levels, triggers local and remote warning systems, and communicates threat information over standard communication systems. Using laser-induced fluorescence, the trigger/detector continuously evaluates the atmospheric background for traces of potential biological agents. When the system detects something of a suspicious nature, the collector/concentrator is initiated to sample hundreds of liters of air per minute, providing a small amount of liquid containing the collected aerosol sample (JBPDS, 2016).

i. *JBSDS®,* Joint Biological Stand-Off Detection System is capable of providing standoff detection, ranging, tracking, discrimination (man-made vs. naturally occurring aerosol) and generic detection (biological vs. non-biological) of large-area biological warfare aerosol clouds for advanced warning, reporting, and protection. JBSDS® passes detection information and warnings through existing and planned communications networks using JWARN®. Key benefits of JBSDS® include the following: provides early warning to commanders and supports timely decision-making, detects and tracks aerosol clouds out to 15 kilometers and discriminates biological from non-biological particles in aerosol clouds out to three kilometers (JCS, 2011).

x. *Advanced Sensor Technologies*: sensor technologies as a key technology enabler in the prevention, during, and aftermath of a CBRN-E attack. Detectors have three main functions: confirm the results of early identification, collect evidence for the use of international banned substances—forensic parlance, and to confirm the area is safe for reoccupation after decontamination. Before an event, detectors are used as part of a continuous monitoring to either prevent a CBRN-E incident (detect-to-protect) or for early warning in the event of an incident (detect-to-treat). Either case allows early diagnosis and treatment protocols (NATIBO, 2001).

xi. *Individual Protective Equipment (IPE)*: CBRN-E protective equipment is one of the most critical areas of a CBRN-E response strategy. An integral consideration is that if IPE is too cumbersome then it affects the performance of first time responders and military operators. On the other hand, if the protective level is insufficient, then the health and the life of the wearer are put at risk. To make it even more complicated, decontamination procedures have to be adapted to the level of risk and the decontamination chemistry must not interfere with, for example, the protective layers in the IPE or with the detector equipment necessary for tracing the level of contamination (Richardt & et al., 2013).

Given these operational and tactical advances and key enabling technologies, one of the most significant challenges for the future is to more effectively detect, identify and operate in areas contaminated by CWAs.

This leads us to our next section on the evolution of the U.S. Army's need for CBRN-E Homeland Defense.

4.1.1 CBRN-E: U.S Army's Evolving Need

The U.S. Army CINC/JROC has established objectives pertaining to use of state of the art technologies involving predictive modeling and simulation tools. These objectives, part of the U.S Army's 2020-2023 strategic efforts delivered in 2013 at the 7th Gap Analysis, Army Capabilities Integration Center (ARCIC), cites CBRN-E modeling as an important strategic consideration (DOD, 2006).

Strategic Levels of War - Objectives:

Missions for the U.S. Armed Forces from Sustaining U.S Global Leadership: Priorities for 21st Century Defense guidance at the national policy and theater-strategy level.

i. Counterterrorism and Irregular Warfare:
ii. Deter and Defeat Aggression
iii. Counter Weapons of Mass Destruction
iv. Defend the Homeland and Provide Support to Civil Authorities
v. Project Power despite Anti-Access/Area Denial Challenges
vi. Operate Effectively in Cyberspace
vii. Operate Effectively in Space
viii. Maintain a Safe, Secure and Effective Nuclear Deterrent
ix. Providing a Stabilizing Presence
x. Conduct Stability and Counterinsurgency Operations
xi. Conduct Humanitarian Assistance, Disaster Relief and other Operations

Operational Levels of War - Objectives:

This operational theme describes the character of the dominant major operation being conducted at any time within a land force commander's area of operations. The operational theme helps convey the nature of the major operation to the force to facilitate common understanding of how the commander broadly intends to operate. This is enabled by developed capabilities to fill gaps at the campaign-levels.

i. Regional alignment
ii. Mission tailorability
iii. Operationally adaptive

iv. Modernize the network

v. Conventional/SOF integration

vi. Maintain Global stabilizing presence

vii. Active and Reserve balance

viii. CBRN-E for Homeland Defense

ix. Set Theater Support forces

Tactical Levels of War - Objectives:

Because Army forces conduct full spectrum operations combining offensive, defensive, and stability or civil support operations simultaneously as part of an interdependent joint force to seize, retain, and exploit the initiative, accepting prudent risk to create opportunities to achieve decisive results at the engagement-small-unit arms levels, where value of SE-CAS is fully realized:

i. *Protect Force in Counterinsurgency Operations (COIN)*, prevent or mitigate hostile actions against personnel, resources, facilities, and critical information during: military, paramilitary, political, economic, psychological, and civic actions taken to defeat insurgency:

    i. Tailor-able protective counter-mobility and survivability support. Standoff Improvised Explosive Device (IED) detection, neutralization, destruction and detonation, ability to remotely clear dangerous areas of ordnance with robots.

    ii. 360 degree-view detection, warning and ID-ing of indirect fire in the vicinity.

iii. Maximum protection of the soldier while on a platform (air or ground). Armor / ballistic protection, active and passive platform / FOB protection from (air or ground) from flame, thermal, chemical, biological and electromagnetic threats.

iv. Fixed Site protection [Identify, target, intercept, and neutralize direct/ indirect fires, physical security, portable barriers, vehicle inspection system, and explosives detection. Base defense requires a defense operations center and larger caliber small arms/crew served weapons].

v. Ability to detect and warn soldiers of CBRN-E and toxic industrial agent and hazard releases, provide mass casualty decontamination, and detect CBRN-E loaded IED.

vi. Inadequate situational awareness (SA) and mass notification systems support by network-enabled platforms.

vii. Convoy security, survivability, and lethality against weapons, ring mounts, drivers vision devices, combat optics, crew communications, jammers, and navigation aids and rocket-propelled Grenade (RPG) attacks.

viii. Common joint target identification to aid in the tactical shoot / no-shoot decision of captured personnel, identification of non-combatants and enemy combatants.

ii. *Network Enabled Battle Command*: network-enabled battle command enables leaders of Joint and Expeditionary Forces with the capability to command and control large maneuver formations, sustain the force with minimal forward presence, and achieve broad political-military objectives across the full spectrum of operations:

i. Common Operational Picture (COP) / SA Scalable, Deployable Command Post (CP) for communications equipment, power, etc.
ii. Organic communications for all platforms and dismounted soldiers
iii. Net-centric fires, maneuver, and intelligence, surveillance, reconnaissance (ISR) in near real time to close with and destroy the enemy.
iv. Fully integrated battle command from strategic to tactical level linking Army operations to Joint and interagency operations, including access to space assets.
v. Networked on-the-move battle command to include scalable bandwidth.
vi. Open, multi-layered architecture with multiple paths that provide redundancy for assured communications.
vii. Ability to communicate in complex terrain, over extended ranges (space / aerial layer) OTM and dismounted, in an electronic warfare (EW) environment.
viii. Secure, collaborative, information exchange environment.
ix. Horizontal fusion of logistics and intelligence.
x. Incompatible and inadequate C4ISR systems resulted in lack of situational awareness during disaster relief.
xi. Common Operational Picture (COP) / Situational Awareness (SA).
xii. Limited wideband on the move.
xiii. Organic communications for all platforms and dismounted soldiers.

xiv. Net-centric fires, maneuver, and Intelligence, Surveillance, Reconnaissance (ISR) in near real-time to negotiate with and destroy the enemy.

xv. Networked on-the-move battle command to include scalable bandwidth.

xvi. Open, multi-layered architecture with multiple paths that provide redundancy for assured communications.

xvii. Communication in complex terrain, over extended ranges (space / aerial layer) and in an electronic warfare (EW) environment.

xviii. Secure, collaborative, information exchange environment.

xix. Horizontal fusion of logistics and intelligence.

xx. Incompatible and inadequate Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C^4ISR) systems.

iii. *Logistics and Medical in COIN and Non-Contiguous Battlespace*: actions and efforts to promote efficient delivery and consumption of supplies at all levels by all units: incorporates actions to improve combat service, combat service support, and medical units' visibility, distribution, accountability, and operations.

i. Limited network logistical information systems.

ii. Provide the right materiel to the right place at the right time, integrated supply chain management, automatic data capture of supply point data to include supply point receipt (in-bound) and supply point issue (out bound).

iii. Develop processes, procedures, and provide assets to deliver support for Joint Forcible Entry operations to other than fixed bases.

iv. Enhance force health protection, and adequate and effective combat casualty care.

v. Robust Command, Control, Communications (C3) and planning for medical/evacuation operations.

vi. Armor for logistics vehicles, ambulances, contract vehicles.

vii. Subdue or incapacitate individuals using non-lethal means.

viii. Reach back capability to link combat engineers in field with outside theater experts (data / voice / video).

ix. Immature joint operational logistical doctrine and organization exists for theater level HQs.

x. Maintenance for non-standard equipment is too dependent upon warranties and service contracts that may fail to provide timely technical support and CL IX repair parts at the point of system malfunction or failure.

xi. FOB life support equipment

iv. *Soldier Protection in Counterinsurgency Environment:* actions and efforts to promote efficient delivery and consumption of supplies at all levels by all units: incorporates actions to improve combat service, combat service support, and medical unit visibility, distribution, accountability, and operations. Soldiers medically and psychologically healthy by easing combat stress before, during, and following deployment:

i. Limited network logistical information systems.

ii. Soldier active and passive protection systems that enhance survivability against enemy lethal and non-lethal effects.

iii. Provide improved situational awareness and relevant tactical information for the dismounted soldier.

iv. Multi-functional soldier, equipped with body armor, elbow/knee pads, eye protection, night vision systems, qualified in multiple crew weapons, networked to a SA source.

v. Minimize injury and endemic diseases and provide for mental health before/after operations.

vi. Ordnance disposal teams with full spectrum battle equipment, M4 carbines, a night vision goggle compatible bomb suite, and a small UAV for reconnaissance.

vii. Squad Designated Marksman (SDM) equipment to support unit with an accurate precision weapon.

viii. Flight crews lacking adequate ballistic protection, and equipment, which allows ability to operate effectively in night or adverse environmental conditions.

ix. Inadequate personnel recovery equipment and counter sniper equipment.

v. *Tactical Communications*: voice, data, and video communication support to the tactical fight. The capacity and ability to communicate dismounted-to-dismounted, dismounted-to-mounted at tactical level in all environments:

i. Small unit tactical communications for mounted / dismounted with vehicle intercom interface.

ii. Secure high capacity headquarters communications with redundant capability, division through battalion.

iii. Secure, long range, beyond line of sight, communications.

iv. Secure communications with redundant capability for company, platoon, and squad.

v. Communication in complex terrain or over extended ranges (space / aerial layer) OTM and dismounted.

vi. *Joint Interoperability, Coalition, and Interagency Operations:* conducting tactical and operational level operations for US units of all services, coalition units, and allied units. Interoperability seeks to maximize effectiveness of joint, coalition, and allied forces as well as minimize fratricide among those forces. Includes the ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use the services to enable effective operation together:

i. Communications, coordination, and collaboration with joint partners and agencies to include state governments and NG units during disaster relief.

ii. Joint interdependence: Joint battle command, joint fires / ISR / terminal attack control, airspace, air and missile defense, force projection, sustainment and biometrics personnel identification data collection & sharing.

iii. Increased support to advisory training team that support indigenous forces/

iv. Captured personnel recovery capability.

v. Improved SA by sharing relevant tactical information, to include combat identification, through networking the platform to the rest of the force.

vi. Joint standard for vehicle / personnel markings to facilitate combat identification.

vii. Real time spectrum de-confliction collaboration.

viii. Limited ability to secure and deny waterways.

vii. *Train the Force How and As it Fights*: implementation of tough, realistic training, include training in theater both before and after combat operations taking full advantage of existing and emerging technologies, and actions to understand the culture and customs of the region in order to improve the understanding of the contemporary operating environment:

i. Training support system to improve individual soldiers, crew, and small unit collective training.

ii. Implementation of a realistic full spectrum joint training capability focused on irregular warfare, intelligence, urban operations, non-kinetic effects, special operation and conventional forces.

iii. Convoy operations training across large & distributed area of operations: dispersion of communication & logistics, urban environment, driving tactics.

iv. Combat vehicle (air and ground) identification training standards across Services to support shoot / don't shoot decision training, rules of engagement concept and implementation training across the services.

v. Lack of utilizing EW capabilities and equipment for countering IED.

vi. The ability to understand and leverage information operations at the tactical level, including HUMINT questioning.

vii. Enhanced spectrum management training.
viii. Ability to communicate with local population.
ix. Training units to understand culture of their operational area.
x. Familiarization with civilian disaster response organizations.

viii. *Timeliness of Analysis and Information Dissemination:* analyzing intelligence and other information sources in order to permit operations. Timely delivery of time-sensitive intelligence to tactical units, or the accessibility by tactical units to this information:

i. Accurate and timely intelligence, surveillance and reconnaissance collection.
ii. Accumulate intelligence/information from reporting elements quickly and sharing information via a flattened and integrated command and control.
iii. Intelligence support to effects including national and theater level (IO, targeting, and combat assessment).
iv. Create / integrate geospatial intelligence data manipulate imagery, build/update mission specific data (MSD) sets locally. Create three-dimensional models to support tactical missions.
v. Web information management service (operator friendly software requiring minimal bandwidth) for the sharing, managing, and critical situational awareness data/product at all echelons.
vi. Generate, manage, analyze and disseminate geospatial data. Continuously update digital maps.
vii. Timely forensics investigation / analysis of IED sites.

viii. Army active duty home stations, Army Reserve Centers, and Army National Guard Armories require SIPRnet® capability.

ix. Intel support to COIN capabilities were limited to BNs and did not effectively cover all the daily requirements, especially in the areas of HUMINT, SIGINT, UAS, and imagery processing, and interrogation.

x. Capability to receive full motion live video feeds, to include man-portable capability to receive live video feeds from various types of UAVs.

ix. *Ability to Conduct Joint Urban Operations*: joint operations planned and conducted across range of military operations on or against objectives on a terrain where manmade construction or civilians is dense:

i. Combat identification to include Blue/Red force tracking in urban environment.

ii. Communication for dismounted command and control down to platoon / individual.

iii. Adequate detection equipment / appropriate weapons / vehicles to enable maneuver.

iv. Delivering needed firepower precisely and with minimal collateral damage.

v. Quick analysis of target buildings (search) from standoff distance.

vi. Distinguish / mark / track enemy from local populace / crowds.

vii. Subdue, suppress, control, or disperse crowds using non-lethal means.

x. *Information Operations*: actions taken to affect adversary information and information systems while defending one's own information and information systems. The integrated employment of the core capabilities of electronic warfare, computer network operations, psychological operations, military deception, and operations security, in concert with specified supporting and related capabilities, to influence, disrupt, corrupt or usurp adversarial human and automated decision making while protecting our own:

i. Electronic battle space including tactical employment, de-confliction with communications, electronic suite interoperability, and programming in a dynamic threat environment.
ii. Interfacing with local population to establish conditions for favorable operations.
iii. Limited or no situational awareness prior to arrival in area of operations.
iv. Surveillance of electronic (television and radio) broadcast and printed materials.
v. Ability to provide capability to meet electronic warfare requirements in multiple signal sets.

Given the evolution of Army needs, at the tactical levels of war, the use of predictive modeling and simulation tools for CBRN-E defense can be boiled down to the following objectives (DAU, 2014):

i. Detection, collection & identification of CWA by type.
ii. Early warning of CWAs.
iii. Identification of CWAs by type out 2 km [kilometer] day or night.
iv. Transmittal of information into a force wide warning and reporting database.
v. Identification of source information within threat environment: before, during, and after CWA release.

vi. Support of intelligent information and decision tools for effective threat response strategy.

It is this particular subset of tactical objectives specific to CBRN-E defense, that SE-CAS is designed to provide meaningful MS&A capabilities and to examine the central question of this research.

4.1.2 Chemical Warfare Agents: Chemical, Physical & Biological Properties

The properties of CWAs that leads it to being equally effective when weaponized, relates to its chemical, physical, and biological properties, and method of dissemination. CWAs are in the form of solids, liquids or gasses, carries an odor or smell relative to its host, behaves in accordance to principle of thermodynamics and heat exchange i.e. boiling point, flash point, melting point, is viscous from state change with applicable ratios of specific heat for its constituents, and reactive with metals, plastics, fabrics and paints. Based on these properties, CWAs are grouped based on route of entry, toxicity, environment stability, and mechanism of action. Here, we offer up specific description for the properties described (Richardt & et al., 2013):

i. *Route of Entry:* both solid substances and liquids can be dispersed into the air as aerosols, which are small particles or droplets sprayed into the air that penetrate the body through the percutaneous (skin), percutaneous (ocular), respiratory and gastrointestinal tract.

ii. *Toxicity/Concentration*: toxic CWAs through its chemical processes, cause death, temporary incapacitation, or permanent deformation. Empirical approximations deriving toxicity estimates with established boundaries for dosage ranges, incubation period expected to cause symptoms in troops exposed.

iii. *Environmental Stability/Mobility*: ambient conditions are the single most important factor driving the effective penetration and absorption of a given CWA (Richardt & et al., 2013). Time of day, year and season, are very much relevant properties as well, as such the degree of vaporization of a solid/liquid agent in the four different seasons of the moderate climate zones is considered. This vaporization is based on physicochemical data for a given CWA. Volatile substances that mainly contaminate the air as they vaporize rapidly, especially when the temperature rises (short-term effect) persistent substances with low volatilities, which therefore mainly contaminate surfaces with a long-term effect. Dosage concentration and symptomology is affected by the vapor pressure of substances relative to change in temperature, terrestrial heating, adiabatic flow, and increases in vapor pressure and volatility.

iv. *Spreading System*: technologies for dissemination includes: missile warheads, aerial bombs, chemical mines, pyrotechnics, aerodynamic forces, and artillery shells. Different types of CWAs based on environmental conditions are more or less applicable. In distributing the contaminant, losses of substances are considered to be to the advantage of the attacked soldiers. High impact on troops occurs when the explosion, including contamination homogenous densities over the area, realizes the intended particle size and coverage area of the solid or liquid agents. Explosive dissemination produces uncontrollable droplet size with fine and coarse particles. Artillery shells provide contamination densities from a few milligrams per square meter to several hundred grams per square meter around the point of detonation. Another aspect is agent loss by incineration in the initial blast, which is normal additionally, CWAs may be forced onto and in the ground by the blast, which has to be considered for decontamination later. Airburst munitions overcome these aspects and thus provide a higher threat and impact on the attacked force structure. Besides dissemination by explosion, spraying from tanks or aircrafts via non-explosive dispersion can carry out dispersal. Additional factors, such as wind speed and direction, change of the wind, the delivering vehicle, and so on, influence the operation and the attacked troops significantly (Richardt & et al., 2013).

4.1.3 Chemical Warfare Agents: Sulfur Mustard (HD)

In the forward Forcible Entry / Civil Support use case, and demonstration of SE-CAS's utility, the agent of choice is the blister agent—dichlorodiethyl sulfide [$Cl-CH_2-CH_2-S-CH_2-CH_2-Cl$], also-called (sulfur) mustard, mustard gas, or distilled mustard, abbreviated (HD) (U.S ARMY, 2014). HD is a colorless and odorless liquid, with odor similar to mustard or garlic. It ranges from colorless to pale yellow, as well as to dark yellow for nitrogen mustard, and is very persistent. The motivation for this decision is due to the availability of well researched physiological and psychological effects of its inhalation on the human body, and verified toxicity values based on empirical observations conducted by NATO. HD is a type of vesicant (causing blisters), producing local effects in the regions of the body exposed, with skin, ocular and respiratory regions mostly affected. Second order effects are also present in the gastrointestinal tract, including hemopoietic (blood cells) and central nervous systems. Consistent with aerosol releases, as in the case of a weaponized HD attack, skin contact with HD results in erythema accompanied by an itching or burning sensation (as early as 45 minutes, or as late as 48 hours given lethality of dose received). These effects gradually worsen with time, culminating in formation of fluid-filled blisters on the surface of the skin or areas affected within as little as 120 minutes. Necrotic lesions are soon to follow, as the magnitude of the skin disease is dependent on the exposed area of the body, levels of moisture within the atmosphere and on the affected area (skin tissues). Genitals, mouth armpits, neck and eyes are mostly affected due to high moisture content, of which is further worsened in humid environments. The eyes, when in contact with HD, renders personnel incapacitated. At high dosages, in case of vapor exposure, the eyes develop severe conjunctivitis, corneal damage, and scarring and nerve damage, evidenced by repeated twitching of the eyes or blepharospasm (Curling & et al., 2010).

The effect surrounding inhalation of HD is also dose-dependent. On the lower spectrum, irritations of the nose, sinuses, pharynx with symptomatic runny nose, frequent sneezing, nosebleed and dry unproductive cough are all common. At higher doses, tightness in the chest develops, sputum producing cough, sloughing of the airway's epithelial tissue. These effects ultimately result in blocked airways and eventual lung failure. Most extreme cases is accompanied by pulmonary edema and hemorrhaging.

The central nervous system is also affected by weaponized release of HD. Low dose releases have a tendency to cause lethargy, apathy, and depression in musculoskeletal systems. At higher dosage, hyper-excitability, jitters, convulsions and abnormal muscle movement affecting dexterity. Regarding impact to blood cells and tissues, HD infections slows the body's natural ability to regenerate damaged cells, particularly fighting secondary infections. Effects on the upper gastrointestinal tract are minimal. Nausea and vomiting are most common initially, resulting in mild frequent bouts of diarrhea and constipation (Curling & et al, 2010).

Given the affected areas and routes described, and the dependency on dosage amount in influencing lethality, the associated HD toxicity values and respective ranges are listed in Table 3:

Table 3. HD Toxicity Values (Vapor).

Route of entry	Mild	Severe	Lethal
Ocular	25 mg	75 mg	
Inhalation	1,000 mg		
Percutaneous	50 mg	500 mg	10,000 mg

Here, the effective dosages represents the amount of vapor agent expected to cause *mild or severe* effects in 50% of troops exposed. *Lethal* ranges are the amount of vapor expected to kill 50% of troops exposed. Independent of route of entry, HD exposure at the most lethal levels will result in death within 5-10 minutes post-exposure from the body producing a paralyzing reaction leading to asphyxiation, second order pneumonia and severe lung infections and sepsis 3 to 6 days downstream. Degenerative events occur in as little as 1 to 2 weeks, internal sepsis of tissues, bone marrow suppression, suppressed immune system to fight off common infections, are all common and likely outcomes.

4.1.3.1 Sulfur Mustard (HD): Injury Progression

Injury progression of HD is correlated and represented across its level of impact on the four specific systems already discussed: ocular, respiratory, skin and gastrointestinal tracts. Summarized in Table 4 below, are severity indices relative to the physiological systems impacted from weaponized release of HD. These thresholds are defined based on the AMedP-8(C) casualty estimation methodology put forth by NATO and Institute for Defense Analyses (IDA) planning guidance on estimating exposure impact of CBRN-E attacks. Both signs and symptoms are their severity across physiological systems enable planners to draw useful injury profiles, and are listed in Table 4 and Table 5 (Curling & et al., 2010).

Table 4. HD Severity Scale (Ocular & Respiratory System).

Severity	Ocular	Respiratory
0	No observable effect	No observable effect
1	Irritation with eye pain, conjunctival erythema and/or edema	Mild shortness of breath, tight chest, coughing, and runny nose
2	Eye pain and/or irritation with eye pain, conjunctival erythema and/or edema, blepharospasm, difficulty opening the eyes and sensitivity to light	Frank shortness of breath, difficulty breathing, wheezing breath, respiratory congestion, and bronchorrhea
3	Severe eye inflammation and pain leading to an inability to open eyes	Severe dyspnea
4		Breathing stops completely, or prostration

Table 5. HD Severity Scale (Skin & Gastrointestinal Tract):

Severity	Skin	Upper Gastrointestinal
0	No observable effect	No observable effect
1	Skin sensitive to touch in crotch, armpits, and on inside of elbow and knee joints	Upset stomach and nausea, watering mouth and frequent swallowing to avoid vomiting
2	Skin sore in crotch, armpits, elbow and knee joints, and painful when moving, red swollen skin, tiny blisters on hands and neck	Episodes of vomiting, possibly including dry heaves, severe nausea and possibility of continued vomiting
3	Skin raw and painful in crotch, armpits, elbow and knee joints, red swollen body skin, large blisters on hands and neck	
4	Skin sloughing after blisters or swollen skin	

Dosage ranges previously described corresponds to symptoms progression that is time-dependent, discontinuous, step-wise and exact (dosage within specified range yield same symptom progression). Because boundaries describing each dosage is represented numerically, change in symptoms progression is instantaneous, as is represented in the SE-CAS meta-models. Look-up tables define the dosage threshold for each physiological system, and are plotted in minutes post-exposure along the logarithmic x-axis shown below (Curling & et al., 2010). Sourced from the NATO / IDA Reference Manual for each physiological system depicted.

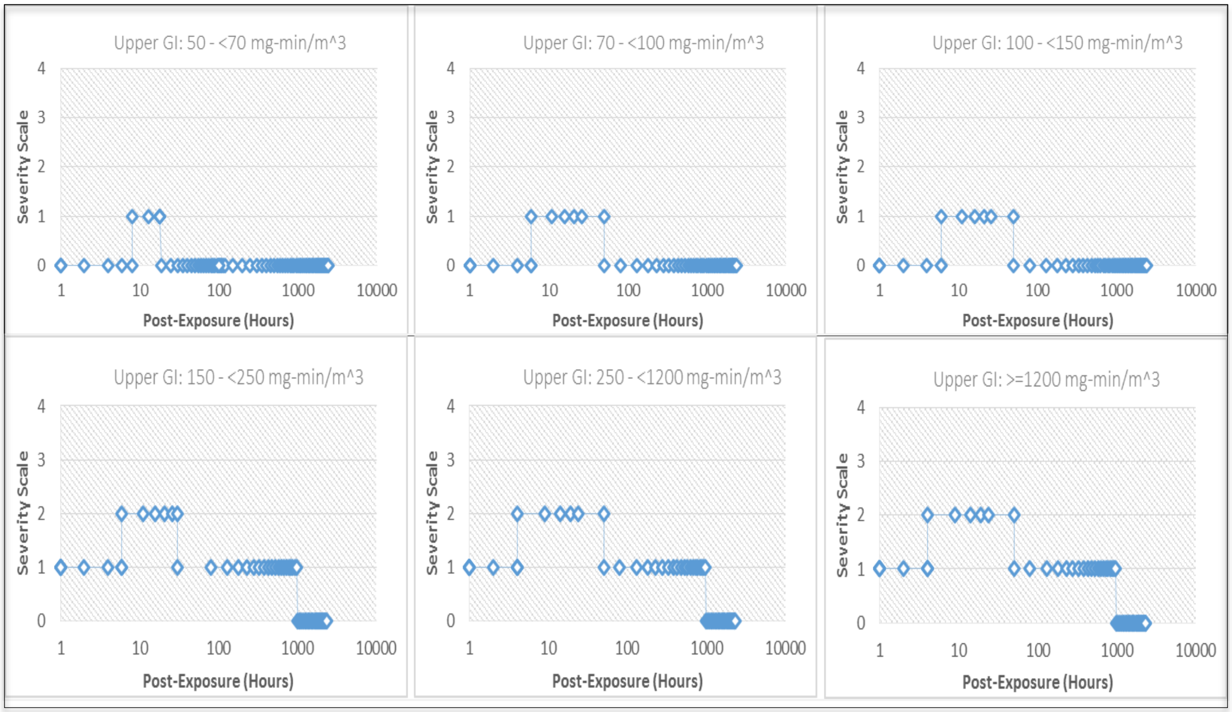


Figure 10. HD Injury Profile (Upper GI). Curling, C., et al. Technical Reference Manual: NATO Planning Guide for the Estimation of Chemical, Biological, Radiological, and Nuclear (CBRN-E) Casualties, Allied Medical Publication-8(C). (2011). North Atlantic Treaty Organization *Allied Medical Publication*. 8:1-365

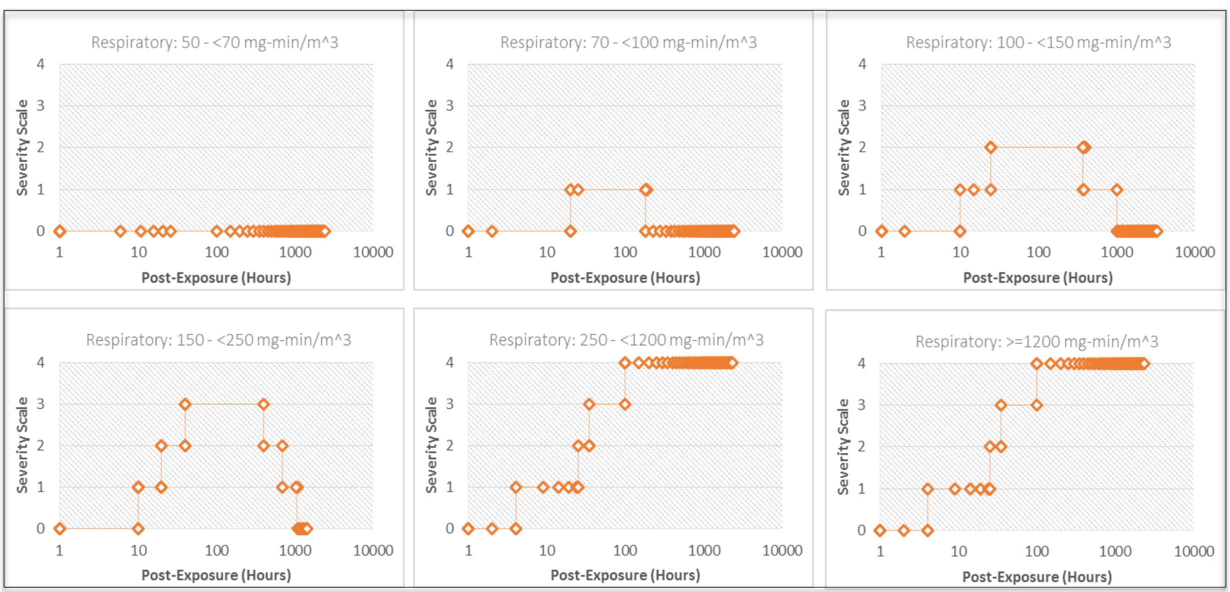


Figure 11. HD Injury Profile (Respiratory). Curling, C., et al. Technical Reference Manual: NATO Planning Guide for the Estimation of Chemical, Biological, Radiological, and Nuclear (CBRN-E) Casualties, Allied Medical Publication-8(C). (2011). North Atlantic Treaty Organization *Allied Medical Publication*. 8:1-365

