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Case studies in developing comprehensive decision making environments for engineering design and analysis

by

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in partial fulfillment of the requirements for the degree of
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This is to certify that the master's thesis of

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has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy

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ABSTRACT

As engineering systems become more complex, new tools and mechanisms are needed that enable engineers to effectively manage complexity in system design and analysis. To fully understand a complex system, an engineer often needs to utilize multiple simulation and analysis tools. Today these tools are often uncoupled and their impact on the overall performance of the system is unknown. Effectively implementing multiple disparate models in design and analysis requires integration of models in an environment which supports decision making through human interaction. As a first step, this requires developing a framework that can support a comprehensive decision making environment in which an analyst can develop a complete engineering system. In this thesis, a portion of this framework was developed that links together intuitive user interfaces, high fidelity models, and Microsoft™ Office tools. This enables decision makers to utilize well developed and familiar analysis tools, such as spreadsheet models for economic or simple physical calculations, integrated with more complex and specialized tools such as computational fluid dynamics to facilitate complete system simulation. This development is implemented through the software framework of VE-Suite, an open-source library of tools being developed at Iowa State University that enables virtual engineering processes. The development and implementation is demonstrated with two engineering examples. These are 1) the analysis of fire hazards within an auxiliaries room in a nuclear power plant and 2) interactive design of heat transfer systems within biomass cookstoves. In both examples, the analysis requires integration of computational tools, geometrical models, and user control interfaces to create an environment which supports an engineer's ability to supplement the analysis with human experience and intuition. In analyzing fire hazards the engineer needs to be able to walk through a virtual representation of the space in question, place and build a fire, and interactively work with results displaying the impact of fire. In interactive cookstove design, the analyst needs an intuitive mechanism for making design changes, the ability to perform high fidelity analysis on the fly, and an effective means for understanding the computational results. In both cases, several disparate models are linked together using the tools developed as part of this master's thesis to create a comprehensive decision making environment.

CHAPTER 1. INTRODUCTION

Complexity in engineering systems is increasing along with our ability to model and simulate systems. For engineers to effectively manage this increasing complexity, it is important to be able to seamlessly interact with complete engineering systems. This interaction requires an advanced level of model integration in an extensible user-centered environment. Creating an environment which integrates analysis with human interaction requires the development of a framework that immerses the analyst in necessary decision support tools. This thesis describes development which facilitates the integration of the decision support tools needed for two engineering design and analysis problems.

Complex engineering systems often require multiple unique analysis tools to develop an understanding and intuition about the system. These analysis tools and models are commonly disjoint and difficult to integrate leaving a decision maker the task of extracting and distributing important information within the system of models through a manual and labor intensive process. This characteristic of the design and analysis process is slow, expensive, and often facilitates human error during the extraction and manipulation of data.

Technologies such as CAD, Rapid Prototying, Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), and Virtual Reality (VR) have become well utilized in engineering design and analysis (Yan et al., 1996; Craig et al., 1999; Ryken et al., 2000; Furlong et al., 1999; Kihonge et al., 2002), but the disparate nature of these technologies currently requires engineers to work with each tool individually. Analyzing design alternatives then involves a difficult, time intensive, and mistake prone process of making the necessary changes in each individual model, then manually distributing information. To effectively use these technologies in engineering decision making it is useful and even important to integrate multiple design and analysis models into a single decision making tool (Giachetti, 2004; Deng et al., 2002).

The work discussed in this thesis implements an integrated interactive decision-making environment for two engineering design and analysis problems, fire hazard analysis in nuclear power plants, and interactive design of biomass cookstoves. Included is a description of the software framework utilized to create the environments, as well as an introduction to the concepts behind virtual engineering technologies. The design problems explored in this work present interesting case studies for virtual engineering concepts by requiring the decision maker to 1) utilize multiple models in their analysis, 2) interact with high fidelity models, 3) be able to review design alternatives quickly to develop an intuition about the solution search space, and 4) interact with the models from within a virtual representation of the physical space to fully understand the impact of the computational results. The development needed to approach these problems provides the ability to integrate a wide range of analysis tools within a virtual engineering framework. This range of tools includes familiar software packages, such as spreadsheets, used regularly by decision makers to perform a number of numerical tasks, as well as highly specialized commercial numerical solvers and multifunctional software development libraries. The development work discussed in this thesis describes the techniques used to facilitate the integration of spreadsheets, numerical solvers, design interfaces, and other decision support tools to make faster and more informed engineering decisions.

Identifying and assessing fire hazards within nuclear power plants requires a combination of computational models, statistical analysis, and engineering judgment. Fire protection engineers have many tools at their disposal to assist in their analysis. A large amount of work has been done developing computational and probabilistic risk assessment (PRA) capabilities. Much of this work has focused on developing computer codes, statistical models, or simple algebraic models for assessing specific fire hazards or regulatory concerns. The complexity, fidelity, and capability of these models can vary significantly depending on the specific application for which they were developed. Fire hazard analysis tools are often disparate and individualized in their capability. Many times this means that to understand the full impact and risk of particular fire hazards multiple analysis tools must be utilized in conjunction with the experience and expertise of the fire protection analyst. These characteristics of the current analysis toolkit leave the fire protection engineer with the difficult task of identifying and implementing an appropriate combination of technologies needed to perform a particular fire hazard assessment.

Dealing with multiple computational and statistical models can make fire hazard assessment a difficult, time-intensive, and manual process. As an analyst works through the investigation, they will be responsible for directing the system of models to a solution. This can include having to work in several software packages simultaneously, as well as manually extracting information from models and distributing that information to the other elements of the system. Further complicating the analysis effort is the fact that the computational and statistical data developed through the system of models needs to be extracted to the actual physical space in question. This process can potentially be as painstaking as working with hard copies of results and a tape measure within the physical space. Not only is this interaction difficult and mistake prone, it also restricts the ability of the fire protection engineer to interject their own experience, expertise and intuition throughout the analysis.

A more effective approach to performing fire hazard analysis is integrating the system of models and analysis tools within a comprehensive decision making environment. This integrated environment will abstract the interaction between analysis tools from the user allowing them to more quickly and effectively develop an intuition about the problem. It is extremely important that this environment supports the integration of the many types of computational and statistical models needed to perform the analysis. It is also important for fire hazard assessment that the environment effectively presents analysis data, and the impact of that data, within a physical representation of the space in question.

As mentioned previously, CFD has become well utilized in engineering design. There are several difficulties in efficiently and effectively using CFD in the design process. Using CFD to support the interactive design of baffle configurations in the heat transfer chamber of biomass cookstoves requires fast converging models and the ability to integrate CFD solvers, immersive CAD models, and intuitive user controls to make design changes. Biomass cookstove design and construction is often an ad hoc process of building and testing utilizing very little analysis. A single design iteration requiring jig assembly, stove construction, and testing can easily require multiple days.

Economic and manufacturability concerns are also key design factors in developing cookstoves. Stoves are typically built locally in third world countries out of materials which happen to be available. For a designer to fully understand the impact of a stove design models providing economic and manufacturing analysis must be used in coordination with the CFD results. The cookstove design problem also benefits from implementing a highly integrated decision making framework to give the designer a single set of intuitive controls allowing them to quickly design and analyze cookstove designs.

In both cases, to completely model the system, disparate software tools need to be brought together and integrated to form a single system model that better supports engineering design in analysis. Chapter two discusses the evolution of engineering decision making processes and reviews previous work recognizing the benefit of creating more complete environments to support design and analysis. Chapter three discusses the virtual engineering tools utilized in this work and describes the development required to perform the design and analysis efforts. A complete description of the fire hazard analysis decision making environment created with this work can be found in Chapter four. Chapter five looks at the environment developed for the design of biomass cookstoves. Chapter six concludes the thesis with a summary of the development work as well as provides some insight as to the future direction of the work.

CHAPTER 2. BACKGROUND

The growing need to develop products more quickly and at a lower cost is driving an increasing dependence on computational modeling and simulation in engineering design and analysis. The geometric growth in computational power and speed continuously invites exploration of more robust and complete modeling and simulation tools for analysts. Ongoing efforts at cost reduction and process streamlining are also encouraging the development of more complete computational environments. The ability to effectively create and analyze a product in a computer generated environment can reduce both cost and time in making engineering decisions (Cao et al., 2004). Furthermore, the increasing dependence on synthetic computational environments to support design and analysis is driving an evolution of engineering decision making processes.

2.1 Engineering Decision Making

Over the past half century the principles and methods directing engineering decision-making have changed significantly. The complexity of systems is continuously increasing, which along with a highly competitive socio-economic environment make it difficult for a single decision maker to consider all relevant aspects of a problem (Kim et al., 1999). The dynamic of group decision making has become common as a way of managing complexity. In moving from a single decision maker dynamic to a group decision making dynamic, even more complexity is often introduced to the analysis. The key in a group decision making process is establishing a consensus among the individuals as to which decisions have the greatest benefits. In these situations, decisions made by one individual or group are affected by other decision makers. The impact of this interaction has lead to significant changes in engineering design and analysis processes.

Engineering decision making has commonly been a linear process. Each engineer performed a particular analysis as part of a complete system and their results and conclusion are simply passed on to the next analyst in line. Interaction within these linear processes is limited and changes at any point in the system are difficult and time consuming to deal with. As product development times have been shortened, more efficient and parallelized decision making processes have replaced linear processes. Many organizations have been restructured into cross-functional, multi-disciplinary units to improve their processes (Krishnan, 1997). The focus of these efforts is the idea that several individuals from different disciplines work collaboratively and simultaneously to improve the decision making process. These concepts are very important in the development of virtual decision making environments. Clear successes can be found in performing engineering design and analysis tasks from within integrated and collaborative social frameworks. Several more important components must be brought together to create a fully comprehensive decision making environment.

2.2 Interactive Environments

As stated by Comparto, 2003, synthetic three-dimensional environments can facilitate human capacities for evaluation and decision-making by accurately representing real-world experiences. A key realization from this work is that when information is presented effectively, human perception is very efficient at recognizing complex patterns, synthesizing opportunities, and evaluating alternative processes. For complex engineering systems, it is often essential to utilize human perception and intuition in analysis. In many cases the solution search space is simply too large and/or complicated to investigate computationally. In other cases the complexity of high fidelity analysis data creates the need for human perception in developing an understanding of the system.

For many complex engineering problems high fidelity information is required to develop an understanding and intuition about the system. Many CFD and FEA tools are well developed and adapted to facilitate high fidelity analysis. One difficulty in using these tools can be a decision makers' ability to extract valuable design information from the analysis data. A large amount of work has been done developing interactive visualization tools to assist engineers, designers, and decision makers in utilizing high fidelity data in the design process. One project (Chhugani et al., 2005) has focused on developing highly efficient rendering methods to enable immersive virtual walkthroughs of three dimensional geometric datasets. Other data visualization applications have included image-based diagnosis medical data (Manssour et al., 2005), airborne laser scanner data (Soderman et al., 2005), and mechanical and thermal data for large scale structures (Hoffmann et al., 2005). Work done by Malkawi et al., 2005 has focused on creating a more complete and interactive visualization environment for working with high fidelity information by allowing the user to change analysis parameters and perform new simulations in real time.

This type of environments can be valuable in helping decision makers understand a system, but it is difficult to efficiently and effectively explore design alternatives within simple visualization environments without integrating the analysis packages together into the visualization environment. For example, in the case of a thermal or fluid system, changes to a design must be made in the CAD models by a specialized CAD analyst, and then given to a CFD analyst to implement the changes within the computational model. The changes must then be imported into the visualization environment again once the analysis is complete. To create a more comprehensive simulation environment which supports exploration, this process must be abstracted from the end user. Within this type of environment the user needs to be able to interactively control the entire integrated set of models used to represent the design problem.

2.3 Virtual Simulation Environments

In a software framework called The Building Design Advisor (Papamichael et al., 1997) a tool supporting an object-oriented representation of buildings and their contexts was introduced. Through this object-oriented approach the software environment supports the integrated use of interactive analysis and visualization tools. This integration of interactive models allows a building designer to quickly and effectively investigate many aspects of a building's design entirely within a computer generated environment. This work was later extended to include a more comprehensive set of virtual simulation tools (Papamichael et al., 1999; Reichard et al., 2005). These tools were expanded to include regulatory and energy analysis models. Using this package a designer or decision maker is able to use performance and regulatory code compliance simulation to understand the full impact of a building design during the early schematic phases from within the virtual environment. The ability of the designer to interact with these models throughout all stages of the building design process helps them identify problems quickly and make the necessary changes quickly and at low cost.

2.4 Comprehensive Decision Making Environments

A comprehensive decision making environment must not only be interactive and integrated, but also complete. A complete environment, in this context, will represent all aspects of the system needed for decision making. In Kalay, 1998, the author describes in detail the collaborative issues that arose from design team fragmentation in the construction of highly integrated facilities (e.g. choked information flow, conflicting objectives in decision making, and professional specialization). In these types of construction projects, performance of processes and products is severely hindered by the fragmented nature of the design teams. With professional specialization of the design team, the knowledge needed to complete the design and construction of a facility is distributed among several individuals representing diverse disciplines, but the facility itself is highly integrated. The work is subsequently focused on supporting design collaboration through the development of a computational environment that facilitates informed and unified decision-making. Developing this unified decision-making environment requires a fully inclusive computational framework integrating all of the necessary data and knowledge tools. The work presented in Fernando et al., 1999, acknowledges the need for complete virtual environments in three dimensional assembly modeling. Simulating three dimensional assembly requires an extensive integration of technologies, including intricate interaction with geometry, near real time numerical modeling, and advanced visualization. These efforts concentrate on creating an assimilated virtual environment which gives a user access to each of these analysis tools. The constraint-based virtual environment presented is supported through a software framework bringing together virtual reality, constraint-based modeling, assembly modeling, CAD, and three dimensional direct manipulation techniques. As demonstrated in Al-Bin-Ali, 2004, a complete environment also must support intelligent interaction. This involves providing the users with context, supporting self configuration, and providing mechanisms for appropriate user intervention.

While each of these technologies provides important tools to support advanced decision making, they in general lack the robust integration capabilities necessary to analyze a wide range of difficult engineering problems. As complexity in engineering systems continues to grow, it will become far too difficult to use and maintain application specialized decision support frameworks. Design and analysis of these systems requires a robust, extensible, and complete software framework generalized in structure to accommodate integration of an ever growing set of analysis tools.

This complete decision making framework can be well represented in engineering design through the implementation of virtual engineering technologies. Virtual engineering technologies (Bryden et al., 2004) are focused on creating a comprehensive and collaborative decision-making environment which provides an engineer with a complete set of tools to design and analyze a system. The work discussed in this paper represents an implementation of virtual engineering technologies in solving fire hazard analysis and thermal system engineering design problems.

CHAPTER 3. FRAMEWORK DEVELOPMENT

3.1 VE-Suite

VE-Suite is composed of three main software engines VE-CE, VE-Xplorer, and VE-Conductor which, coordinate the flow of data from the engineer to the virtual components being designed (Fig. 1). VE-Suite provides features including distributed computing, platform independence, extensibility for component models, support for a hierarchy of component models, and comprehensive graphics capabilities including support for immersive facilities. The overall goal of VE-Suite is to enable users to incorporate component models and corresponding two-dimensional and three-dimensional graphical representations to create new, plug-and-play components (Bryden et al., 2004). By design, these components can be distributed across computational resources to make the most efficient use of resources.

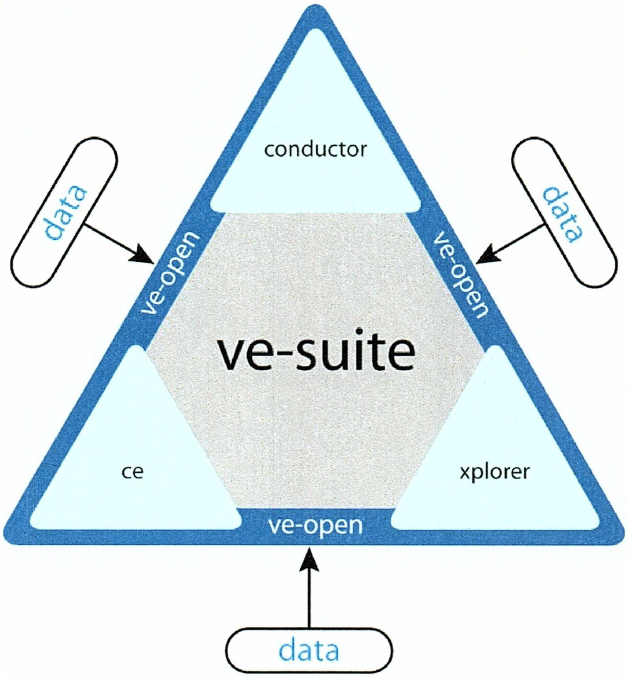


Figure 1. VE-Suite basic software structure

VE-CE is responsible for the synchronization of the data among the various analysis and process models and the engineer. VE-CE serves as a direct CORBA link to the VE-Suite software environment for external analysis packages. Through VE-CE, and compliance with the VE-Open standard, analysis tools can be integrated with distributed and cross-platform networking.

VE-Xplorer is the decision-making environment that allows the engineer to interact with the equipment models in a visual manner. VE-Xplorer is extensible for a vast set of visualization environments ranging from standard desktop or portable computers all the way to fully immersive virtual reality facilities. VE-Xplorer provides the user access to several robust data visualization pipelines. Through this combination of functionality VE-Xplorer allows the engineer to seamlessly interact with analysis data presented in an intuitive format within the associated equipment models.

VE-Conductor is the engineer's mechanism to control models and other information. Within VE-Conductor the user has access to controls which oversee high level virtual environment functionality including application startup and shutdown, general graphics controls, and global simulation commands. VE-Conductor also provides the mechanisms the user needs to assemble systems of models and interact with each of the components of the system. These operations are performed in VE-Conductor's design canvas as seen in Fig. 2.

VE-Open is a proposed open-source communication standard being developed at Iowa State University and the Ames National Laboratory. VE-Open, allows the VE-Suite software engines and components to be integrated seamlessly and consequently gives the engineer and other stakeholders access to the information in their virtual system. The VE-Open standard utilizes self-describing XML data structures to facilitate communication between the core VE-Suite engines. The VE-Open standard also serves as an API for integration of outside software.

