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Simulation Enabled Safeguards Assessment Methodology

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It is expected that nuclear energy will be a significant component of future supplies. New facilities, operating under a strengthened international nonproliferation regime will be needed. There is good reason to believe virtual engineering applied to the facility design, as well as to the safeguards system design will reduce total project cost and improve efficiency in the design cycle. Simulation Enabled Safeguards Assessment MEthodology has been developed as a software package to provide this capability for nuclear reprocessing facilities. The software architecture is specifically designed for distributed computing, collaborative design efforts, and modular construction to allow step improvements in functionality. Drag and drop wireframe construction allows the user to select the desired components from a component warehouse, render the system for 3D visualization, and, linked to a set of physics libraries and/or computational codes, conduct process evaluations of the system they have designed.

I. INTRODUCTION

The use of nuclear energy for electricity production is expected to be a significant component of future energy supply.[1] Recently, U.S. President Bush and Russian President Putin jointly declared their intent to make the peaceful use of nuclear energy available to a wide range of interested States, while at the same time preventing the spread of nuclear weapons.[2] A strengthened nonproliferation regime and enhanced national safeguards and security systems are therefore vital elements of future nuclear energy programs, and the Simulation Enabled Safeguards Assessment MEthodology (SESAME) project directly supports these objectives in a variety of ways.

Virtual engineering (VE) is the application of modeling, simulation and visualization within a virtual environment to explore multidisciplinary solutions to engineering challenges. The primary advantages of VE are manifest in improved collaborative capabilities, increased efficiencies of the design cycle, and, ultimately, in reduced cost to design, construct and operate new products or facilities.[3] Many industries have embraced VE techniques. A noteworthy and well known industrial example of VE is the Boeing 777 aircraft, where all phases of the design process were performed virtually.[4] Other examples include such diverse fields as agricultural combines[5], naval weapons and design[6,7], and coal-fired power plants.[8]

The SESAME project will apply modeling and simulation to the design and operation of nuclear fuel cycle facilities. This will facilitate the design of the safeguards systems (both national/domestic and international safeguards) to accompany and even inform the design of the overall plant which will manifest in shorter design times, less total project cost, while achieving increased integration between the various design disciplines.

SESAME is a tool being developed to visualize the design and subsequent operation of nuclear facilities, with current emphasis on aqueous reprocessing plants. The safeguards systems can then be demonstrated, tested, evaluated and improved as part of the overall design process. This will be particularly useful as advanced safeguards approaches are developed that may use a broad variety of new types of operational and process data, to include the sensor and instruments need to collect that data. The SESAME architecture is specifically designed to enhance collaborative capabilities and user specific module design. The remainder of this paper instantiates a preliminary version of the vision described by Bjornard et. al.[9]

II. SESAME Functions and Architecture

A key aspect of safeguards (to include nuclear material accounting, physical protection of nuclear material, and nonproliferation verification) is to obtain timely information on the location, form, and movement of nuclear materials. Accordingly, a simulation and design tool for safeguards must be able to properly track the nuclear material through software calculations as it moves through the plant systems. Additionally, the software architecture must be adaptable to specific user needs, and modular in nature to allow seamless integration of step improvements to various functions and components.

The architecture and functional design of SESAME is specifically directed towards controlled, collaborative development, as depicted in Fig. 1. Adapting IEEE standards as appropriate, a Software Project Management Plan describes the overall effort.[10] The framework team has developed the control executive and the interfaces needed to connect with the physical submodels. The software design details have been documented.[11] With input from the extensive group of collaborators, the software requirements have been drafted.[12] As design improvements proceed, the collaborators will have access to the requirements.

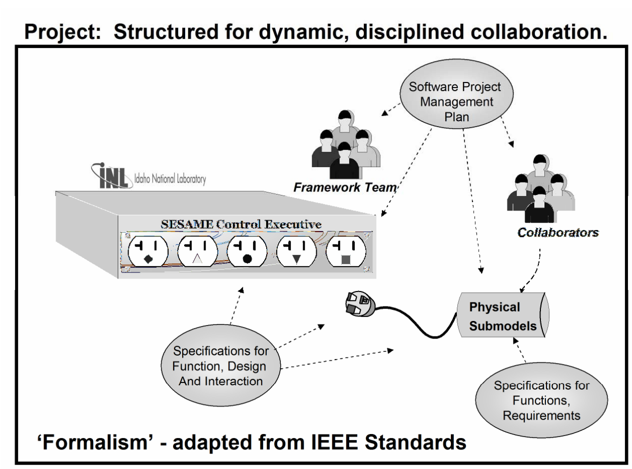

Fig. 1. The design of SESAME specifically promotes collaboration on the interfaces and physical submodels.