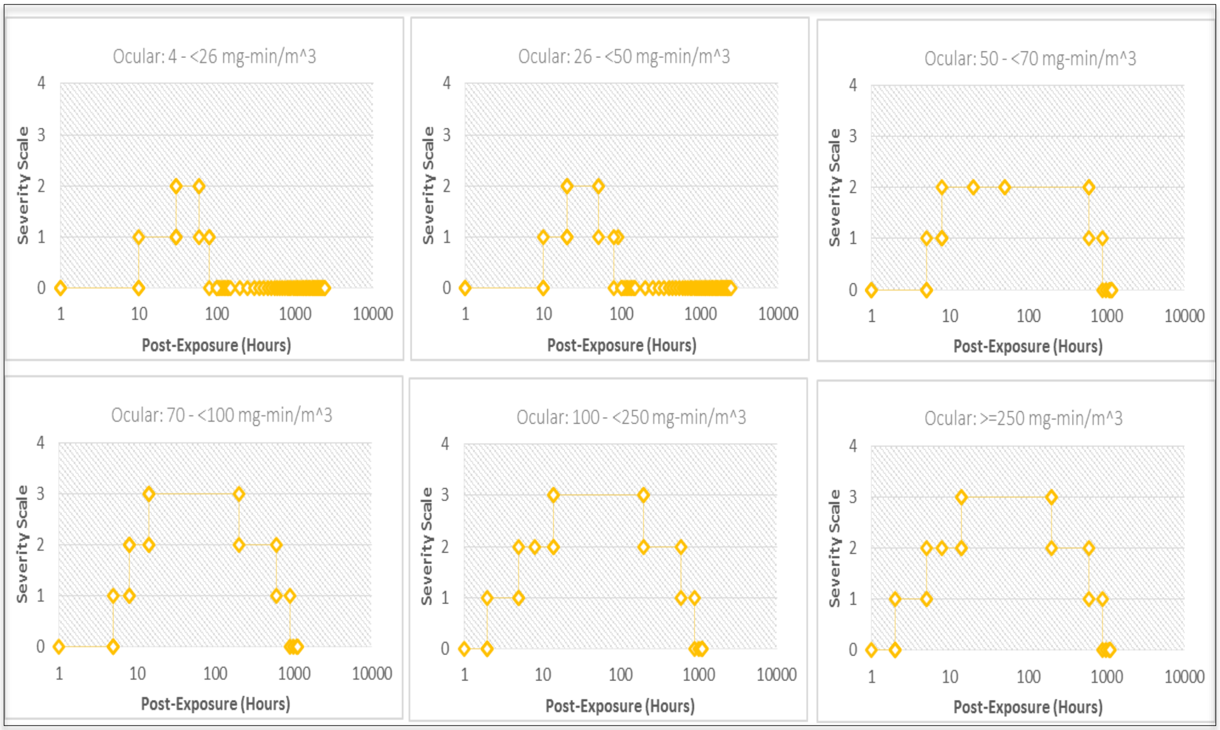


Figure 12. HD Injury Profile (Ocular). Curling, C., et al. Technical Reference Manual: NATO Planning Guide for the Estimation of Chemical, Biological, Radiological, and Nuclear (CBRN-E) Casualties, Allied Medical Publication-8(C). (2011). North Atlantic Treaty Organization *Allied Medical Publication*. 8:1-365

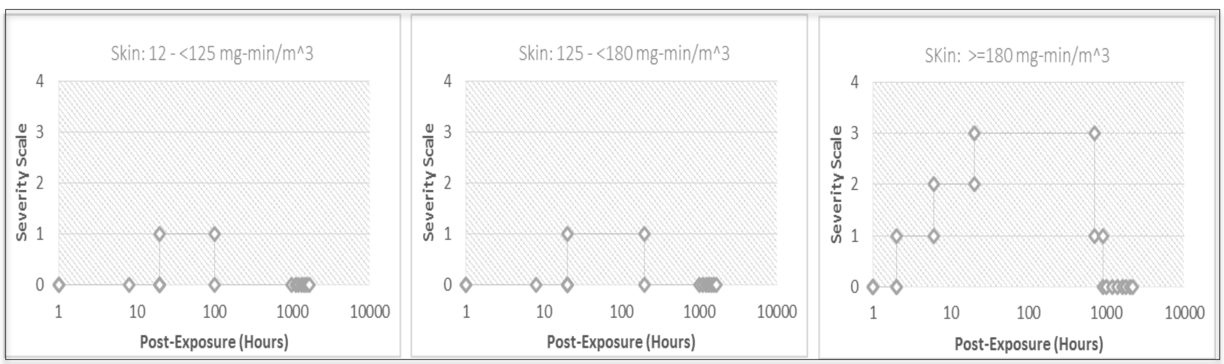


Figure 13. HD Injury Profile (Skin). Curling, C., et al. Technical Reference Manual: NATO Planning Guide for the Estimation of Chemical, Biological, Radiological, and Nuclear (CBRN-E) Casualties, Allied Medical Publication-8(C). (2011). North Atlantic Treaty Organization *Allied Medical Publication*. 8:1-365

From the referenced individual plots, a summary profile can be aggregated to form a composite injury profile. The composite injury profile correlate symptom progression as a function of exposure hours at a particular severity class with maximum exhibited physiological symptoms having occurred at each point. SE-CAS is designed to provide a composite view of varying effects and symptoms in instantaneous time.

Next, we'll explore the SE-CAS architecture, simulation definition and general functionality within the context of a Forcible Entry / Civil Support use case.

Chapter 5

5. Systems Engineering Casualty Analysis Simulation (SE-CAS)

5.1 SE-CAS: Application & Intended Use

The Systems Engineering Casualty Analysis Simulation (SE-CAS) is a simulation framework for conducting scenario-based performance trades. SE-CAS compiles user-defined scenario inputs, simulation components and services with integrated analytical models. Users are able to obtain numerical results for a given scenario and visualize insitu playback. The overall SE-CAS process begins with the need to assess impact of weaponized release during military operations. The user sets starting conditions through the scenario input editor, selects simulation mode, and parameters to randomize for each run. Parameter inputs cover a vast range of descriptor to include: emission rate, type, altitude, latitude and longitude, spread and cloud cell capacity, wind speed, heading, to name a few, including CBRN-E agent of choice, environment conditions, and platform performance parameters. Inputs are passed through the simulation components and service layers, including processor logic for terrain, task, time, and simulation management, visualization and observer services and utilities as depicted in the SE-CAS architectural framework in Figure 14. Results are output via text format and visualized within the simulation real-time.

5.2 SE-CAS: Model Derivation, Evolution and Form

SE-CAS was developed to serve the interests of the U.S. Army by providing an M&S solution to evaluate steering strategies during weaponized release of CBRN-E agents. This fundamental need, already outlined in earlier sections of this dissertation, helps satisfy U.S Army's vision in Figure 14 for Operational Alignment and Integration, consistent with tactical objectives operating in environments contaminated by CBRN-E agents. This includes leveraging detection system solutions, information management, and data visualization to shape casualty forecast and planning strategies driving operational execution. From this, was the initial development of a Microsoft Excel® based engineering-level model taking into account core elements: ambient temperatures, meteorological conditions, CBRN-E detection and tracking probabilities, alongside agent concentration and correlated with inhalation product and symptom progression (NAVSEA, 2004).

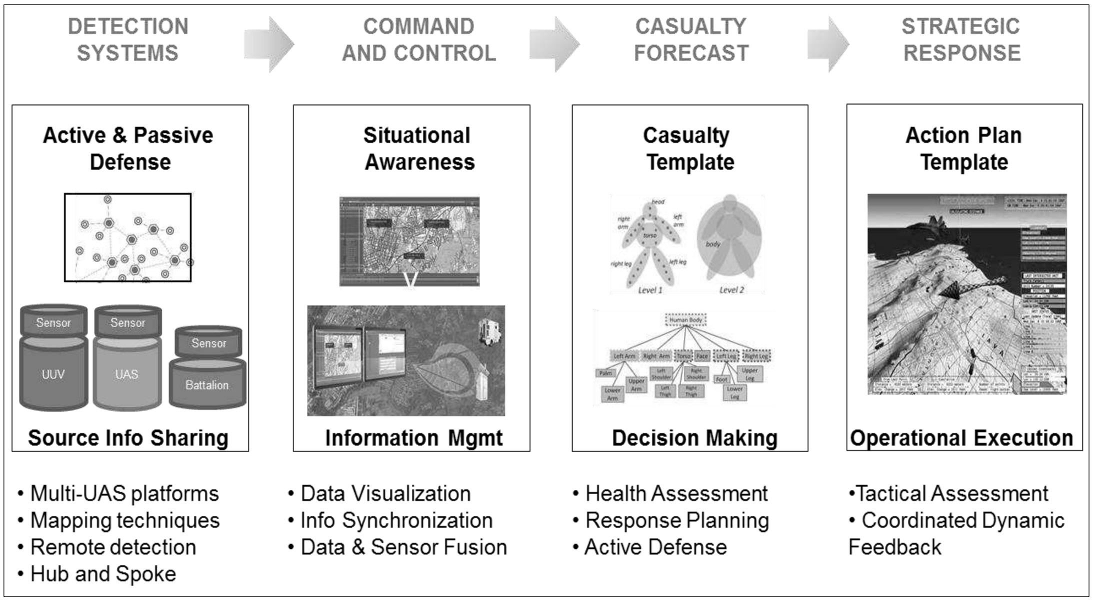


Figure 14. U.S Army's Operational Alignment & Integration. Naval Surface Warfare Center: Dahlgren Division. (2004). Technical Report. Over-water Simulant Release Testing for the joint Services Lightweight Standoff Chemical Agent Detector (JSLSCAD). .

Highlighted in Figure 15, initial data points was extracted from Naval Sea Systems Command (NAVSEA) chemical release exercises, of which is extrapolated for statistical significance in its use within the depicted Excel® model.

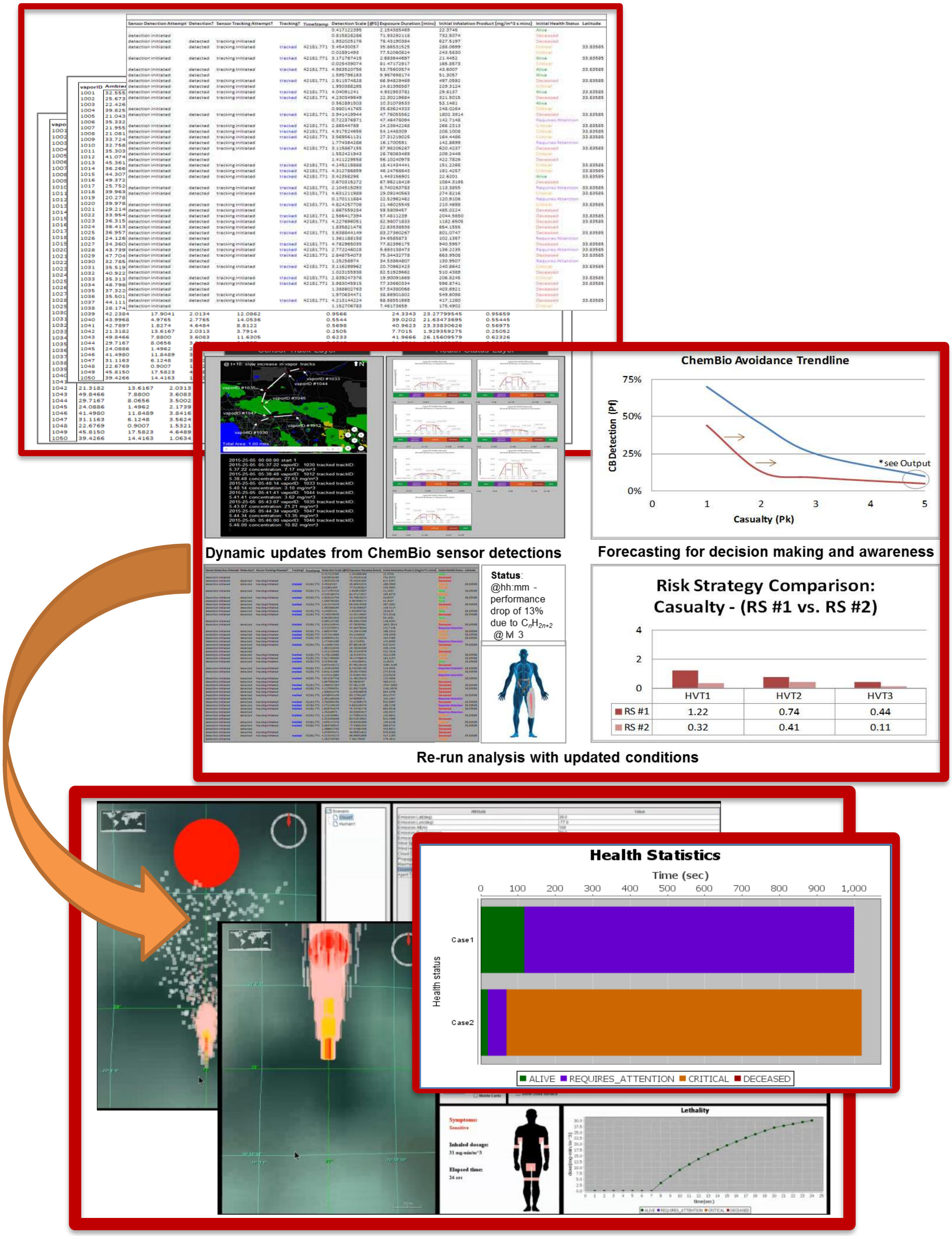


Figure 15. SE-CAS: Model Evolution and Form

5.3 SE-CAS: Architecture and Data Structures

SE-CAS is a simulation framework developed to simulate, analyze and visualize human exposure to CWA plume release within the ambient environment. Referenced in Figure 19, SE-CAS' architectural framework includes: core simulation components & services, editor and several integrated analytic models.

5.3.1 SE-CAS: Component Layout

SE-CAS is composed of a collection of plots and displays shown in Figure 16 correlated in time to intuitively visualize and assess CWA exposure effects. Users can quickly build a scenario and configure modeled parameters. Source code is compiled and results are saved as .XML files.

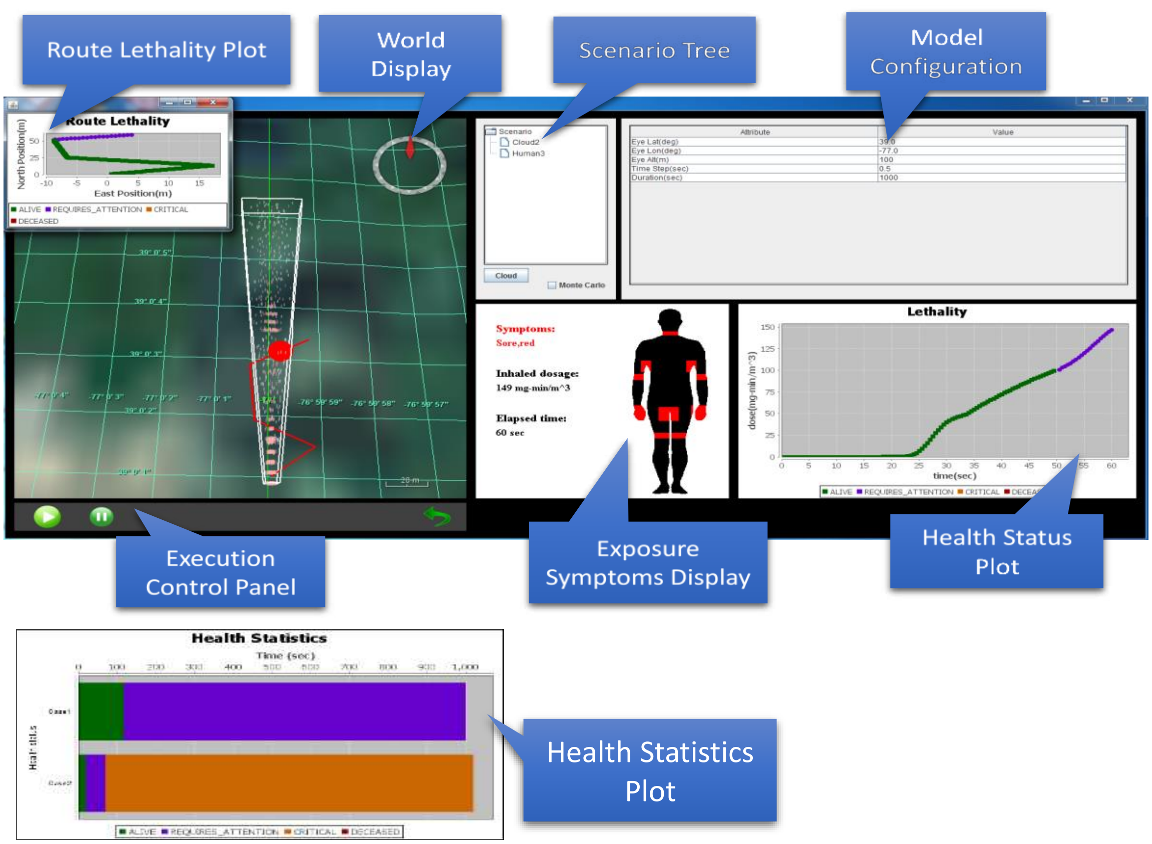


Figure 16. SE-CAS: Component Layout

SE-CAS enables execution in monte-carlo mode for analysis (as opposed to a single run), the Lethality Status Plot (used only for single runs) is replaced by the Heath Statistics Plot (exclusive to monte-carlo mode).

5.3.2 SE-CAS: Execution Control Panel

The Execution Control Panel enables users the interface to control simulation execution. There are three functions supported: simulation play, simulation pause, and simulation restart. Addition functions may be supported in the future such as scaling the execution speed.

5.3.3 SE-CAS: Scenario Tree

The Scenario Tree enables users interface to define a scenario as a tree. A scenario tree is composed of a hierarchy of components. The root component is the scenario itself, which may comprise of any number of clouds, human models as sub-components. The scenario panel also has additional options, for example, when the human model is selected to be configured, a checkbox appears on the panel that the user can select to access a route editor panel and define a route for the human model (or platform). Other options include a checkbox to run the simulation in Monte-Carlo mode.

5.3.4 SE-CAS: Model Configuration

Model Configuration allows users interface to configure each component defined in the scenario tree. Here, the scenario component can be configured with several parameters, such as: total execution time, time step, and default world map view. The cloud component can be configured to define cloud dispersion behavior parameters including the initial location of emission, emission rate, wind speed, wind velocity and CWA plume type. Similarly, the human model component can be configured with an initial location and speed.

5.3.5 SE-CAS: NASA WorldWind® Display

This display, borrowed from NASA WorldWind®, supports 3D visualization of the scenario laydown and model interactions.

5.3.6 SE-CAS: Health Status Plot

The Health Status Plot captures or plots the amount of cumulative inhaled dosage of CWA plumes over time with periodic updates during simulation execution. The plot is also color coded to indicate troop health status at specific points in time. The status indicates whether the troop is alive, requires attention, in critical condition or deceased.

5.3.7 SE-CAS: Route Lethality Plot

The Route Lethality Plot is a dynamic plot very similar to the Health Status Plot. This plot updates the 2D geo-location (latitude & longitude) of the human entity periodically during simulation execution. This is also color coded to visually identify health risks along the route.

5.3.8 SE-CAS: Exposure Symptoms Display

The Exposure Symptoms Display captures human image dynamically updated to visually identify developed symptoms based on CWA plume exposure. In addition to coloring regions of the body, the total inhaled dosage and total elapsed time since start of exposure (T+0) is also updated on this display during simulation execution.

5.4 SE-CAS: Scenario and Model Definition

Executing SE-CAS requires three functions, configuration of modeled parameters in accordance to CONOPS. Next, configuration of human model (force structure or troop) and selecting type of analysis: single versus multi-runs.

5.4.1 SE-CAS: Configuring CWA Weapon

Here the user selects the CWA to be delivered as a weaponized attack on the human or troop platform.

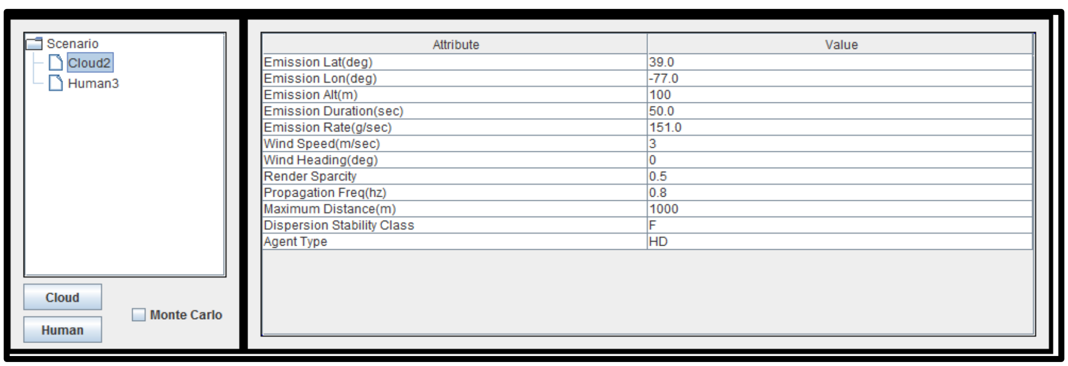


Figure 17. SE-CAS: Configuring CWA Attack

Table 6. SE-CAS Configuring CWA Attack Parameters.

Attribute	Description
Emission Latitude (deg)	Latitude of CWA plume emission origin
Emission Longitude (deg)	Longitude of CWA plume emission origin
Emission Altitude (m)	Altitude of CWA plume emission origin
Emission Duration (sec)	Duration of emission. Past this time, the tail of the CWA plume starts dispersing and propagating away from the point of origin
Emission Rate (g/sec)	Rate of CWA plume emission that determines the CWA plume dispersion behavior based on the Pasquil-Gifford Dispersion Model (see section Mathematical Model). A higher rate of emission implies greater CWA plume concentration at a given location
Wind Speed (m/sec)	Speed of CWA plume propagation
Wind Heading (deg)	Direction of CWA plume propagation relative to true north
Cloud Cell Sparsity	(Visualization performance) Determines the average number of CWA plume particles to generate on the world display. For example if the sparsity is set to 0.5, then each cell particle to cover the CWA plume is generated with 50% probability. The purpose is to prevent significant slowdown of the visualization by not generating too many particles
Propagation Frequency (Hz)	(Visualization performance) Determines refresh rate of CWA plume model on the world display. For instance, a propagation frequency of 0.5 Hz updates and renders the new CWA plume position every 2 seconds. The purpose is to prevent significant slowdown of the visualization by not updating the CWA plume and all its internal particles too frequently.
Dispersion Stability Class	Determine CWA plume dispersion behavior based on the Pasquil-Gifford Dispersion Model (see section Mathematical Model). Current 6 stability classes are defined: A = extremely unstable, B = moderately unstable, C = slightly unstable, D = neutral conditions, E = slightly stable, F = moderately stable.
Agent Type	Determines the CWA plume exposure symptoms of the casualty based on CWA plume concentration. Currently only agent type modeled is HD.

5.4.2 SE-CAS: Configuring Force Structure

Next, user configures the force structure (troop) and establishes location and range of motion in SE-CAS.

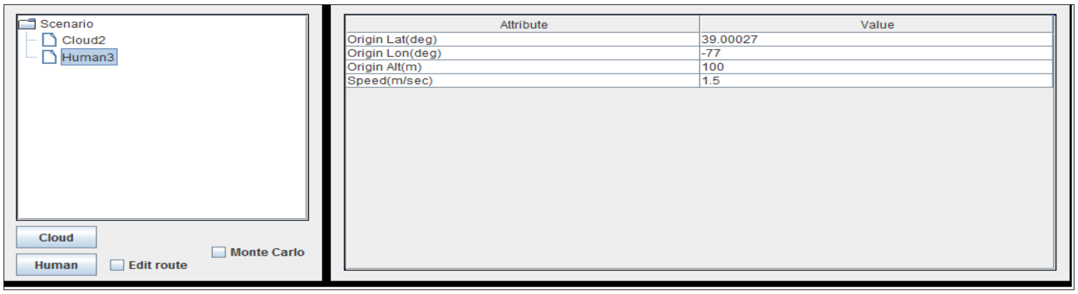


Figure 18. SE-CAS: Configuring Force Structure

Table 7. SE-CAS Configuring Force Structure Parameters.

Attribute	Description
Origin Latitude (deg)	Starting latitude of human
Origin Longitude (deg)	Starting longitude of human
Origin Altitude (m)	Starting altitude of human
Speed (m/sec)	Speed at which human moves

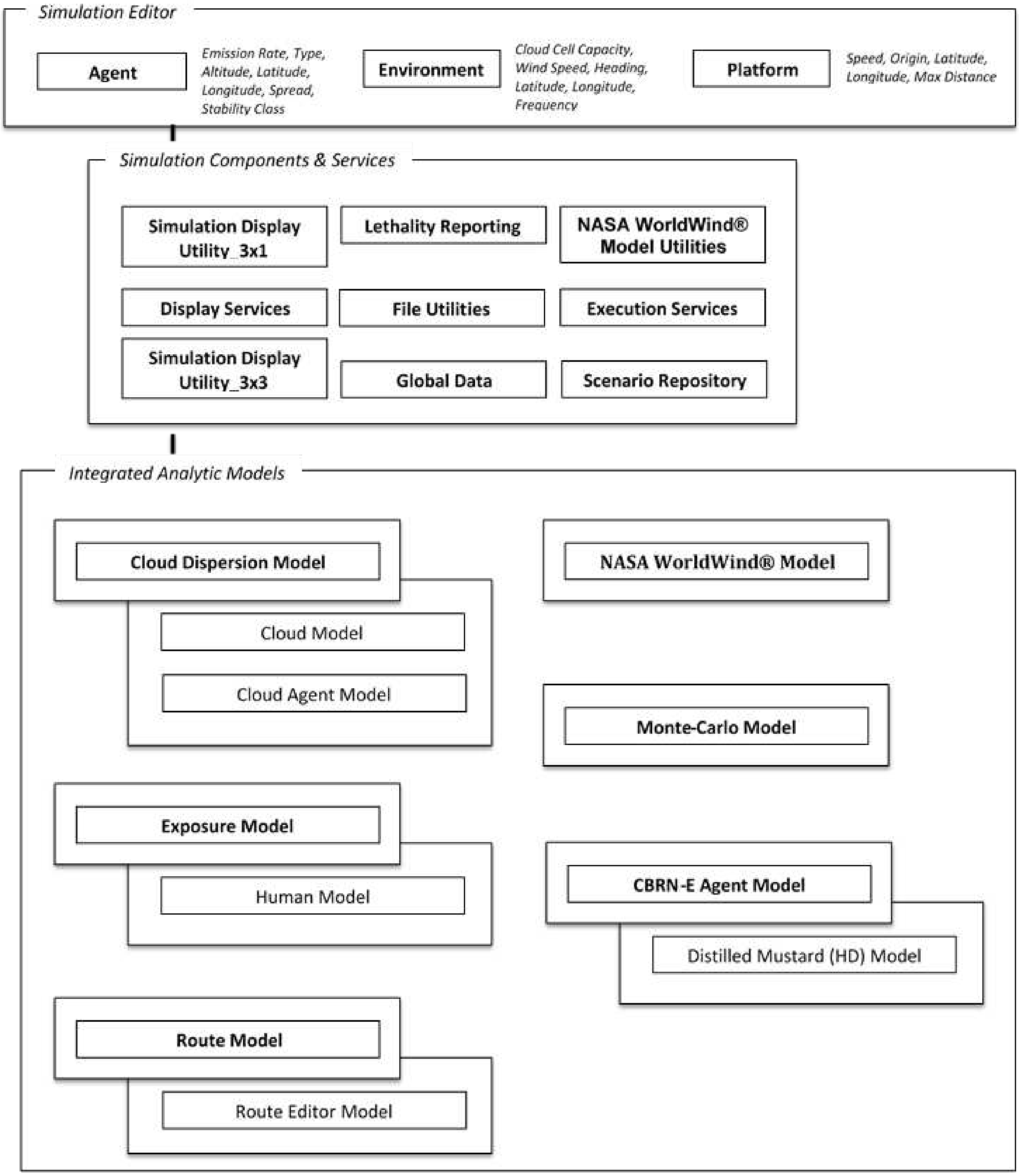


Figure 19. SE-CAS: Architectural Framework

5.4.2.1 SE-CAS: Configuring Routes

The following snapshot shows how to define a route according to parameters in Table 8. Currently, the route editor panel can only be used to view added waypoints (latitude, longitude, altitude) and to remove them. However, an existing waypoint cannot be updated by editing the table.