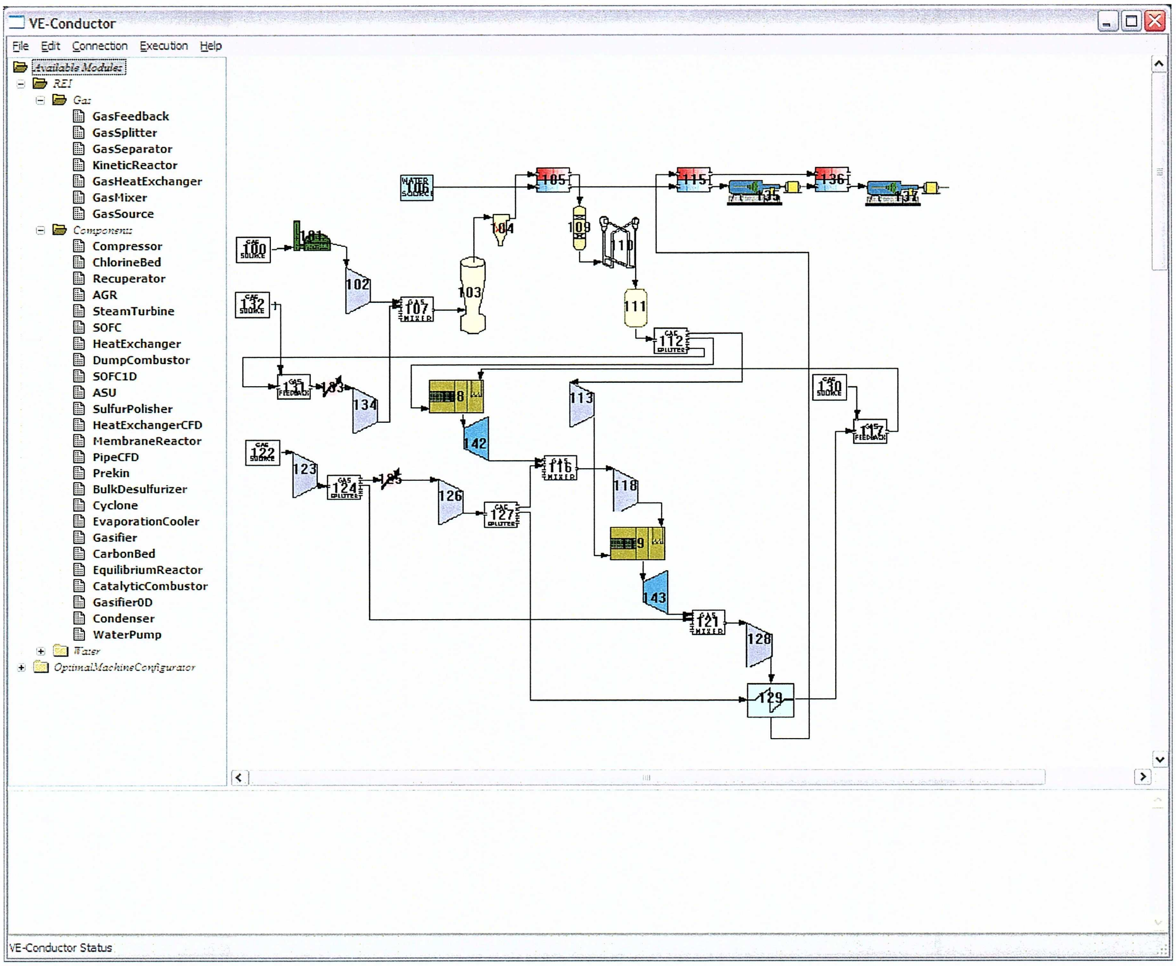


Figure 2. VE-Conductor design canvas

3.2 Development of VE-Suite Plug-ins

To develop an interactive application within the VE-Suite framework, three separate plug-ins are needed. The graphical plug-in, graphical user interface (GUI) plug-in, and the computational unit plug-in are built to adhere to VE-Suite's VE-Open specification for communication. Plug-ins are developed to run distributed, cross platform, and cross network. Through the VE-Open specification and VE-CE's data and command synchronization capabilities, changes and results from within the plug-ins are automatically updated throughout the rest of the environment. Plug-ins provide a software structure for integrating representational models needed to describe a system. To virtually describe and interact with an engineering system, a software framework needs to provide the user with geometric models of system components, computational representations capable of describing the physical relationships of the components, and user interface representations which allow the user to assemble and interact with system components.

The GUI plug-in provides an engineer with a complete set of controls necessary to make decision changes or development analysis parameters. The GUI plug-in is customized to give the user access to the parameters needed within the environment. The GUI plug-in interface is built using wxWidgets, an open source C++ cross-platform GUI framework. The wxWidgets library gives access to a number of controls which allow for development of an intuitive and intelligent interface.

The computational unit plug-in is developed and built as a stand alone application adhering to the communication specification established within VE-Open. The unit plug-in receives user established design and analysis variables from VE-CE, then uses the collected data to direct the computations. The computational unit plug-in is responsible for supplying functionality needed to interact with software packages to be integrated within VE-Suite.

The graphical plug-in is responsible for bringing all of the CAD and graphics models into the environment. The graphical plug-in presents that physical space to the user through

VE-Suite's graphical engine, VE-Xplorer. The graphical plug-in also inherits VE-Xplorer's advanced data visualization capabilities Geometric models are loaded onto a scene graph which can be presented in several visualization environments. VE-Xplorer supports visualization hardware configurations ranging from standard personal computers to fully immersive virtual reality caves.

3.3 Development of Integration Capabilities

To extend VE-Suite to perform various new engineering tasks, several new capabilities were added as a part of this thesis. These additions were user interface advancements, integration of Microsoft™ Office tools, specifically Excel, and the ability to interactively utilize high fidelity analysis tools within VE-Suite's framework.

3.3.1 User Interface Development

A specialized interface has been developed to make simple geometric changes to the physical system, in this case baffle configurations within the heat exchange chamber of the stoves. The user interface is built using wxWidgets, an open source C++ cross-platform GUI framework. A canvas was built allowing an engineer to use a mouse or other input device to draw simple design changes which can be passed along and represented in the physical models. A unique and powerful tool from within the wxWidgets library called an OpenGL™ Canvas was used to develop this capability. The OpenGL™ Canvas class gives the developer direct access to raw OpenGL™ functionality. Through the use of OpenGL™, geometrical changes can be drawn on a flexible design canvas in an intuitive manner which allows to user to very simply draw each of the desired baffles. The implementation of the OpenGL™ Canvas allows the engineer to interact with the design canvas similarly to working in a paint program. A pre-determined set of operations using commands from an input device allow the user to make geometrical changes to system components. The OpenGL™ design canvas allows the user to interact with component in two or three dimensions. In the case of designing baffle configurations, a two dimensional grid is effective is giving the engineer perspective on the design changes they are making. In other cases it may be important to give the user access to a three dimensional representation of a component within the OpenGL™ design canvas to support intuitive design changes. The software structure used in developing the OpenGL™ design canvas allows the canvas to reside as a child of the GUI plug-in window. With this relationship established, design changes created on the canvas can be accessed from the parent GUI plug-in window and the design information then shared with the rest of the virtual environment including the computational models and geometric models which will utilize the new design data to describe the system.

3.3.2 Integrating Microsoft™ Excel

In this section the process of integrating Microsoft™ Excel spreadsheets into a virtual engineering environment is described. The task of interacting with Excel is handled within the computational unit plug-in. The unit plug-in is a simple stand-alone application that operates as a CORBA server communicating with VE-CE. Specific and powerful functionality has to be exposed to the unit plug-in to support the integration of Excel. This functionality comes from the use of Microsoft™ Foundation Classes (MFC). MFC is a Microsoft™ library which wraps portions of the Windows ™ API in C++ classes. The first step in developing a computational unit plug-in which allows Excel integration is using wizard functionality built into Microsoft's™ software development environment, Visual Studio C++, to create the base class structure for an MFC application. Several options are available within the MFC application wizard which may be useful for specialized needs in working with the suite of Microsoft^{TM} Office tools. Upon creating the base MFC class structure, functionality must be added to support the CORBA communications with VE-CE. A wizard is also available with VE-Suite which develops base class structures for standard, non MFC, computational unit plug-ins. Running both the MFC application wizard and the VE-Suite wizard allows a merging of functionality within the MFC structured class which supports communication with VE-CE.

Upon establishing the class structure for the MFC capable unit plug-in, several header files providing access to the specific functionality needed to interact with Excel need to be included. For standard interaction with the spreadsheets these files are as follows: CApplication.h, CWorkbooks.h, CWorkbook.h, CWorksheets.h, CWorksheet.h, CRange.h. Other header files may need to be included if unique Excel functionality needs to be utilized. These Microsoft^{TM} distributed header files are included in a new class which is created manually with the specific purpose of exchanging data with the Excel spreadsheet or spreadsheets. This new class can be considered an Excel wrapper and an instance of the wrapper class within our MFC capable unit plug-in with provide direct access to Excel and all of its functionality.

To get to Excel several MFC defined classes are initialized including CApplication, CWorkbooks, CWorkbook, CWorksheets, CWorksheet, and CRange. Using these classes requires initializing an instance of a COleVariant data type which is another MFC class which communicates data within Microsoft^{TM} applications. With each of these classes initialized, the process of opening and working a spreadsheet can move forward. Each of these classes is responsible for accessing a specific level of the Excel spreadsheet. Starting with the CApplication an Excel executable can be started. The CWorkbooks class then accesses the executable starts the generic Excel workbook functionality. The CWorkbook class then uses the CWorkbooks class to access a particular Excel workbook. This structure of inheritance and control continues through until CRange is used to interact with individual cells within the spreadsheet.

3.3.3 Integrating StarCD^{TM}

In this section the process of integrating StarCD^{TM}, a commercial CFD solver, into a virtual engineering environment is described. The API which is exposed for system level control of StarCD^{TM} processes is a well defined scripting language. Through an implementation of system calls to start StarCD^{TM} executables, with associated command scripts, CFD analysis can be performed completely abstracted from direct user interaction. Through StarCD's^{TM} command language entire CFD models can be built from start to finish, but for developing interactive design applications the preferred approach is to start with well defined models that are known to converge. Design change iterations often involve small changes to component geometry or physical parameters. Starting with a well developed converging model and scripting a small design change requires much less processing time and much smaller scripts.

The method of interacting with StarCD^{TM} through the computational unit plug-in utilized is this work starts by loading an existing standard design scenario CFD model. Design change information is collected by the unit plug-in and multiple software classes which handle various tasks in manipulating data, script development, and system calls are initialized. The following steps direct the StarCD^{TM} model into implementing the design changes and running the analysis. First, the design information is processed and arranged into data structures which facilitate script development. Previous work (Bryden, 2003) has implemented these scripting techniques for developing StarCD^{TM} models of cookstoves. In this work the scripting techniques were used to facilitate CFD analysis for optimization routines. The scripts can then be written directing StarCD^{TM} to make the necessary changes to component of the model including boundary conditions, inlet and outlet definitions, and cells definitions. For example, the following set of commands uses a file, baff.cel, which is created in the preprocess step in order to define a new baffle structure design received by the unit plug-in to place the baffle cells within the StarCD™ grid.

```
cset none
cset news baff
cdel cset
cread baff.cel 0 all add coded 0
close baff.cel
```

Upon completing all of the development of the scripts necessary to create the design changes within the model, system calls are coded into the unit plug-in which start the StarCD™ executables and run the model setup scripts. Utilizing well constructed scripts, model setup is typically fast, a few minutes or less, even for large models. With the model setup complete and the executables running, yet another script is used to instruct StarCD™ to begin solving and once the model has converged, to export the analysis data to files which can be accessed for further processing.

3.3.4 Graphical Decision Support Tools

Several additional decision support tools are required to effectively perform engineering analysis and design. As described previously interaction with the CFD solver is automated all the way through the output of the converged analysis dataset. Further automation is then needed to preprocess the CFD solver output to load and display the data within VE-Suite's graphical engine, VE-Xplorer. Existing tools, developed by several different people working on development of the VE-Suite library, are used to handle the preprocessing (McCorkle et al., 2003). The existing tools are the result of several years of collaborative development with a growing group of VE-Suite users which has directed the capability to integrate a wide range of analysis data within the VE-Suite environment. These tools are again wrapped up into the automated processes controlled through application plug-ins. A combination of system level application calls and script development are used to automatically direct the data preprocessing.

To intuitively represent the calculated impact of engineering scenarios several more tools are integrated into the decision environment. By using the plug-in structure as described through this thesis, an engineer is able to access a number of general interaction capabilities which are inherent in VE-Suite's core engines. These tools can be utilized with application plug-ins to assist with specific interaction and display tasks. Furthermore, the libraries on which VE-Suite's core engines are built have a number of tools which can be utilized to support specific plug-in application tasks.

For example, when performing fire hazard analysis, the user is given access to functionality through the graphical plug-in which allows for interactive placement of fires within the three dimensional graphical representation of the fire area. Upon receiving model results for a given fire scenario, algorithms within the graphical plug-in perform several hazard assessments. Using the location of the fire and a number of the calculated results these algorithms are able to check for damage to components of interest throughout the room and subsequently inform the user of the assessed damage by turning the color of the component red. Other tools are integrated within the environment which displays hypothetical flame engulfment zones, as well as representing a fire's ability to produce smoke within the room.

CHAPTER 4. INTERACTIVE FIRE HAZARD ANALYSIS

The analysis problem presented in this chapter is performing fire hazard analysis within an auxiliary's room in a nuclear power plant. This particular fire area is interesting due to concerns about fires which can potentially damage cables which run through overhead cable trays throughout the fire area. The room is houses several different equipment items, piping runs, and cable trays. This leads to a number of maintenance operations which must be carried out in the fire area. These operations along with a vast collection of potential equipment failure scenarios have made fire hazard analysis within the room, a difficult task.

4.1 Background

Several of these tools have been introduced as a means to analyze particular fire scenarios or physical situations. One example (Dikerman et al., 1986) looks at the assessment of cables for fire resistance. In this work, models were used to pull all relevant physical parameters together with cable design information to determine combustibility. More recent work has seen the development of modeling capability for fires in electrical cabinets (Avidor et al., 2003). This modeling effort successfully identifies minimum fire sizes that can be maintained within individual cabinets as a function of several physical parameters. In Floyd, 2002 the author identifies the need to develop a consensus on which computational tools are acceptable for numerical fire simulation, then applies three different simulation methods to a specific compartment fire. The methods tested varied in fidelity from a simple hand calculation to a zone model code, and a CFD code. The conclusion was that all three methods were potentially suitable depending on what information was needed from the simulation. Large scale PRA assessment technologies have been developed for fire scenario assessment also. The work described in Grobbelaar et al., 1995 discusses a full scale probabilistic fire risk assessment model for a complete power station unit. This work was successful in statistically identifying where fires may start, as well as the statistical risk of core damage, but the model is not able to physically describe a fire or the impact of the fire on the plant.

As an extension to work developing computational and statistics modeling capabilities, some projects have looked beyond the models to further developing the application methodology. In order to develop a more complete simulation environment, it is important to understand the methods which can be used to pull existing disparate models together to more completely represent the system. In Siegel et al., 1984 the authors describe work on a methodology which implements probabilistic models in a manner which allows for assessment of the overall plant risk due to fire. Work done in Azarm et al., 1999 looks at fire-risk analysis from a more general perspective. Specifically the interest here is evaluating methodologies as to how they support risk-informed regulation. A key contribution in this work is the identification of the need for more complete system simulation through integration of existing models. This need is recognized even more directly through work developing a framework and methodology for analyzing fire detection and suppression (Siu et al., 1986). This framework is based on the existence of models, data, and knowledge capable of facilitating an understanding of the system, but also the need of a methodology for integration of the existing tools.

The previously discussed work demonstrates the need for a robust integration framework to support interactive fire hazard assessment. To utilize the wide range of work done developing computational and statistical models, an analysis framework needs to be generic, extensible, and easily adapted to interact with multiple models. A complete framework must also provide the user the ability to interact with the computational models and their output data from within a representation of the physical space. This complete analysis framework must also be user-centered to facilitate the application of user intuition and experience. As demonstrated in Siu et al., 1984, for many fire scenarios the number of variables and randomness of events can restrict the ability to model the system completely. In these situations where the system can not be fully simulated it is important that the decision making tools facilitate the interjection of knowledge and intuition by the user. The need for engineering judgment in performing fire hazard analysis is discussed further in Apostolakis, 1986. The requirement for a complete analysis framework in combination with the importance of human expertise creates the need for a comprehensive decision making environment for performing fire hazard analysis. The need for this type of computer generated decision making environment to perform fire hazard analysis was identified and outlined in Poskas et al., 2005. This work is focused on providing the user an integrated set of modeling tools in coordination with a decision making module. While successful in achieving its direct goals, this development work lacks the generality and robustness necessary to create a fully comprehensive decision making environment where wide ranging sets of models and databases can be easily integrated and utilized.

4.2 Problem Description

Fire hazard analysis is an important issue for nuclear power plants. The Nuclear Regulatory Commission (NRC) closely evaluates fire areas to ensure that regulations are met and hazards are held within preset standards. Fire protection engineers have a continuously evolving task in monitoring fire areas with the nuclear power plant. Maintenance, reorganization, expansion, and many other factors require fire protection engineers to perform new hazard analyses and update existing hazard analyses. Implementing virtual engineering technologies to assist in these analyses can help the engineer understand the systems more quickly, completely, and accurately than existing processes.

4.2.1 The Physical Space

The specific fire hazard analysis examined in this thesis looks at a fire in an auxiliaries room at the Ft. Calhoun Nuclear Station owned and operated by Omaha Public Power District. The room includes a utilities and auxiliaries area approximately 220 ft long, 26 ft wide, and 21 ft tall (Fig. 3). The fire area in question contains several components including three air compressor units, two auxiliary feedwater pumps, and a number of piping and cable tray runs. The fire area also contains automatic fire detection and suppression equipment throughout the room. One of the key interests in evaluating fires within this area is any potential damage to both sets of cables running overhead, as the cables are responsible for redundant reactor shutdown protection.

There are four primary fire scenarios of key interest which have been identified within this fire area. The three air compressor units located side by side at the end of the room are considered a single fire concern. Equipment failure could potentially expose multiple flammable agents in and around the air compressors. The next two fire scenarios involve the two auxiliary feedwater pumps. Given the distance between them, they have been identified as separate concerns. Again the issue with the feedwater pumps is the potential exposure of flammable agents due to equipment failure. The final fire scenario identified is a general transient hazard. Transient hazards are most prevalent with maintenance and overhaul operations where flammable substances and materials may need to be brought into a space. The transient scenario can be present anywhere in the fire area and needs to be modeled to include any materials or substances that are allowed into the fire area.