II.A Major SESAME Functions

The major functions of SESAME are depicted in Fig. 2. The upper part of Fig. 2 is the Facility Module. This is the model of the overall facility or system that is of interest to the user. The Facility Module includes plant architecture and equipment such as pumps, valves, tanks, centrifugal contactors, and the like, in connection with the physical libraries and computational codes used to model those components. The Facility Module also includes plant and system instrumentation, process models and other computational tools as necessary to model the nuclear material flow.

The central feature is the Control Executive (CE), shown in the center of the diagram. The CE is the "boss" and handles the communications, interfaces, resource scheduling, component access, and otherwise manages the relations between the SESAME models and modules.

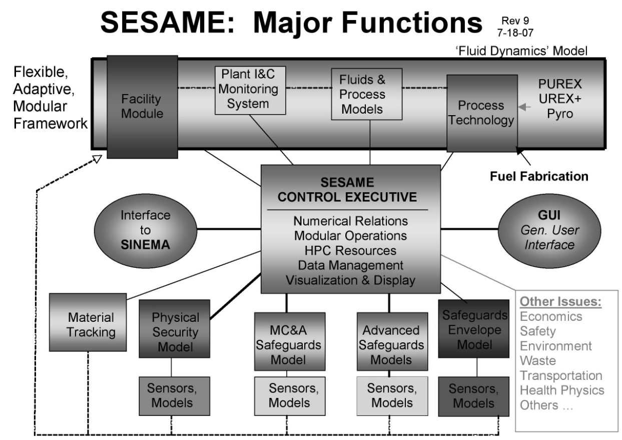

Fig. 2. The major functions in SESAME for a Typical Safeguards Application

Finally, some of the other models of interest are depicted along the bottom of Fig. 2. These functions represent some of the components and calculation tools to simulate and model various safeguards functionality. This includes sensors (cameras, radiation detectors, motion sensors, etc.), as well as calculation of effects (radiation levels, mass changes, etc.) applicable to safeguards system evaluation.

II.B SESAME Software Architecture

At the highest level the architecture of SESAME consists of the Control Executive, a component warehouse, a physical model library, the graphical user interface and high performance computing (HPC) resources. This structure has been designed to support collaborative development, modular construction, and stepwise improvements to existing modules.

II.B.1 Control Executive

The Control Executive is the very heart of the SESAME framework, it essentially directs the activities of all modules and functions. All interactions between the functions and modules of SESAME are through the CE, as shown in Fig. 2. The CE manages the data streams, the HPC resource scheduling, interfacing the modules and the output, both data and visual to the user.

II.B.2 Component Warehouse

The component warehouse houses the components used in the creation, design and modeling and simulation of systems. The Inventory Manager controls the versions of components in stock, allowing users to check out a component for improvements and check in the new version. Each component has a broad variety of attributes and capabilities, including information about its looks, its social behavior, and its profession (role).

Each component contains graphical information about its size, shape, and appearance. The graphical representation can range from a simple representation (i.e. block flow diagrams), to a full 3D visualization of the component, depending on which version of the component the user selects or creates.

The discovery model is responsible for the functionality that makes each component sentient and socially- aware. Each component knows its role and how it relates to the other components and computational tools, as well as the HPC resources required. As an example, a component that is a water pump knows that its role is to pump fluids, that it has social needs that can only be satisfied when it is connected to other components – in this case an inlet, an outlet, and a power supply. It knows that it needs to be anchored to another component (e.g. the floor), and it knows that it requires a physical model of some kind to describe its operation – e.g. the flow of fluid through its openings. When a user selects this component from the warehouse, the component will actively seek to ensure that its role and social needs are met.

The computational model provides the connection from the component to the physical model that computes its physical behavior. The linked tool may be a simple relation or equation, or it may be a connection to a full-featured external code, such as thermal-hydraulics, radiation transport, or other codes as built in by users.

II.B.3 Physics Library and High Performance Computing

The final pieces of the SESAME architecture are the physics library and the HPC resources. The HPC resources have been described briefly in connection with the Control Executive.

SESAME must have the capability to model all of the physical processes relevant to the tracking of nuclear material through an aqueous reprocessing facility, thus this is clearly a multi-disciplinary problem. These models are checked in and out of the library, and are activated as needed to model the operation of the components in use.

III. SESAME Software Capabilities

The SESAME framework contains multiple features that will be useful in the design process of nuclear facilities (with current effort on aqueous reprocessing plants). The graphical user interface (GUI), through an n-tiered network using thin clients, allows the user access to pre-built components and pre-assigned computational libraries and HPC resources.