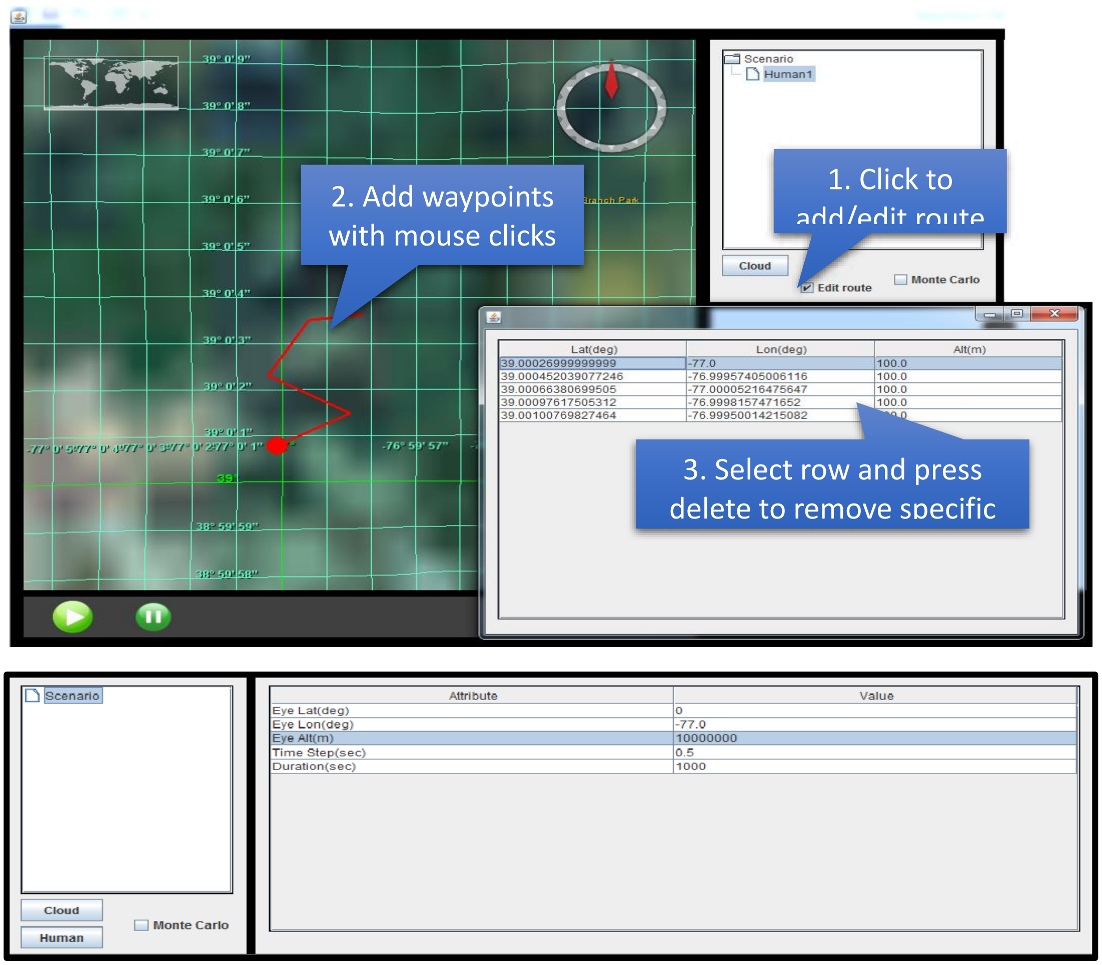


Figure 20. SE-CAS: Configuring Routes

Table 8. SE-CAS Configuring Route Parameters.

Attribute	Description
Eye Latitude (deg)	Latitude of initial viewpoint of world display
Eye Longitude (deg)	Longitude of initial viewpoint of world display
Eye Altitude (m)	Altitude of initial viewpoint of world display
Time Step (sec)	Time step at which simulation is executed
Duration (sec)	Total time of simulation execution

5.4.3 SE-CAS: Configuring Analysis Mode

SE-CAS can also be executed in Monte-Carlo mode. In Monte-Carlo mode dynamic displays are deactivated to complete the runs as quickly as possible. Users check the Monte-Carlo box, the simulation switches to Monte-Carlo mode, and a monte-carlo component is created under the root Scenario in the scenario tree. Similar to the root component Scenario, the Monte-Carlo component cannot be deleted in this mode. The Monte-Carlo component can be configured to specify the number of runs as shown in Figure 21. In Monte-Carlo mode, the user can add cases to analyze as shown in Figure 22.

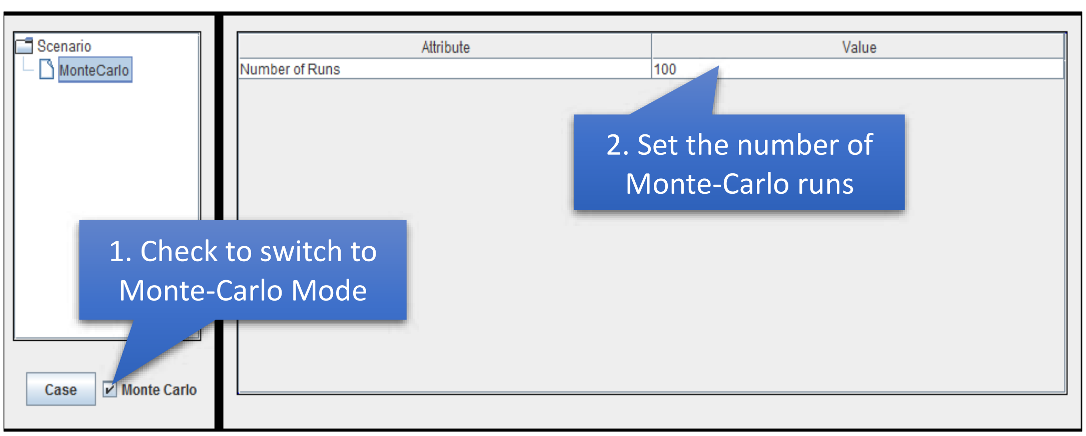


Figure 21. SE-CAS: Configuring Analysis Mode

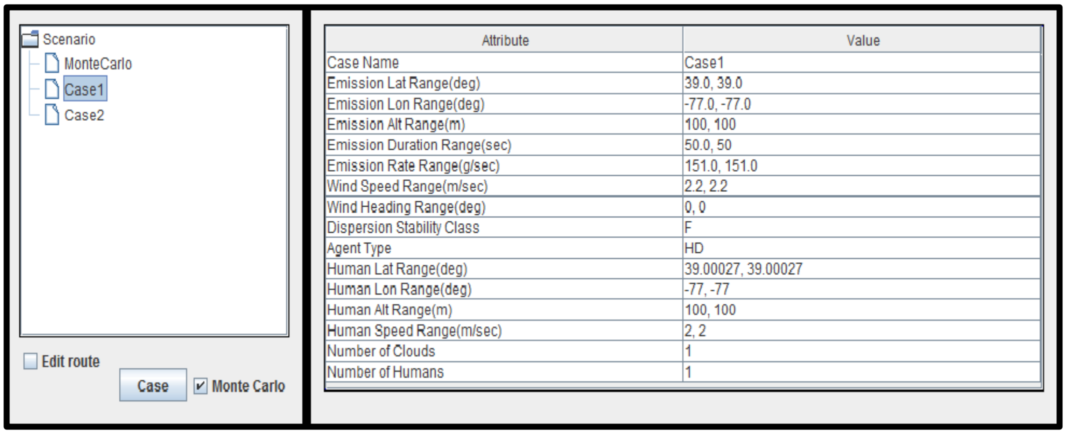


Figure 22. SE-CAS: Configuring Analysis Mode Parameters

In Monte-Carlo mode, the user can add cases to analyze as shown in Figure 22.

Each case incorporates both the CWA plume and the human model parameters with some key differences. As an example, variables identified by the suffix *Range* allow the user to specify a minimum and maximum value, separated by comma. During each run, the simulation will uniformly at random generate a value in that range.

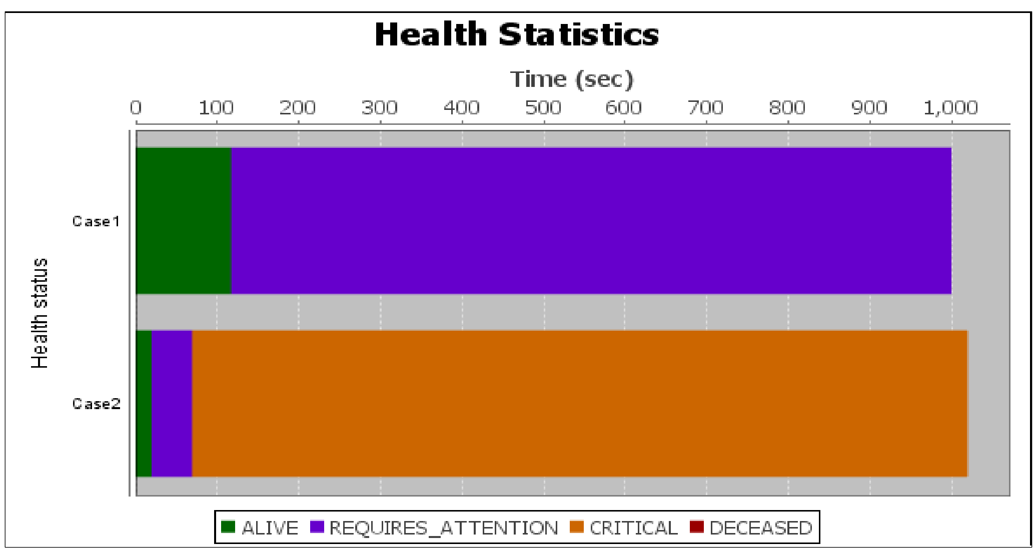


Figure 23. SE-CAS: Monte-Carlo Output

To further illustrate, if the user sets a value of 2.30 for the variable *Wind Speed Range* (m/sec), during each run a random wind speed will be generated between 2 m/s and 30 m/s to cover that range. Therefore, with each run, randomly parameterized CWA plume and human models are generated based on the user input values provided. Trivially, if the minimum and maximum values are set equal, then the same constant value is generated for each run for that variable.

Routes are also assigned to a case rendering allowing the human model or platform to move during run execution. Moreover, if the speed is randomized, for each run, the human will move at random speed. As an example, consider the two cases over 100 runs: Case 1 and Case 2. Case 1 and Case 2 are identical with the exception that Case 1 has an assigned route. In Figure 23, for Case 1, the human platform suffers enough exposure to warrant a state change to *Require Attention*. Conversely, in Case 2, the human on average achieve the *Requires Attention* state earlier, and in fact suffers enough exposure to reach *Critical State*. The results are intuitive, in Case 1, the human platform is moving and enjoy higher probability of survival from moving away of the path of the CWA plume. On the other hand, in Case 2, a stationary human platform experiences the full brunt of the CWA plume and suffers more severe damage.

5.5 SE-CAS: Mathematical Description and Definition

The Pasquil-Gifford Dispersion Model is used to mathematically describe the CWA plume propagation (Pasquill, 1976). The CWA plume propagates along the X-axis while dispersing in the Y-Z plane following a Gaussian type distribution as show in in Figure 24. The cloud concentration at coordinate (X, Y, Z) is defined as follows:

$$C(x, y, z) = \frac{\dot{Q}}{2\pi\sigma_y\sigma_z\dot{U}} e^{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2 - \frac{1}{2}\left(\frac{z}{\sigma_z}\right)^2} \quad (4.5.1)$$

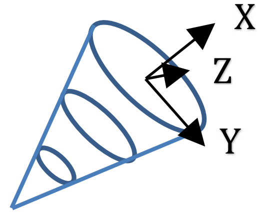


Figure 24. SE-CAS: Pasquil-Gifford Propagation

This function is a simplified version of the complete dispersion model under the following assumptions.

i. The origin of the CWA plume emission is at ground level.
ii. No CWA plume reflection off the ground is included in the concentration function.

User selects the emission rate and the wind speed as part of configuring the CWA plume for attack scenario.

$\dot{Q}$ – Emission Rate

$\dot{U}$ – Wind Speed

User can also select the CWA plume stability class (A, B, C, D, E, F) from the CWA plume configuration panel to compute dispersion coefficients σ_y, σ_z. The dispersion coefficient σ_z, is also a function of the total distance, X, traveled by the CWA plume at employment. With consideration to the ambient environment i.e. wind speed, the elapsed time since start of emission, X is computed as $x = \dot{U}\,\Delta t$, where Δt is the elapsed time since start of emission. Dispersion coefficients corresponding to each of the stability class computed are shown below (EPA, 1995).

Stability Class A:

$$\sigma_y = 0.493x^{0.88} \quad (4.5.2)$$

$\sigma_z = 0.087x^{1.10}, \quad \text{for } 100 \leq X \leq 300$
$\sigma_z = 10^{-1.67+0.902\, log_{10}x+0.181(log_{10}x)^2}, \quad \text{for } 300 < X \leq 3000$

Stability Class B:

(4.5.3)

$\sigma_y = 0.337x^{0.88}$
$\sigma_z = 0.135x^{0.95}, \quad \text{for } 100 \leq X \leq 500$
$\sigma_z = 10^{-1.25+1.09\, log_{10}x+0.0018(log_{10}x)^2}, \quad \text{for } 500 < X \leq 20{,}000$

Stability Class C:

(4.5.4)

$\sigma_y = 0.195x^{0.90}$
$\sigma_z = 0.112x^{0.91}, \quad \text{for } 100 \leq X \leq 100{,}000$

Stability Class D:

(4.5.5)

$$\sigma_y = 0.128x^{0.90}$$
$\sigma_z = 0.093x^{0.85}, \quad \text{for } 100 \leq X \leq 500$
$\sigma_z = 10^{-1.22+1.08\, log_{10}x-0.061(log_{10}x)^2}, \quad \text{for } 500 < X \leq 100{,}000$

Stability Class E:

(4.5.6)

$\sigma_y = 0.091x^{0.91}$
$\sigma_z = 0.082x^{0.82}, \quad \text{for } 100 \leq X \leq 500$
$\sigma_z = 10^{-1.19+1.04\, log_{10}x-0.070(log_{10}x)^2}, \quad \text{for } 500 < X \leq 100{,}000$

Stability Class F:

(4.5.7)

$\sigma_y = 0.067x^{0.90}$
$\sigma_z = 0.057x^{0.80}, \quad \text{for } 100 \leq X \leq 500$
$\sigma_z = 10^{-1.91+1.37\, log_{10}x-0.119(log_{10}x)^2}, \quad \text{for } 500 < X \leq 100{,}000$

Note: *All units for x, y, z, σ_y, σ_z are in meters [m]*

The cumulative CWA plume concentration is computed through summation of individual cloud cells at the location of employment. Given (X, Y, Z) location of the CWA plume, individual cloud cells concentration is computed as follows:

$$C(x,y,z) = \sum_{k=1}^{N} C_k(x_k, y_k, z_k) \qquad (4.5.8)$$

Here, (x_k, y_k, z_k) represents the location of the casualty relative to the k_{th} CWA plume emission origin transformed to the k_{th} CWA plume coordinate frame. This assumes the absolute location (e.g. in Earth Centered Earth Fixed system) would be first transformed to local coordinate frame, before applying the dispersion model to compute the concentration, and ultimately the total exposure dosage.

5.5.1 SE-CAS: Exposure Model

Symptoms are determined by the total accumulated dosage of CWA plume as a function of time, shown in Figure 9. Because CWA plumes and troops are moving (in cases where platform has route enabled) total concentration of CWA plume is also commuted as a function of time:

$$C(t) = C\big(x(t), y(t), z(t)\big) = \sum_{k=1}^{N} C_k(x_k(t), y_k(t), z_k(t)) \tag{4.5.1.1}$$

Hence the dosage is computed by integrating the CWA plume concentration in Equation 10 from start of exposure t_0 to the desired time (t_{0+n}):

$$D(t) = \int_{t_0}^{t} C\big(x(\tau), y(\tau), z(\tau)\big)d\tau \tag{4.5.1.2}$$

Given that the simulation is executed at a discrete sequence of times t_0, t_1 …. t_M, , as depicted in Figure 25, the total inhaled dosage is updated by approximating the above integral with its Riemann sum:

$$D(t_M) = \sum_{j=1}^{M} C\left(x(t_{j-1}), y(t_{j-1}), z(t_{j-1})\right)\Delta t_j \tag{4.5.1.3}$$

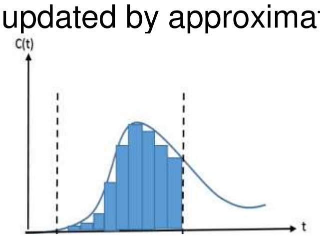


Figure 25. SE-CAS: Approximation with Riemann Sum.

Once the dosage is computed, symptomology is determined based on the referenced thresholds (mg-min/m^3).

i. $0 \leq D_{(t)} < 25$, Human shows no effects
ii. $25 \leq D_{(t)} < 100$, Human shows sensitivity in tender areas of body
iii. $100 \leq D_{(t)} < 250$, Human develops sore in tender areas of body
iv. $250 \leq D_{(t)} < 500$, Human develops blisters and swelling
v. $500 \leq D_{(t)} < 750$, Human develops raw ulcers
vi. $750 \leq D_{(t)} < 1500$, Human shows systemic effects
vii. $1500 \leq D_{(t)} < 4000$, Human exposes raw skin
viii. $4000 \leq D_{(t)} < 12000$, Human shows intoxication (~50% die)
ix. $12000 \leq D_{(t)}$, Human goes into shock with a high mortality rate

The above dosage levels are further grouped to provide health statistics and status.

i. $0 \leq D_{(t)} < 100$, Human is Alive
ii. $100 \leq D_{(t)} < 500$, Human Requires Attention
iii. $500 \leq D_{(t)} < 4000$, Human Condition is Critical
iv. $4000 \leq D_{(t)}$, Human is Deceased

The symptom progression is shown in the Health Status Plot, Route Lethality Plot and Health Statistics Plot displays, using consistent color-coding.

Below, Figure 26, is a snapshot of two CWA plume attacks (two attacks), of stability Class A and Class F set up for monte-carlo analysis mode. While stability Class A covering a wider area, exposure to a CWA plume of stability Class F proves more lethal to troop. With emission being concentrated to a narrow region (pencilbeam), the victim inhales significantly higher dosage in the same amount of time compared Class A, and develops fatal symptoms sooner.

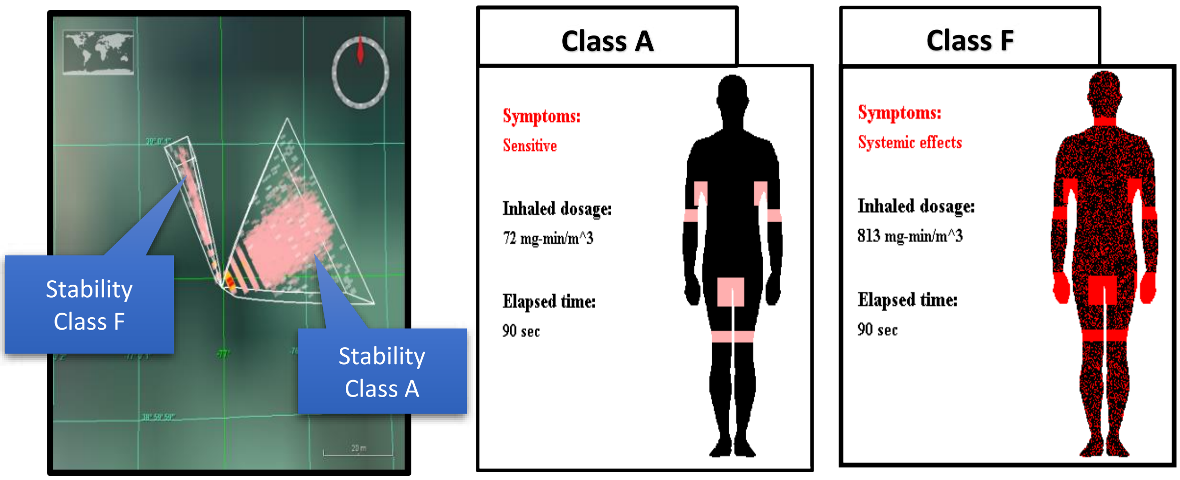


Figure 26. SE-CAS: Monte-Carlo Use Case

In the figure above, exposure to Class A, CWA plume is less concentrated and impacts a finite area for the same unit time opposed to Class F. Instinctively, a CWA plume covering a larger area would elicit greater collateral losses, whereas a direct attack restricted to a specific area is highly lethal to that region. Performance trades via monte-carlo mode, can be used to better understand optimization of route planning when CWA attack is done in an intelligent fashion.

5.6 SE-CAS: Design and Interface

The design and interface of SE-CAS' suite of analytical models, simulation components and services is represented below.

5.6.1 SE-CAS: Simulation Analytic Display Interface

Displays that are generate as a result of multiple runs such as monte-carlo of various case studies referenced in Figure 27. Model initialization and implementation of model classes *Analytic Display* and *Analytic Lethality Display*. *Analytic Lethality Display* summarizes lethality aspect of the CWA plumes, given defined case studies for monte-carlo analysis. Member functions include, incorporation of health status average duration from grep of lethality charts.

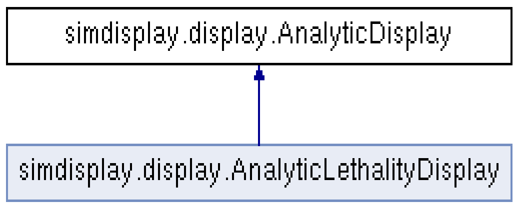


Figure 27. SE-CAS: Analytic Display Interface

5.6.2 SE-CAS: Analytic Report Interface

Report of lethality due to CWA plume exposure. Generation of lethality report. Include computing average CWA plume exposure time, summarizing results, report reset and new report generation. Implementation with *Analytic Lethality Report* and *Analytic Report*, shown in Figure 28.

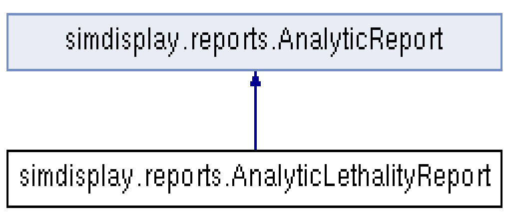


Figure 28. SE-CAS: Analytic Report Interface

5.6.3 SE-CAS: Base Model Interface

The Base Model interface, in Figure 29, contains a common set of methods implemented by all analytic models. Functions include: finalize model, initialize model, and update model. Implemented with *Cloud Model* and *Human Model*.

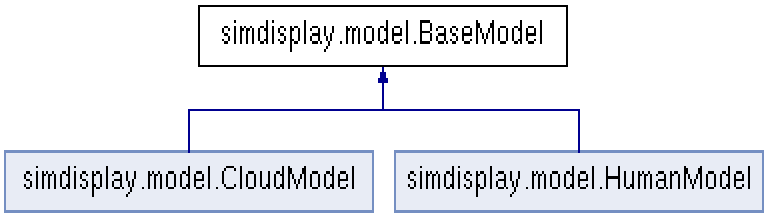


Figure 29. SE-CAS: Base Model Interface

5.6.4 SE-CAS: Simulation Display Scenario Global Data

The *Simulation Display Scenario Global Data Case Data* is a class with member functions and attributes to define scenario data, and allows return of requisite parameters represented in Table 9 below:

Table 9. SE-CAS Global Data.

Parameters	Description	Returns
agentTypeRangeStr	the agentTypeRangeStr to set	the agentTypeRange
cloudStabilityRangeStr	the cloudStabilityRangeStr to set	the cloudStabilityRange
emissionAltRangeStr	the emissionAltRangeStr to set	the emissionAltRange
emissionDurationRangeStr	the emissionDurationRangeStr to set	the emissionDurationRange
emissionLatRangeStr	the emissionLatRangeStr to set	the emissionLatRange
emissionLonRangeStr	the emissionLonRangeStr to set	the emissionLonRange
emissionRateRangeStr	the emissionRateRangeStr to set	the emissionRateRange
humanAltRangeStr	the humanAltRangeStr to set	the humanAltRange
humanLatRangeStr	the humanLatRangeStr to set	the humanLatRange
humanLonRangeStr	the humanLonRangeStr to set	the humanLonRange
humanSpeedRangeStr	the humanSpeedRangeStr to set	the humanSpeedRange
name	the name to set	the name
numCloudsStr	the numCloudsStr to set	the numClouds
numHumansStr	the numHumansStr to set	the numHumans
route	the route to set	the route
windHeadingRangeStr	the windHeadingRangeStr to set	the windHeadingRange
windSpeedRangeStr	the windSpeedRangeStr to set	the windSpeedRange

5.6.5 SE-CAS: Analytic Lethality Report

The *Analytic Lethality Report* manages data streams, in Table 10, for lethality data and statistics for a given case study. Allows return of requisite parameters represented below:

Table 10. SE-CAS Analytic Lethality Report.

Parameters	Description	Returns
mildEffectStartTimes *Str*	the mildEffectStartTimes Str to set	the mildEffectStartTimes
severeEffectStartTimes *Str*	the severeEffectStartTimes to set	the severeEffectStartTimes
deceasedStartTimes *Str*	the deceasedStartTimes Str to set	the deceasedStartTimes
name	the name to set	the name
moderateEffectStartTimes *Str*	the moderateEffectStartTimes Str to set	the moderateEffectStartTimes

5.6.6 SE-CAS: Cloud Model

The *Cloud Model* defines a single or individual cloud (CWA plume) particle. Functions include grepping NASA WorldWind ® sphere, and setting NASA WorldWind ® sphere. Also, Figure 30 described interface, simulates cloud propagation and characteristics, new cloud surface segment, cloud concentration at given location and time, summation of concentration of all neighboring clouds at given location and time (multiple clouds overlap a region of space), color of cell, processing cloud concentration within elliptical element, checks whether given rectangle is bounded by the ellipse centered at origin, grep cloud outline (in azimuth), update cloud state, add a back face to the cloud surface (volume), reinitialize the cloud model, and remove expired cells. Allows return of requisite parameters represented below.

5.6.7 SE-CAS: CWA (HD) Model Interface

The CWA (HD) Model Interface represents the HD agent and its exposure effects on a human model (target). Associated functions include description of exposure effects given dosage (mg-min/m^3) format and grepping health status based on dosage. Includes implementation with generic *Cloud Agent Model* and Cloud Agent HD model.

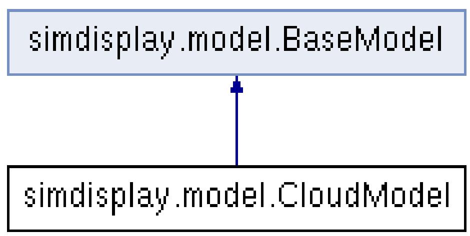


Figure 30. SE-CAS: Cloud Model Interface

5.6.8 SE-CAS: Cloud Dispersion Model

The *Cloud Dispersion Model* to enable CWA employment. Includes stability of the cloud plume to moderate based on stability classes. Allows return of requisite parameters from interface with Cloud Agent Type and Cloud Model shown in Figure 31.

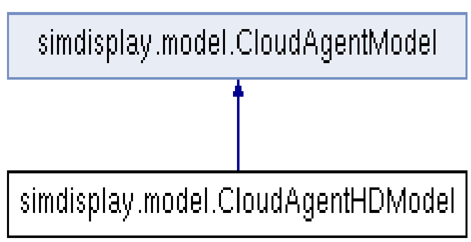


Figure 31. SE-CAS: CWA (HD) Interface

Table 11. SE-CAS Cloud Dispersion Model.

Parameters	Description	Returns
emissionRate *Str*	the emissionRate to set	the emissionRate
time*Str*	the time to set	the σ_y and σ_z array
creationTime*Str*	the creationTime to set	the creationTime
windSpeed	the name to set	the σ_y and σ_z array
stability*Str*	the stability to set	the stability

5.6.9 SE-CAS: Dynamic Display Interface

The *Dynamic Display* Interface in Figure 32 enables updates on execution across

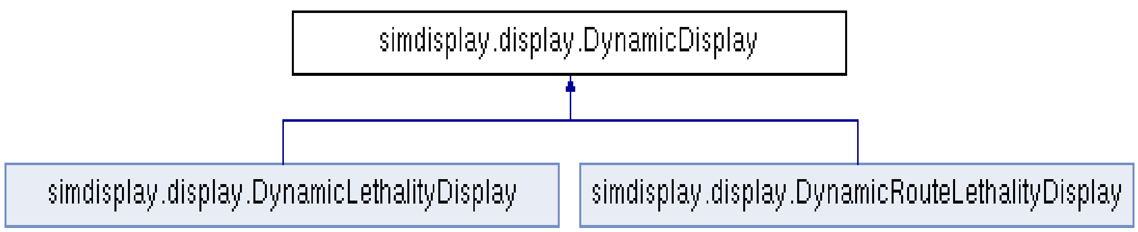


Figure 32. SE-CAS Dynamic Display Interface

Lethality and Route displays. Also include, model update and finalization.