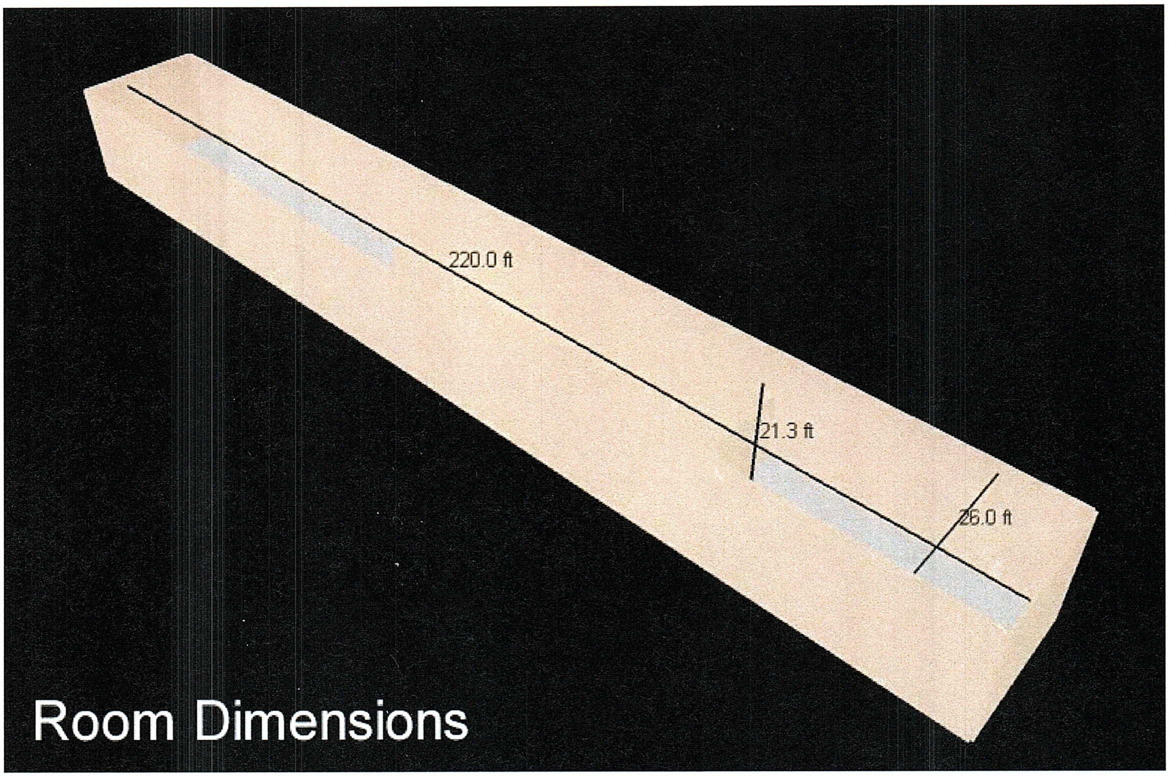


Figure 3. Schematic layout of fire area being analyzed

4.2.2 Current Analysis Process

The primary modeling tool used to investigate the fire scenarios within the fire area is a set of eleven Microsoft Excel^{TM} Spreadsheets (NUREG-1805) developed and certified by the Nuclear Regulatory Commission (NRC) for on-site fire scenario hazard analysis. Individual spreadsheets utilize standardized and accepted algebraic modeling techniques to provide a number of different fire hazard analyses. Included in these models are calculations for flame heights, burning durations, cable heat release rates, detector activation times, and plume temperatures. There are also a series of calculations included to provide temperatures relative to a number of ventilation scenarios. Visibility through smoke calculations is also provided. These models are dispersed among eleven different spreadsheets necessary for this fire hazard analysis. Each of the spreadsheets is designed to work as an independent modeling entity taking the necessary inputs and providing the user with a particular specialized output. One result of this characteristic is that the user will often need to manually enter several input values in multiple spreadsheets to develop a complete understanding of a fire scenario. It is also common that outputs from one or more models are inputs for other models requiring further manual entry and transfer of data. The end result is that utilizing multiple models in this effort requires significant manual interaction by the user. This significantly increases the time to solution as well as the potential for human error.

Upon attaining an acceptable solution from the system of models, the fire protection analyst still faces the task of abstracting the numerical results to the physical space. For example, given a lube oil fire from one of the air compressors, the fire protection engineer must first manually work through the system of models to obtain results. With the results in hand the engineer must then place the hypothesized fire in the physical space either through a schematic or in the actual room. If the question of interest is whether this fire scenario will damage a particular cable way, the engineer must apply the results to look at the calculated flame height within the physical space. Depending on how the flame height abstracts to the physical space, the engineer must work with plume temperature or hot gas layer temperature calculations to understand the exposure of the cables. Further complicating this effort is the consideration of detection and suppression mechanisms. In the fire area investigated here detector activation times must be factored into the evaluation along with burning durations to develop a sufficient understanding of the potential cable damage.

Performing a thorough investigation of the fire area requires several iterations through this process. In order to be complete, a fire protection analyst has to painstakingly step through all of the potential fire scenario combinations including locations, flammable agents, quantities, and a number of other transient variables. The process of abstracting the numerical data to the physical space must be done for each scenario. This process requires several weeks to complete a fire hazard analysis. These characteristics all direct the need for fully integrated interactive decision making environment from which the engineer can interact with representational models of the fire scenario as well as the physical space.

4.2.3 Integration of Analysis Tools

To support fire hazard scenario analysis the decision making environment must be flexible in allowing the integration of disparate models of varying computational fidelities. For the analysis in this work the modeling strategy has been outlined as using the NUREG-1805 spreadsheets developed by the NRC. These models present an interesting case study for an integrated environment in that they require a large amount of model to model interaction to provide descriptions of a fire scenario. This characteristic leads to the conclusion that the system of models utilized for this fire hazard analysis can be most effectively used by wrapping the models and giving the fire protection analyst access and control to the models as if it were a single comprehensive fire hazard model. Along with the capability to abstract the user from the system of models the decision environment must also provide the fire protection engineer with the ability to interact with the models and their numerical results from within an accurate representation of the physical space. For this analysis problem the integration of computational data and spatial geometry is carried out with a plug-in wrapping the NUREG-1805 Excel spreadsheets and the importing of laser scan data into VE-Suite's visualization environment. The plug-in allows the engineer to remotely access the spreadsheets while interacting with the room geometry. The laser scan data, provided by OPPD, was filtered through PRO Engineer^{TM} to perform some simple cleanup operations as well as redrawing some components to better represent the room in its current state. Implementing virtual engineering tools and concepts can guide the development of a comprehensive decision making environment satisfying all of these constraints to support fast and accurate investigation of fire hazard scenarios.

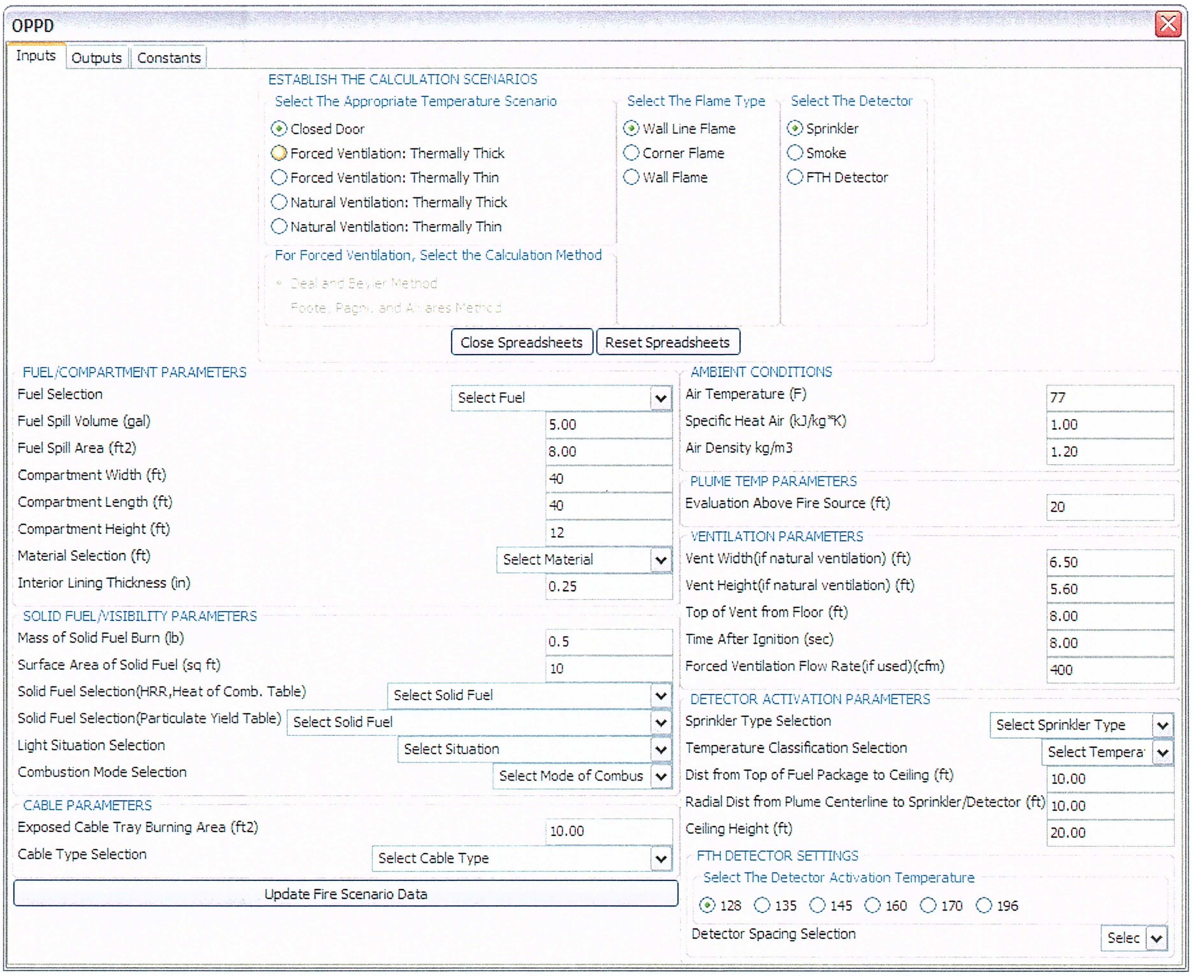
To develop an interactive application within the VE-Suite framework, three separate plug-ins are needed. The graphical plug-in, graphical user interface (GUI) plug-in, and the computational unit plug-in are built to adhere to VE-Suite's VE-Open specification for communication. Plug-ins are developed to run distributed, cross platform, and cross network. Through the VE-Open specification and VE-CE's data and command synchronization capabilities, changes and results from within the plug-ins are automatically updated throughout the rest of the environment.

The GUI plug-in provides the fire protection engineer with a complete set of controls necessary to develop the possible fire scenarios. The GUI plug-in is customized to give the user access to the parameters needed to effectively model a particular fire (Fig. 4). The interface is sectioned off to assist the user in identifying the inputs they need for a particular analysis. It is clear that for each individual fire scenario not all of the inputs are necessary. The interface is assembled in a manner which helps direct the input selection process. The

GUI plug-in is also built with functionality which will resort to pre-established default values in the case of missing inputs.

The GUI plug-in interface is built using wxWidgets, an open source C++ cross-platform GUI framework. The wxWidgets library gives access to a number of controls which allow for development of an intuitive and intelligent interface for developing fires. The arrangement of radio selection boxes, combination selection boxes, and text controls allows the user to move through the construction of fire scenarios while being protected from inadvertently building infeasible cases. The presence of intelligence is also apparent in the abstraction of the user from redundant inputs throughout multiple spreadsheets. The wrapping of multiple algebraic spreadsheet models has to be supported within the GUI plug-in fire scenario development interface which requires the ability to perform a level of processing which is left to the user when interacting directly with the models. While difficult to quantify, standard use of the GUI plug-in interface saves time in contrast to interacting directly with multiple spreadsheets.

The computational unit plug-in is developed and built as a stand alone application adhering to the communication specification established within VE-Open. The unit plug-in receives user established fire scenario variables from VE-CE, and then uses the collected data to perform the computations. As stated previously the unit plug-in wraps a set of eleven NUREG-1805 spreadsheets as the computational model. The computational unit gains access to Excel via the use of Microsoft^{TM} Foundation Classes (MFC). Upon receiving the fire scenario parameters from VE-CE the computational unit plug-in directs the NUREG-1805 models through the calculations.



ESTABLISH THE CALCULATION SCENARIOS

Select The Appropriate Temperature Scenario
● Closed Door
○ Forced Ventilation: Thermally Thick
○ Forced Ventilation: Thermally Thin
○ Natural Ventilation: Thermally Thick
○ Natural Ventilation: Thermally Thin

For Forced Ventilation, Select the Calculation Method
● Deal and Beyler Method
○ Foote, Pagni, and Alvares Method

Select The Flame Type
● Wall Line Flame
○ Corner Flame
○ Wall Flame

Select The Detector
● Sprinkler
○ Smoke
○ FTH Detector

FUEL/COMPARTMENT PARAMETERS
Fuel Selection: Select Fuel
Fuel Spill Volume (gal): 5.00
Fuel Spill Area (ft2): 8.00
Compartment Width (ft): 40
Compartment Length (ft): 40
Compartment Height (ft): 12
Material Selection (ft): Select Material
Interior Lining Thickness (in): 0.25

SOLID FUEL/VISIBILITY PARAMETERS
Mass of Solid Fuel Burn (lb): 0.5
Surface Area of Solid Fuel (sq ft): 10
Solid Fuel Selection(HRR,Heat of Comb. Table): Select Solid Fuel
Solid Fuel Selection(Particulate Yield Table): Select Solid Fuel
Light Situation Selection: Select Situation
Combustion Mode Selection: Select Mode of Combus

CABLE PARAMETERS
Exposed Cable Tray Burning Area (ft2): 10.00
Cable Type Selection: Select Cable Type

AMBIENT CONDITIONS
Air Temperature (F): 77
Specific Heat Air (kJ/kg*K): 1.00
Air Density kg/m3: 1.20

PLUME TEMP PARAMETERS
Evaluation Above Fire Source (ft): 20

VENTILATION PARAMETERS
Vent Width(if natural ventilation) (ft): 6.50
Vent Height(if natural ventilation) (ft): 5.60
Top of Vent from Floor (ft): 8.00
Time After Ignition (sec): 8.00
Forced Ventilation Flow Rate(if used)(cfm): 400

DETECTOR ACTIVATION PARAMETERS
Sprinkler Type Selection: Select Sprinkler Type
Temperature Classification Selection: Select Tempera
Dist from Top of Fuel Package to Ceiling (ft): 10.00
Radial Dist from Plume Centerline to Sprinkler/Detector (ft): 10.00
Ceiling Height (ft): 20.00

FTH DETECTOR SETTINGS
Select The Detector Activation Temperature
● 128 ○ 135 ○ 145 ○ 160 ○ 170 ○ 196
Detector Spacing Selection: Selec

Figure 4. GUI plug-in fire scenario interface

The computational unit plug-in is constructed to step through the NUREG-1805 models accurately and efficiently to minimize redundancy within the system of models. In keeping with the intuitive structural layout of the GUI plug-in interface, first the calculation scenario parameters are established within the models. Next the unit steps through the models setting the compartment and fuel parameters. With these more universal settings taken care of, the unit plug-in finishes solving each model with the only remaining dependencies being some model to model data transfer. For example, the heat release rate calculated in a flame height calculation model must subsequently be passed to the detector activation and cable assessment models. Upon completion of all the calculations, the unit plug-in gathers results from the models and returns them to the other components in the environment.

The graphical plug-in is responsible for bringing all of the CAD and graphics models into the environment (Fig. 5). As stated previously, one of the biggest challenges in fire hazard analysis is the transfer of numerical data into the physical space being analyzed. The graphical plug-in presents that physical space to the user through VE-Suite's graphical engine, VE-Xplorer. Geometric models are loaded onto a scene graph which can be presented in several visualization environments. VE-Xplorer supports visualization hardware configurations ranging from standard personal computers to fully immersive virtual reality caves.

To create an effective decision making environment for this analysis, the fire area being investigated is represented graphically by high fidelity laser scan` data. A laser scan of the entire fire area was used to create a dimensionally accurate CAD representation of the space. Laser scanning is an efficient and accurate way to gather as-built geometric data (Bruno, 1992). Model laser scanners have the ability to map the geometry of a room within hundredths and even thousandths of an inch. For existing facilities which have gone through years of maintenance, expansion, and reorganization, original drawings are typically no longer accurate representations of the current layouts. Laser scanning is more efficient and accurate than measuring every component of the room and letting a CAD expert redraw the entire space based on the measurements. Through the graphical plug-in, the fire protection engineer can access and review numerical data within a laser scan generated virtual model of the physical space.