5.6.10 SE-CAS: Dynamic Lethality Display Interface

The *Dynamic Lethality Display* Interface enables plot in Figure 33 updates in real-time for dosage inhalation over time. Includes initialization to display, update to cloud exposure data and establishing container panel.

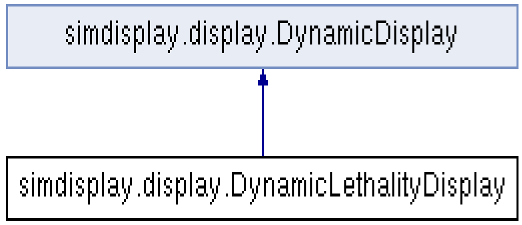


Figure 33. SE-CAS: Dynamic Lethality Display Interface

5.6.11 SE-CAS: Dynamic Route Lethality Display Interface

The *Dynamic Route Lethality Display* in Figure 34 Interface enables plots that update in real-time depicting dosage inhalation over time. Include functions to hide charts data, initialize display, update display, grep chart data, and update cloud exposure data

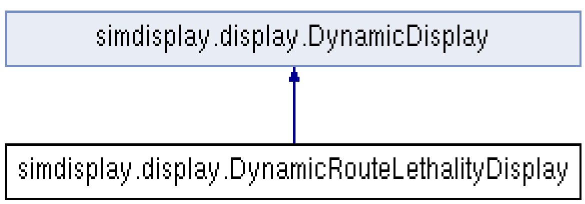


Figure 34. SE-CAS: Dynamic Route Lethality Display Interface

5.6.12 SE-CAS: Human Model Interface

The H*uman Model* Interface in Figure 35 enables effects simulation of human platform (troop) reaction to exposure.

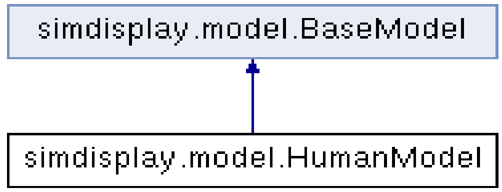


Figure 35. SE-CAS: Human Model Interface

The model interface includes core functions to finalize the model, remove graphical representation of the human model, refresh the human display, color tender areas of the body based on the calculated concentration and symptomology, initialize the human model with default values, add human symbol to the NASA WorldWind® display, create human symbol, and assess injury related exposure dosage in accordance to the categories described.

Table 12. SE-CAS: Human Model Interface Grid

Symptomology	Color Code	Dosage (mg-min/m^3)
No Effect	Red	0 – 25
Sensitive	Red	25 – 100
Sore	Red	100 – 250
Blister, Swelling	Red	250 – 500
Systemic	Red	1500 – 4,000
Intoxication	Red	4,000 – 12,000
Shock, High Mortality	Red	>12,000

Additional tasks include updates to model performance after every iteration of the simulation. Updates are made to the position of the human model and CWA attack origin. Evaluation of levels of exposure to clouds in the area and calculating the total concentration of all clouds, are some of the other tasks occurring as part of this interface. Next, is CWA HD Model initialization with calls to its function to gather health status data (dosage x 1000/60), calculation of symptom progression, and subsequent report of health status, plots updates and updates to model dosage (previousDosage + concentrationLastExposure x timeSinceLastExposure) for the next iteration relative to time.

Core SE-CAS Simulation Functions are summarized in Table 13.

Table 13. SE-CAS: Simulation Functions.

Simulation Models	Core Simulation Function (x)	Simulation Services	Simulation Visualization
Base Model	Interface with common set of methods implemented by all models	Scenario Repository	Main Display
Route Model	Waypoint definition (time, location, ECEF conversion in XYZ coordinates)	Sim Display Utilities_3x1	Health Display
Route Editor Model	Route repositioning, formation and drawlines	Sim Display Utilities_3x3	Analytical Lethality Display
Monte-Carlo Model	Constructor function allowing execution of monte-carlo methods regenerating and executing scenarios inputs	Analytical Lethality Reporting	Dynamic Lethality Display
Cloud Model	Formation, propagation, concentration, particle sizing	Analytical Reporting	Analytical Display
Human Model	Human reaction to cloud model, exposure, injury level, and body composite coloring	File Utilities	Dynamic Route Lethality Display
CBRN-E Agent Model	Interface for cloud agent and its exposure effects on human model or target	Execution Services	Dynamic Display
Distilled Mustard (HD) Model	Exposure effects based on cloud model output specific to distilled mustard agent	Global Data	NASA WorldWind Display
Cloud Dispersion Model	Execution of Pasquil-Gifford dispersion stability classes	Execution Services	Sim Display
NASA WorldWind® Model	Execution of terrain model functions	NASA WorldWind Utilities	Sim Display

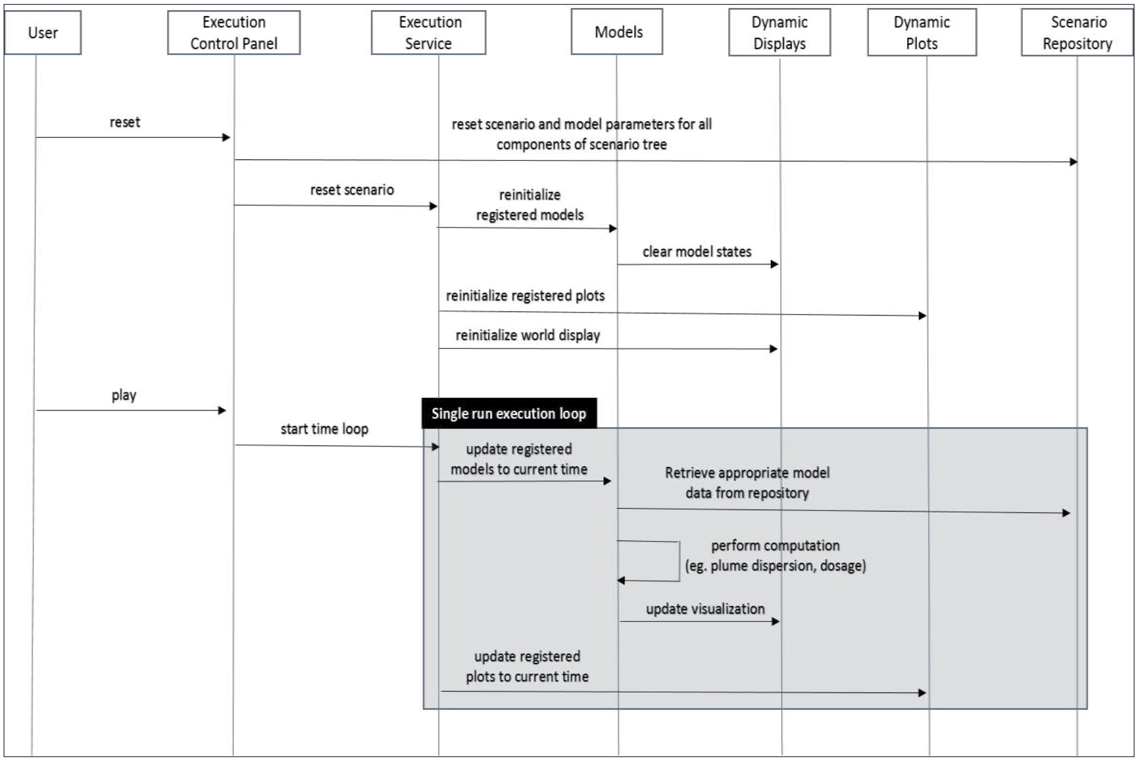


Figure 36. SE-CAS: Simulation Execution

5.6.13 SE-CAS: Integration of Model Components

Simulation execution is summarized in the sequence diagram depicted in Figure 36. While several separate sequence diagram could be realistically generated for the scenario building process where the components are registered within the execution service, here, we will limit to a single scenario run.

In addition to the overall execution steps, the internal steps of the CWA plume model, and human platform model, are discussed further. In particular, the illustration depicts aspects of the overall process where analytical models: Pasquil-Gifford and dosage exposure model are invoked, including associated and visualizations outputs.

In the case of monte-carlo analysis mode, SE-CAS runs an identical series of steps except, suspension of dynamic plots. In this particular case, the human platform model update follows all the steps up until updating the world display and the symptoms display, instead, case outputs are reported to further generate final plots.

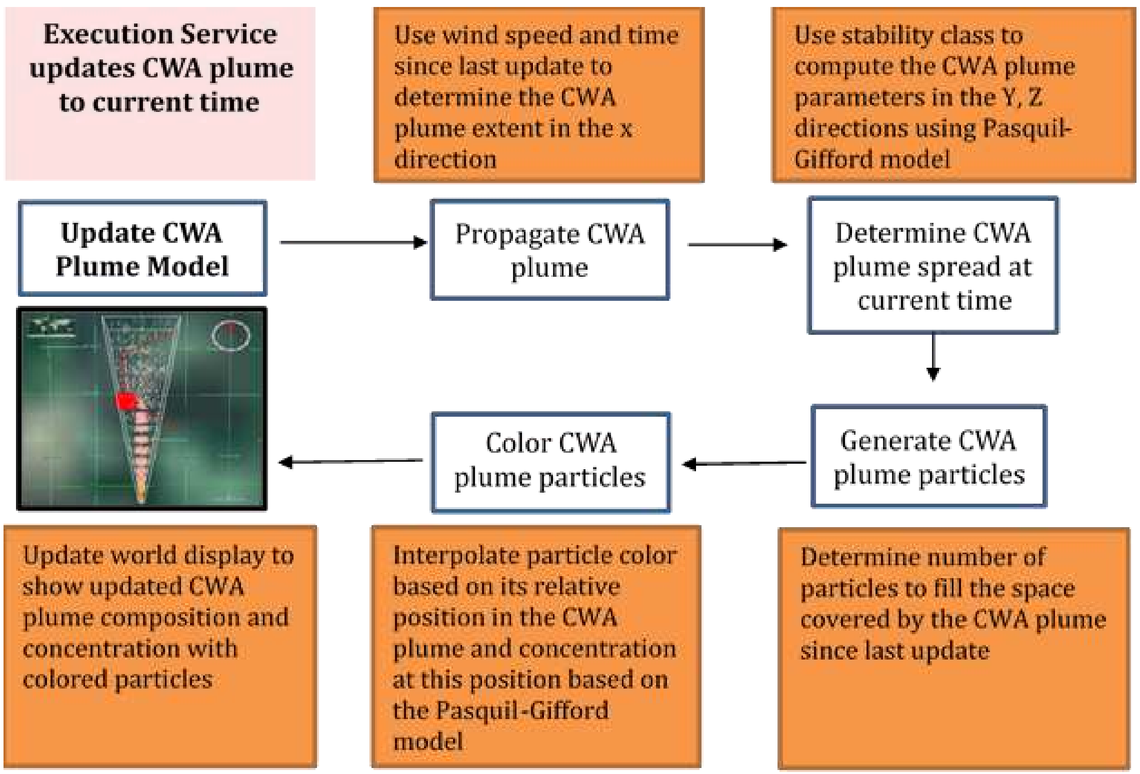


Figure 37. SE-CAS: CWA Plume Update Process

The CWA plume model update process for a single run is depicted in Figure 37 below. The human platform model update process for a single run is depicted in Figure 38 below.

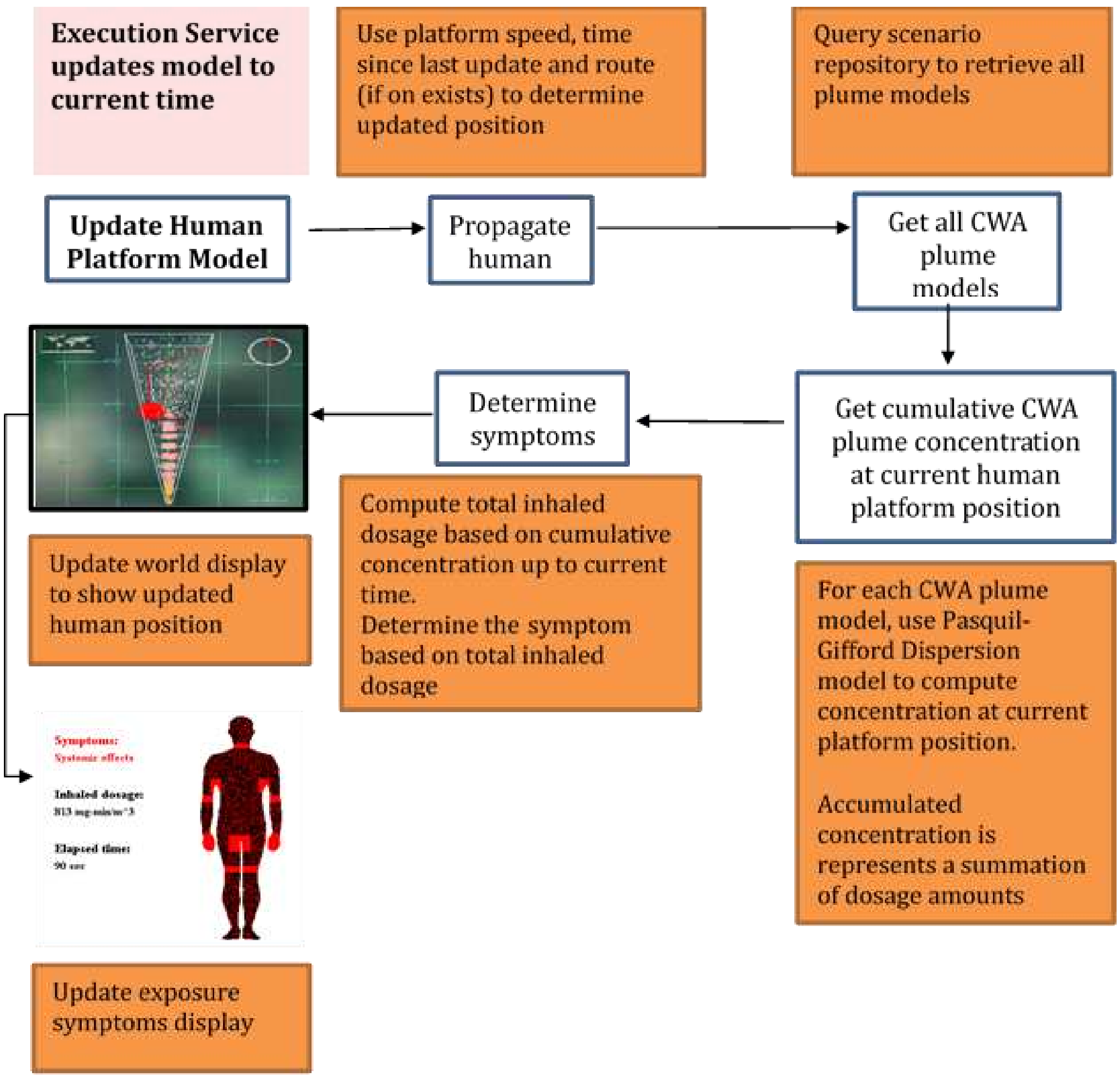


Figure 38. SE-CAS: Human Platform Update Process

5.6.14 SE-CAS: General Assumptions and Limitations

Below are some general assumptions and limitations of the SE-CAS simulation and interfaces, functions amongst integrated analytic meta-models.

General Assumptions:

i. Injury profile as a time-dependent function of physiological system symptoms to describe human response is based the AMedP-8(C) casualty estimation methodology.

ii. The AMedP-8(C) casualty estimation methodology assumes that individuals are normally health with no pre-existing physiological injuries or physiological conditions that would be expected to increase susceptibility and alter human response the CWA exposure.

iii. Based on the AMedP-8(C) casualty estimation methodology relative to chemical agents, toxicity data is expressed in mass per kilogram and which assume exposure to a 70 kg man. This body weight may not be typical of most military personnel, who can be significantly heavier (or lighter) than 70 kg. Being heavier may result in a less severe injury from a specified dose or dosage, as the amount of agent is distributed in a larger mass of tissue.

iv. The AMedP-8(C) casualty estimation methodology does not model medical countermeasures.

v. The AMedP-8(C) casualty estimation methodology does not estimate the number of individuals who recover or the time at which they would do so. This is due to the methodology not considering medical countermeasures or treatment.

vi. The AMedP-8(C) casualty estimation methodology does not represent duration of illness and time of recovery.

vii. The AMedP-8(C) casualty estimation methodology does not estimate battle stress (also commonly referred to as “psychological” or “psychological effects”) casualties.

viii. The AMedP-8(C) casualty estimation methodology models human response as agent/insult-related and time-dependent injury severity. In this methodology, human response is modeled by a series of injury profiles, which combine the time-dependent severities of symptoms as they are manifested in various physiological systems.

ix. Injury profiles induced by multiple routes of exposure or multiple insults are not synergistic. Although data exist that indicate that simultaneous injuries caused by multiple simultaneous insults may result in higher injury severity than would result from any single insult alone not enough information currently exists to determine the extent to which injury severity might be expected to change. As a result, when two or more injury profiles are combined, the resulting composite injury profile will follow the maximum severity level of the individual profiles at each point in time.

x. The chemical toxicity data underlying the AMedP-8(C) casualty estimation methodology are taken from the U.S. multiservice publication Potential Military Chemical/Biological Agents and Compounds, also published as U.S. Army Field Manual 3-11.9 (FM 3-11.9).

xi. Dosage is expressed as milligrams-minute per meter cubed ($\frac{mg-min}{m^3}$) for 70 kg.

xii. The toxicity data underlying the AMedP-8(C) casualty estimation methodology for chemical agents assumes exposed individuals are breathing at a rate of 15 liters per minute, which is the rate associated with light exertion.

xiii. Inhaled agents are retained and has negligible impact for chemical agents, since the mass of agent that would be exhaled and not retained is expected to be very small relative to the total mass of agent in the inhaled air.

xiv. The AMedP-8(C) casualty estimation methodology uses Haber's Law, which assumes that human response is a function of the dosage rate multiplied by the duration of exposure. Although battlefield chemical agent exposures are likely to be of varying lengths, the methodology assumes for chemical agents that all cumulative dosages and doses provide the same human response as would result from a two-minute exposure to the same amount of agent.

xv. For blister agents, like sulfur mustard (HD) from exposure to inhaled aerosol vapor, percutaneous HD vapor are assumed to be independent of one another and are represented by three separate injury profiles.

xvi. Inhaled HD vapor results in an injury profile based on symptoms manifested in the respiratory and upper gastrointestinal systems. Percutaneous HD vapor and equivalent percutaneous HD vapor (the vapor dosage equivalent to the composite percutaneous HD vapor dosage) result in injuries and symptoms manifested in the ocular system and skin respectively.

xvii. Shielding and exposure factor assumed value of '1'.

xviii. Physical protection factor, without employment of Mission Oriented Protective Posture (MOPP > Level 3), base protective gear, etc. assumed value of '0.1'.

General Limitations:

i. The AMedP-8(C) casualty estimation methodology is not suitable for estimating casualties among civilian populations, since civilian populations may be more susceptible to CBRN agents or effects.

ii. The physiological systems from which the injury profiles were derived do not necessarily represent all systems that might be impacted by exposure to a CBRN-E agent or effect. Rather, they represent those systems that would be expected to cause individuals to seek medical attention soonest—those that would be expected to manifest symptoms earliest and at the highest severity.

iii. Toxic-load is not considered (repair and recovery mechanisms which naturally occurs in the body and as such, exposure ranges independent of agent types, but volume of exposure).

iv. Representation of human exposure to partial dosages and the changes in human response as the dosage increases over time not considered or scientifically validated. Therefore, for ease of modeling, the human response and associated symptoms and injury had to be assumed to begin at the completion of exposure.

xix. It is possible that the interaction of human response resulting from exposure to inhaled HD and percutaneous HD may be synergistic, therefore, the assumption of the independence of human response given three routes of exposure may result in an underestimate of the number and severity of casualties.

xx. Second order casualty or fatality i.e. civilian fatality not considered.

xxi. Reflection of particulates with terrain surface not considered.

xxii. Employment of medical countermeasures or treatment plans is not considered.

xxiii. Ignore synergistic interaction of agents relative to composite systems impacted i.e. no super exposure state (no super exposure).

xxiv. Modeled distribution of response to exposure represents the ‘average’ outcome for the ‘average’ troop.

xxv. Partial dosage is not considered (exposure considered full exposure) human response begins at the completion of exposure.

xxvi. Weaponized release of liquid HD is not considered.

xxvii. Multiple routes of impact by same agent is not considered.

xxviii. Detoxification of CWA within the human model is not considered.

xxix. Allows single platform component per scenario (both single run and monte-carlo).

xxx. Monte-Carlo analysis includes average duration statistics of symptom progression reported as health status.

xxxi. Dispersion model’s motions are deterministic and linear (determined by fixed wind speed and direction).

5.6.15 SE-CAS: Use Case Exemplar – Forcible Entry / Civil Support

The Forcible Entry/Civil Support Mission CONOPS is presented to demonstrate the utility of SE-CAS to inform steering strategies. The Mission Tasks List is presented in Table 14 to orient the reader, followed by study question, approach, assumptions and supporting analysis results and discussion.

Table 14. Forcible Entry / Civil Support Mission Task List.

	Offensive Operations	Defensive Operations	Stability Operation	Civil Support Operations
Purpose	a) Dislocate, isolate, disrupts, and destroy enemy forces b) Seize key terrair c) Deprive the enemy of resources d) Develop intelligence e) Deceive and divert the enemy f) Create a secure environment anc stable operation	a) Deter or defea enemy offensive operations b) Gain time c) Achieve economy of force d) Retain key terrain e) Protect the populace, critical assets, and infrastructure f) Develop intelligence	a) Provide a secure environment b) Secure land areas c) Meet the critica needs of the populace d) Gain support fc host-nation government e) Shape the environment fo interagency an host-nation success	a) Save lives b) Restore essential services c) Maintain or restore law and order d) Protect infrastructure and property e) Maintain or restore local government f) Shape the environment foi interagency success
Primary Tasks	a) Movement to contact b) Attack c) Exploitation d) Pursuit	a) Mobile defens b) Area defense c) Retrograde	a) Civil security and security force assistanc b) Civil Control c) Restore essential services d) Support to economic and infrastructure development	a) Provide suppor for domestic disasters b) Provide suppor for domestic, CBRN-E high-yield explosive incidents c) Provide suppor for domestic civilian law enforcement agencies d) Provide other designated support

5.6.15.1 SE-CAS: Use Case Analysis of Steering Strategies

Strategic Statement:

Blue Force structure requires the ability to operate in areas contaminated by CBRN-E agents. Blue Force stands to benefit greatly should route of minimal exposure be determined before ingress.

Mission Decomposition:

a. Blue CONOPS requires seizure of Red high value asset (HVA).
b. Red deploys weaponized CWA plumes upon Blue breaking the defense zone.
c. Blue secure HVA and returns to base (FOB).

Scenario Assumptions:

a. Multiple CWA plumes deployed of varying concentration.
b. CWA plumes are steady state, continuous and instantaneous.
c. Operational area up to 1500 m.
d. Constant emission rate (Q) g/s.
e. Constant wind speed (U) m/s.
f. Variable distance downwind and dispersion stability class.
g. Blue is indestructible (zero fatality during mission. Blue Forces returns home).
h. Red Force capability intelligence delayed.

Approach:

a. Resolve Forcible Entry / Civil Support Mission CONOPS to an optimization brute force sub-problem to understand possible outcomes.

b. Determine shortest route to limit CWA exposure with minimal resource expended.

i. SE-CAS performance trades to enhance Red offensive capability i.e. most lethal CWA plumes based on pairing i.e. dispersion stability class, downwind distance, etc.

c. Employ technique in combinatorial mathematics and application of exhaustive search algorithm.

d. Total CWA plumes launched is 15 from spread across region at distances of: 500 m, 800 m, 1500 m, 3000 m and 5000 m.

e. Variable wind speed across fixed stability class (Class F: Stable)

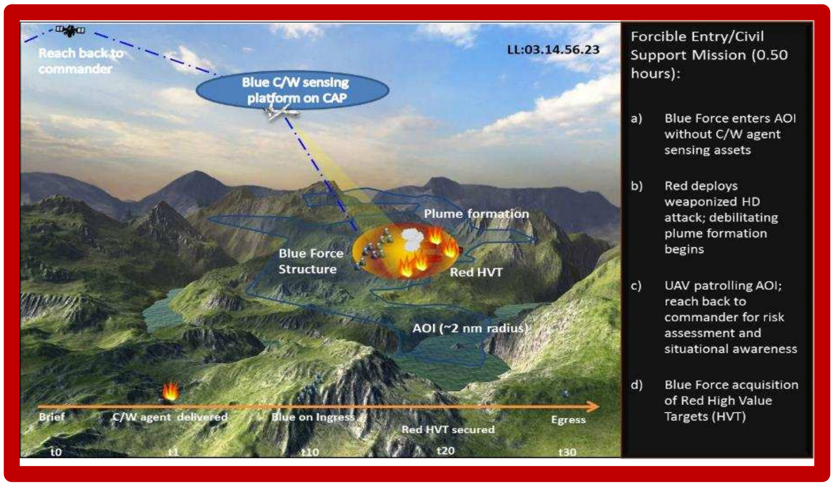
f. SE-CAS performance trades informs tables for concentration matrix

g. Maximum walking speed of 1.4 m/s or 1.5 minutes per 100 meters traveled.

Benefit*:*

a. SE-CAS, as a constructive simulation framework, enables performance trades of mission CONOPS to inform optimal steering strategy.

Case 1 – Dispersion Stability Class D (Neutral):



Forcible Entry / Civil Support Mission CONOPS

CONOPS expressed as Brute Force optimization sub-problem:

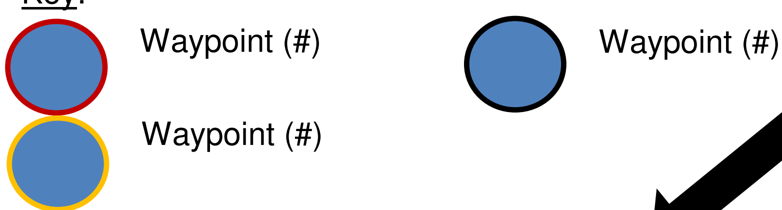
Dedicated Blue waypoints (numerated) along route.

Blue departs START point to secure Red assets, and return back to START point.

CWA Launch distance:

i. Red – 500m
ii. Yellow – 800m
iii. Black – 1500m

Key:



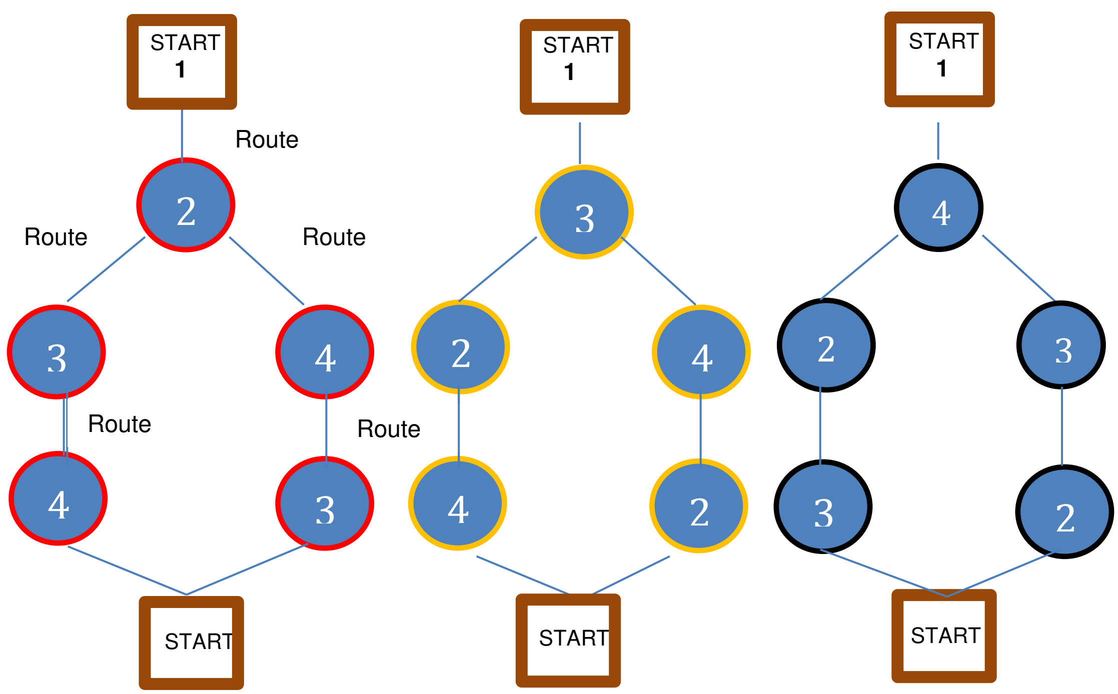


Figure 39. SE-CAS: Optimization Approach

SE-CAS is used to determine level of concentration at each relative distance, across all launch locations, as depicted in Table 15. Concentration is determined through offline analysis based on the listed conditions and initial parameters passed through SE-CAS.

Table 15. Use Case 1: Scenario Initial Conditions.

Emission Rate:	1	m/s
Emission Duration:	**1080**	s
Maximum Distance:	1500	m
	@ 500 m	
	@ 800 m	
	@**1500 m**	
Stability Class:	5 x Class A	
	5 x Class D	
	5 x Class F	
Emission Latitude:	39.00	deg
Emission Longitude:	-77.00	deg
CWA Agent Type:	HD	
Emission Altitude:	1	m
Wind Speed:	1	m/s
Wind Heading:	360	deg
Cloud Cell Sparcity:	1	
Propogation Frequency:	1	Hz
Human Platform Latitude:	39.00	deg
Human Platform Longitude:	-77.00	deg
Human Platform Altitude:	1	m
Human Platform Speed:	**0.00**	m/s

Sample injury profile output in Figure 40 represents Case 1. This serves as input into Table 16 Use Case 1 Cumulative Concentration Matrix.

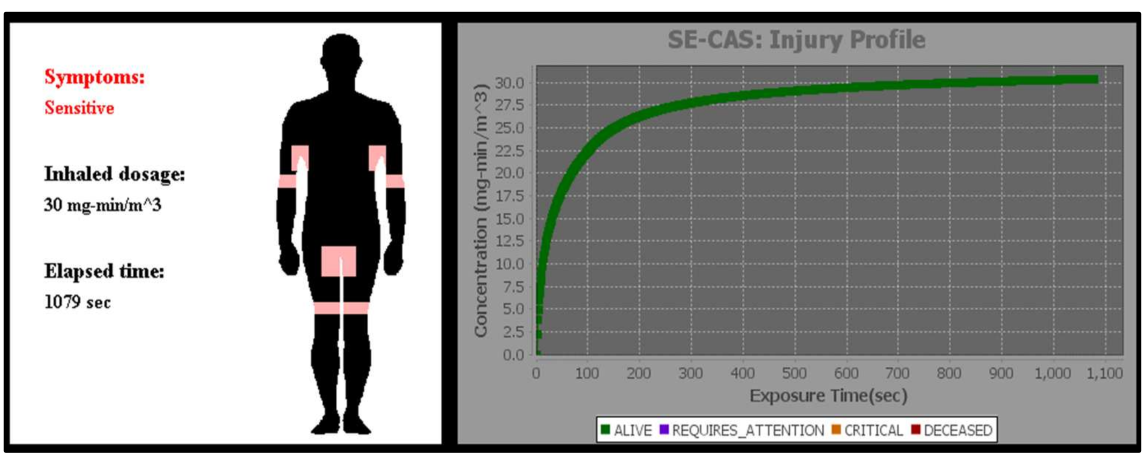


Figure 40. Use Case 1: Injury Profile

A matrix of concentration values (15 cases x 100 run per case) is determined and assigned accordingly, which are inputs used in the forward mathematical expression to address the study question of this analysis.

Table 16. Use Case 1: Cumulative Concentration Matrix

	Waypoint #1	Waypoint #2	Waypoint #3	Waypoint #4
WP #1	0 mg/m^3	30.121 mg/m^3	30.111 mg/m^3	30.123 mg/m^3
WP #2	30.115 mg/m^3	0 mg/m^3	30.114 mg/m^3	31.114 mg/m^3
WP #3	30.122 mg/m^3	30.122 mg/m^3	0 mg/m^3	31.111 mg/m^3
WP #4	30.121 mg/m^3	30.111 mg/m^3	30.112 mg/m^3	0 mg/m^3

Assigning arbitrary values i.e. (*1, 2, 3* and *4*) allows for mathematical representation in the general form: $g(1, \{2,3,4\}) = \min[c_{ik} + g\,(k, \{2,3,4\} - \{k\})]$. $Where\ k\ =\ (2,3,4)$ Based on this expression, concentration parameters is determined for each 15 CWA launch site, therefore each leg of the route from Blue FOB to secure the HVA within the 1500 m operational area, and back.

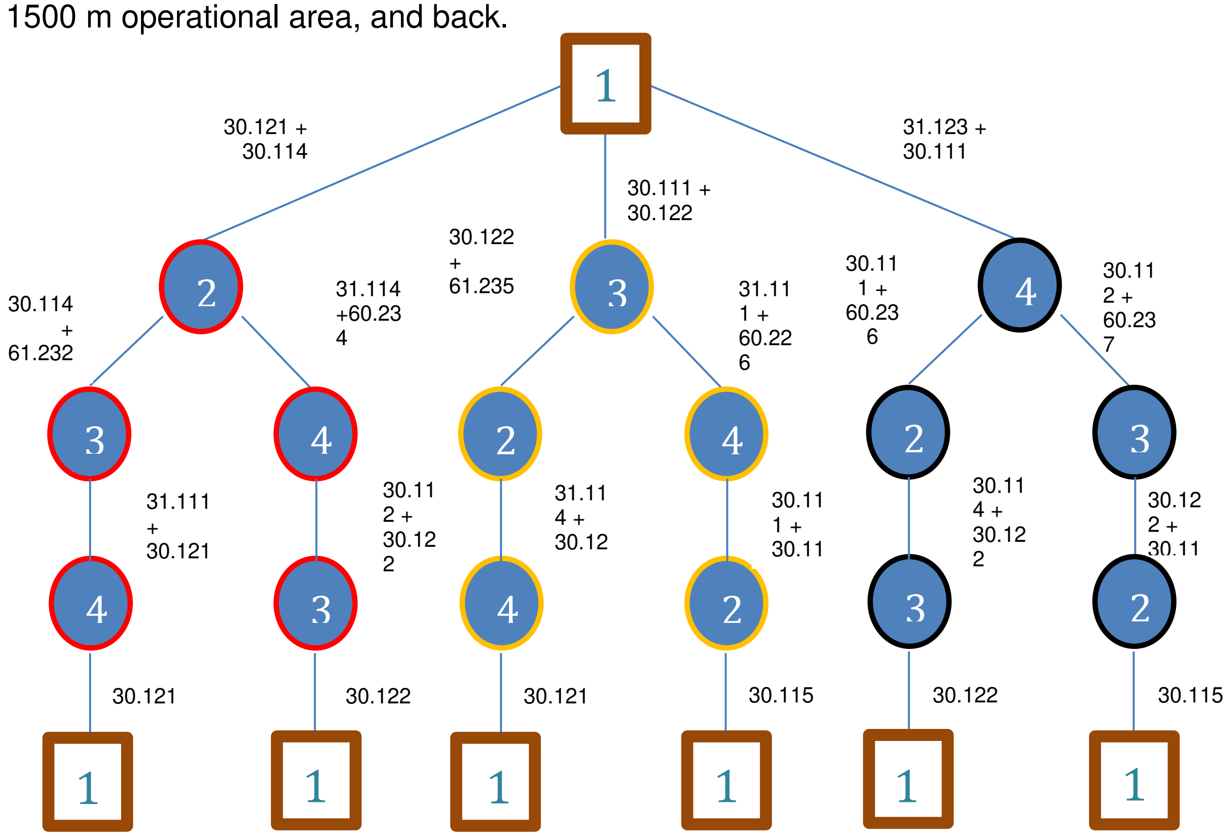


Figure 41. Use Case 1: Optimization

Respectively, the general mathematical expression is reduce to the following form: $g(i,s) = \min_{k<-s}[c_{ik} + g\ (k, s - \{k\})]$. Computation of concentration along each route as represented in Figure 42, resolves itself to the route of least exposure based on: $g(1) = 121.448 \frac{mg}{m^3}$, indicated in red.

Class D: Neutral	
level 1	
g(2,1)	30.115
g(3,1)	30.122
g(2,1)	30.115
g(4,1)	30.121
g(3,1)	30.122
g(4,1)	30.121

level 2	
g(3,2)	60.237
g(2,3)	60.236
g(4,2)	60.226
g(2,4)	61.235
g(4,3)	60.234
g(3,4)	61.232

level 3	
g(4,3)	90.349
g(4,2)	90.347
g(3,4)	91.337
g(3,2)	91.357
g(2,4)	91.348
g(2,3)	91.346

level 4	
g(1,4)	121.470
g(1,3)	121.448
g(1,2)	121.467

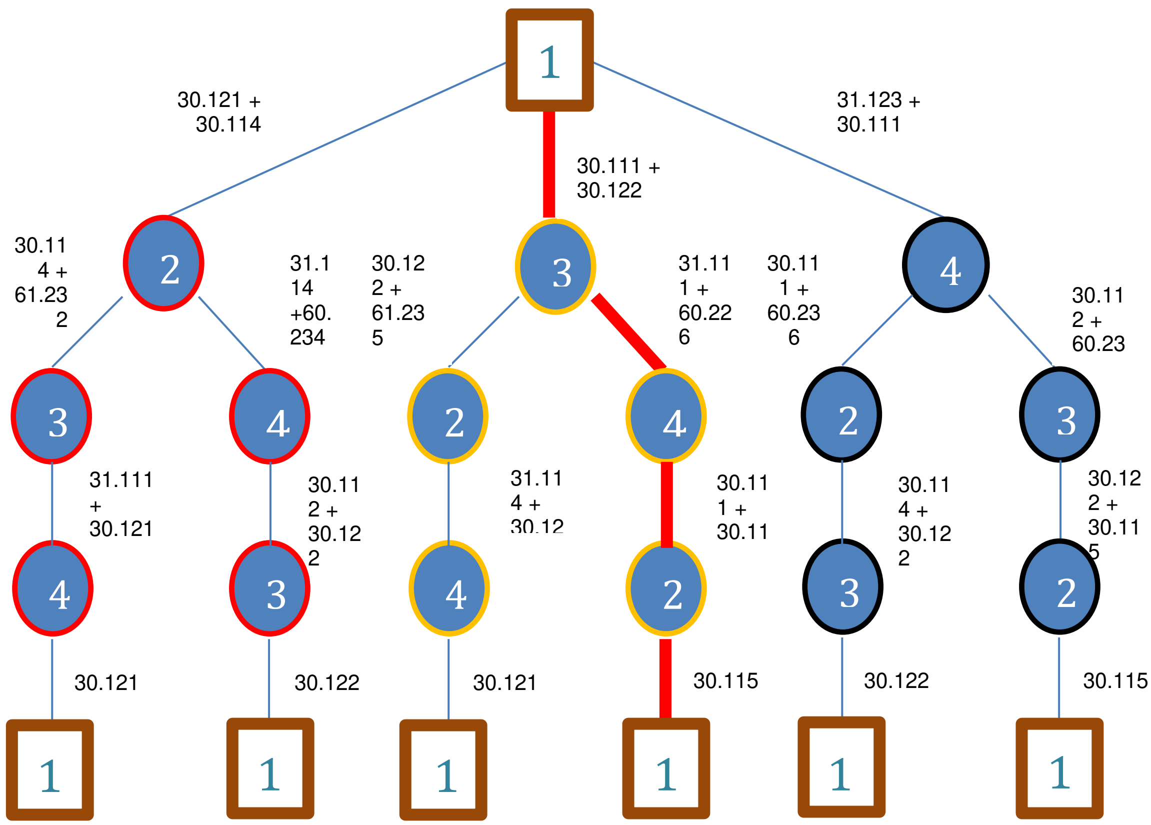


Figure 42. Use Case 1: Optimization Outcomes

The results of Case 2 and Case 3 are presented in the following sections based on updated concentration values given performance trades done in SE-CAS.

<u>Case 2 – Stability Class A (Unstable)</u>:

Taking Case 2 updated scenario initial conditions from Table 17 below, results in the change to the stability class and downwind distance as follows.

Table 17. Use Case 2: Scenario Initial Conditions.

Emission Rate:	1	m/s
Emission Duration:	**1080**	s
Maximum Distance:	1500	m
	@ 500 m	
	@ **800 m**	
	@1500 m	
Stability Class:	**5 x Class A**	
	5 x Class D	
	5 x Class F	
Emission Latitude:	39.00	deg
Emission Longitude:	-77.00	deg
CWA Agent Type:	HD	
Emission Altitude:	1	m
Wind Speed:	1	m/s
Wind Heading:	360	deg
Cloud Cell Sparcity:	1	
Propogation Frequency:	1	Hz
Human Platform Latitude:	39.00	deg
Human Platform Longitude:	-77.00	deg
Human Platform Altitude:	1	m
Human Platform Speed:	**0.00**	m/s

Figure 43 provide a sample injury profile output for Case 2. This serves as input into Table 18 Use Case 2 Cumulative Concentration Matrix.

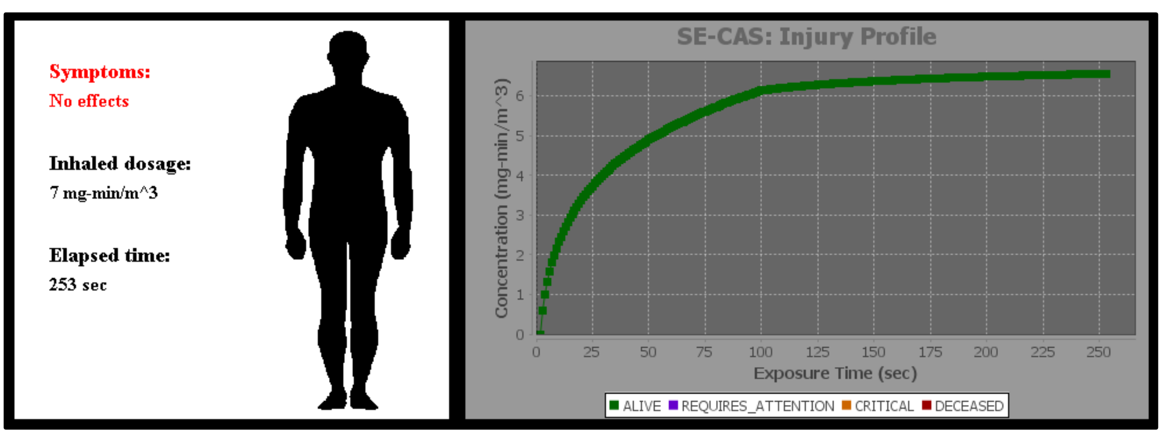


Figure 43. Use Case 2: Injury Profile

These conditions passed through SE-CAS results in updated concentration data shown in Table 18, which is further used to determine path of minimum exposure to weaponized release of CWA.

Table 18. Use Case 2: Cumulative Concentration Matrix.

	Waypoint #1	Waypoint #2	Waypoint #3	Waypoint #4
WP #1	0 mg/m^3	7.881 mg/m^3	7.885 mg/m^3	7.885 mg/m^3
WP #2	7.887 mg/m^3	0 mg/m^3	7.887 mg/m^3	7.882 mg/m^3
WP #3	7.885 mg/m^3	7.881 mg/m^3	0 mg/m^3	7.883 mg/m^3
WP #4	7.883 mg/m^3	7.881 mg/m^3	7.881 mg/m^3	0 mg/m^3

In Figure 44, based on numeric value where $g(1) = 31.531 \frac{mg}{m^3}$, the path of least exposure to CWA in Case 2, indicated in red, is:

Class A: Unstable

level 1	
g(2,1)	7.887
g(3,1)	7.885
g(2,1)	7.887
g(4,1)	7.883
g(3,1)	7.885
g(4,1)	7.883

level 2	
g(3,2)	15.768
g(2,3)	15.772
g(4,2)	15.768
g(2,4)	15.765
g(4,3)	15.766
g(3,4)	15.766

level 3	
g(4,3)	23.649
g(4,2)	23.653
g(3,4)	23.651
g(3,2)	23.646
g(2,4)	23.648
g(2,3)	23.653

level 4	
g(1,4)	31.534
g(1,3)	31.531
g(1,2)	31.535

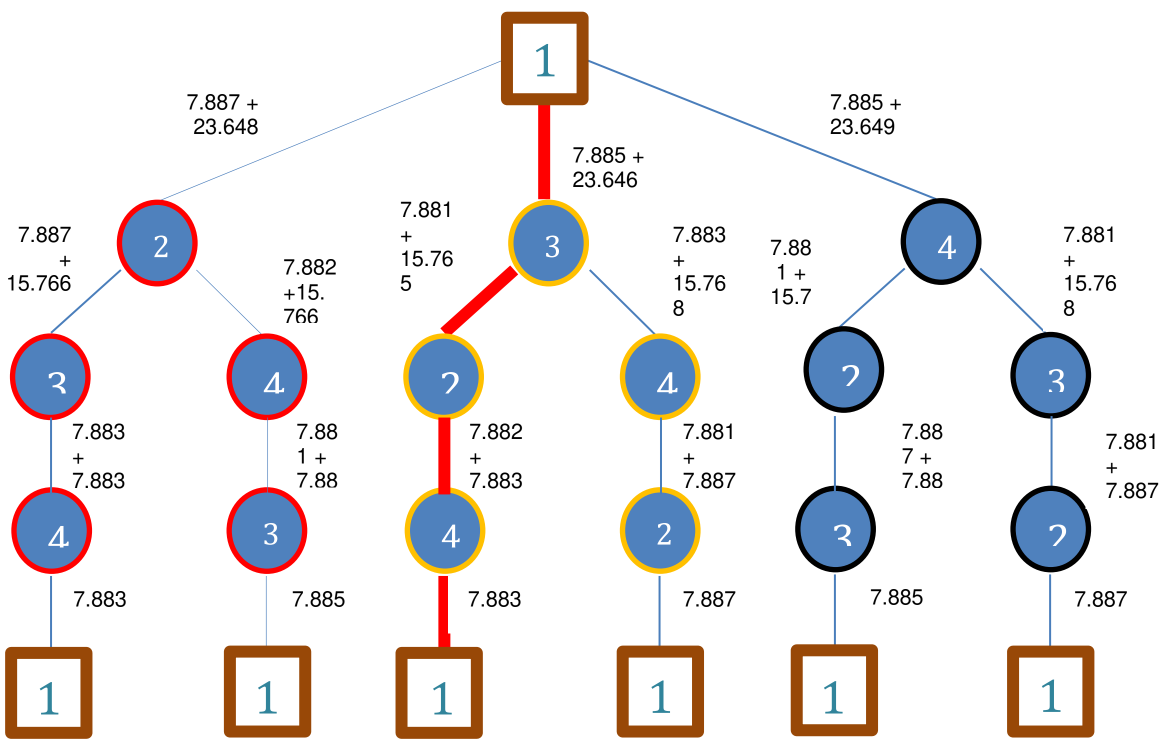


Figure 44. Use Case 2: Optimization

Case 3 – Stability Class F (Stable):

Case 3 follows suit with variation in dispersion stability class according to Table 19, to a cloud system stable in its makeup.

Table 19. Use Case 3: Scenario Initial Conditions

Emission Rate:	1	m/s
Emission Duration:	1080	s
Maximum Distance:	1500 @ 500 m @ 800 m @1500 m	m
Stability Class:	5 x Class A 5 x Class D 5 x Class F	
Emission Latitude:	39.00	deg
Emission Longitude:	-77.00	deg
CWA Agent Type:	HD	
Emission Altitude:	1	m
Wind Speed:	1	m/s
Wind Heading:	360	deg
Cloud Cell Sparcity:	1	
Propogation Frequency:	1	Hz
Human Platform Latitude:	39.00	deg
Human Platform Longitude:	-77.00	deg
Human Platform Altitude:	1	m
Human Platform Speed:	0.00	m/s

Sample injury profile output in Figure 45 represents Case 3. This serves as input into Table 20 Use Case 3 Cumulative Concentration Matrix.

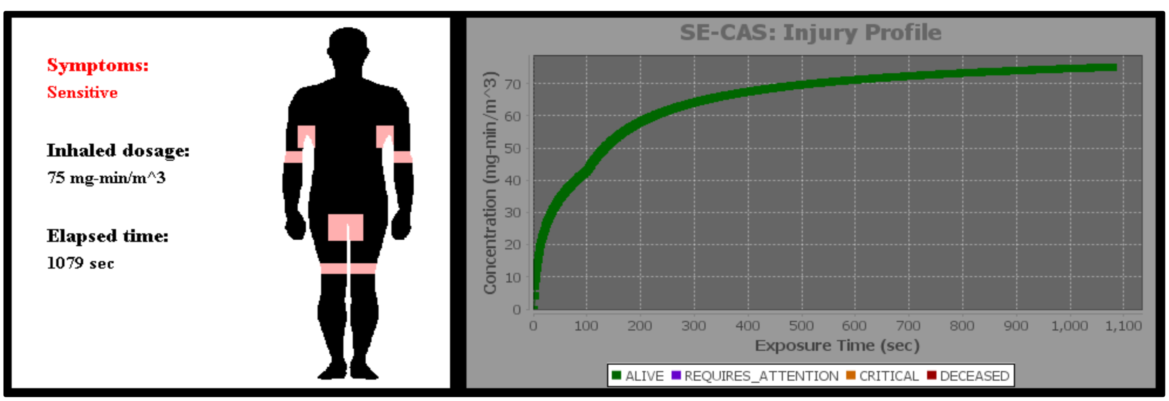


Figure 45. Use Case 3: Injury Profile

	Waypoint #1	Waypoint #2	Waypoint #3	Waypoint #4
WP #1	0 mg/m^3	75.019 mg/m^3	75.017 mg/m^3	75.005 mg/m^3
WP #2	75.019 mg/m^3	0 mg/m^3	75.014 mg/m^3	75.007 mg/m^3
WP #3	75.017 mg/m^3	75.001 mg/m^3	0 mg/m^3	75.003 mg/m^3
WP #4	75.008 mg/m^3	75.008 mg/m^3	75.001 mg/m^3	0 mg/m^3

In Case 3, the path to minimal exposure to CWA indicated in red in Figure 46,

where $g(1) = 300.239 \frac{mg}{m^3}$, is:

Class F: Stable		level 2		level 3		level 4	
level 1							
g(2,1)	75.019	g(3,2)	150.020	g(4,3)	225.613	g(1,4)	300.618
g(3,1)	75.017	g(2,3)	150.031	g(4,2)	236.126	g(1,3)	328.149
g(2,1)	75.019	g(4,2)	150.027	g(3,4)	261.881	g(1,2)	300.239
g(4,1)	75.008	g(2,4)	150.015	g(3,2)	253.132		
g(3,1)	75.017	g(4,3)	150.018	g(2,4)	236.182		
g(4,1)	75.008	g(3,4)	150.011	g(2,3)	225.220		

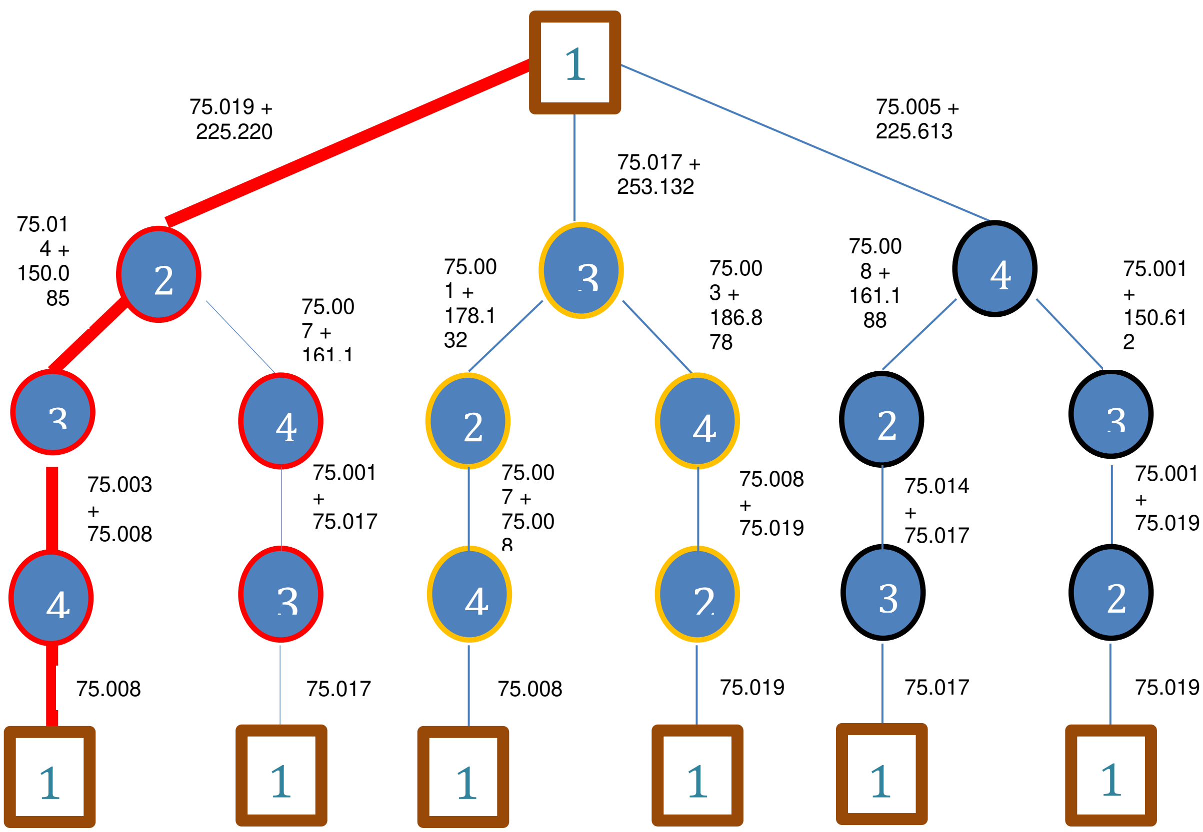


Figure 46. Use Case 3: Optimization Outcomes

Comparing outcome across each case presented, reveals some interesting insights for the purposes of planning and response strategies:

i. *Case 1 - Neutral (Class D)*: conditions at, $g(1) = 121.448\frac{mg-min}{m^3}$ across 1500 m operational area, would cause immediate impact to ocular systems, having exceeded the 75 mg-min/m^3 threshold. This aligns with Severity 2, becoming 3 with increased exposure. Here troops will experience eye pain and or irritation with conjunctival erythema (constant eye twitching), difficulty opening eyes for prolong periods creating obvious implication towards mission success.

ii. *Case 2 - Unstable (Class A)*: the instability of cloud conditions to support the median of CWA plume transfer over the 800 m operation area, is the single limiting factor. At concentration of $g(1) = 31.531\frac{mg-min}{m^3}$, this constitutes mild toxicity and corresponds to Severity 0 relative to ocular systems, and negligible to respiratory and gastrointestinal systems.

iii. *Case 3 - Stable (Class F)*: with concentration of $g(1) = 300.239\frac{mg-min}{m^3}$, is equally critical to ocular systems and registers well above the 75 mg-min/m^3 threshold, and is deemed sever with Severity 3. Here, moisture levels within the eyes and surrounding tissues bring on deep symptoms quickly. Troops are likely to experience an inability to open their eyes, with death likely with a lethal dose (LD) resulting in death at a 50% rate.

5.6.16 SE-CAS: Comparative Assessment of Cloud Dispersion Models

SE-CAS is developed to support quick-turn analysis during weaponized release of CWA. Having detailed the primary simulation components and integrated analytic models in previous sections, we look to compare the cloud dispersion model for reasonableness against a standardized industry variant, the Pasquill-Gifford Gaussian Model. Because the cloud dispersion model is integral to SE-CAS, available for reference in existing published sources, and is mathematically represented, it is most suitable for comparative assessment.

A test for reasonableness was done against both model variants to understand likely convergence of concentration outputs in a simplified case. SE-CAS' cloud dispersion equation for (*X, Y, Z*) points in space shown in (Eq. 4.6.16.1) was resolved to (Eq. 4.6.16.2) to enable a 1-for-1 model comparison of concentration at ground level, against the Pasquill-Gifford variant.

$$C(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} e^{-\frac{y^2}{2\sigma_y{}^2}} \left(e^{-\frac{(z+H)^2}{2\sigma_z{}^2}} + e^{-\frac{(z-H)^2}{2\sigma_z{}^2}} \right) \qquad (4.6.16.1)$$

$$C(x,0,0) = \frac{Q}{\pi u \sigma_y \sigma_z} e^{-\frac{H^2}{2\sigma_z{}^2}} \qquad (4.6.16.2)$$

In this simplified case, monte-carlo analysis was performed varying wind speed and distance from CWA release point downwind to determine average concentration output. A total of 50 runs were completed, spread across 10 cases. Monte-carlo data output is captured in Appendix A through Appendix J for all 10 cases modeled. Inputs passed to both SE-CAS and Pasquill-Gifford models include:

i. Emission Rate (Q)
ii. Wind Speed (U); varying [1,3,5,7,9,11,13,15,17, 19] m/s
iii. Coefficient or standard deviation in horizontal direction (σ_y)

iv. Coefficient or standard deviation in vertical direction (σ_z)

v. Stack Height (H); set at 1 m by default (negligible)

vi. Stability Class; Class F by default

vii. Downwind distance; varying [0.5,0.8,1.5,3,5] m

A summary of modeled results below is tabulated and plotted for comparison. Figure 47 highlights concentration values from SE-CAS, and is similar in output to the Pasquill-Gifford model shown in Figure 48. Both figures are based on concentration at ground level along centerline (mg/m^3) at referenced distances (km) from the emission source under dispersion stability Class F (Stable).