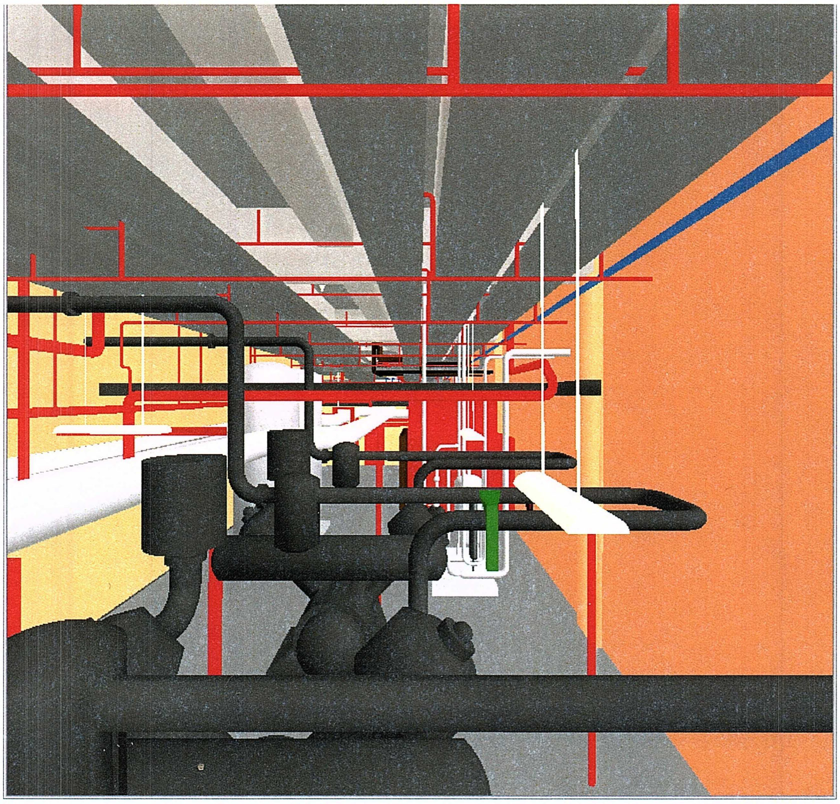


Figure 5. Virtual CAD model

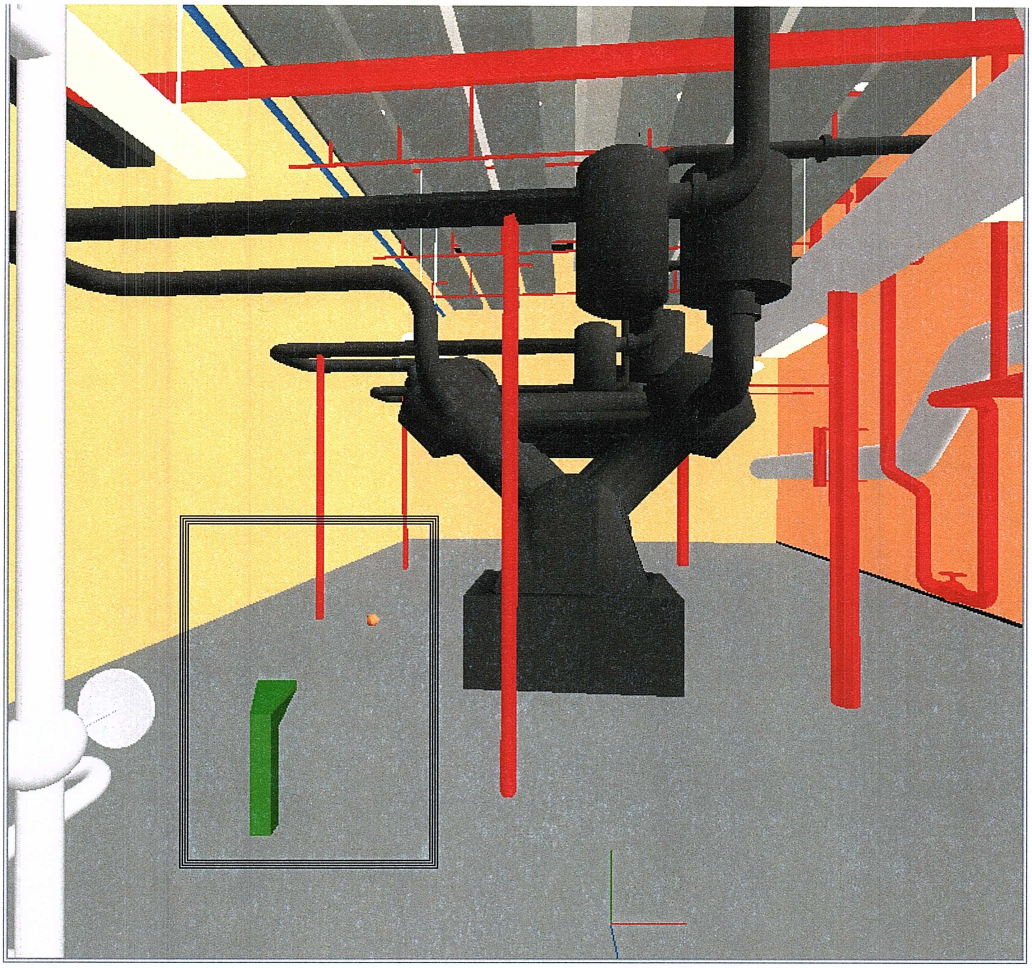


Figure 6. Located within the box is the pointer mechanism used to place fires

The graphical plug-in also provides the fire protection analyst with a number of decision support tools. The GUI plug-in allows the engineer to construct the computational representation of a particular fire scenario, but in order to understand how that fire may impact the space, the graphical plug-in allows the user to place the fire within the graphics environment (Fig. 6). This is important in being able to understand the result of a fire scenario. With the location of the fire identified and the computational analysis complete, the graphical plug-in can look at the results data and check on whether equipment or components in the room have been damaged. The plug-in has access to several algorithms utilizing pre-determined damage criteria which it uses in performing this assessment. Upon establishing the presence of damage to a component, the graphical plug-in informs the user of the damage by turning the component red (Fig. 7). The presence of damage can come from multiple circumstances. The compressors, for example, can be set to receive damage upon direct interaction with a flame only; or the cables running overhead can be set to display damage when the hot gas layer temperature exceeds their threshold. Along with the damage assessment functionality, the graphical plug-in can show the user where the fire plume may be present. Utilizing flame height calculations, the plug-in presents the user with a half sphere showing the user a potential flame engulfment zone (Fig. 8). This functionality utilizes the Visualization Toolkit (VTK) (www.vtk.org) library. VTK is an open source C++ library for three dimensional computer graphics, image processing, and data visualization. Access to VTK functionality provides the graphical plug-in with a number of opportunities for advanced data visualization. The graphical plug-in is also equipped with more advanced graphics decision tools including the ability to represent the smoke created from a fire scenario (Fig. 9). This functionality utilizes a visibility through smoke calculation along with functionality from the Open Scene Graph (OSG) (www.openscenegraph.org) library. OSG is an open source 3D graphics toolkit developed to support high performance graphics applications. This capability presents interesting virtual fire suppression training opportunities.

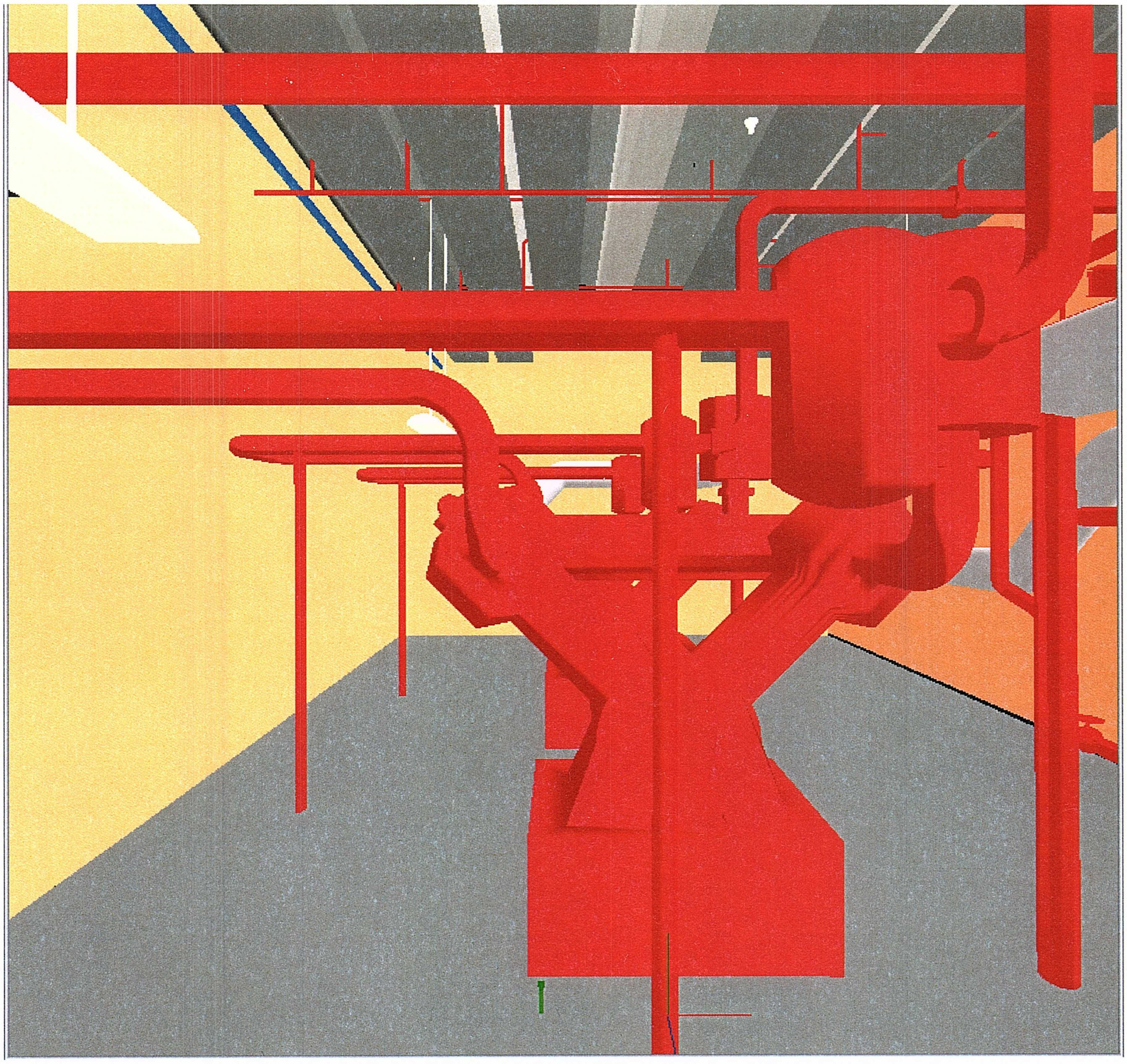


Figure 7. Damaged component shown as red

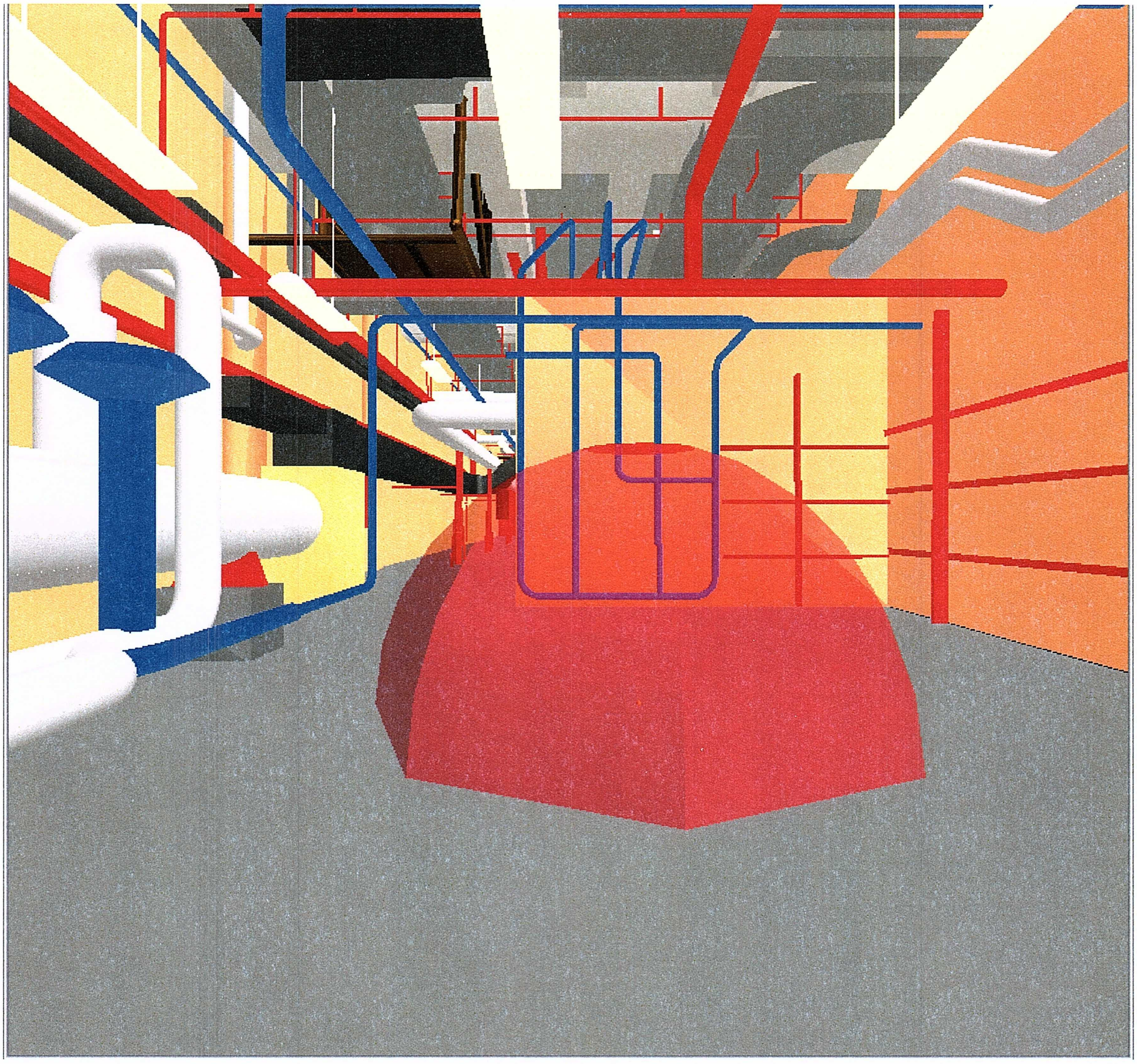


Figure 8. Flame height representation

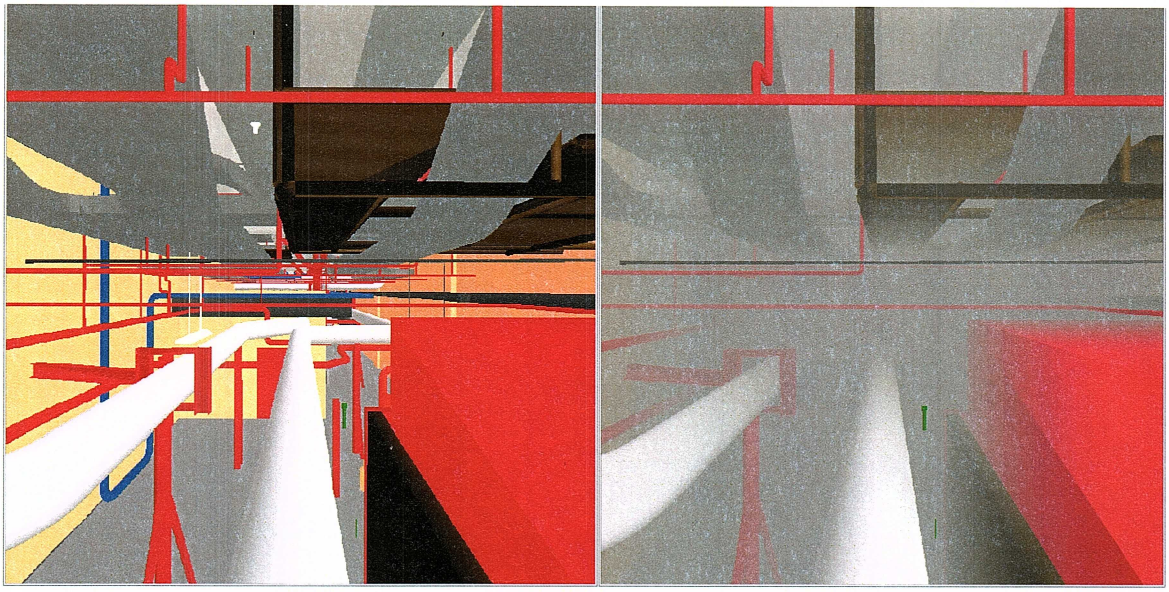
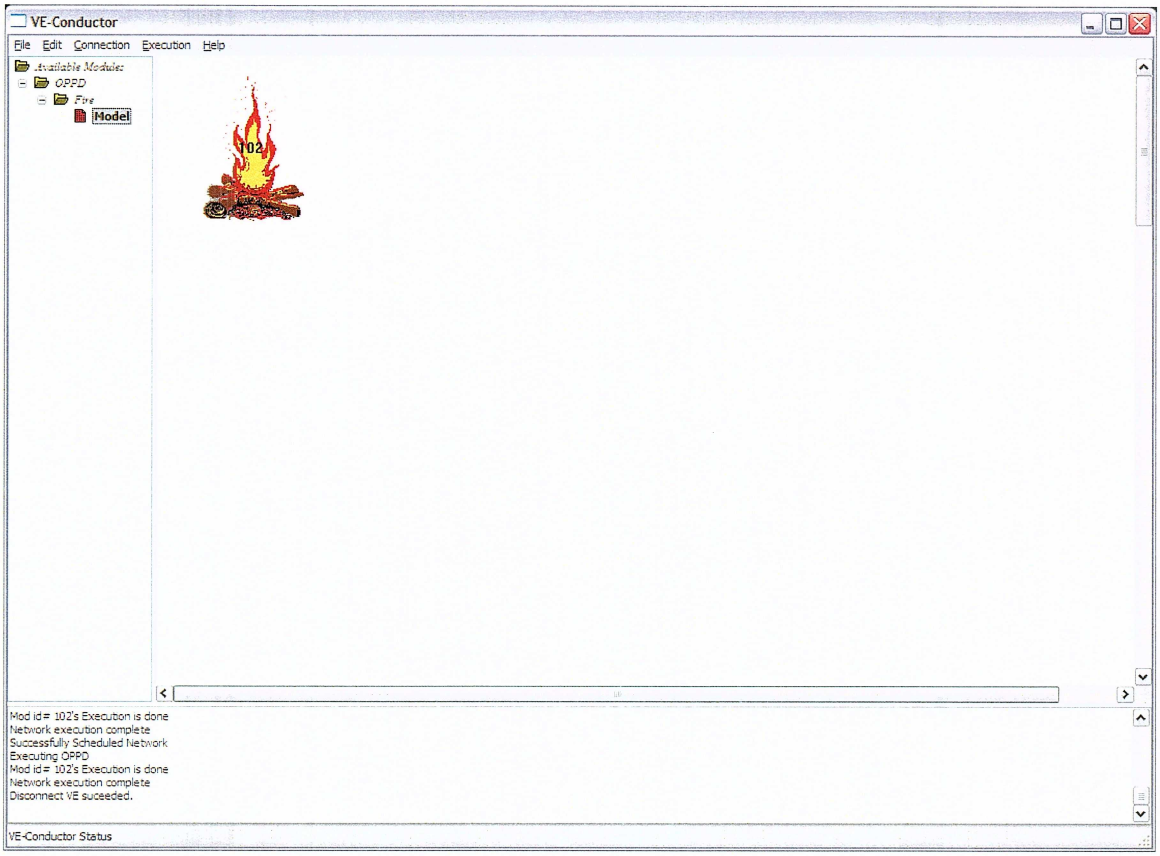