SE-CAS Cloud Dispersion Model

Distance Downwind (KM)

Wind Speed (M/S)	**0**	**0.5**	**0.8**	**1.5**	**3**	**5**
1	**0**	114.710115	95.148351	38.001913	5.986918	0.505491
3	**0**	68.486174	41.328945	14.029616	2.082580	0.170883
5	**0**	48.267518	11.599608	3.203972	0.466739	0.045803
7	**0**	37.407299	2.420932	0.546227	0.095596	0.019044
9	**0**	30.607072	0.411838	0.070137	0.012403	0.003656
11	**0**	25.945179	0.056982	0.049044	0.006892	0.001283
13	**0**	22.547843	0.008746	0.002774	0.002845	0.001207
15	**0**	19.947791	0.000847	0.000390	0.000861	0.000176
17	**0**	17.898640	0.000479	0.000172	0.000121	0.000659
19	**0**	16.233506	0.000204	0.000339	0.000201	0.000893

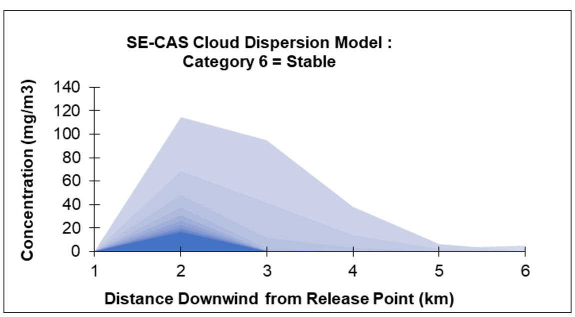


Figure 47. SE-CAS: Data Table for Comparative Analysis

Pasquill-Gifford Gaussian Model

Distance Downwind (KM)

Wind Speed (M/S)	**0**	**0.5**	**0.8**	**1.5**	**3**	**5**
1	**0**	114.711166	95.156184	37.967573	5.986432	0.508985
3	**0**	68.482289	41.331375	14.039205	2.087112	0.180370
5	**0**	48.284347	11.590065	3.233561	0.443224	0.049128
7	**0**	37.409372	2.414541	0.561622	0.095428	0.010943
9	**0**	30.615774	0.410667	0.070489	0.012206	0.003190
11	**0**	25.943652	0.055242	0.046691	0.006095	0.001363
13	**0**	22.549282	0.008905	0.002941	0.002912	0.001244
15	**0**	19.952186	0.000724	0.000189	0.000123	0.000129
17	**0**	17.893950	0.000414	0.000182	0.000101	0.000404
19	**0**	16.227008	0.000214	0.000409	0.000290	0.000157

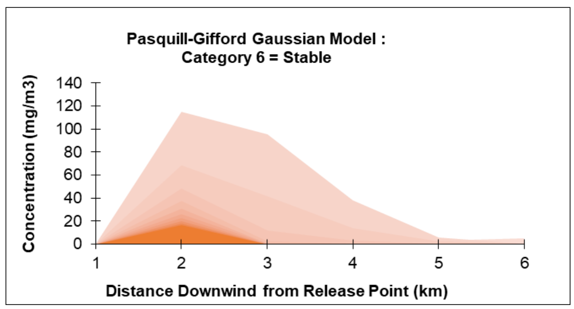


Figure 48. Pasquill-Gifford: Data Table for Comparative Analysis

Consistent with Figure 49 plot display, SE-CAS and the Pasquill-Gifford models behave similarly when determining average concentration beyond the release point at varied wind speeds.

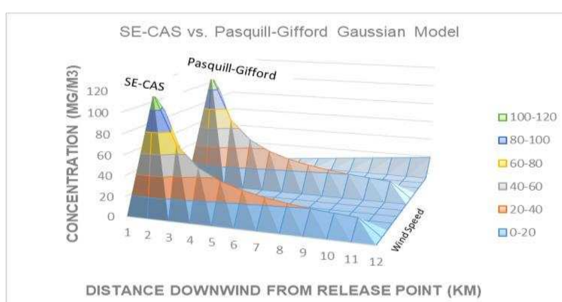


Figure 49. Cloud Dispersion Model Comparison

Chapter 6

6. Conclusion

This dissertation presented a robust systems engineering framework to satisfy the primary study objective:

Provide a robust systems engineering framework for creating chemical warfare simulations that is modular and customizable.

Current CBRN-E M&S tool offerings provide limited capabilities to visualize areas of chemical warfare agent dispersion, symptomology and exposure effects, and prescription of optimal survival factors. Development of the SE-CAS framework to fill this gap required detailed understanding of customer needs, industry tools: their capabilities and assessment of strengths and weaknesses, specialize topic in CBRN-E casualty estimation and response planning. This led to clearly defined performance parameters, system and software requirements, interface sequence diagrams and appropriate mission CONOPS to demonstrate utility.

Combining the reference subject matter led to a key finding early in the process. The need for use of dynamic models enhanced the capabilities of SE-CAS by enabling exploration of several survival factors in a manner not presently available in CBRN-E M&S tools. The results of this led to development of a Human Platform Model and CWA (HD) Platform Model that both responded dynamically to the ambient environment to more accurately determine CWA propagation, concentration, exposure dosage and symptomology.

Studies performed in this dissertation, as part of the research questions explored, provide an optimal response plan during weaponized releases of CWA, which is the direct result of the use of the SE-CAS framework as a practical solution to fill the gap in CBRN-E M&S tool offerings. The tool, analysis and methods prescribed will advance the state of the systems engineering practice in modeling, simulation and analysis of chemical warfare agents during simulated military operations.

6.1 Contributions of this Dissertation

The primary contributions of this dissertation are:

i. Advanced the state of the systems engineering practice in modeling, simulation and analysis of chemical warfare agents during simulated military operations.
ii. Created robust systems engineering framework for creating chemical warfare simulations that is modular and customizable.
iii. Developed a practical, software solution to fill gaps in CBRN-E M&S tool offerings.
iv. Integrated newly created dynamic models compatible with CBRN-E platforms.
v. Applications include Live, Virtual and Constructive training and operational planning for joint warfare integrated systems assessments.

6.2 Future Work

Adopting SE-CAS as a simulation of choice to evaluate response strategies with weaponized release of CWAs is best achieved as an add-on to existing mission and engagement-models at the constructive level of simulation. This will require further refinement of core analytical models, and requisite utilities, visualization interfaces and simulation components. Here is a comprehensive list of core improvements to enhance applicability and adaption amongst practitioners.

i. *Cloud Particle Size Scattering*: cloud scattering growth on CWA release is achieved by cloud cell particle sparsity, which is randomized and dispersed following a simple exponential growth algebraic function. This be further refined or replace with for precision. [Level of Impact - Low].

ii. *CBRN-E Agent Modeling*: effects of HD release is modeled in SE-CAS, integration of engineering-level HD model for higher levels of fidelity and representation further enhances overall capabilities of SE-CAS. [Level of Impact - Medium].

iii. *Equations of Motions*: use of physical systems in SE-CAS is bolstered through application of mathematical functions in terms of dynamic variables, momentum and time components. [Level of Impact - Medium].

iv. *CBRN-E Agents:* SE-CAS was built with HD as the default CWA. Incorporation of additional CWAs, and or biological warfare (B/W) agents, could enhance the performance trade space. [Level of Impact - High].

v. *CBRN-E Agent Multi-Effects*: moving beyond singular effects to multi-effects that are both independent and interdependent improves rigor of analysis. [Level of Impact - High].

vi. *Human Model & Platforms*: availability of troop force structure, multiple platforms (e.g. platoons, brigades, etc.) within the performance trade space improves evaluation of steering strategies. [Level of Impact - Medium].

vii. *Cloud Dispersion Modeling*: incorporation of stochastic propagation techniques due to random environmental effects for added fidelity. [Level of Impact - High].

viii. *CONOPS & CONEMP*: solving the optimization problems by leveraging concepts from evolutionary algorithms, artificial neural networks and game theory enhance SE-CAS' utility for application outside military scenarios. Possible applications include:

   a. (Blue Strategy). Route planning to minimize casualty under a given distribution of CWA plumes. [Level of Impact - Medium].

   b. (Red Strategy). Strategy to launch minimum number of CWA plumes to cause maximum damage. Possible control variables include agent types, emission locations and dispersion behavior. [Level of Impact - Medium].

ix. *Operator-In-the-Loop (OITL)*: incorporation of man in the loop capability, where one side plays Red (cause maximum casualty given CWA release), and the other side plays Blue (minimize casualty) to shore up level of confidence with SE-CAS results. [Level of Impact - High].

x. *Design of Experiments (DOE)*: supported formal design of experiments set up as part of the overall analysis capability within SE-CAS. [Level of Impact - High].

xi. *Optimization Techniques:* SE-CAS in its current state employs brute force optimization technique to inform steering strategy based on route of minimal CWA plume exposure. Future revision could foreseeably employ

Weighted Mixture, *Genetic Search* or *Quickest-Intercept* optimization techniques for future insight.

xii. *SE-CAS System Test*: validation of SE-CAS, as depicted in Figure 50 below, describe employment of live aerosol plumes detected by CBRN-E sensors. Live plumes are synthetically represented in SE-CAS, then is passed to simulation trainer to evaluate responses real-time.

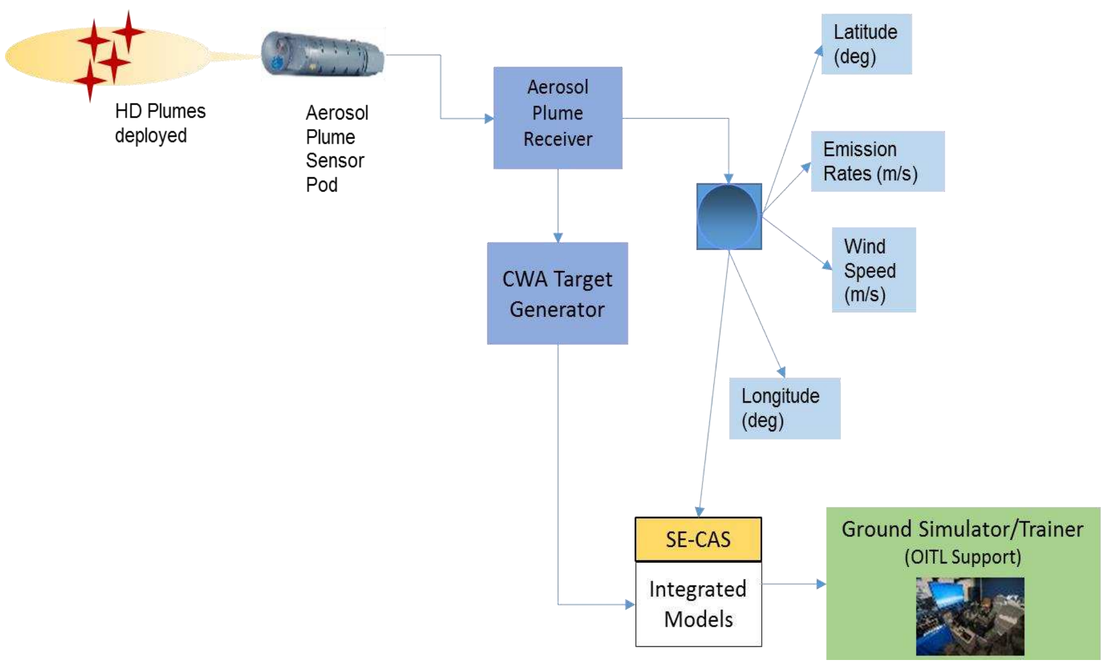


Figure 50. SE-CAS: Validation Approach

xiii. *Sensitivity Analysis*: because SE-CAS integrates several analytical models, an element of building, testing and using models in analysis is need understand each model's sensitivity to some trigger i.e. which parameters are of greatest influence to some outcome of interest. Outcomes will inform need for further model refinement or shed light into possible anomalous outcomes with these model or SE-CAS as a simulation framework.

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Appendix A: Case 1 Data for Reasonableness Test

	case_1_ws_1_x_0.5		case_1_ws_1_x_0.8		case_1_ws_1_x_1.5		case_1_ws_1_x_3		case_1_ws_1_x_5	
	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford
run_1	114.710115	114.711166	95.148351	95.156184	38.001913	37.967573	5.986918	5.986432	0.505491	0.508985
run_2	114.717974	114.720784	95.156342	95.160468	38.011697	37.969122	5.993906	5.991586	0.505823	0.509324
run_3	114.710201	114.720165	95.150474	95.165595	38.003199	37.975653	5.992699	5.987781	0.506167	0.509335
run_4	114.710253	114.715463	95.157101	95.157317	38.003785	37.972824	5.991514	5.986980	0.506281	0.509823
run_5	114.720588	114.718445	95.152768	95.158235	38.010398	37.976277	5.992537	5.989026	0.506112	0.509449
run_6	114.716406	114.712015	95.155570	95.164623	38.008783	37.971759	5.990450	5.987331	0.505823	0.509072
run_7	114.717345	114.718478	95.156189	95.165193	38.005036	37.969389	5.997255	5.987527	0.506060	0.509356
run_8	114.710684	114.719869	95.157638	95.165634	38.002404	37.970440	5.995972	5.995427	0.506177	0.509854
run_9	114.712437	114.719125	95.150183	95.162179	38.004934	37.976457	5.988566	5.993793	0.505977	0.508994
run_10	114.712664	114.713960	95.154426	95.156451	38.008520	37.972241	5.991420	5.991598	0.506276	0.509222
run_11	114.721008	114.711510	95.152877	95.160329	38.010486	37.976616	5.989239	5.992824	0.505734	0.509314
run_12	114.713628	114.715070	95.148542	95.162551	38.010650	37.969311	5.988297	5.987014	0.506159	0.509264
run_13	114.716249	114.713899	95.159150	95.165464	38.004086	37.970511	5.988647	5.994283	0.506149	0.509824
run_14	114.711255	114.718725	95.148771	95.158862	38.004248	37.977574	5.990157	5.992648	0.505944	0.509010
run_15	114.719339	114.715148	95.152162	95.162681	38.008735	37.972020	5.994027	5.991472	0.505782	0.509134
run_16	114.718060	114.716074	95.157008	95.166799	38.004562	37.969744	5.988837	5.995304	0.505881	0.509862
run_17	114.718248	114.711305	95.153973	95.163433	38.003940	37.974953	5.994615	5.992617	0.505886	0.509105
run_18	114.710728	114.715409	95.156018	95.165809	38.010749	37.973820	5.989624	5.993057	0.506074	0.509435
run_19	114.720224	114.711412	95.153678	95.159183	38.003590	37.969637	5.995346	5.995802	0.505801	0.509484
run_20	114.716663	114.718872	95.156998	95.156551	38.002304	37.975721	5.994503	5.991307	0.505712	0.509015
run_21	114.714434	114.717255	95.152823	95.158018	38.005398	37.978324	5.997907	5.994057	0.505911	0.509083
run_22	114.714685	114.711652	95.148718	95.157763	38.010213	37.978269	5.995922	5.995852	0.506034	0.510003
run_23	114.713709	114.711972	95.155903	95.163182	38.009935	37.970393	5.989672	5.994410	0.506344	0.509168
run_24	114.718604	114.720079	95.149841	95.166349	38.006175	37.975074	5.994767	5.995389	0.505630	0.509126
run_25	114.710192	114.718604	95.152007	95.158633	38.012826	37.974785	5.991928	5.990819	0.505743	0.509019
run_26	114.710257	114.715887	95.157328	95.164225	38.003466	37.970054	5.992388	5.986857	0.506524	0.509845
run_27	114.713414	114.716778	95.148578	95.157451	38.007859	37.972168	5.996977	5.996146	0.505543	0.509380
run_28	114.720164	114.714071	95.150670	95.162777	38.006190	37.978120	5.996460	5.995857	0.506180	0.509226
run_29	114.710122	114.719058	95.153407	95.162383	38.005333	37.973092	5.995838	5.988384	0.506094	0.509490
run_30	114.715159	114.719816	95.155375	95.166123	38.002943	37.976228	5.992030	5.991053	0.505548	0.509559
run_31	114.720367	114.719329	95.149896	95.161546	38.002121	37.977380	5.994036	5.990772	0.506346	0.510013
run_32	114.718752	114.721865	95.151043	95.165005	38.007986	37.969004	5.987733	5.989016	0.506129	0.509586
run_33	114.715685	114.715052	95.154134	95.163730	38.012314	37.974416	5.989163	5.991940	0.506295	0.509321
run_34	114.712102	114.719700	95.149454	95.158717	38.008068	37.973471	5.995360	5.994594	0.505827	0.509745
run_35	114.718637	114.719731	95.157517	95.161906	38.010735	37.970178	5.995346	5.995997	0.505531	0.509710
run_36	114.714570	114.715743	95.155876	95.166099	38.005987	37.971042	5.993419	5.987569	0.506501	0.509935
run_37	114.711510	114.711537	95.148429	95.164260	38.007172	37.969356	5.988151	5.994698	0.506516	0.509727
run_38	114.718608	114.718405	95.149963	95.158126	38.003492	37.976076	5.987972	5.987278	0.506150	0.509804
run_39	114.715148	114.711657	95.149168	95.166568	38.011217	37.977502	5.991896	5.995903	0.505677	0.509088
run_40	114.720265	114.719950	95.155081	95.163086	38.008118	37.968758	5.989651	5.988828	0.505854	0.509249
run_41	114.711090	114.716180	95.150461	95.164267	38.001944	37.975105	5.987531	5.991440	0.506200	0.510045
run_42	114.711780	114.712296	95.152433	95.164742	38.007419	37.971557	5.992848	5.993707	0.506338	0.509078
run_43	114.714809	114.719110	95.157788	95.166986	38.007675	37.968203	5.995592	5.989152	0.506339	0.509577
run_44	114.716866	114.711293	95.155396	95.163914	38.005398	37.977646	5.993081	5.995618	0.506301	0.509081
run_45	114.710212	114.711916	95.156635	95.161689	38.011453	37.973734	5.992188	5.994086	0.505576	0.509307
run_46	114.711775	114.719663	95.156105	95.159429	38.008483	37.978210	5.987212	5.995585	0.505572	0.509446
run_47	114.711059	114.721629	95.158047	95.161090	38.003220	37.977228	5.996081	5.995139	0.506373	0.509169
run_48	114.721025	114.722117	95.150003	95.158838	38.010265	37.973432	5.994731	5.986903	0.505562	0.509342
run_49	114.714202	114.717731	95.149701	95.165209	38.008514	37.975033	5.989093	5.993863	0.505759	0.509492
run_50	114.711946	114.714367	95.155315	95.166521	38.007826	37.975670	5.994063	5.995143	0.505517	0.509793

Case 1 Concentration Output: Distance Downwind (0.5 – 5 KM), Stability Class (Stable) and Wind Speed at (1.0 M/S).

Appendix B: Case 2 Data for Reasonableness Test

	case_2_ws_3_x_0.5		case_2_ws_3_x_0.8		case_2_ws_3_x_1.5		case_2_ws_3_x_3		case_2_ws_3_x_5	
	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford
run_1	68.486174	68.482289	41.328945	41.331375	14.029616	14.039205	2.082580	2.087112	0.170883	0.180370
run_2	68.489150	68.485120	41.337679	41.334700	14.032059	14.040171	2.083224	2.087661	0.171473	0.180404
run_3	68.486806	68.485961	41.332926	41.338051	14.034913	14.045779	2.082742	2.087347	0.171732	0.180411
run_4	68.486767	68.486778	41.336168	41.338699	14.035667	14.041795	2.083023	2.087159	0.171187	0.180373
run_5	68.488795	68.488249	41.339767	41.336082	14.034149	14.040889	2.083070	2.087358	0.171548	0.180456
run_6	68.486629	68.486828	41.335913	41.335356	14.031573	14.046344	2.082713	2.087982	0.171175	0.180385
run_7	68.486485	68.490710	41.331336	41.340910	14.033234	14.049697	2.083365	2.087216	0.171269	0.180454
run_8	68.492571	68.490047	41.337792	41.341448	14.039210	14.048248	2.083101	2.087193	0.171601	0.180435
run_9	68.491211	68.486975	41.330603	41.338171	14.038900	14.049353	2.083467	2.087707	0.171859	0.180397
run_10	68.491828	68.491231	41.335578	41.340151	14.034894	14.048926	2.083455	2.088019	0.171288	0.180436
run_11	68.486815	68.489622	41.335860	41.331889	14.030114	14.049757	2.083653	2.087901	0.171162	0.180395
run_12	68.488800	68.490719	41.330791	41.341098	14.032198	14.047434	2.083438	2.087307	0.171526	0.180381
run_13	68.492493	68.487824	41.335423	41.334981	14.032936	14.042308	2.083436	2.087598	0.171569	0.180410
run_14	68.488234	68.486388	41.329394	41.340226	14.031976	14.040475	2.082622	2.087609	0.171337	0.180441
run_15	68.491348	68.486856	41.335435	41.337744	14.039625	14.039910	2.083100	2.087313	0.171594	0.180423
run_16	68.486283	68.491663	41.338928	41.335986	14.032724	14.041307	2.083309	2.087242	0.171537	0.180437
run_17	68.487953	68.488530	41.332112	41.335742	14.033177	14.042734	2.083226	2.087400	0.170924	0.180371
run_18	68.496759	68.483927	41.336232	41.334515	14.038795	14.047012	2.082886	2.087405	0.170885	0.180388
run_19	68.487349	68.488520	41.334606	41.338338	14.039168	14.046628	2.083153	2.087352	0.171469	0.180423
run_20	68.487649	68.490955	41.337970	41.338266	14.035830	14.044772	2.083347	2.087732	0.171509	0.180413
run_21	68.495874	68.484213	41.332028	41.338114	14.038798	14.049057	2.083434	2.087744	0.171552	0.180387
run_22	68.488910	68.484761	41.333765	41.339658	14.035081	14.044597	2.083578	2.087843	0.171659	0.180398
run_23	68.486847	68.484113	41.338398	41.342169	14.033429	14.049328	2.082916	2.087351	0.171313	0.180465
run_24	68.490628	68.486296	41.333407	41.338731	14.039799	14.041523	2.082588	2.088068	0.171253	0.180467
run_25	68.496940	68.491486	41.330391	41.339865	14.039395	14.045379	2.082887	2.087451	0.171594	0.180419
run_26	68.486437	68.483422	41.338392	41.341799	14.035791	14.050169	2.083088	2.088117	0.171786	0.180384
run_27	68.493709	68.486669	41.333319	41.333225	14.033352	14.039755	2.082983	2.087122	0.171524	0.180378
run_28	68.492031	68.492443	41.331608	41.341746	14.036249	14.040260	2.082681	2.087827	0.171490	0.180430
run_29	68.489401	68.484641	41.336712	41.333251	14.039880	14.039229	2.083212	2.088130	0.171460	0.180455
run_30	68.488740	68.489458	41.338683	41.331584	14.034066	14.049892	2.083562	2.088179	0.170971	0.180423
run_31	68.488972	68.486907	41.333263	41.331729	14.030294	14.039583	2.083539	2.087669	0.171536	0.180463
run_32	68.495745	68.485848	41.331762	41.341955	14.035031	14.046569	2.083223	2.087218	0.170961	0.180443
run_33	68.491438	68.485800	41.338198	41.332112	14.030596	14.049111	2.083557	2.088029	0.171191	0.180441
run_34	68.491377	68.492797	41.337817	41.333801	14.034736	14.044106	2.083401	2.087839	0.171604	0.180393
run_35	68.492959	68.487354	41.329520	41.340793	14.032830	14.046905	2.083075	2.087593	0.171224	0.180457
run_36	68.493211	68.482840	41.330994	41.336989	14.039445	14.049038	2.082931	2.087489	0.171005	0.180465
run_37	68.494062	68.484427	41.337511	41.332927	14.036554	14.042408	2.083271	2.087964	0.171649	0.180469
run_38	68.493432	68.491167	41.338159	41.332640	14.035611	14.039354	2.083437	2.088132	0.171279	0.180460
run_39	68.489649	68.485899	41.335087	41.334530	14.033750	14.044844	2.083304	2.087252	0.171512	0.180427
run_40	68.492116	68.485587	41.339589	41.342151	14.037936	14.044707	2.083040	2.088146	0.171442	0.180418
run_41	68.489917	68.487159	41.332646	41.334949	14.037186	14.042295	2.083369	2.087407	0.171562	0.180446
run_42	68.488204	68.486078	41.332522	41.336343	14.030548	14.049812	2.083553	2.087680	0.171566	0.180406
run_43	68.496054	68.492175	41.332387	41.333836	14.038753	14.046902	2.083193	2.087557	0.171313	0.180461
run_44	68.487708	68.483600	41.336253	41.342002	14.033429	14.040852	2.083642	2.087523	0.170956	0.180457
run_45	68.491662	68.491004	41.335526	41.334083	14.038110	14.043537	2.083257	2.088199	0.171243	0.180419
run_46	68.490839	68.485819	41.332056	41.336734	14.030211	14.049641	2.082682	2.088027	0.170916	0.180455
run_47	68.492055	68.489167	41.339280	41.341331	14.033998	14.049332	2.083188	2.087970	0.171385	0.180416
run_48	68.492644	68.488437	41.334062	41.333222	14.030419	14.043143	2.083604	2.087852	0.171762	0.180445
run_49	68.486544	68.486729	41.336409	41.331403	14.032530	14.039996	2.082784	2.087574	0.171870	0.180406
run_50	68.487913	68.485543	41.329061	41.340977	14.030414	14.043604	2.083496	2.087599	0.171032	0.180406

Case 2 Concentration Output: Distance Downwind (0.5 – 5 KM), Stability Class (Stable) and Wind Speed at (3.0 M/S).

Appendix C: Case 3 Data for Reasonableness Test

	case_3_ws_5_x_0.5		case_3_ws_5_x_0.8		case_3_ws_5_x_1.5		case_3_ws_5_x_3		case_3_ws_5_x_5	
	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford
run_1	48.267518	48.284347	11.599608	11.590065	3.203972	3.233561	0.466739	0.443224	0.045803	0.049128
run_2	48.276702	48.286789	11.609988	11.600151	3.211946	3.239882	0.466743	0.443460	0.046363	0.049215
run_3	48.270071	48.289203	11.608515	11.591197	3.212952	3.239405	0.466783	0.443281	0.046337	0.049163
run_4	48.270854	48.286478	11.606111	11.593392	3.205581	3.236961	0.466774	0.443851	0.046219	0.049214
run_5	48.269484	48.291594	11.608403	11.593339	3.207659	3.243573	0.466745	0.443871	0.046560	0.049205
run_6	48.269351	48.286283	11.608225	11.593490	3.209414	3.244458	0.466792	0.443601	0.046538	0.049139
run_7	48.276424	48.286708	11.604437	11.595234	3.207771	3.240018	0.466812	0.443490	0.045954	0.049159
run_8	48.278081	48.285329	11.605117	11.590179	3.205072	3.239100	0.466846	0.443919	0.045902	0.049223
run_9	48.271686	48.284709	11.604990	11.592197	3.211494	3.240218	0.466762	0.443343	0.046662	0.049190
run_10	48.274798	48.287810	11.609612	11.599863	3.213856	3.241617	0.466740	0.443316	0.045903	0.049219
run_11	48.274093	48.292202	11.604864	11.590484	3.206528	3.244365	0.466843	0.443914	0.046369	0.049145
run_12	48.277088	48.292587	11.606854	11.599875	3.206097	3.239554	0.466825	0.443534	0.046092	0.049170
run_13	48.271971	48.293466	11.602683	11.597219	3.205571	3.235341	0.466778	0.444172	0.046054	0.049143
run_14	48.271438	48.286819	11.603371	11.600805	3.205677	3.236816	0.466840	0.443489	0.046181	0.049181
run_15	48.268977	48.288973	11.604744	11.600930	3.214427	3.240766	0.466830	0.443815	0.046774	0.049222
run_16	48.277001	48.294537	11.601383	11.590159	3.207555	3.238788	0.466754	0.444171	0.046466	0.049168
run_17	48.269293	48.284970	11.610491	11.593092	3.208653	3.234782	0.466751	0.443759	0.046478	0.049204
run_18	48.269780	48.290293	11.600010	11.598627	3.208681	3.242416	0.466796	0.443876	0.046153	0.049139
run_19	48.271646	48.289717	11.600355	11.590507	3.211287	3.236500	0.466820	0.443665	0.046219	0.049210
run_20	48.276565	48.287404	11.601569	11.600050	3.207571	3.233821	0.466820	0.443581	0.045875	0.049198
run_21	48.269360	48.285415	11.606454	11.590780	3.213936	3.236527	0.466829	0.443930	0.046215	0.049218
run_22	48.268800	48.295324	11.609361	11.590380	3.211395	3.236523	0.466811	0.444148	0.045807	0.049169
run_23	48.267688	48.289247	11.606663	11.592262	3.206041	3.237310	0.466806	0.443708	0.045955	0.049180
run_24	48.276465	48.290029	11.609175	11.598687	3.211132	3.243199	0.466775	0.443293	0.045891	0.049177
run_25	48.276179	48.290591	11.599632	11.595282	3.205987	3.234197	0.466766	0.443403	0.046159	0.049180
run_26	48.271178	48.285739	11.601667	11.599064	3.210710	3.240628	0.466839	0.444086	0.046135	0.049204
run_27	48.277313	48.291479	11.607815	11.595619	3.204507	3.243393	0.466780	0.444060	0.045806	0.049145
run_28	48.278065	48.291031	11.607626	11.601001	3.211942	3.239344	0.466836	0.444117	0.045820	0.049213
run_29	48.269069	48.293434	11.601884	11.593903	3.204357	3.240330	0.466810	0.443686	0.045980	0.049217
run_30	48.274061	48.285706	11.602372	11.592808	3.211145	3.239616	0.466826	0.443238	0.046672	0.049138
run_31	48.275685	48.288622	11.602604	11.598321	3.213888	3.243020	0.466844	0.443354	0.046231	0.049162
run_32	48.276798	48.293151	11.609046	11.598751	3.210679	3.234780	0.466760	0.443976	0.045902	0.049219
run_33	48.272970	48.293685	11.606523	11.598760	3.209683	3.234580	0.466764	0.444216	0.046386	0.049212
run_34	48.277926	48.285496	11.603002	11.599872	3.210682	3.243317	0.466751	0.444120	0.046600	0.049152
run_35	48.269430	48.287101	11.606719	11.600868	3.213452	3.240795	0.466800	0.443877	0.046689	0.049225
run_36	48.275962	48.289789	11.601385	11.591308	3.212169	3.240703	0.466763	0.443229	0.046061	0.049212
run_37	48.271965	48.293180	11.610552	11.600402	3.212383	3.242875	0.466746	0.443538	0.046362	0.049172
run_38	48.273532	48.285079	11.605159	11.591991	3.211223	3.237922	0.466765	0.443228	0.046109	0.049162
run_39	48.275140	48.294626	11.609809	11.590151	3.212441	3.242681	0.466839	0.443650	0.046471	0.049169
run_40	48.270659	48.291751	11.599803	11.595757	3.205133	3.235367	0.466813	0.443579	0.046676	0.049165
run_41	48.274550	48.284598	11.601448	11.590335	3.214280	3.243440	0.466821	0.443323	0.046351	0.049175
run_42	48.273961	48.285198	11.606429	11.597046	3.209516	3.242437	0.466834	0.443766	0.046602	0.049179
run_43	48.277181	48.288130	11.603987	11.598919	3.212979	3.244094	0.466785	0.443803	0.046282	0.049225
run_44	48.277774	48.293042	11.601428	11.600173	3.213798	3.239847	0.466789	0.443803	0.046282	0.049130
run_45	48.272207	48.291351	11.601375	11.592646	3.211734	3.234207	0.466754	0.443420	0.046195	0.049133
run_46	48.274132	48.289021	11.604071	11.597658	3.205363	3.237006	0.466834	0.443878	0.045810	0.049174
run_47	48.267556	48.292916	11.599827	11.598367	3.213815	3.237752	0.466790	0.443706	0.045957	0.049224
run_48	48.269015	48.294494	11.609556	11.598209	3.207436	3.239102	0.466777	0.443699	0.046803	0.049216
run_49	48.269534	48.289068	11.610012	11.590654	3.209896	3.235346	0.466824	0.443733	0.046266	0.049146
run_50	48.273387	48.286204	11.608694	11.600795	3.209691	3.238588	0.466739	0.443730	0.046300	0.049153

Case 3 Concentration Output: Distance Downwind (0.5 – 5 KM), Stability Class (Stable) and Wind Speed at (5.0 M/S).