Figure 9. View of the room with and without smoke

4.3 Using the Fire Analysis Environment

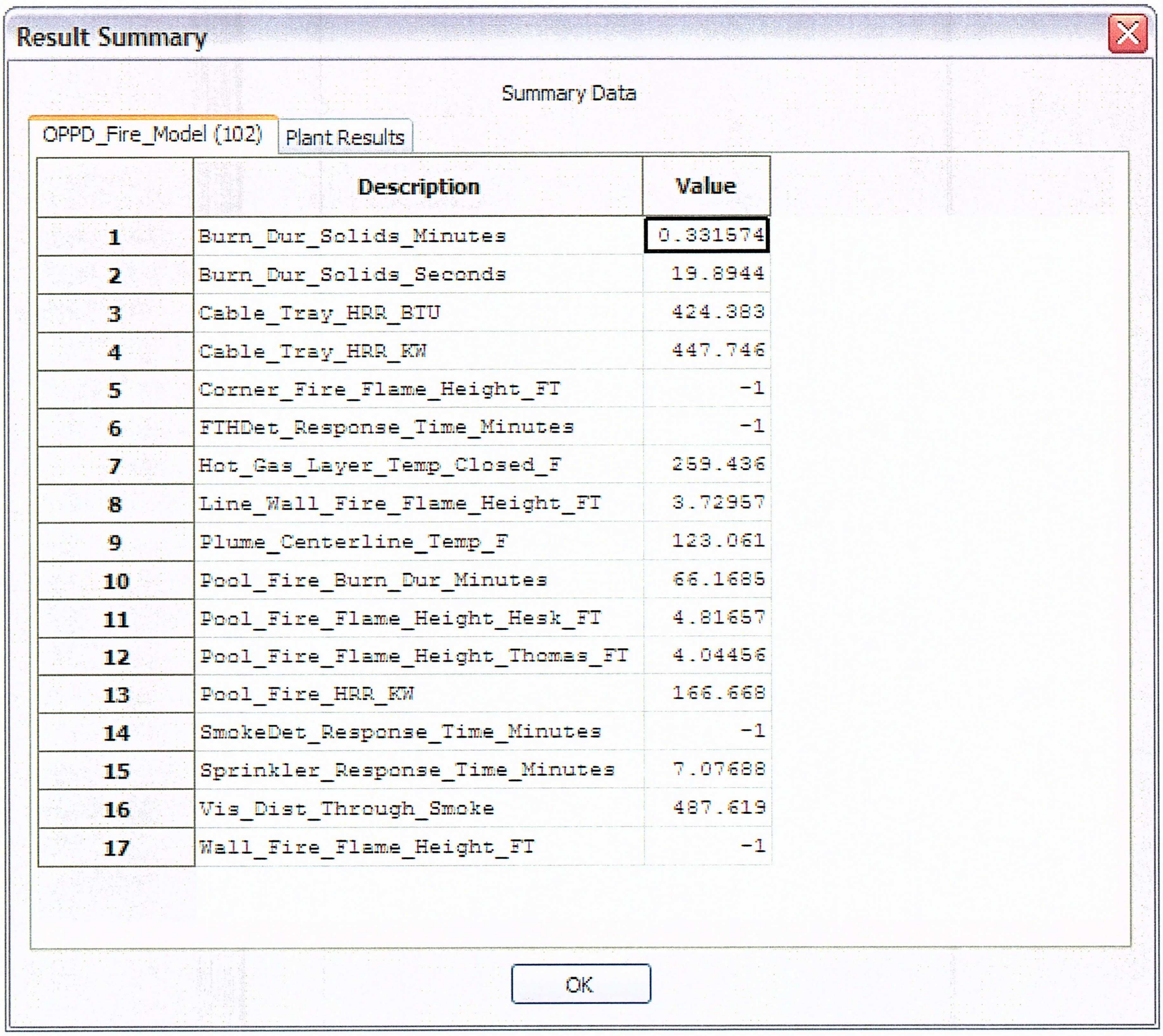
The integration of these technologies provides the fire protection engineer with a complete interactive decision making environment for performing fire hazard analyses. Upon starting VE-Suite the user will first interact with VE-Conductor by loading the icon representing the fire analysis component module onto the design canvas (Fig. 10). Through this action the core VE-Suite engines load the fire analysis plug-ins. The graphics environment updates with the geometrical models of the fire area and the computational unit is ready to receive fire scenario parameters. The user can then work with the GUI plug-in interface to set up a fire scenario of interest. As part of the setup process, the user can also work within the graphics environment, via keyboard and mouse commands, to place the fire within the geometric model of the physical space. After determining placement and setting the parameters of the fire, the configuration data is submitted to VE-CE. The computational unit receives the configuration data and begins to work with the NUREG-1805 models.



```
Mod id= 102's Execution is done
Network execution complete
Successfully Scheduled Network
Executing OPPD
Mod id= 102's Execution is done
Network execution complete
Disconnect VE suceeded.
```

Figure 10. VE-Conductor with the fire analysis module loaded on the design canvas

The spreadsheets' interactions are handled entirely at the system level, but based on the analyst's preference; individual sheets can be opened and presented to the user by the computational unit. As described previously, the calculations and distribution of fire scenario data within the system of models is handled entirely by the unit plug-in. Upon completion of the calculations, results are given back to VE-Suite's core engines. VE-Xplorer supplies the result data to the graphical plug-in and runs the plug-in's decision support functionality. The appropriate updates are made in the graphics environment to demonstrate to the user the impact of the selected fire scenario. The calculation results are given back to VE-Conductor for the user to access in a tabular format also (Fig. 11). Fig. 12 demonstrates the operational flow for investigating an individual fire scenario.



	Description	Value
1	Burn_Dur_Solids_Minutes	0.331574
2	Burn_Dur_Solids_Seconds	19.8944
3	Cable_Tray_HRR_BTU	424.383
4	Cable_Tray_HRR_KW	447.746
5	Corner_Fire_Flame_Height_FT	-1
6	FTHDet_Response_Time_Minutes	-1
7	Hot_Gas_Layer_Temp_Closed_F	259.436
8	Line_Wall_Fire_Flame_Height_FT	3.72957
9	Plume_Centerline_Temp_F	123.061
10	Pool_Fire_Burn_Dur_Minutes	66.1685
11	Pool_Fire_Flame_Height_Hesk_FT	4.81657
12	Pool_Fire_Flame_Height_Thomas_FT	4.04456
13	Pool_Fire_HRR_KW	166.668
14	SmokeDet_Response_Time_Minutes	-1
15	Sprinkler_Response_Time_Minutes	7.07688
16	Vis_Dist_Through_Smoke	487.619
17	Wall_Fire_Flame_Height_FT	-1

Figure 11. Results in tabular format in VE-Conductor

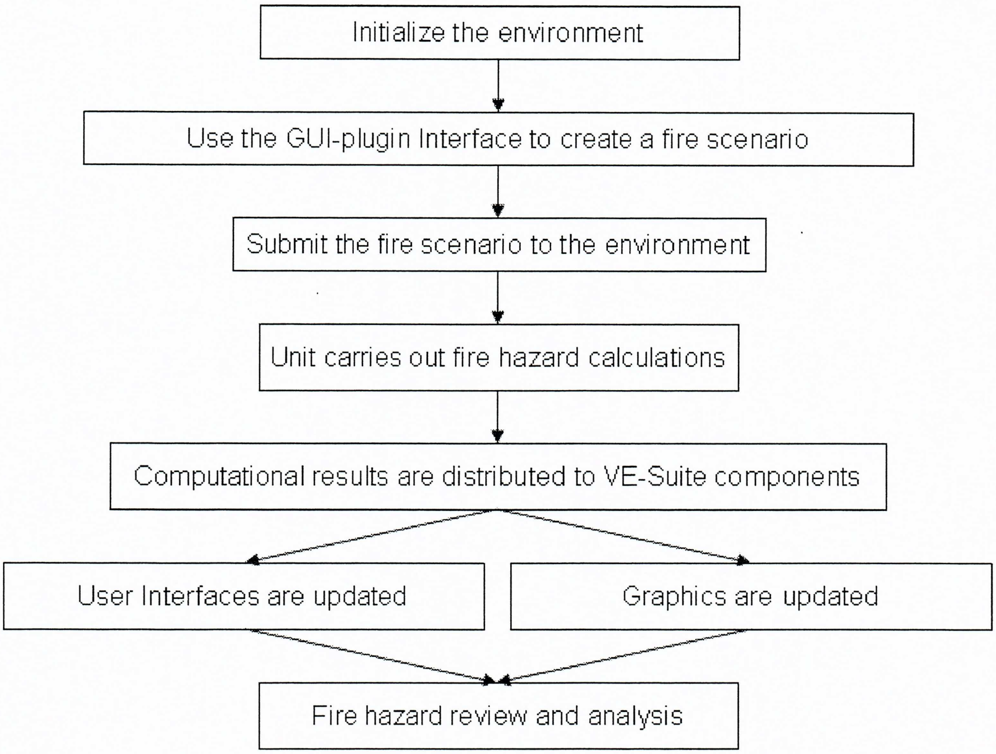
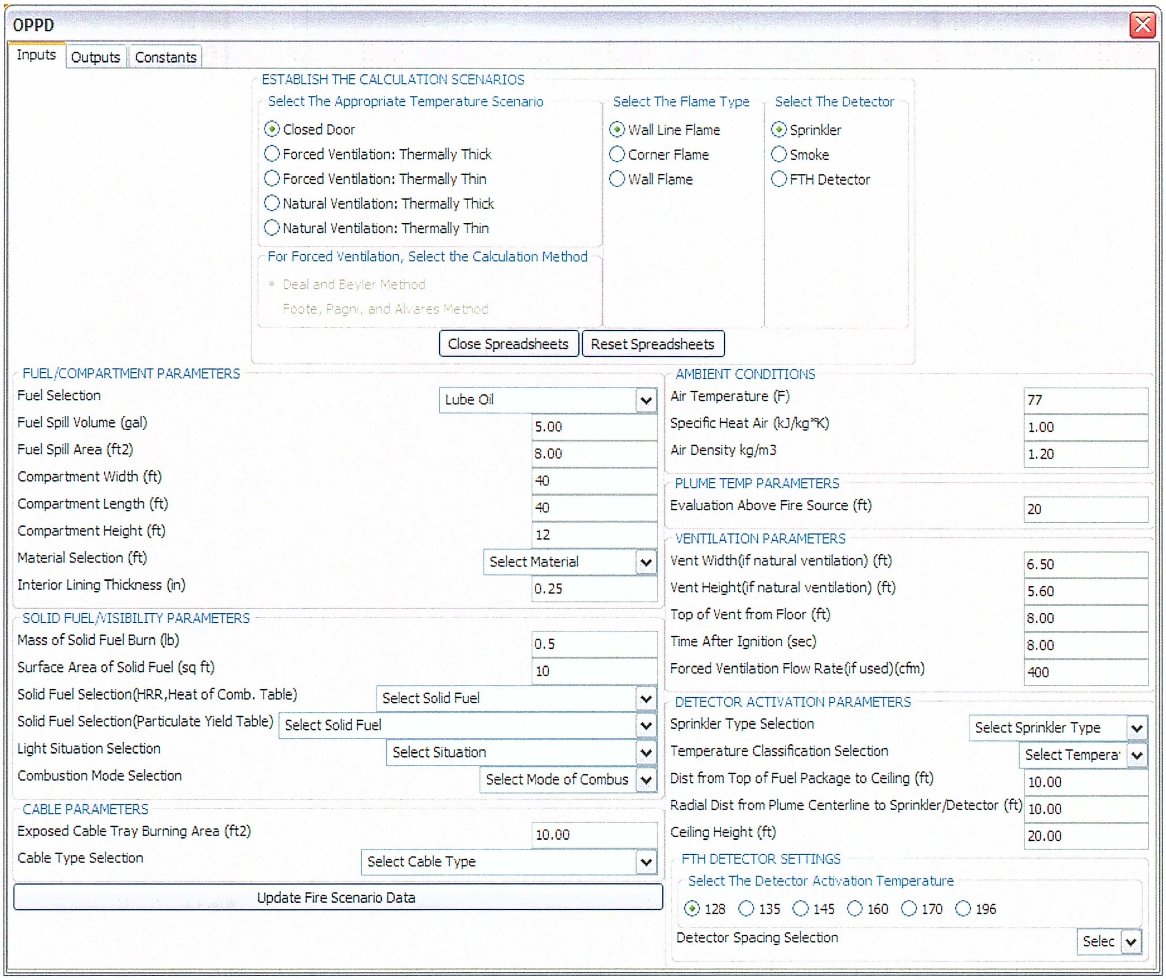


Figure 12. Hazard analysis procedural flowchart

Through this decision making environment, the fire protection engineer can quickly investigate the fire scenarios identified as primary hazards in the fire area. Looking at a potential lube oil spill created from a hypothetical equipment malfunction within one of the three air compressors, the analyst could set up the fire scenario parameters as shown in Fig. 13. Various constants and assumptions are catalogued on the user interface as seen in Fig. 14 for the engineer to reference in constructing a particular fire. This page can be continuously updated as the engineer identifies more assumptions and constants s/he would like to catalogue. As part of the fire scenario construction, the user can utilize VE-Xplorer's



ESTABLISH THE CALCULATION SCENARIOS

Select The Appropriate Temperature Scenario
- ● Closed Door
- ○ Forced Ventilation: Thermally Thick
- ○ Forced Ventilation: Thermally Thin
- ○ Natural Ventilation: Thermally Thick
- ○ Natural Ventilation: Thermally Thin

For Forced Ventilation, Select the Calculation Method
- ● Deal and Beyler Method
- ○ Foote, Pagni, and Alvares Method

Select The Flame Type
- ● Wall Line Flame
- ○ Corner Flame
- ○ Wall Flame

Select The Detector
- ● Sprinkler
- ○ Smoke
- ○ FTH Detector

FUEL/COMPARTMENT PARAMETERS
Fuel Selection: Lube Oil
Fuel Spill Volume (gal): 5.00
Fuel Spill Area (ft2): 8.00
Compartment Width (ft): 40
Compartment Length (ft): 40
Compartment Height (ft): 12
Material Selection (ft): Select Material
Interior Lining Thickness (in): 0.25

SOLID FUEL/VISIBILITY PARAMETERS
Mass of Solid Fuel Burn (lb): 0.5
Surface Area of Solid Fuel (sq ft): 10
Solid Fuel Selection(HRR,Heat of Comb. Table): Select Solid Fuel
Solid Fuel Selection(Particulate Yield Table): Select Solid Fuel
Light Situation Selection: Select Situation
Combustion Mode Selection: Select Mode of Combus

CABLE PARAMETERS
Exposed Cable Tray Burning Area (ft2): 10.00
Cable Type Selection: Select Cable Type

AMBIENT CONDITIONS
Air Temperature (F): 77
Specific Heat Air (kJ/kg*K): 1.00
Air Density kg/m3: 1.20

PLUME TEMP PARAMETERS
Evaluation Above Fire Source (ft): 20

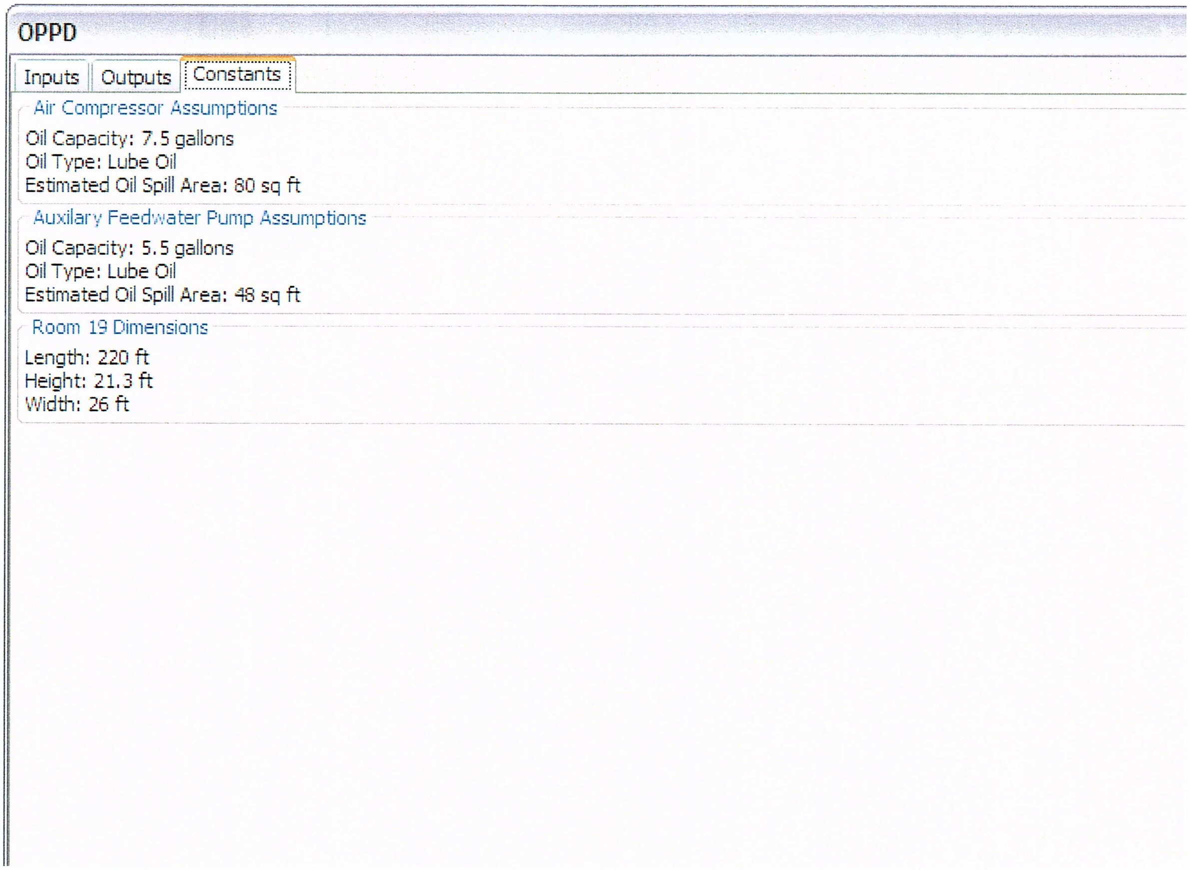
VENTILATION PARAMETERS
Vent Width(if natural ventilation) (ft): 6.50
Vent Height(if natural ventilation) (ft): 5.60
Top of Vent from Floor (ft): 8.00
Time After Ignition (sec): 8.00
Forced Ventilation Flow Rate(if used)(cfm): 400

DETECTOR ACTIVATION PARAMETERS
Sprinkler Type Selection: Select Sprinkler Type
Temperature Classification Selection: Select Tempera'
Dist from Top of Fuel Package to Ceiling (ft): 10.00
Radial Dist from Plume Centerline to Sprinkler/Detector (ft): 10.00
Ceiling Height (ft): 20.00

FTH DETECTOR SETTINGS
Select The Detector Activation Temperature
● 128 ○ 135 ○ 145 ○ 160 ○ 170 ○ 196
Detector Spacing Selection: Selec

Figure 13. Fire parameter settings for air compressor lube oil spill fire

interactive capabilities through the graphical plug-in to place this lube oil spill next to the air compressor. Based on the parameters chosen in Fig. 13, the results of the calculations and application of the graphical plug-in decision support tools will demonstrate that damage will be incurred to the air compressor units as well as the cables running in the overhead trays (Fig. 15). One potential corrective measure to deal with the damage to the cables from this particular fire scenario is to reduce the oil spill area by building a dike around the air compressors. The fire protection engineer can investigate this as a possible



Air Compressor Assumptions

Oil Capacity: 7.5 gallons
Oil Type: Lube Oil
Estimated Oil Spill Area: 80 sq ft

Auxilary Feedwater Pump Assumptions

Oil Capacity: 5.5 gallons
Oil Type: Lube Oil
Estimated Oil Spill Area: 48 sq ft

Room 19 Dimensions

Length: 220 ft
Height: 21.3 ft
Width: 26 ft

Figure 14. Partially filled list of constants and assumptions on the GUI plug-in interface

solution by adjusting the fire scenario parameters. The result of reducing the spill area from eight sq. ft. to one sq. ft. is the elimination of damage to the overhead cables (Fig. 16). The complete integration of this decision making environment allows the fire protection engineer to identify a hazard and subsequent solution in a matter of minutes.