Appendix D: Case 4 Data for Reasonableness Test

	case_4_ws_7_x_0.5		case_4_ws_7_x_0.8		case_4_ws_7_x_1.5		case_4_ws_7_x_3		case_4_ws_7_x_5	
	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford
run_1	37.407299	37.409372	2.420932	2.414541	0.546227	0.561622	0.095596	0.095428	0.019044	0.010943
run_2	37.416998	37.413244	2.426375	2.417088	0.552274	0.562897	0.095618	0.096201	0.019196	0.010946
run_3	37.408651	37.417305	2.427134	2.422560	0.547189	0.570602	0.095604	0.095897	0.019556	0.010949
run_4	37.414572	37.409840	2.428499	2.424121	0.552701	0.564202	0.095617	0.096109	0.019527	0.011001
run_5	37.412749	37.414643	2.430256	2.425444	0.553852	0.567745	0.095669	0.095706	0.020027	0.011033
run_6	37.412840	37.416762	2.422631	2.423852	0.556252	0.561837	0.095678	0.095658	0.019059	0.011005
run_7	37.417141	37.419010	2.421426	2.419511	0.546536	0.569265	0.095693	0.095436	0.019996	0.011038
run_8	37.414503	37.417388	2.424384	2.415747	0.551997	0.568129	0.095612	0.096405	0.019174	0.011039
run_9	37.408613	37.410385	2.425642	2.415373	0.549765	0.561704	0.095641	0.095645	0.019134	0.011008
run_10	37.408990	37.415713	2.423404	2.420954	0.551114	0.567180	0.095647	0.096132	0.019708	0.010984
run_11	37.418092	37.415448	2.429332	2.419938	0.546438	0.566295	0.095629	0.095656	0.019095	0.011010
run_12	37.409181	37.416194	2.421986	2.415223	0.553283	0.563931	0.095621	0.096343	0.019299	0.011034
run_13	37.412679	37.409907	2.421188	2.419190	0.552990	0.564260	0.095603	0.096082	0.019507	0.011011
run_14	37.411389	37.410261	2.429795	2.424921	0.553437	0.570861	0.095613	0.096011	0.019780	0.010977
run_15	37.414051	37.417672	2.424881	2.419127	0.546754	0.570990	0.095698	0.096402	0.019663	0.011020
run_16	37.417514	37.409912	2.428624	2.422633	0.553977	0.565179	0.095608	0.095810	0.019612	0.011017
run_17	37.407647	37.416605	2.430666	2.422982	0.548778	0.566430	0.095672	0.096019	0.019702	0.011004
run_18	37.416510	37.410727	2.431909	2.417229	0.546821	0.565436	0.095608	0.095912	0.019933	0.010990
run_19	37.413312	37.416484	2.427720	2.415614	0.546663	0.562325	0.095666	0.096387	0.019505	0.011011
run_20	37.414915	37.411863	2.423842	2.414569	0.549199	0.568801	0.095608	0.096076	0.019129	0.010945
run_21	37.414285	37.411796	2.422295	2.421844	0.548632	0.568456	0.095603	0.095772	0.020025	0.011037
run_22	37.410649	37.416703	2.431536	2.414888	0.551594	0.567150	0.095689	0.096271	0.019709	0.010978
run_23	37.413893	37.412400	2.425521	2.421056	0.546489	0.571454	0.095698	0.095866	0.019067	0.010964
run_24	37.413751	37.415152	2.427656	2.422821	0.549035	0.561650	0.095637	0.096188	0.019505	0.010986
run_25	37.412876	37.419706	2.424319	2.421829	0.550239	0.566049	0.095608	0.096413	0.019851	0.010947
run_26	37.408998	37.418876	2.430290	2.418110	0.551289	0.563901	0.095666	0.096033	0.019413	0.010980
run_27	37.407957	37.413198	2.423959	2.418971	0.547716	0.572533	0.095626	0.096060	0.019405	0.010987
run_28	37.413673	37.420049	2.425130	2.415550	0.552541	0.571424	0.095702	0.096259	0.019492	0.010958
run_29	37.412864	37.411297	2.430625	2.421072	0.546914	0.572527	0.095659	0.095796	0.019410	0.010984
run_30	37.417921	37.413370	2.431308	2.423011	0.552958	0.564703	0.095684	0.096338	0.019209	0.010953
run_31	37.409915	37.418245	2.427124	2.422540	0.554068	0.572448	0.095644	0.096515	0.019240	0.010978
run_32	37.410405	37.413795	2.428163	2.420008	0.546386	0.571577	0.095645	0.096458	0.019177	0.011021
run_33	37.411116	37.419503	2.424330	2.419327	0.555125	0.567083	0.095635	0.096000	0.019493	0.011034
run_34	37.408974	37.417942	2.429413	2.422042	0.553658	0.571203	0.095668	0.095707	0.019971	0.010978
run_35	37.409578	37.419704	2.430317	2.419311	0.546812	0.563877	0.095623	0.095874	0.019486	0.011026
run_36	37.416564	37.416429	2.422852	2.421187	0.556083	0.564145	0.095649	0.095978	0.019421	0.011005
run_37	37.412122	37.417765	2.431018	2.421836	0.551210	0.570215	0.095611	0.095519	0.019158	0.010951
run_38	37.411853	37.412135	2.422594	2.423026	0.550594	0.565517	0.095670	0.095511	0.019597	0.010968
run_39	37.408714	37.420288	2.421836	2.422874	0.556458	0.561939	0.095695	0.096228	0.019570	0.011041
run_40	37.409608	37.416020	2.430354	2.425325	0.552432	0.568548	0.095697	0.096519	0.019518	0.010975
run_41	37.408692	37.416732	2.429091	2.423771	0.552018	0.569067	0.095626	0.096324	0.019613	0.010972
run_42	37.411110	37.416392	2.425651	2.414990	0.548835	0.564370	0.095693	0.095890	0.019366	0.011011
run_43	37.416931	37.411010	2.428959	2.421848	0.549930	0.564609	0.095647	0.095520	0.019582	0.011016
run_44	37.414077	37.419839	2.422052	2.422434	0.556411	0.566483	0.095688	0.096451	0.019610	0.010951
run_45	37.407686	37.412734	2.421699	2.423475	0.549494	0.566694	0.095692	0.096176	0.019102	0.010981
run_46	37.416171	37.419080	2.422542	2.424521	0.547339	0.567293	0.095638	0.095515	0.019995	0.010996
run_47	37.413443	37.416987	2.429528	2.424864	0.549745	0.567393	0.095612	0.096448	0.019750	0.010980
run_48	37.415397	37.411435	2.423167	2.415873	0.547452	0.570286	0.095619	0.095998	0.019325	0.011004
run_49	37.412423	37.419351	2.426263	2.419268	0.551434	0.571242	0.095690	0.096411	0.019599	0.010961
run_50	37.415604	37.415245	2.427201	2.423896	0.550498	0.568303	0.095636	0.096022	0.019811	0.010945

Case 4 Concentration Output: Distance Downwind (0.5 – 5 KM), Stability Class (Stable) and Wind Speed at (7.0 M/S).

Appendix E: Case 5 Data for Reasonableness Test

	case_5_ws_9_x_0.5		case_5_ws_9_x_0.8		case_5_ws_9_x_1.5		case_5_ws_9_x_3		case_5_ws_9_x_5	
	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford
run_1	30.607072	30.615774	0.411838	0.410667	0.070137	0.070489	0.012403	0.012206	0.003656	0.003190
run_2	30.612099	30.619327	0.417887	0.417574	0.070974	0.075912	0.012900	0.012260	0.003718	0.003245
run_3	30.610587	30.618183	0.412608	0.417234	0.078200	0.079303	0.013067	0.012210	0.003734	0.003204
run_4	30.608639	30.625257	0.412314	0.411562	0.073883	0.079596	0.013357	0.012241	0.003754	0.003233
run_5	30.609015	30.619572	0.412853	0.412742	0.073865	0.078293	0.013016	0.012276	0.003743	0.003273
run_6	30.610322	30.620051	0.420117	0.418173	0.076764	0.078764	0.013473	0.012254	0.003714	0.003195
run_7	30.610710	30.622838	0.412757	0.421243	0.076264	0.072600	0.012652	0.012303	0.003740	0.003243
run_8	30.614341	30.618999	0.414161	0.413123	0.078109	0.080578	0.012912	0.012218	0.003670	0.003210
run_9	30.616763	30.618470	0.416220	0.417247	0.081008	0.073661	0.013333	0.012310	0.003700	0.003231
run_10	30.613196	30.626716	0.416466	0.421224	0.080878	0.071950	0.013333	0.012274	0.003696	0.003236
run_11	30.611426	30.618407	0.413399	0.418250	0.079487	0.079046	0.013489	0.012272	0.003751	0.003201
run_12	30.609985	30.621965	0.418146	0.418750	0.072933	0.073239	0.012671	0.012271	0.003744	0.003247
run_13	30.612815	30.617626	0.414796	0.413840	0.073180	0.078837	0.012628	0.012287	0.003720	0.003282
run_14	30.610071	30.625694	0.413443	0.410670	0.078848	0.073224	0.013232	0.012261	0.003676	0.003194
run_15	30.608625	30.621730	0.421076	0.420811	0.070462	0.078007	0.012435	0.012300	0.003695	0.003219
run_16	30.612517	30.620663	0.420385	0.414527	0.070412	0.071855	0.012842	0.012252	0.003663	0.003222
run_17	30.607509	30.623552	0.420518	0.415842	0.072863	0.074042	0.012448	0.012314	0.003732	0.003214
run_18	30.607517	30.621692	0.418540	0.420426	0.075419	0.075454	0.012937	0.012215	0.003664	0.003244
run_19	30.608291	30.625028	0.421423	0.414392	0.080509	0.078787	0.012415	0.012287	0.003685	0.003217
run_20	30.614780	30.621618	0.418557	0.420295	0.076246	0.077616	0.012547	0.012312	0.003707	0.003235
run_21	30.609497	30.623506	0.420574	0.415974	0.076040	0.076249	0.013347	0.012236	0.003676	0.003216
run_22	30.616128	30.619455	0.420999	0.412745	0.080586	0.079880	0.012640	0.012255	0.003704	0.003264
run_23	30.615737	30.625427	0.416423	0.410824	0.073361	0.081377	0.012488	0.012213	0.003720	0.003269
run_24	30.609398	30.617121	0.420312	0.417639	0.070415	0.071929	0.012742	0.012289	0.003692	0.003263
run_25	30.614726	30.621218	0.420072	0.414795	0.070726	0.079328	0.013022	0.012215	0.003686	0.003218
run_26	30.611177	30.624803	0.416845	0.417565	0.073680	0.077981	0.013146	0.012233	0.003733	0.003213
run_27	30.608563	30.620685	0.416891	0.415305	0.080473	0.079232	0.012859	0.012248	0.003693	0.003257
run_28	30.614254	30.622323	0.417627	0.415105	0.073375	0.078437	0.013067	0.012254	0.003686	0.003253
run_29	30.617830	30.622570	0.422611	0.412496	0.079020	0.070816	0.013429	0.012277	0.003739	0.003250
run_30	30.611266	30.622315	0.412208	0.412469	0.077219	0.077809	0.012459	0.012234	0.003687	0.003245
run_31	30.607177	30.625326	0.422404	0.420647	0.079461	0.079867	0.012755	0.012243	0.003676	0.003203
run_32	30.615306	30.621818	0.419648	0.421426	0.080800	0.070791	0.012654	0.012308	0.003702	0.003254
run_33	30.611349	30.623030	0.412047	0.416184	0.076592	0.073576	0.012872	0.012243	0.003713	0.003246
run_34	30.610559	30.615840	0.412379	0.414059	0.070991	0.080445	0.012616	0.012224	0.003674	0.003244
run_35	30.615046	30.622097	0.420029	0.412653	0.080588	0.080390	0.012761	0.012253	0.003728	0.003211
run_36	30.609338	30.624155	0.413270	0.418327	0.077860	0.071483	0.013043	0.012231	0.003742	0.003249
run_37	30.611388	30.623644	0.417246	0.418896	0.079036	0.072074	0.013387	0.012210	0.003725	0.003267
run_38	30.617528	30.616724	0.420962	0.419967	0.070388	0.078219	0.012475	0.012286	0.003719	0.003268
run_39	30.616158	30.622220	0.416534	0.418895	0.074830	0.072617	0.013065	0.012304	0.003708	0.003212
run_40	30.608136	30.622806	0.416337	0.411378	0.076001	0.072122	0.012919	0.012269	0.003740	0.003250
run_41	30.616327	30.618971	0.415210	0.420441	0.074092	0.074045	0.012403	0.012307	0.003718	0.003207
run_42	30.611946	30.617529	0.415137	0.412877	0.080654	0.078961	0.012782	0.012231	0.003723	0.003211
run_43	30.616694	30.616234	0.418403	0.420756	0.072731	0.074081	0.013077	0.012213	0.003705	0.003209
run_44	30.609612	30.623381	0.421535	0.412956	0.073809	0.080594	0.012627	0.012296	0.003659	0.003279
run_45	30.610497	30.617895	0.422109	0.412546	0.076704	0.073138	0.013145	0.012224	0.003694	0.003288
run_46	30.617996	30.625164	0.418364	0.415481	0.073919	0.071861	0.012710	0.012263	0.003717	0.003244
run_47	30.609618	30.626461	0.422581	0.420114	0.075887	0.076709	0.013497	0.012247	0.003737	0.003248
run_48	30.612862	30.624040	0.414708	0.416277	0.072698	0.077816	0.013163	0.012293	0.003730	0.003274
run_49	30.609808	30.624868	0.413250	0.420994	0.071855	0.071445	0.013485	0.012268	0.003679	0.003275
run_50	30.617332	30.621688	0.412800	0.414681	0.076519	0.072366	0.013395	0.012261	0.003658	0.003255

Case 5 Concentration Output: Distance Downwind (0.5 – 5 KM), Stability Class (Stable) and Wind Speed at (9.0 M/S).

Appendix F: Case 6 Data for Reasonableness Test

	case_6_ws_11_x_0.5		case_6_ws_11_x_0.8		case_6_ws_11_x_1.5		case_6_ws_11_x_3		case_6_ws_11_x_5	
	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford
run_1	25.945179	25.943652	0.056982	0.055242	0.049044	0.046691	0.006892	0.006095	0.001283	0.001363
run_2	25.949466	25.952862	0.067872	0.064728	0.058353	0.053956	0.006990	0.006189	0.001364	0.001390
run_3	25.954515	25.948896	0.059218	0.062419	0.054545	0.049078	0.006949	0.006142	0.001314	0.001441
run_4	25.946537	25.946862	0.062882	0.059604	0.054115	0.055285	0.006915	0.006183	0.001366	0.001409
run_5	25.954245	25.946501	0.063367	0.061223	0.056022	0.049028	0.006894	0.006182	0.001311	0.001375
run_6	25.948097	25.945218	0.067085	0.065917	0.053270	0.048836	0.006906	0.006106	0.001363	0.001405
run_7	25.955330	25.945862	0.064273	0.056707	0.054773	0.046975	0.006995	0.006172	0.001310	0.001384
run_8	25.955886	25.953844	0.064862	0.058914	0.056671	0.055670	0.006905	0.006110	0.001298	0.001442
run_9	25.947276	25.947367	0.064899	0.058926	0.051016	0.051186	0.006955	0.006108	0.001306	0.001414
run_10	25.950691	25.950696	0.062431	0.056978	0.051113	0.056234	0.006956	0.006126	0.001315	0.001422
run_11	25.950567	25.950912	0.064347	0.057983	0.051019	0.048870	0.006901	0.006191	0.001356	0.001460
run_12	25.954791	25.943902	0.057703	0.058743	0.052219	0.051117	0.006987	0.006198	0.001370	0.001383
run_13	25.947851	25.954444	0.060736	0.063285	0.054779	0.049864	0.006979	0.006115	0.001378	0.001456
run_14	25.948499	25.951309	0.058966	0.063266	0.058191	0.052654	0.006958	0.006194	0.001334	0.001422
run_15	25.945835	25.946484	0.067682	0.064793	0.058276	0.048811	0.006920	0.006128	0.001334	0.001419
run_16	25.945948	25.947110	0.061598	0.064993	0.052847	0.048324	0.006940	0.006167	0.001376	0.001363
run_17	25.952406	25.950841	0.064561	0.057662	0.058469	0.050520	0.006955	0.006193	0.001284	0.001439
run_18	25.953088	25.950088	0.060738	0.064215	0.050928	0.051328	0.006995	0.006108	0.001309	0.001442
run_19	25.951607	25.946677	0.067835	0.063671	0.052961	0.053926	0.006992	0.006114	0.001311	0.001387
run_20	25.946800	25.953800	0.057280	0.059790	0.052540	0.047286	0.006981	0.006177	0.001293	0.001428
run_21	25.948676	25.944183	0.067164	0.064760	0.049682	0.053928	0.006994	0.006124	0.001339	0.001416
run_22	25.950191	25.952752	0.060990	0.063598	0.051749	0.051786	0.006959	0.006175	0.001311	0.001427
run_23	25.950636	25.948861	0.059902	0.060796	0.053499	0.055001	0.006936	0.006190	0.001322	0.001367
run_24	25.952363	25.949346	0.064672	0.056251	0.052841	0.048212	0.006974	0.006117	0.001376	0.001376
run_25	25.947417	25.950453	0.057083	0.060698	0.052825	0.052768	0.006999	0.006179	0.001338	0.001431
run_26	25.952619	25.946964	0.065148	0.064034	0.052131	0.056085	0.006919	0.006103	0.001345	0.001397
run_27	25.952146	25.953524	0.059320	0.062445	0.059468	0.048653	0.006910	0.006189	0.001345	0.001438
run_28	25.947972	25.952817	0.064302	0.063250	0.059889	0.056175	0.006925	0.006157	0.001376	0.001455
run_29	25.946043	25.951988	0.067339	0.057679	0.052055	0.055510	0.006957	0.006142	0.001283	0.001442
run_30	25.954218	25.944572	0.057317	0.061080	0.053666	0.047763	0.006972	0.006159	0.001327	0.001370
run_31	25.946514	25.950296	0.065370	0.055538	0.058329	0.056222	0.006993	0.006197	0.001333	0.001445
run_32	25.955074	25.945799	0.058495	0.061521	0.053846	0.053964	0.006966	0.006114	0.001319	0.001384
run_33	25.951263	25.946281	0.065178	0.055301	0.056197	0.048331	0.006920	0.006172	0.001323	0.001411
run_34	25.952165	25.946396	0.058244	0.056956	0.056886	0.049731	0.006919	0.006115	0.001292	0.001363
run_35	25.947643	25.954347	0.063000	0.059934	0.057341	0.054278	0.006919	0.006149	0.001308	0.001436
run_36	25.955868	25.948928	0.067284	0.061262	0.051305	0.054525	0.006910	0.006163	0.001349	0.001440
run_37	25.954977	25.951024	0.064633	0.061562	0.053868	0.053553	0.006989	0.006172	0.001299	0.001403
run_38	25.945575	25.951876	0.059441	0.064274	0.051245	0.055782	0.006976	0.006172	0.001379	0.001420
run_39	25.954544	25.952342	0.066755	0.056280	0.051104	0.053082	0.006989	0.006124	0.001295	0.001393
run_40	25.948735	25.947011	0.057122	0.060617	0.053187	0.049923	0.006969	0.006172	0.001309	0.001375
run_41	25.952563	25.946157	0.063836	0.063178	0.057229	0.057580	0.006951	0.006186	0.001357	0.001396
run_42	25.955060	25.951747	0.057531	0.065416	0.059218	0.052657	0.006976	0.006193	0.001362	0.001407
run_43	25.950402	25.946873	0.063730	0.060463	0.051407	0.052297	0.006904	0.006192	0.001285	0.001417
run_44	25.950964	25.953749	0.064757	0.057376	0.057140	0.050639	0.006912	0.006145	0.001295	0.001404
run_45	25.952839	25.950448	0.067607	0.065454	0.059551	0.056097	0.006990	0.006148	0.001332	0.001373
run_46	25.953953	25.951581	0.061141	0.058698	0.058622	0.054077	0.006903	0.006144	0.001331	0.001449
run_47	25.949579	25.947767	0.061189	0.058868	0.054228	0.051472	0.006989	0.006119	0.001378	0.001407
run_48	25.946965	25.946294	0.058237	0.058783	0.055799	0.056361	0.006962	0.006100	0.001318	0.001426
run_49	25.946274	25.953605	0.063149	0.062160	0.053472	0.052690	0.006910	0.006149	0.001287	0.001435
run_50	25.952902	25.946629	0.067820	0.065700	0.054531	0.056488	0.006911	0.006192	0.001288	0.001396

Case 6 Concentration Output: Distance Downwind (0.5 – 5 KM), Stability Class (Stable) and Wind Speed at (11.0 M/S).

Appendix G: Case 7 Data for Reasonableness Test

	case_7_ws_13_x_0.5		case_7_ws_13_x_0.8		case_7_ws_13_x_1.5		case_7_ws_13_x_3		case_7_ws_13_x_5	
	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford
run_1	22.547843	22.549282	0.008746	0.008905	0.002774	0.002941	0.002845	0.002912	0.001207	0.001244
run_2	22.553816	22.556645	0.009494	0.009247	0.008650	0.003946	0.002883	0.002916	0.001223	0.001304
run_3	22.557251	22.558346	0.015170	0.009139	0.010231	0.013447	0.002849	0.003020	0.001257	0.001320
run_4	22.557059	22.558503	0.011326	0.009904	0.005137	0.004516	0.002913	0.002980	0.001291	0.001309
run_5	22.548556	22.557642	0.013369	0.009371	0.003832	0.008435	0.002951	0.002954	0.001299	0.001338
run_6	22.557709	22.555270	0.011567	0.009902	0.012810	0.004964	0.002914	0.002976	0.001272	0.001274
run_7	22.554591	22.556172	0.015654	0.009942	0.005950	0.004947	0.002922	0.002984	0.001239	0.001320
run_8	22.550091	22.550893	0.014908	0.009026	0.010007	0.013408	0.002928	0.002955	0.001263	0.001293
run_9	22.554832	22.556888	0.010954	0.009392	0.007952	0.003210	0.002922	0.002931	0.001300	0.001319
run_10	22.550783	22.560086	0.017284	0.008971	0.007950	0.011628	0.002882	0.002953	0.001262	0.001319
run_11	22.553636	22.552574	0.012195	0.009694	0.009632	0.007235	0.002884	0.002994	0.001246	0.001326
run_12	22.555979	22.555575	0.015715	0.009587	0.010573	0.010634	0.002859	0.002927	0.001238	0.001298
run_13	22.557244	22.550978	0.014326	0.008976	0.008295	0.011166	0.002945	0.002925	0.001280	0.001295
run_14	22.550282	22.551510	0.017269	0.009840	0.011842	0.004511	0.002857	0.002945	0.001307	0.001268
run_15	22.555396	22.549753	0.014785	0.009372	0.003727	0.011200	0.002883	0.002941	0.001219	0.001331
run_16	22.556070	22.557000	0.010030	0.009434	0.012810	0.010356	0.002884	0.003012	0.001225	0.001323
run_17	22.554724	22.552914	0.017669	0.009141	0.007868	0.008790	0.002857	0.002926	0.001281	0.001315
run_18	22.550735	22.552503	0.016471	0.009408	0.011637	0.007871	0.002941	0.002949	0.001300	0.001265
run_19	22.550863	22.552150	0.016610	0.009508	0.009908	0.011058	0.002870	0.002984	0.001247	0.001343
run_20	22.554408	22.556958	0.019428	0.009659	0.006993	0.005078	0.002854	0.002914	0.001219	0.001256
run_21	22.549509	22.552235	0.015333	0.009941	0.004132	0.011334	0.002892	0.003011	0.001267	0.001282
run_22	22.548558	22.552889	0.010797	0.009135	0.008821	0.004841	0.002945	0.003004	0.001238	0.001343
run_23	22.557065	22.554545	0.010291	0.009144	0.007487	0.010901	0.002867	0.003015	0.001272	0.001304
run_24	22.558279	22.551432	0.018538	0.009840	0.011515	0.009610	0.002846	0.002953	0.001249	0.001244
run_25	22.555719	22.555576	0.016121	0.009602	0.005977	0.004315	0.002943	0.002955	0.001250	0.001279
run_26	22.550764	22.560109	0.014435	0.009236	0.004682	0.011975	0.002909	0.002965	0.001237	0.001272
run_27	22.548872	22.553974	0.013578	0.009475	0.011306	0.008564	0.002910	0.002970	0.001223	0.001263
run_28	22.550221	22.553740	0.016021	0.009496	0.010862	0.003488	0.002883	0.002940	0.001261	0.001282
run_29	22.555911	22.553756	0.018474	0.009795	0.007799	0.009471	0.002913	0.003007	0.001220	0.001342
run_30	22.557092	22.558553	0.011929	0.009883	0.009942	0.011760	0.002911	0.002915	0.001304	0.001245
run_31	22.550130	22.556440	0.016458	0.009650	0.006365	0.004293	0.002861	0.002973	0.001208	0.001322
run_32	22.555283	22.552136	0.010452	0.009119	0.012761	0.005129	0.002851	0.002916	0.001283	0.001257
run_33	22.556950	22.550594	0.010635	0.009111	0.003842	0.003735	0.002870	0.002950	0.001271	0.001304
run_34	22.556901	22.554665	0.015874	0.009256	0.008689	0.007595	0.002857	0.002974	0.001259	0.001339
run_35	22.555372	22.555317	0.016203	0.009168	0.003507	0.007763	0.002945	0.003001	0.001287	0.001289
run_36	22.548510	22.549896	0.016823	0.009379	0.012272	0.011399	0.002905	0.002963	0.001276	0.001269
run_37	22.550563	22.550814	0.012602	0.009717	0.007995	0.003292	0.002906	0.002942	0.001269	0.001307
run_38	22.551998	22.549554	0.016386	0.008932	0.006917	0.008860	0.002912	0.003004	0.001263	0.001269
run_39	22.557883	22.550421	0.019350	0.009953	0.004034	0.008938	0.002913	0.002950	0.001242	0.001277
run_40	22.553880	22.550870	0.010113	0.009970	0.007026	0.008280	0.002924	0.003020	0.001221	0.001327
run_41	22.548383	22.552460	0.011884	0.009231	0.004851	0.003194	0.002884	0.002980	0.001299	0.001267
run_42	22.555432	22.554691	0.013825	0.009914	0.006937	0.003338	0.002869	0.002997	0.001300	0.001324
run_43	22.552023	22.553767	0.010384	0.009485	0.008424	0.003133	0.002901	0.002977	0.001285	0.001316
run_44	22.554081	22.555579	0.016712	0.009013	0.010795	0.011525	0.002918	0.003021	0.001299	0.001328
run_45	22.548654	22.552641	0.012904	0.009058	0.003738	0.006034	0.002939	0.003015	0.001258	0.001254
run_46	22.557730	22.559780	0.016530	0.009196	0.004967	0.005849	0.002848	0.002971	0.001237	0.001305
run_47	22.549593	22.552022	0.013274	0.009291	0.013479	0.011760	0.002858	0.003007	0.001247	0.001260
run_48	22.552953	22.549449	0.016883	0.008982	0.009167	0.004026	0.002929	0.002943	0.001305	0.001295
run_49	22.548543	22.558111	0.012626	0.009440	0.010627	0.007127	0.002904	0.003000	0.001247	0.001246
run_50	22.555119	22.551885	0.016978	0.009091	0.007258	0.003295	0.002894	0.002952	0.001304	0.001334

Case 7 Concentration Output: Distance Downwind (0.5 – 5 KM), Stability Class (Stable) and Wind Speed at (13.0 M/S).

Appendix H: Case 8 Data for Reasonableness Test

	case_8_ws_15_x_0.5		case_8_ws_15_x_0.8		case_8_ws_15_x_1.5		case_8_ws_15_x_3		case_8_ws_15_x_5	
	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford
run_1	19.947791	19.952186	0.000847	0.000724	0.000390	0.000189	0.000861	0.000123	0.000176	0.000129
run_2	19.956942	19.952939	0.001390	0.001601	0.000773	0.000366	0.000918	0.000869	0.001073	0.000185
run_3	19.957822	19.955341	0.001535	0.001215	0.000589	0.000516	0.000960	0.000914	0.000456	0.000225
run_4	19.952624	19.956414	0.000848	0.001379	0.001017	0.001166	0.000950	0.001122	0.000653	0.000132
run_5	19.954158	19.952229	0.001816	0.000745	0.000792	0.000558	0.000910	0.000662	0.000811	0.000170
run_6	19.952526	19.963176	0.001877	0.000926	0.000715	0.000224	0.000894	0.000846	0.001044	0.000147
run_7	19.949476	19.961887	0.001217	0.000920	0.001121	0.001108	0.000955	0.001219	0.000805	0.000210
run_8	19.954769	19.958643	0.001697	0.001283	0.000967	0.000336	0.000862	0.000739	0.000599	0.000221
run_9	19.948616	19.952285	0.000967	0.000827	0.000811	0.000908	0.000958	0.000352	0.000741	0.000196
run_10	19.957479	19.960489	0.001762	0.001188	0.001330	0.000384	0.000895	0.000199	0.000619	0.000191
run_11	19.958429	19.958909	0.001266	0.000947	0.000936	0.000335	0.000862	0.000784	0.000326	0.000210
run_12	19.957767	19.962587	0.001041	0.000772	0.001368	0.000596	0.000918	0.001165	0.000799	0.000187
run_13	19.956822	19.953288	0.001243	0.000899	0.001382	0.000259	0.000947	0.001071	0.000356	0.000131
run_14	19.956862	19.955411	0.001480	0.000807	0.000868	0.001074	0.000935	0.000685	0.000264	0.000163
run_15	19.951463	19.955534	0.001199	0.001484	0.001128	0.000704	0.000913	0.000552	0.000916	0.000218
run_16	19.956650	19.955359	0.001467	0.001527	0.001438	0.000859	0.000875	0.000577	0.000517	0.000205
run_17	19.952153	19.953028	0.001455	0.001227	0.000638	0.000795	0.000920	0.001188	0.000431	0.000229
run_18	19.957207	19.955730	0.001453	0.001090	0.000823	0.000702	0.000947	0.000573	0.000947	0.000172
run_19	19.955457	19.954064	0.001868	0.001769	0.001140	0.000665	0.000862	0.000295	0.000459	0.000211
run_20	19.954619	19.958058	0.001505	0.001072	0.000672	0.001115	0.000927	0.000286	0.000793	0.000195
run_21	19.950370	19.958084	0.001527	0.001037	0.000427	0.000274	0.000944	0.000522	0.000965	0.000148
run_22	19.950957	19.960707	0.001350	0.001061	0.001471	0.000656	0.000960	0.000215	0.000729	0.000157
run_23	19.955097	19.963166	0.001893	0.001353	0.001450	0.000724	0.000880	0.001125	0.000828	0.000180
run_24	19.954650	19.955086	0.001680	0.001547	0.001117	0.000341	0.000872	0.001137	0.000413	0.000151
run_25	19.949407	19.958759	0.001526	0.001426	0.001234	0.001253	0.000885	0.000492	0.001096	0.000160
run_26	19.952976	19.958565	0.001436	0.000918	0.000512	0.000618	0.000901	0.000147	0.000537	0.000201
run_27	19.957875	19.958318	0.001671	0.000970	0.000461	0.001156	0.000901	0.000582	0.001090	0.000205
run_28	19.948488	19.954328	0.001076	0.000783	0.000788	0.000948	0.000902	0.000625	0.000613	0.000195
run_29	19.956772	19.963016	0.001486	0.001604	0.001420	0.000345	0.000910	0.000793	0.001147	0.000171
run_30	19.950583	19.955272	0.001563	0.001775	0.001461	0.000237	0.000890	0.000925	0.000335	0.000132
run_31	19.954040	19.960282	0.001620	0.000764	0.000504	0.000218	0.000956	0.001056	0.001026	0.000144
run_32	19.957279	19.959320	0.001751	0.001302	0.000847	0.001189	0.000943	0.000527	0.000834	0.000220
run_33	19.953306	19.961995	0.001940	0.001406	0.001094	0.001129	0.000899	0.000650	0.001004	0.000149
run_34	19.954225	19.953571	0.001083	0.000776	0.000403	0.001158	0.000880	0.000241	0.000867	0.000214
run_35	19.956362	19.961001	0.001019	0.001802	0.000521	0.000520	0.000961	0.000450	0.000449	0.000161
run_36	19.953765	19.958611	0.000934	0.001774	0.001276	0.001251	0.000969	0.000130	0.000952	0.000137
run_37	19.952767	19.961433	0.001051	0.001160	0.001318	0.000196	0.000962	0.000890	0.000381	0.000174
run_38	19.956094	19.956997	0.001184	0.001128	0.001120	0.001245	0.000908	0.000982	0.000326	0.000227
run_39	19.956420	19.952479	0.001367	0.001632	0.001048	0.000215	0.000874	0.000824	0.000795	0.000203
run_40	19.954067	19.958849	0.001525	0.001175	0.000800	0.000455	0.000865	0.000629	0.000901	0.000224
run_41	19.954644	19.961493	0.001688	0.000738	0.000975	0.000571	0.000928	0.000672	0.000734	0.000157
run_42	19.954881	19.954580	0.001362	0.000903	0.000743	0.001176	0.000862	0.000794	0.000193	0.000219
run_43	19.948124	19.956633	0.000910	0.001252	0.000832	0.000709	0.000904	0.001206	0.000467	0.000168
run_44	19.952010	19.960917	0.001755	0.001375	0.001152	0.001110	0.000964	0.000516	0.001141	0.000224
run_45	19.956374	19.958898	0.001050	0.001492	0.000602	0.001231	0.000967	0.000292	0.000214	0.000195
run_46	19.958540	19.961085	0.001360	0.000970	0.001179	0.000657	0.000915	0.000857	0.000865	0.000191
run_47	19.955948	19.952306	0.001512	0.001598	0.001139	0.001217	0.000880	0.001155	0.000627	0.000218
run_48	19.948766	19.956313	0.001422	0.001317	0.000905	0.001064	0.000893	0.000600	0.000491	0.000184
run_49	19.952001	19.962952	0.001608	0.000798	0.001178	0.001288	0.000960	0.000853	0.001122	0.000229
run_50	19.953291	19.959749	0.000922	0.001589	0.001080	0.000287	0.000942	0.000389	0.000359	0.000153

Case 8 Concentration Output: Distance Downwind (0.5 – 5 KM), Stability Class (Stable) and Wind Speed at (15.0 M/S).

Appendix I: Case 9 Data for Reasonableness Test

	case_9_ws_17_x_0.5		case_9_ws_17_x_0.8		case_9_ws_17_x_1.5		case_9_ws_17_x_3		case_9_ws_17_x_5	
	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford
run_1	17.898640	17.893950	0.000479	0.000414	0.000172	0.000182	0.000121	0.000101	0.000659	0.000404
run_2	17.909243	17.898006	0.000943	0.001174	0.000232	0.000251	0.000161	0.000146	0.000769	0.000416
run_3	17.908311	17.898634	0.000854	0.000867	0.000268	0.000260	0.000188	0.000110	0.000751	0.000459
run_4	17.902231	17.903764	0.001285	0.001070	0.000199	0.000289	0.000174	0.000121	0.000674	0.000479
run_5	17.900174	17.903928	0.001463	0.000866	0.000261	0.000238	0.000203	0.000101	0.000730	0.000449
run_6	17.899813	17.896070	0.000545	0.001281	0.000281	0.000282	0.000141	0.000121	0.000729	0.000502
run_7	17.901966	17.899973	0.001163	0.000876	0.000210	0.000187	0.000227	0.000109	0.000727	0.000446
run_8	17.908885	17.901873	0.000645	0.001312	0.000192	0.000268	0.000163	0.000199	0.000720	0.000442
run_9	17.909226	17.895109	0.001447	0.000734	0.000256	0.000242	0.000160	0.000114	0.000734	0.000405
run_10	17.907945	17.894531	0.000804	0.001459	0.000182	0.000193	0.000169	0.000137	0.000691	0.000479
run_11	17.903990	17.900717	0.000817	0.001221	0.000203	0.000194	0.000125	0.000169	0.000717	0.000460
run_12	17.909510	17.898436	0.001102	0.000535	0.000213	0.000207	0.000213	0.000107	0.000751	0.000447
run_13	17.900633	17.894387	0.000886	0.001082	0.000269	0.000192	0.000165	0.000133	0.000676	0.000413
run_14	17.908075	17.897442	0.000659	0.000747	0.000241	0.000245	0.000215	0.000146	0.000702	0.000485
run_15	17.907719	17.904136	0.001040	0.000415	0.000239	0.000276	0.000147	0.000191	0.000743	0.000433
run_16	17.908002	17.901910	0.000602	0.000953	0.000244	0.000192	0.000124	0.000174	0.000673	0.000495
run_17	17.902180	17.897185	0.001050	0.001412	0.000197	0.000191	0.000136	0.000106	0.000710	0.000478
run_18	17.901612	17.901889	0.001572	0.000642	0.000192	0.000260	0.000149	0.000113	0.000745	0.000467
run_19	17.899301	17.899853	0.001302	0.000480	0.000176	0.000224	0.000137	0.000159	0.000699	0.000460
run_20	17.900321	17.897470	0.000714	0.001034	0.000180	0.000287	0.000188	0.000198	0.000712	0.000440
run_21	17.900651	17.895999	0.001320	0.001392	0.000223	0.000266	0.000134	0.000151	0.000680	0.000499
run_22	17.908193	17.900246	0.001268	0.000489	0.000260	0.000212	0.000159	0.000194	0.000745	0.000478
run_23	17.904077	17.898123	0.001134	0.000593	0.000204	0.000244	0.000122	0.000171	0.000677	0.000498
run_24	17.904820	17.902546	0.001026	0.000634	0.000257	0.000202	0.000126	0.000145	0.000673	0.000492
run_25	17.900689	17.902904	0.001077	0.000515	0.000260	0.000284	0.000149	0.000209	0.000725	0.000488
run_26	17.899874	17.897237	0.001293	0.000468	0.000224	0.000212	0.000188	0.000153	0.000719	0.000421
run_27	17.909256	17.898156	0.000767	0.001300	0.000204	0.000270	0.000169	0.000118	0.000664	0.000437
run_28	17.905461	17.896850	0.001490	0.001019	0.000196	0.000206	0.000141	0.000145	0.000767	0.000440
run_29	17.906565	17.904527	0.000645	0.000956	0.000213	0.000287	0.000188	0.000157	0.000755	0.000469
run_30	17.902950	17.901680	0.001525	0.000563	0.000205	0.000214	0.000121	0.000191	0.000741	0.000439
run_31	17.905679	17.902173	0.000801	0.000655	0.000266	0.000277	0.000140	0.000159	0.000729	0.000416
run_32	17.903930	17.894094	0.001148	0.001433	0.000280	0.000204	0.000145	0.000153	0.000749	0.000447
run_33	17.904465	17.898195	0.001283	0.000865	0.000269	0.000288	0.000223	0.000190	0.000755	0.000491
run_34	17.907736	17.894755	0.001552	0.000828	0.000192	0.000256	0.000138	0.000142	0.000668	0.000493
run_35	17.901495	17.902172	0.000590	0.000860	0.000239	0.000286	0.000186	0.000194	0.000719	0.000414
run_36	17.899036	17.904532	0.001150	0.001421	0.000241	0.000281	0.000227	0.000124	0.000728	0.000503
run_37	17.901083	17.899378	0.001183	0.000797	0.000232	0.000216	0.000192	0.000129	0.000742	0.000449
run_38	17.901999	17.904016	0.001101	0.000641	0.000267	0.000206	0.000124	0.000191	0.000670	0.000497
run_39	17.901128	17.895680	0.001296	0.001158	0.000236	0.000256	0.000134	0.000103	0.000756	0.000496
run_40	17.899860	17.899559	0.000798	0.000495	0.000282	0.000280	0.000137	0.000117	0.000701	0.000447
run_41	17.907186	17.897768	0.001122	0.000629	0.000232	0.000243	0.000155	0.000167	0.000748	0.000452
run_42	17.900639	17.896236	0.001183	0.000573	0.000273	0.000234	0.000174	0.000104	0.000716	0.000475
run_43	17.900714	17.902016	0.000988	0.000868	0.000276	0.000261	0.000136	0.000114	0.000677	0.000421
run_44	17.900888	17.899879	0.000718	0.000613	0.000205	0.000193	0.000135	0.000172	0.000665	0.000457
run_45	17.904129	17.898960	0.001443	0.000699	0.000181	0.000184	0.000141	0.000160	0.000665	0.000452
run_46	17.908546	17.899056	0.000593	0.000763	0.000224	0.000189	0.000219	0.000183	0.000713	0.000461
run_47	17.903194	17.904548	0.000831	0.000700	0.000247	0.000217	0.000146	0.000130	0.000660	0.000489
run_48	17.908427	17.902206	0.001501	0.000861	0.000207	0.000212	0.000176	0.000108	0.000746	0.000446
run_49	17.902847	17.902702	0.001195	0.001362	0.000213	0.000286	0.000126	0.000191	0.000665	0.000478
run_50	17.905701	17.899793	0.000841	0.001458	0.000231	0.000213	0.000184	0.000147	0.000738	0.000405

Case 9 Concentration Output: Distance Downwind (0.5 – 5 KM), Stability Class (Stable) and Wind Speed at (17.0 M/S).

Appendix J: Case 10 Data for Reasonableness Test

	case_10_ws_19_x_0.5		case_10_ws_19_x_0.8		case_10_ws_19_x_1.5		case_10_ws_19_x_3		case_10_ws_19_x_5	
	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford	se-cas	pasquill-gifford
run_1	16.233506	16.227008	0.000204	0.000214	0.000339	0.000409	0.0002	0.00029	0.00089	0.000157
run_2	16.236727	16.229812	0.000259	0.000240	0.004038	0.000456	0.000290	0.000371	0.000998	0.000239
run_3	16.238702	16.231889	0.000257	0.000220	0.004566	0.000508	0.000207	0.000372	0.000918	0.000187
run_4	16.242078	16.231088	0.000292	0.000245	0.006718	0.000485	0.000221	0.000347	0.000985	0.000247
run_5	16.237816	16.231001	0.000276	0.000297	0.003270	0.000463	0.000203	0.000393	0.000999	0.000190
run_6	16.234314	16.234945	0.000244	0.000251	0.005759	0.000462	0.000243	0.000330	0.000981	0.000159
run_7	16.243126	16.230029	0.000286	0.000271	0.005473	0.000420	0.000205	0.000379	0.000984	0.000180
run_8	16.236710	16.232841	0.000307	0.000302	0.009696	0.000515	0.000228	0.000328	0.000909	0.000241
run_9	16.238230	16.231939	0.000255	0.000304	0.005941	0.000488	0.000217	0.000353	0.000939	0.000213
run_10	16.240791	16.233197	0.000308	0.000284	0.000436	0.000486	0.000225	0.000379	0.000993	0.000190
run_11	16.239846	16.234410	0.000299	0.000249	0.004711	0.000413	0.000224	0.000340	0.000964	0.000172
run_12	16.237580	16.235975	0.000220	0.000315	0.001771	0.000409	0.000285	0.000335	0.000954	0.000163
run_13	16.237262	16.234185	0.000303	0.000277	0.002642	0.000509	0.000301	0.000380	0.000974	0.000186
run_14	16.233765	16.237478	0.000222	0.000275	0.006198	0.000493	0.000231	0.000291	0.000987	0.000240
run_15	16.239749	16.235138	0.000307	0.000321	0.006772	0.000474	0.000208	0.000357	0.000978	0.000200
run_16	16.241371	16.230796	0.000242	0.000239	0.011217	0.000432	0.000267	0.000399	0.000896	0.000160
run_17	16.239138	16.233617	0.000275	0.000265	0.007965	0.000483	0.000291	0.000360	0.000929	0.000222
run_18	16.233606	16.228061	0.000212	0.000248	0.008968	0.000496	0.000207	0.000317	0.000978	0.000220
run_19	16.239929	16.233220	0.000291	0.000215	0.005127	0.000471	0.000209	0.000321	0.000917	0.000210
run_20	16.235476	16.227482	0.000219	0.000259	0.004489	0.000481	0.000290	0.000300	0.000917	0.000238
run_21	16.234471	16.233109	0.000257	0.000244	0.010671	0.000456	0.000258	0.000384	0.000993	0.000189
run_22	16.244248	16.236745	0.000229	0.000314	0.004018	0.000465	0.000213	0.000397	0.000912	0.000182
run_23	16.233979	16.229877	0.000229	0.000246	0.001321	0.000431	0.000247	0.000375	0.001001	0.000194
run_24	16.243700	16.236145	0.000286	0.000260	0.001976	0.000506	0.000310	0.000385	0.000954	0.000171
run_25	16.239977	16.229511	0.000241	0.000266	0.003919	0.000504	0.000284	0.000324	0.000903	0.000163
run_26	16.233775	16.234867	0.000219	0.000287	0.008332	0.000518	0.000288	0.000313	0.000984	0.000188
run_27	16.243967	16.227239	0.000231	0.000226	0.006467	0.000456	0.000216	0.000351	0.000927	0.000159
run_28	16.235139	16.228769	0.000208	0.000259	0.011311	0.000511	0.000308	0.000368	0.000995	0.000229
run_29	16.241669	16.233998	0.000255	0.000273	0.005257	0.000457	0.000290	0.000385	0.000917	0.000204
run_30	16.243668	16.227590	0.000289	0.000272	0.003781	0.000505	0.000268	0.000333	0.000999	0.000231
run_31	16.236567	16.229709	0.000313	0.000218	0.009436	0.000445	0.000220	0.000350	0.000922	0.000252
run_32	16.237113	16.227331	0.000252	0.000256	0.008555	0.000429	0.000204	0.000373	0.000994	0.000213
run_33	16.242838	16.230878	0.000275	0.000227	0.011225	0.000493	0.000296	0.000345	0.000924	0.000211
run_34	16.243304	16.227015	0.000229	0.000275	0.000485	0.000430	0.000207	0.000349	0.000905	0.000209
run_35	16.243718	16.232024	0.000290	0.000313	0.002324	0.000453	0.000292	0.000360	0.000953	0.000240
run_36	16.240980	16.233252	0.000269	0.000230	0.004612	0.000429	0.000251	0.000374	0.000923	0.000161
run_37	16.240562	16.231706	0.000267	0.000223	0.004854	0.000514	0.000265	0.000383	0.000963	0.000216
run_38	16.237104	16.235900	0.000213	0.000315	0.011060	0.000421	0.000250	0.000317	0.000963	0.000214
run_39	16.235572	16.229127	0.000277	0.000281	0.007076	0.000493	0.000251	0.000331	0.000937	0.000172
run_40	16.238777	16.237236	0.000256	0.000324	0.008002	0.000472	0.000234	0.000293	0.000929	0.000182
run_41	16.241256	16.231168	0.000222	0.000254	0.004366	0.000503	0.000257	0.000292	0.000912	0.000197
run_42	16.242885	16.237074	0.000277	0.000265	0.004416	0.000451	0.000217	0.000367	0.000937	0.000227
run_43	16.236623	16.231521	0.000223	0.000320	0.000921	0.000442	0.000248	0.000379	0.000929	0.000161
run_44	16.243346	16.234731	0.000233	0.000266	0.003178	0.000464	0.000223	0.000299	0.000978	0.000246
run_45	16.239560	16.236802	0.000263	0.000295	0.008578	0.000457	0.000213	0.000323	0.001000	0.000242
run_46	16.241006	16.230970	0.000290	0.000252	0.001352	0.000441	0.000236	0.000300	0.000979	0.000225
run_47	16.239833	16.227794	0.000268	0.000232	0.005162	0.000480	0.000207	0.000313	0.000978	0.000161
run_48	16.236109	16.236538	0.000275	0.000302	0.009868	0.000414	0.000272	0.000356	0.000896	0.000157
run_49	16.242627	16.231342	0.000276	0.000234	0.003334	0.000452	0.000237	0.000324	0.000924	0.000206
run_50	16.234179	16.235278	0.000310	0.000285	0.005802	0.000467	0.000233	0.000383	0.000909	0.000169

Case 10 Concentration Output: Distance Downwind (0.5 – 5 KM), Stability Class (Stable) and Wind Speed at (19.0 M/S).

Appendix K: HD Physical & Chemical Properties

Alternate Designations: EA 1033; HS; G.34; M.O; Kampstoff "Lost"; Mustard HD; Mustard gas; Mustard Sulfur; Mustard vapor; S-Lost; Schewefel-lost; S mustard; Sulfur mustard gas; Sulfur mustard; Sulphur mustard; Sulphur mustard gas; Yellow Cross liquid; Y; Yperite (French & German)	
Chemical Name: Bis (2-chloroethyl) sulfide	
Synonyms: 2, 2'-dichloroethyl sulfide; 1, 1'-Thiobis(2-chloroethane); β- β '-dichlorodiethyl sulphide; β ,β´-dichloroethylsulfide di – (2-chloro-ethyl) sulfide; Sulfide, bis (2-chloroethyl); Bis (beta-chloroethyl)sulfide; Bis (2-chloroethyl)sulfide; Bis (2-chloroethyl) sulphide; 1-Chloro-2-(beta-chloroethylthio)ethane; 2,2'-Dichlorodiethyl sulfide; Di-2-chloroethyl sulfide; beta,beta'-Dichloroethyl sulfide; beta,beta-Dichlor-ethyl-sulphide; 2,2'-Dichloroethyl sulphide; Gelbkreuz (Czech); 1,1'-Thiobis(2-chloroethane)	
CAS Registry Number: 505-60-2	
RTECS Number: WQ0900000	
Physical and Chemical Properties	
Structural Formula: $Cl\text{-}CH_2\text{-}CH_2\text{-}S\text{-}CH_2\text{-}CH_2\text{-}Cl$ Molecular Formula: $C_4H_8Cl_2S$ Molecular Weight: 159.07	
Physical State	Pale yellow to dark brown oily liquid; [1] colorless when pure [1,2]
Odor	Garlic-like [1,3] or horseradish [3]
Boiling Point	218°C (extrapolated); at atmospheric pressure HD starts to decompose below the boiling point [4]
FP/MP	14.45°C (FP) [2]
Solid Density (g/mL)	1.372 @ 0°C; 1.333 @ 10°C [5]
Liquid Density (g/mL)	1.2685 @ 25°C [6]
Vapor Density (relative to air)	5.5 (calculated)
Vapor Pressure (torr)	1.06×10^{-1} @ 25°C [4]
Volatility (mg/m^3)	9.06×10^2 @ 25°C (calculated from vapor pressure) [4]
Latent Heat of Vaporization (kcal/mol)	15.0 @ 25°C (calculated from vapor pressure) [4]
Viscosity (cP)	3.951 @ 25.0°C, 7.746 @ 0°C (extrapolated)[7]
Viscosity of Vapor (cP)	6.65×10^{-3} @ 25.0°C, 6.00×10^{-3} @ 0°C[7]
Surface Tension (dynes/cm)	42.5 @ 25.0°C, 45.9 @ 0°C[7]
Flash Point	105°C [5]
Decomposition Temperature	180°C [8]
Solubility	HD is practically insoluble in water; solubility of HD in distilled water is 0.92g HD/100g solution at 22°C. HD is freely soluble in fats and oils, gasoline, kerosene, most organic solvents, and CW agents. [5]
Rate of Hydrolysis	$t_{1/2}$ = 5 min @ 25°C via a S_n1 mechanism;[9] $t_{1/2}$ = 60 min @ 25°C in salt water.[10] HD on or under water undergoes hydrolysis only if dissolved. The rate of HD hydrolysis is controlled by the rate of mass transfer and is very slow.[11]
Hydrolysis Products	Hydrogen chloride, thiodiglycol, and sulfonium ion aggregates—one of which is also highly toxic[11]
Stability in Storage	A small amount of degradation occurs when stored in steel ton containers for over 50 years.[12] This degradation appears to be caused by the formation of solid deposits "heels" comprised of a six-membered ring cyclic sulfonium ion {1-(2-chloroethyl) -1,4-dithianium chloride}, HD, and Fe, which were detected at the bottom of the containers.[13]
Action on Metals or Other Materials	Very little when pure.[3] The corrosion rate of HD on steel is 0.0001 inch/month @ 65°C using munitions grade HD. [14]

HD Physical and Chemical Properties. Curling, C., et al. Technical Reference Manual: NATO Planning Guide for the Estimation of Chemical, Biological, Radiological, and Nuclear (CBRN-E) Casualties, Allied Medical Publication-8(C). (2011). North Atlantic Treaty Organization *Allied Medical Publication*. 8:1-365

Appendix L: List of Industry Participants

Military Operations Research Society (MORS)	Corporation	Defense Threat Reduction Agency (DTRA)
Edwin D’Souza	Dr. Carl Freidhoff	Eric Lowstein
Taniesha Simms	Dr. Victor Suchebrow	
	Mashfique Hassan	
	Dulce Castro	
	Rodrigues Bailey	

LIST OF ABBREVIATIONS

INCOSE	International Council of Systems Engineering
CBRN	Chemical, Biological, Radiological, and Nuclear
CBRN-E	Chemical, Biological, Radiological, Nuclear, and Explosive
SE-CAS	Systems Engineering Casualty Analysis Simulation
CWA	Chemical Warfare Agent
M&S	Modeling & Simulation
MS&A	Modeling, Simulation & Analysis
MSA&E	Modeling, Simulations, Analysis & Experimentation
DOD	Department of Defense
LVC	Live, Virtual and Constructive
CINC	Commander-In-Chief
JROC	Joint Requirements Oversight Council
WMD	Weapon of Mass Destruction
TTP	Tactics, Techniques & Procedures
NATO	North Atlantic Treaty Organization
IDA	Institute for Defense Analyses
NAVSEA	Naval Sea Systems Command
HVT	High Value Target
NASA	National Aeronautics and Space Administration
PG	Pasquil-Gifford
AMedP-8©	Allied Medical Publication
GASTAR®	Dense Gas Dispersion Model
ADMS®	Atmospheric Modeling Dispersion System
DEGADIS®	Dense Gas Dispersion Model
INPUFF®	Integrated Puff Model
EPA	Environmental Protection Agency
GPM	Gaussian Plume Model
AMS	American Meteorological Society
AERMOD®	AMS/EPA Regulatory Model
AERMET®	AMS/EPA Regulatory Model Meteorological Preprocessor
PRIME®	Plume Rise Model Enhancements
CALINE®	California Line Source Dispersion Model
ALOHA	Areal Locations of Hazardous Atmospheres
DTRA	Defense Threat Reduction Agency
HPAC®	Hazard Prediction and Assessment Capability
U.S.	United States
SAM	Surface-to-Air Missile
KPP	Key Performance Parameters
TPM	Technical Performance Measures
MOE	Measures of Effectiveness
MOP	Measures of Performance
SysML®	Systems Modeling Language

DODAF®	Department of Defense Architectural Framework
COIN	Counterinsurgency Operations
SE	Systems Engineer
W.R.T	With-Respect-To
DOORS®	Dynamic Object-Oriented Requirements System
SRR	System Requirements Review
PDR	Product Design Review
V&V	Verification and Validation
GUIDEx®	Guide for Understanding and Interpreting Defense Experiments
IPT	Integrated Product Team
AFSIM®	Analytic Framework for Simulation Integration & Modeling
BRAWLER®	Tactical Air-Combat Simulation
SUPPRESSOR®	Mission-level Simulation System
OneSAF®	One Semi-Automated Force
SIMNET®	Simulation Network
ADST®	Advance Distributed Simulation Technology
CCTT®	Close Combat Tactical Trainer
AVCATT®	Aviation Combined Arms Tactical Trainer
DMO®	Distributed Mission Operations
JCIDS®	Joint Capability Identification Database System
CONEMP	Concept of Employment
BAP	Business Acquisition Process
DOE	Design of Experiments
IMP	Integrated Master Plan
IMS	Integrated Master Schedule
FOB	Forward Operating Base
MOPP	Mission Oriented Protective Posture