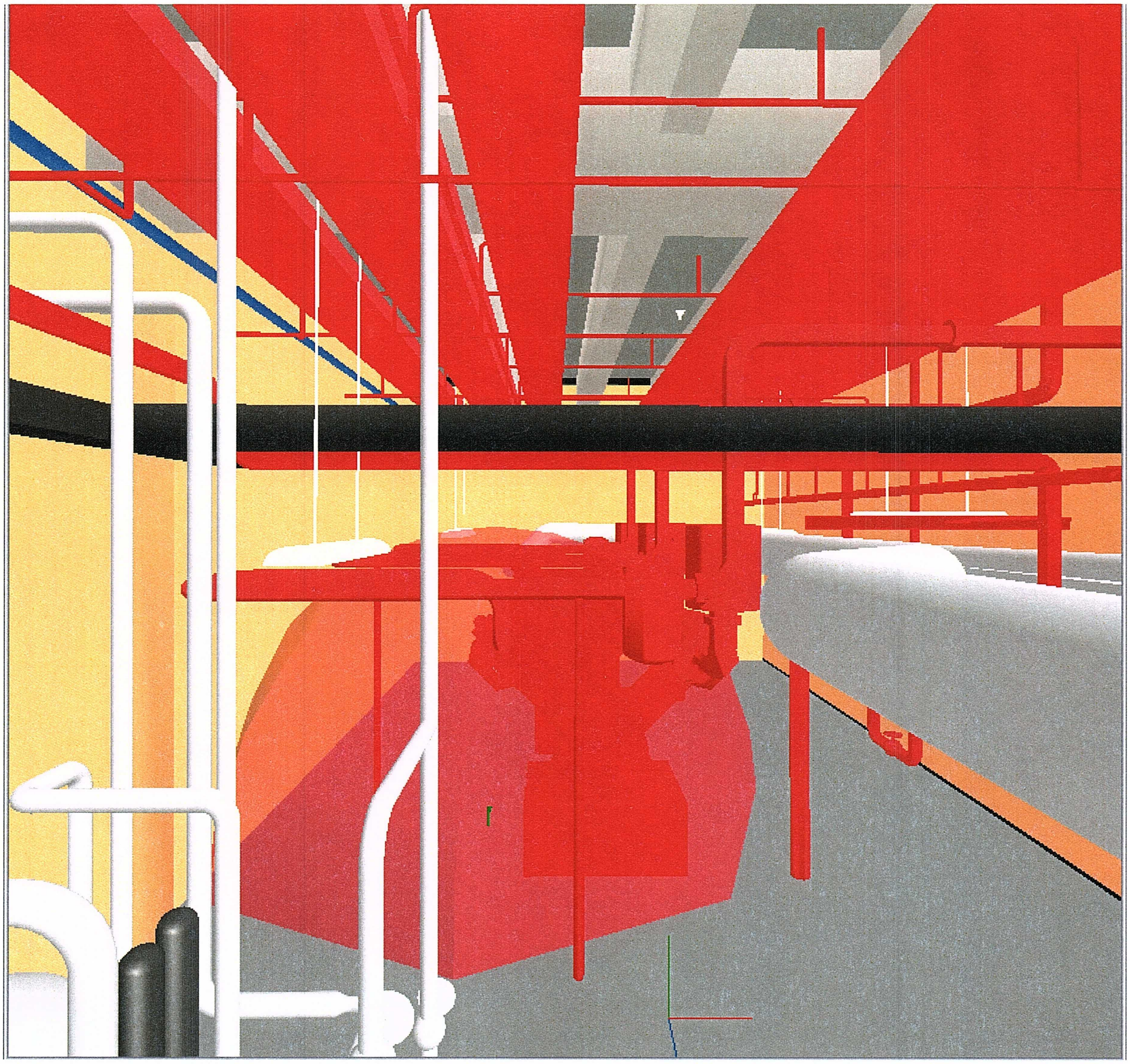


Figure 15. Lube oil spill fire results as seen in the graphics environment

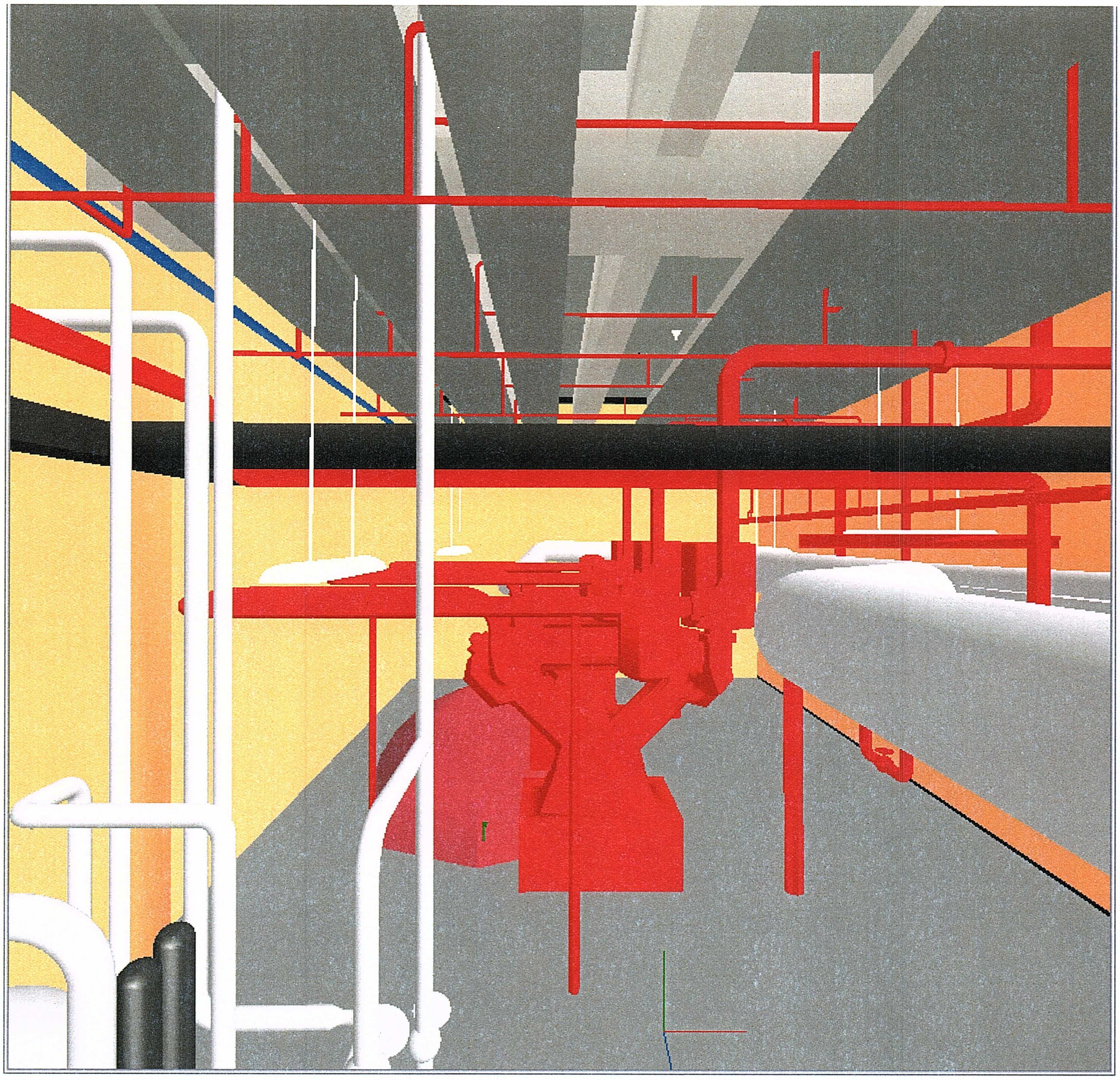


Figure 16. Results of the lube oil spill fire with a simulated dike built around the air compressor

CHAPTER 5. INTERACTIVE DESIGN OF BIOMASS COOKSTOVES

The design problem examined in this chapter is engineering biomass fueled cookstoves being designed for household cooking in developing nations. Biomass combustion is the predominant source of household energy for nearly 50% of residences worldwide (Johnson et al., 2005). These stoves are generally designed and built locally with principal areas of use in Central America, South America, Africa, South Asia, and the Asian-Pacific.

5.1 Background

Cultural, regional, and socio-economic factors contribute to how biomass cookstoves are used. For instance, Latin American families prepare corn tortillas, which are made by simmering dried corn over high heat for hours, as primary food sources. Whereas people in Africa primarily cook corn-meal mush which requires far less heat energy for preparation. Less impoverished stove users may be able to occasionally purchase meat, which clearly adds another level of usage conditions for the stoves. Another factor affecting how stoves operate is the type of biomass used in the combustion. Often wood is the primary solid biomass fuel, but alternative fuels include animal waste, agricultural residues, garbage, and charcoal.

The use of these stoves has significant health and economic impacts. Indoor open fires of this variety are fuel inefficient, unsafe, and can be tied to several health problems. Injuries, including burns, scalds, lacerations and abrasions, are extremely prevalent with the use of biomass cookstoves. Other health problems associated with current stove designs include dangerous CO concentrations, infant mortality, blindness in women, and cancer (Instituto Nicaragüense de Energia, 1997; Hong, 1994; Barnes et al., 1994; Pandey, 1998). Through the implementation of modern, first world design and construction practices, many of these issues can potentially be resolved. The complicating factor is the lack of financial resources for those currently using biomass stoves.

As seen in Fig. 17, another common issue with biomass cookstoves is a highly uneven temperature distribution across the cooking surface (McCorkle et al., 2003; Bryden et al., 2003). Engineering analysis in the field has shown that adding baffles to the flow field can redirect the flue gas flow and help eliminate large temperature variations across the cooking surface.(Fig. 18) Attempts to intuitively place baffles were unsuccessful in creating an ideal temperature distribution. This ideal distribution would have a single hot spot available for boiling water with a majority of the cooking surface operating at a relatively even temperature and possibly one small cooler region to keep fully-cooked products warm until full preparation is complete. The work described in this paper deals with this issue of mechanical heat transfer as well as economic manufacturability through the implementation of virtual engineering technologies.

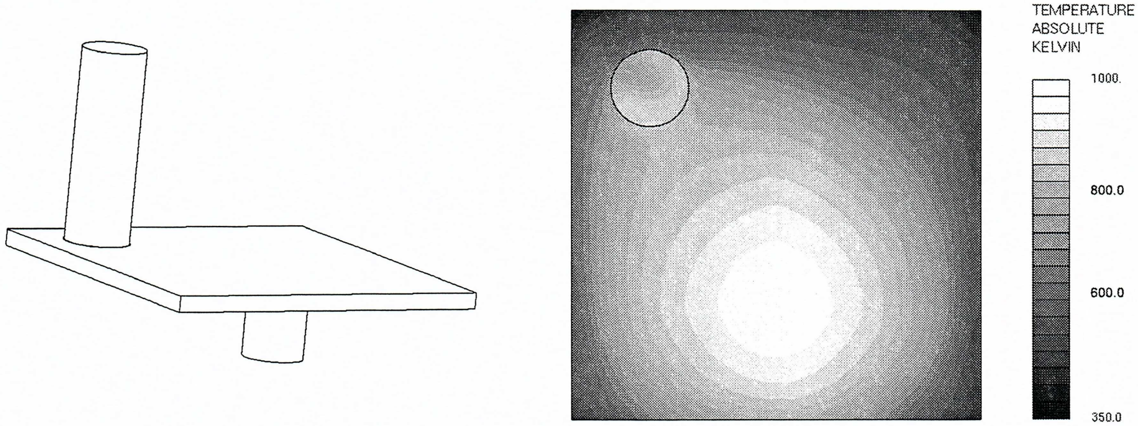


Figure 17. Uneven temperature profile across an unbaffled Plancha stove

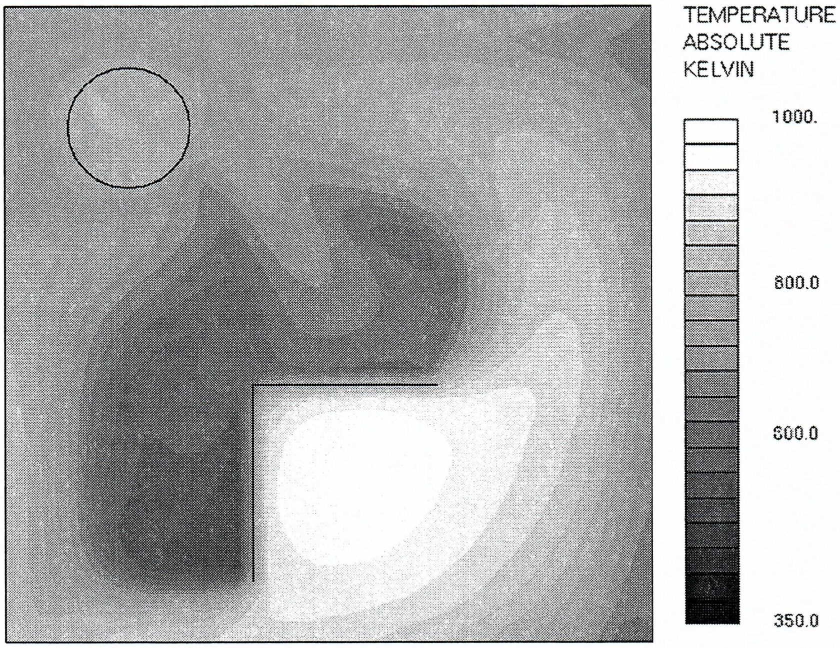


Figure 18. Temperature profile of a baffled Plancha stove

5.2 Problem Description

The stove design analyzed in this work has three major components as seen in Fig. 19. These are 1) a small combustion chamber, 2) the baffled heat transfer chamber under the cooking surface, and 3) the exhaust duct. Wood or other biomass is combusted within the combustion chamber producing hot gases. The hot gases are then utilized to heat the stove's cooking surface through a heat exchange chamber. The combustion gases are then forced out of the stove through an exhaust duct. The shape and size of stoves can vary significantly from one region to another depending on local needs, customs, and resource availability.

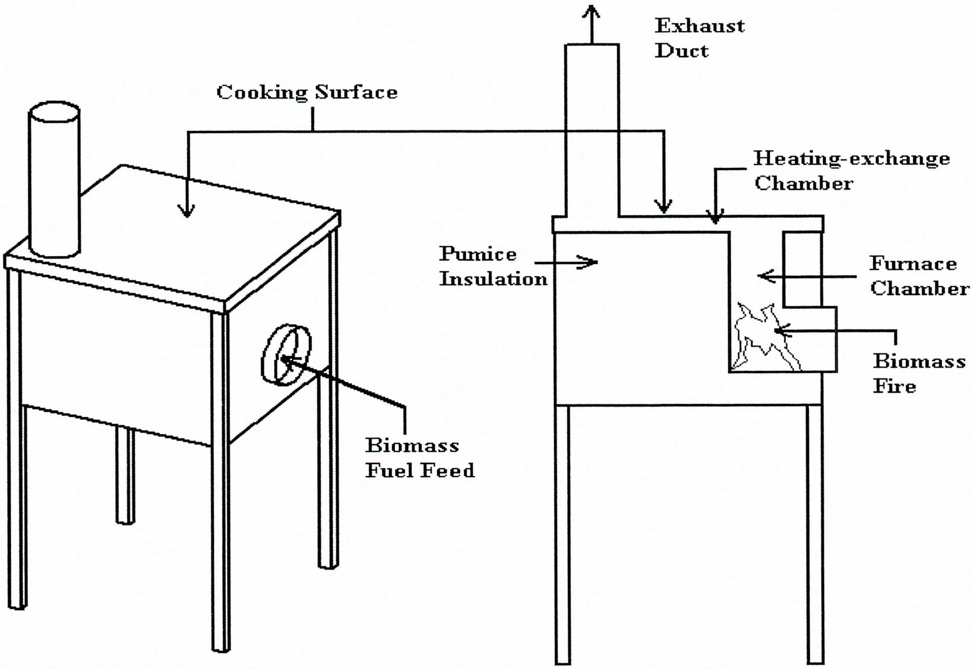


Figure 19. Basic cookstove design

5.2.1 Current Design/Build Process

Several private and government organizations have attempted to address the many issues associated with biomass cookstove use. The US Environmental Protection Agency, HELPs International, Trees Water and People, and the Aprovecho Research Center have all contributed significant work in developing improved cookstove designs. The focus of these efforts has been on increasing fuel efficiency, decreasing fuel use, and reducing particulate emissions (McCorkle et al., 2003; Bryden et al., 2003). Through this work several enhanced stove designs have been introduced and placed in households for further engineering analysis and improvements. The improved stove designs are still subject to cost restrictions and the availability of local materials as well as skilled construction labor to build them. The result is a stove which shows improved characteristics, but still requires several design iterations to become sufficiently effective.

Currently, the process of examining design alternatives for biomass cookstoves in the field is generally cumbersome, inefficient, and often ineffective. The issue of key interest with this work, as described previously, is the placement of baffles within the heat transfer chamber to create a desirable cooking surface temperature profile. Currently, for individual stove designs, baffle configurations are developed based on intuition, experience, and manufacturability. The assembly jigs must then be built to weld the baffles into the heat exchange chamber of the stove. With the baffles in place the stove assembly can be completed. Standard usage conditions must then be duplicated to take measurements necessary to determine the effectiveness of a particular stove design. If a design is determined to create an acceptable temperature profile, manufacturing can continue. More likely, the need for improvements is identified; and the current stove along with the assembly jigs must be deconstructed. This iterative design process continues until the design constraints are met. The flow field and heat transfer physics within the flue gas chamber are complex and it is very difficult to find highly effective baffle configurations employing this methodology. This adds cost, time, and inefficiency to an already difficult design problem.

5.2.2 Current Modeling/Optimization Techniques

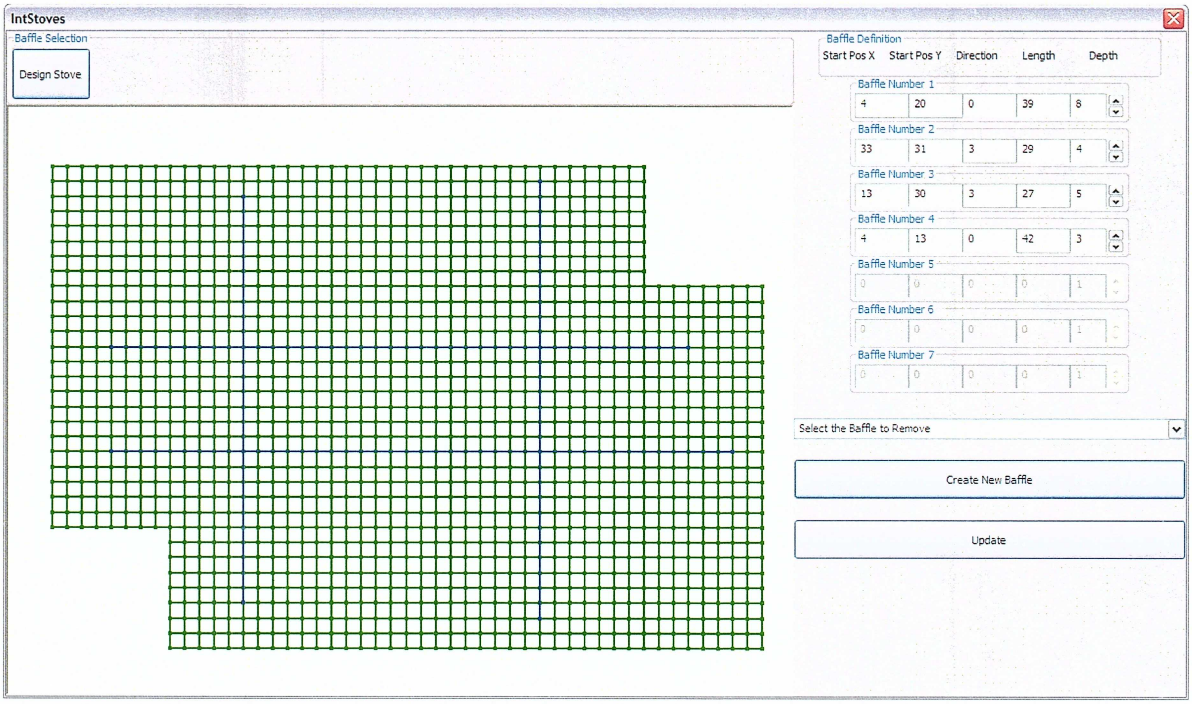
A significant amount of research work has focused on modeling several stove designs. The ability to successfully model the stoves being analyzed reduces many of the previously discussed issues with the current design and construction processes. Making changes to models is considerably faster and less expensive than prototyping and testing each design alternative in the field. Though, it is still time consuming to go through design iterations using disparate models. The analyst must first manually modify the geometric model to reflect each design alternative being considered. Then the model changes must be manually updated and run in the computational solver. Computational results then need to be presented appropriately to fully understand the impact of the change. While clearly an improvement over previous processes, this methodology still limits the set of design alternatives which can be investigated.

Further work has been done using innovative optimization techniques to provide an engineer or decision maker viable stove designs without requiring manual modifications for each design alternative considered (McCorkle et al., 2003; Bryden et al., 2003). This work uses novel techniques implementing Graph Based Evolutionary Algorithms (GBEAs) and has been found to be successful in producing several potential designs providing effective cooking surface temperature profiles without requiring any user intervention in the optimization. While clearly a step forward in efficiently developing stove designs with usable cooking surfaces, this optimization work has not been able to account for economic and manufacturability concerns.

The biomass cookstove design problem is challenging because of the large number of design variables and the fidelity of data required to understand the effectiveness of a particular design. Through the use of CFD models, an engineer can more quickly and effectively analyze design alternatives, but using these models alone still requires a great deal of manual interaction. Sophisticated optimization techniques can be successfully employed to produce good solutions relative to several criteria, but these methods do not allow for human experience and insight to influence the solutions. For a complex and highly multi-objective design problem, such as biomass cookstove design, the designer or decision maker can benefit from a fully integrated interactive decision-making environment from which a problem can be explored to assess the full impact of design changes quickly and effectively.

The comprehensive decision-making environment needed to fully support the type and level of analysis needed for the biomass cookstove problem must provide the user with access to and control over the diverse set of decision-making tools required to represent the system. The CAD representations must be seamlessly integrated with the CFD solver, as well as the visualization tools necessary to present the high fidelity computational results to the user. A comprehensive environment must also include economics and manufacturing models which can calculate the impact of a design change in terms of cost/time for construction, usability concerns, and manufacturability. Furthermore, the environment needs to present the user with a flexible and intuitive interface from which they can quickly make design changes and view the results.

In order to fully represent the biomass cookstove design problem in an interactive application within the VE-Suite framework, three separate plug-ins are needed. The graphical plug-in, graphical user interface (GUI) plug-in, and the computational unit plug-in are built to adhere to VE-Suite's VE-Open specification for communication. Plug-ins are built to run distributed, cross platform, and cross network. Through the VE-Open specification and VE-CE's data and command synchronization capabilities, changes and results from within the plug-ins are automatically updated throughout the rest of the environment.



	Start Pos X	Start Pos Y	Direction	Length	Depth
Baffle Number 1	4	20	0	39	6
Baffle Number 2	33	31	3	29	4
Baffle Number 3	13	30	3	27	5
Baffle Number 4	4	13	0	42	3
Baffle Number 5	0	0	0	0	1
Baffle Number 6	0	0	0	0	1
Baffle Number 7	0	0	0	0	1

Figure 20. Baffle designer interface

The GUI plug-in provides the user with the necessary controls to modify and develop new baffle configurations. Specifically, the user is given a two dimensional grid representing the stove top (Fig. 20). Within the grid, the baffles can be drawn in with a series of intuitive mouse actions. To place a new baffle the user will click the right mouse button on two grid points representing the ends of the baffle. When a point is selected, it will change color and once the two ends are selected, a created new baffle button can be used to put the new baffle in the list. At this point a blue line will appear in the grid representing the newly created baffle. For each new baffle placed in the heat exchange chamber, the integer description of that baffle is also presented to the user on the GUI-Plug-in interface. Within this section of the GUI the user is able to set the depth of each baffle. This allows for quick and accurate visual comparison between existing heat transfer data and the location of new baffles facilitating an engineers' ability to influence a design through intuition and experience. Baffles are represented within the computational environment with five integers declaring a starting location, length, direction, and depth. It is difficult for an engineer to look at five integers and develop a reasonable conceptual picture about how a baffle fits and looks within the heat exchange chamber. Rather than leaving the user the difficult task of trying to develop a mental image of a baffle from five integers, a baffle designer grid is developed to allow them to simply draw baffles into the desired locations.

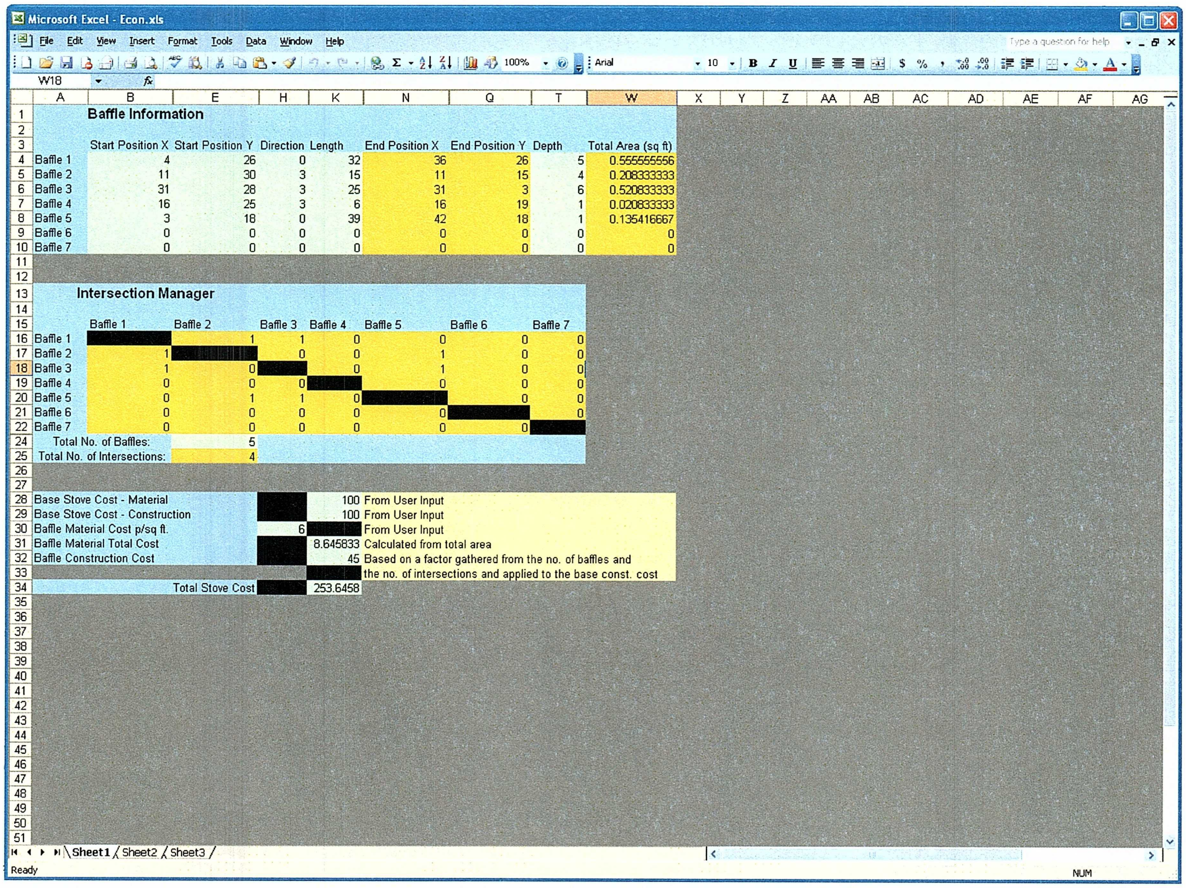
The baffle designer user interface is built using wxWidgets, an open source C++ cross-platform GUI framework. To develop the grid canvas used to place baffles, a unique and powerful tool from within the wxWidgets library called an OpenGL™ Canvas was used. The OpenGL™ Canvas class gives the developer direct access to raw OpenGL™ functionality. Through the use of OpenGL™, the heat exchange chamber of the stove can be drawn on a flexible design canvas in an intuitive manner which allows to user to very simply draw each of the desired baffles. After the user is finished creating the new baffles, an update button is used to send the new design information to the VE-Suite framework for updating throughout the decision making environment.

The computational unit is built as a stand alone application which receives user defined design variables from VE-CE, then performs the necessary computations. The unit wraps CFD code for thermal and fluid analysis and a spreadsheet interface for economic calculations. Upon receiving design variables from VE-CE the computational unit sets up the new baffle configuration within the CFD code, and then directs the fluid dynamics analysis. The results from the CFD analysis, along with dimensional information about the baffle configuration are then fed to a spreadsheet which uses that information to perform some economic calculations about the stove design.

The computational unit performs the airflow and heat transfer analysis within the cookstove with a commercial software package, Star-CD™. The heat exchange chamber is modeled as a simple rectangular prism coupled with the combustion chamber and exhaust duct. In-field measurements are used in determining the boundary conditions for the model. The boundary conditions at the inlet of the heat transfer chamber during typical cooking parameters are measured and used in place of a combustion model. Inlet velocity is set at 3.88 m/s and temperature at the inlet is set at 977 K. The impact on air density from changing temperatures is modeled. A K-$\in$ model with an intensity of 0.1 and entrance length of 4.8 cm is used to model turbulence. Resistance to heat transfer from the cooking surface is modeled using a surface thickness of 1.6 cm, a heat transfer coefficient of $20 W/m^2 \cdot K$, and a thermal conductivity of $30\ W/m \cdot K$. Simulating the pumice insulation commonly used in stove construction, the remaining surfaces are modeled to be adiabatic.

The existing economics and manufacturability models are contained within a Microsoft^{TM} Excel spreadsheet (Fig. 21). There is ongoing work understanding and cataloging the economic dynamics of local cookstove manufacturing, but currently data and models are not available which completely and accurately describe these economic factors. The models used for this work implement first world engineering cost analysis techniques to, at a minimum, develop a feel for the viability of a stove design. The calculations used take the new baffle configuration information and extract the material cost for that particular baffle design. The design pattern is analyzed to review manufacturing cost factors. First the spreadsheet applies a factor for total linear weld distance. Also, in terms of welding cost, an addition factor is applied for the number of different welds needed, as each new weld requires time and adjustment for the welder. Another factor that is represented in this model is the cost factor for cutting materials due to baffle intersections. These factors all work together, not to represent the precise economic impact of a baffle configuration, but rather to provide the decision maker with relative economic impacts as the design review process is carried through.

The computational unit wraps the CFD and economic models removing the need for the user to interact with the models directly. The unit has direct access to the existing validated Star-CD^{TM} CFD model. When a new baffle configuration has been given to the unit along with instruction to recalculate, the unit directs the Star-CD^{TM} model in adding the new baffles to the computational mesh. Once the CFD model has been completely updated for the new design, the computations are carried out. The unit then waits for completion of CFD. When the model is finished the high fidelity dataset is exported from Star-CD^{TM} and post processing data translation to the Visualization Toolkit (VTK) format. The processing is handled by functionality built within VE-Suite and is managed without user intervention. The unit finishes the data processing and proceeds to process spreadsheet calculations. As in the previously discussed applications, the computational unit gains access to Excel via the use of Microsoft^{TM} Foundation Classes (MFC). Upon completion of the CFD and economic calculations the unit sends the results back to the other components within the environment for further processing and display.



Baffle Information

	Start Position X	Start Position Y	Direction	Length	End Position X	End Position Y	Depth	Total Area (sq ft)
Baffle 1	4	26	0	32	36	26	5	0.555555556
Baffle 2	11	30	3	15	11	15	4	0.208333333
Baffle 3	31	28	3	25	31	3	6	0.520833333
Baffle 4	16	25	3	6	16	19	1	0.020833333
Baffle 5	3	18	0	39	42	18	1	0.135416667
Baffle 6	0	0	0	0	0	0	0	0
Baffle 7	0	0	0	0	0	0	0	0

Intersection Manager

	Baffle 1	Baffle 2	Baffle 3	Baffle 4	Baffle 5	Baffle 6	Baffle 7
Baffle 1		1	1	0	0	0	0
Baffle 2	1		0	0	1	0	0
Baffle 3	1	0		0	1	0	0
Baffle 4	0	0	0		0	0	0
Baffle 5	0	1	1	0		0	0
Baffle 6	0	0	0	0	0		0
Baffle 7	0	0	0	0	0	0	

Total No. of Baffles: 5
Total No. of Intersections: 4

Base Stove Cost - Material		100	From User Input
Base Stove Cost - Construction		100	From User Input
Baffle Material Cost p/sq ft.	6		From User Input
Baffle Material Total Cost		8.645833	Calculated from total area
Baffle Construction Cost		45	Based on a factor gathered from the no. of baffles and
			the no. of intersections and applied to the base const. cost
Total Stove Cost		253.6458	

Figure 21. Spreadsheet based economics model

The graphical plug-in is responsible for bringing CAD information into the virtual environment (Fig. 22), as well as changing or modifying geometry based on new design information (Fig. 23). Through VE-Suite's graphical engine, VE-Xplorer, the graphical plug-in loads all geometry onto a scene graph which can be presented in a number of different visualization environments, ranging from standard personal computers to fully immersive virtual reality caves. When new baffle configurations are given to the environment from the user, that information is processed by the graphical plug-in to make the appropriate changes to the CAD. Functionality within VTK, an open source C++ library for three dimensional computer graphics, image processing, and data visualization, is used to represent the new baffles geometrically within the graphics environment. Upon receiving new design information, the graphical plug-in uses VTK to create the new baffle geometry, then places the baffle appropriately within the CAD representation of the heat exchange chamber.

Figure 22. CAD representation of the stove inside a home

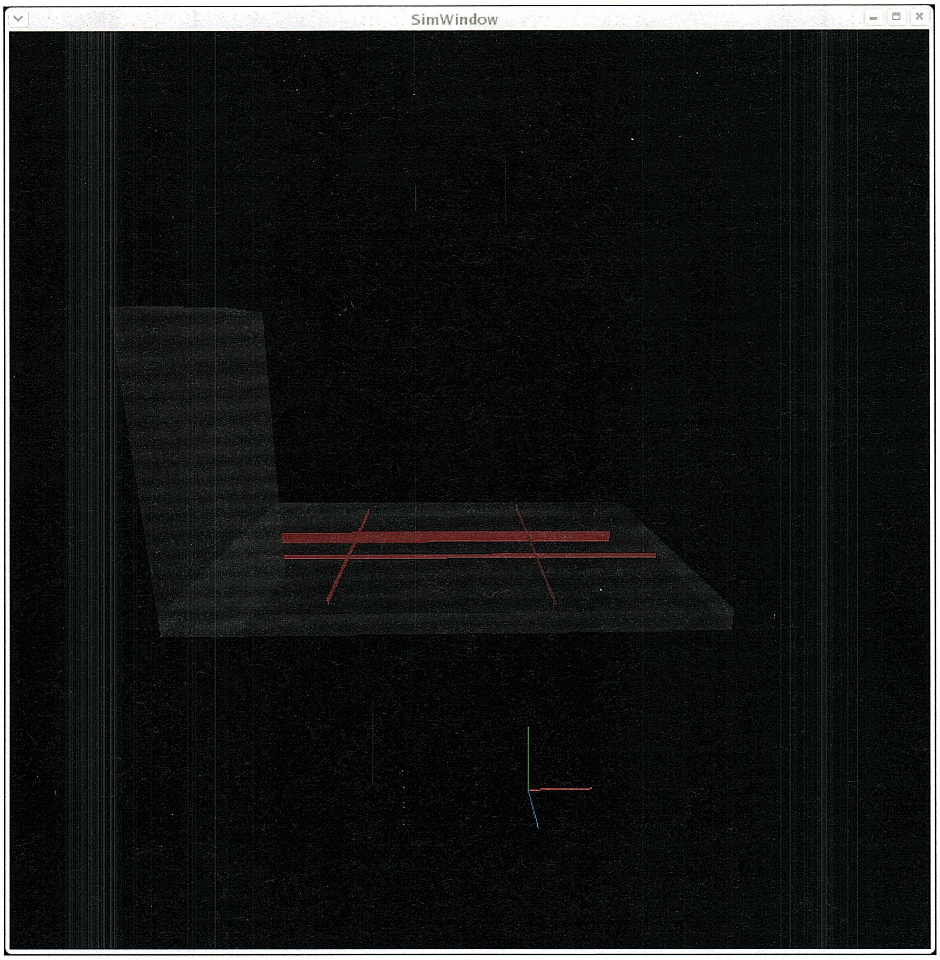


Figure 23. Heat exchange chamber CAD with updated baffle layout

The graphical plug-in also has the functionality needed to visualize computational data as provided by the CFD model (Fig. 24). Also through an implementation of the VTK library, the graphical plug-in gives the user the ability to utilize VE-Suite's inherent visualization tools to work with recalculated computational data. When the computational unit is completed with calculations for a new stove design, a message is sent to the graphical plug-in instructing access to the newly formulated data. VTK is then utilized to present the data within the graphics environment as instructed by the user (Fig. 25).

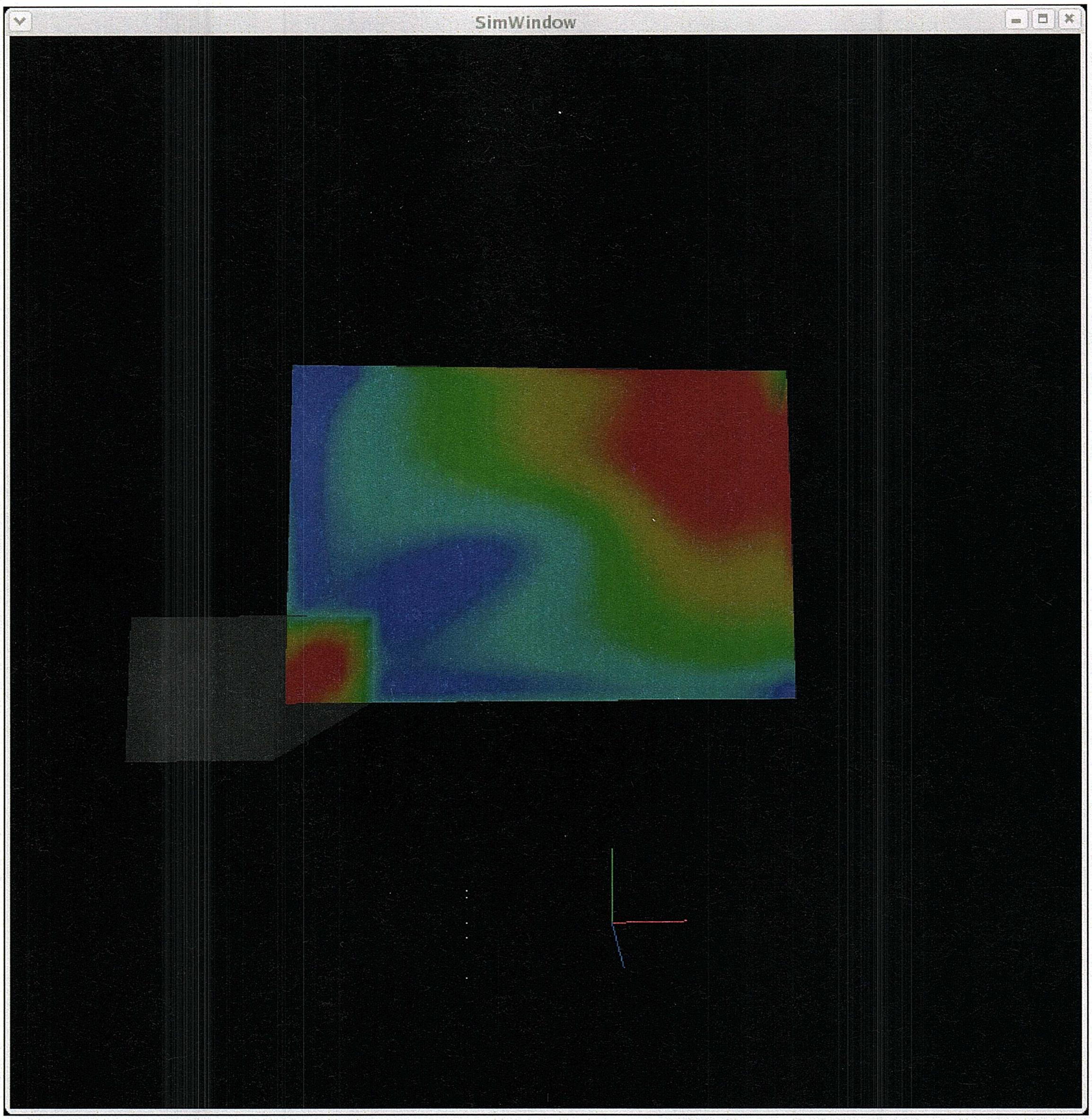


Figure 24. Unbaffled stove top temperature profile as viewed in VE-Xplorer

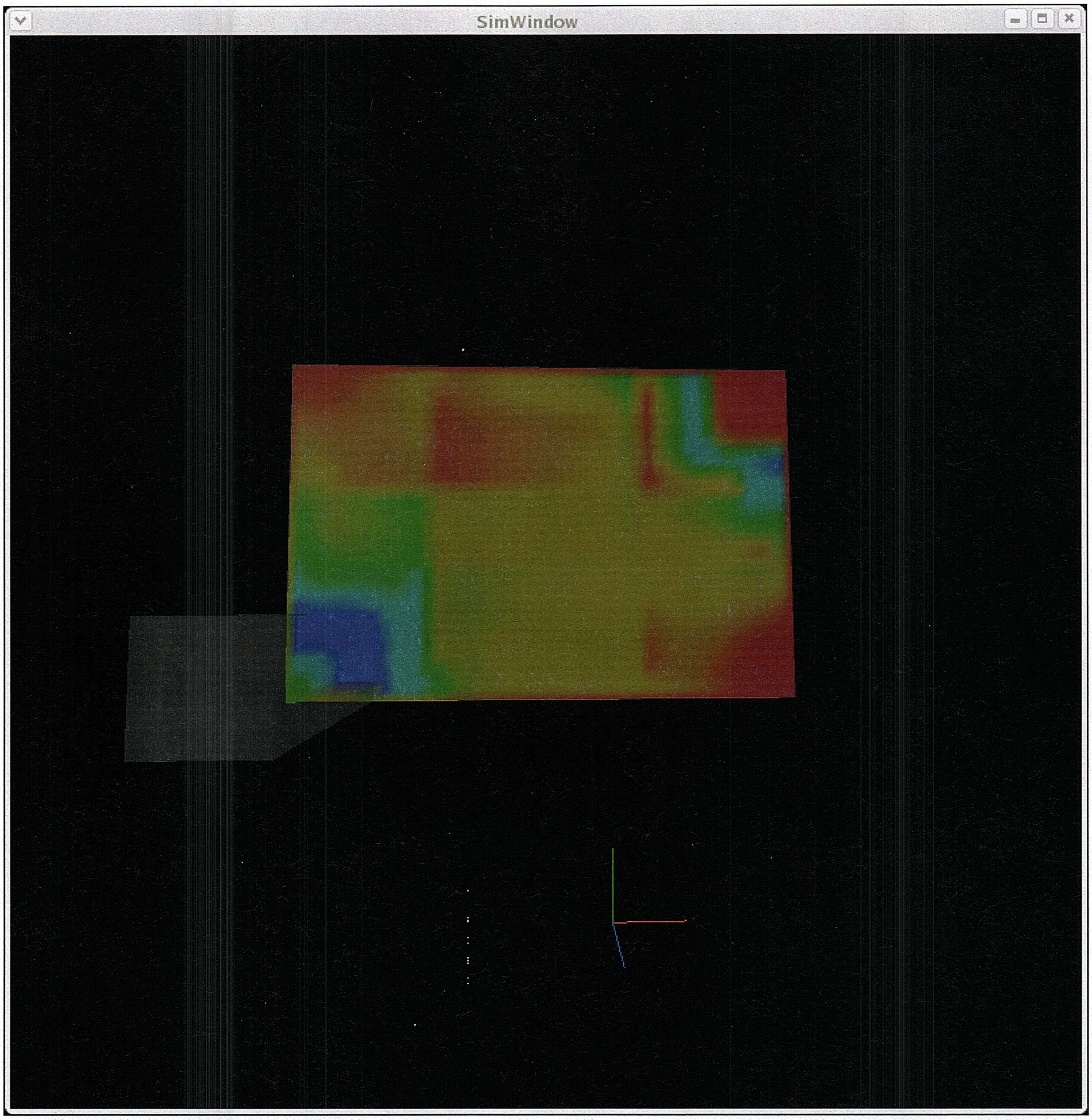
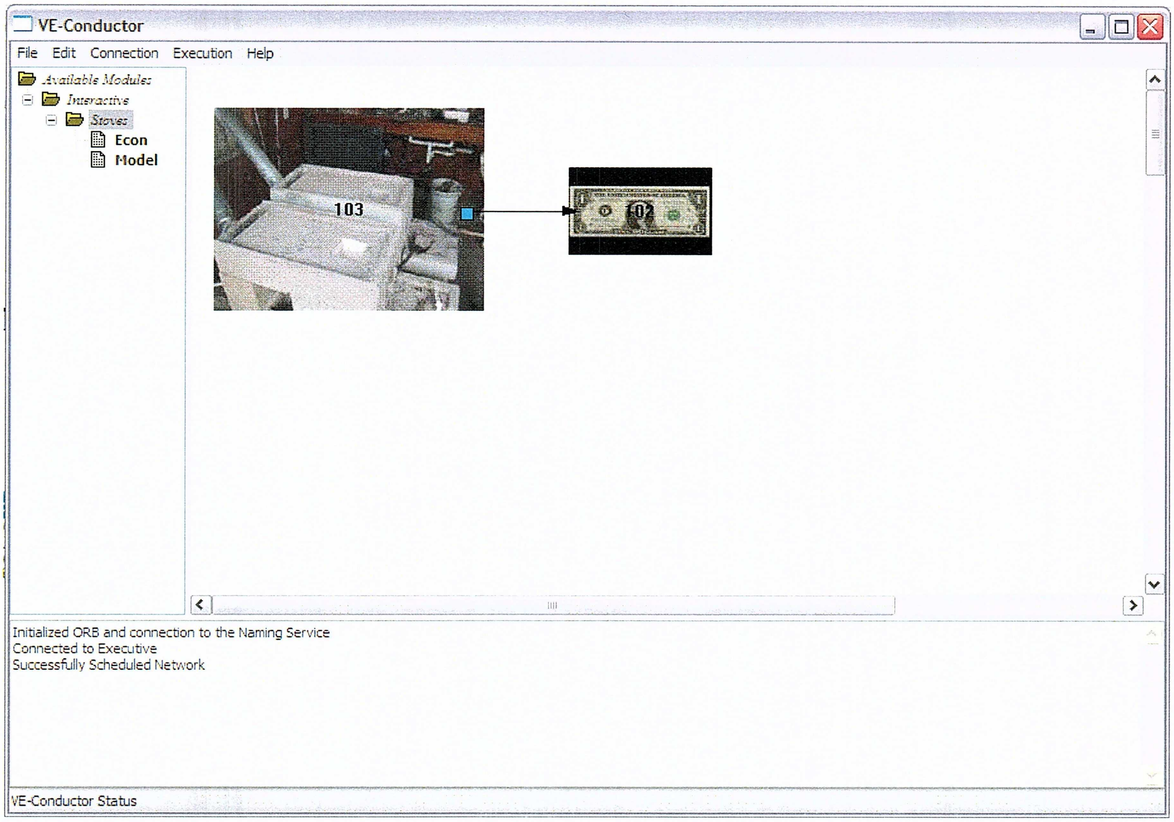


Figure 25. Baffled stove top temperature profile as viewed in VE-Xplorer

5.3 Using the Cookstove Design Environment

The integration of these components within VE-Suite creates an interactive decision-making environment from which a user can develop a baffle configuration, perform computational analysis on the new design, and view results in less than five minutes for a single design iteration. Upon starting VE-Suite the user will first load the interactive stove icon on VE-Conductor's design canvas and instantiate the interactive cookstove (Fig. 26).



Initialized ORB and connection to the Naming Service
Connected to Executive
Successfully Scheduled Network

Figure 26. VE-Conductor design canvas with interactive stove module active

At this point the graphics environment updates the CAD representation of the stove, the UI allows the user to create new baffle configurations, and the computational unit is ready to receive new baffle design information. A baffle configuration can be drawn on the grid and the design submitted to VE-CE. The computational unit receives the design variables, updates the CFD model, and begins calculations. The CFD model has been refined to run in approximately one minute to support the investigation of as many design alternatives as possible. When the CFD models have converge to a solution, VE-Suite's data processing tools are used to prepare the high fidelity data for loading into the graphical environment. The unit will then carry out the economic analysis. Economic calculations within the spreadsheet are nearly instantaneous upon receiving the necessary input variables from the CFD model. When the computations are complete, results are then given back to VE-Suite's core engines. The VE-Xplorer is updated with the computational results, including the CFD dataset, allowing the user to visualize the impact of a given design alternative. The user can apply VE-Suite's visualization tools to explore the fluid dynamics information returned from the CFD model. The results from the economic calculations are passed back to VE-Conductor and displayed in a tabular format. For any given design the user is presented with a variety of result formats from tabular data to full fidelity visualizations available from within VE-Xplorer. Fig. 27 demonstrates the flow of operations for each individual design iteration.

This application provides a decision maker with a comprehensive virtual engineering environment for designing baffle configurations for biomass cookstoves. The environment is created utilizing VE-Suite as the software framework to give the user access to the necessary analysis tools within a single space. A design change can be made without requiring expertise in CAD or other software packages and reflected in the computational models without user intervention. A skilled CFD analyst is not needed to perform the computational analysis significantly reducing the time required to perform a design iteration. The process of presenting analysis data to the decision maker is fully automated within the virtual engineering environment. The end result is fully integrated interactive virtual engineering environment which allows a decision maker to explore design alternatives in minutes rather than hours, days, or even weeks.

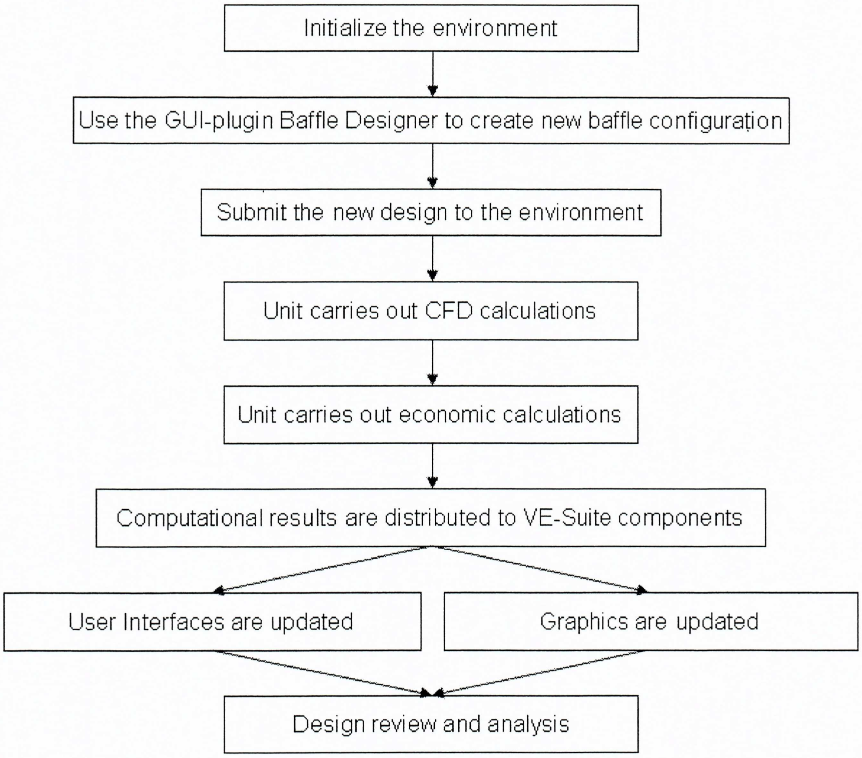


Figure 27. Design iteration procedural flowchart

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

As discussed, this research developed new methods for integrating models representing engineering systems. Specifically, development was advanced to facilitate the integration of Excel spreadsheets within a virtual decision making environment. This functionality is complimented by development which allows seamless access to high fidelity CFD solvers. This work also included the integration of decision support tools which help to complete the decision making environment by assisting the user in understanding the impact of analysis results. The development and capability of these tools is demonstrated through two applications, fire hazard analysis in nuclear power plants and interactive design of heat transfer systems within biomass cookstoves.

Fire hazard analysis tools were integrated to create a complete virtual environment for investigation of fire scenarios within an auxiliaries room of a nuclear power plant. In this application the NUREG-1805 Excel spreadsheets developed by the NRC were integrated into the decision environment as the fire modeling tool. An intuitive user interface was built to allow the fire protection engineer to set up and interact with potential fires. Accurate graphical representations of the fire area components were attained with laser scans and integrated into the environment allowing the fire protection engineer to analyze fire analysis data within a virtual representation of the physical space.

Several more tools were developed and integrated to create an application supporting the interactive design of baffle configurations with the heat exchange chamber of biomass cookstoves. A flexible user interface was built to help the user create baffle configurations in a manner which allows the interjection of experience and intuition to the design problem. Existing scripting functionality was utilized within the software environment to give the user seamless access to a commercial CFD solver. Design changes can be reflected in the CFD solver without any direct user interaction and high fidelity solvers can subsequently be used for fully interactive analysis.

VE-Suite is the virtual engineering software framework utilized in creating these analysis tools. The development work needed to create these tools has provided a significant contribution to the VE-Suite framework. The functionality built as part of this thesis work continues to be utilized and pushed forward as an important part of advancing virtual engineering technologies.

6.2 Future Work

The key issue with this work going forward is developing the capability to handle increasing complexity within engineering systems. To handle this complexity, decision making environments will need support for systems and system components which self organize and self describe. Models will need to be able to place themselves within the system and be able to understand what's needed from them without user direction. This is a challenging integration issue for ongoing research in creating decision making environments. Through several system integration case studies, the development of tools to support self organizing and self describing system integration will be the basis of my doctoral research.

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