III.A Drag and Drop Wireframe Canvas

The user can select components from the component warehouse and arrange them on a wireframe visual canvas. Once connected, they form the system to be simulated, up to and including the entire plant. As appropriate for the specific modeling effort, the design can then be rendered in a 3D visual format to allow walkthroughs and visualization of the system operation.

III.B Computational Results Display

Once the system to be simulated has been created, the user can run simulations based upon the physical models and computational libraries associated with the selected components. The results can be displayed separately (e.g. data files, or visual plots and data through the GUI) or in concert with the 3D visualization, based upon the user specific modeling needs. At times there may be more effective ways than 3D visualization to display data from a simulation, and consequently provision is included for selection or convenient addition of alternative display approaches.

IV. ADDITIONAL APPLICATIONS

While SESAME will be used for demonstrating and testing both conventional and advanced safeguards concepts – such as Operational Accountancy and the Safeguards Envelope – it is also applicable to performing a broad variety of other vital functions. Examples include drag and drop facility and system design and layout, safeguards design and impact on facility layout, integrated material tracking, process design, experiment design and conduct of virtual experiments, diversion/misuse simulations, plant monitoring and control system design and testing, model-based instrumentation and control design, operator training, inspector training, video containment and surveillance system development and testing, optimization studies by the user, and so forth. There are also numerous possibilities for parallel real-time simulation and monitoring applications, including full remote, and simulation based monitoring (e.g. operation of a plant in country X, real-time transmission of key operating data from country X to country Y, and use of this data in real-time mirroring/simulation in country Y).

Coupling the component warehouse, populated with robust components, to the physics library, with a full range of computational choices, will make SESAME an important tool in the 'Safeguards by Design' toolbox. Ultimately, SESAME will facilitate designing and operating a complex facility like the Advanced Fuel Cycle Facility – fully within virtual space - before ever breaking ground.

V. RESULTS AND PATH FORWARD

Initial SESAME development has been conducted using the spiraling prototype design approach, adapting IEEE standards as useful for the specific needs of the project. Substantial progress has been made on the SESAME project since its inception in mid-2005. Two workshops, involving well over 20 experts from more than 15 labs and universities, strongly influenced the requirements specifications for the design. The first prototype, completed in FY06, included the successful demonstration of the high level architecture – including physics coupling - for an example UREX+3 facility. A fixed facility design and rudimentary hard-wired physics were included in this first prototype. Figure 3 shows a screen shot of this prototype wherein the scenario of a worker removing material from a glovebox and the calculated response of the portal monitor is depicted.

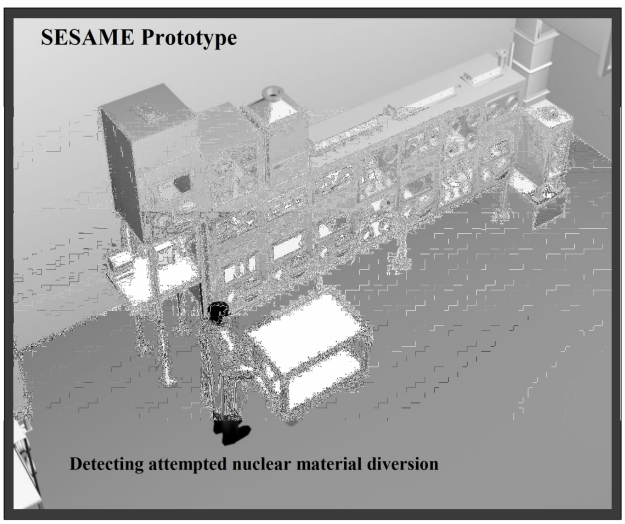

Fig. 3. A screen capture of the SESAME prototype. The scenario is a worker who can remove varying (user selected) amounts of material from the glovebox, and the response of a portal monitor is calculated.

The third design cycle will be completed in FY07, at which time an entirely new prototype containing a functioning component warehouse is expected to be completed, together with the third revision of the project design and specifications.

SESAME has been specifically designed to accommodate contributions by a wide variety of experts, each working in their particular areas of strength, while a team develops the host framework. The modular, IEEE standards based project approach, together with strong, requirements based project management, will facilitate a dynamic - yet controlled - collaborative effort as more experts actively join the development team in FY08. Their focus is expected to be primarily the development and adaptation of physical models.

VI. SUMMARY

The coming nuclear renaissance will most likely involve the design and deployment of new nuclear facilities; power reactors, enrichment plants, processing plants and storage facilities. The SESAME program provides a powerful tool to substantially strengthen the design process and improve these facilities – as a modeling and simulation tool for safeguards by design in an aqueous separations facility. Once fully operational, SESAME will be useful for expanded analysis and support, such as overall plant design, operator training, and safety and quality analysis.

Reduced proliferation risk, together with enhanced safeguards and security effectiveness are crucial to the successful future of nuclear energy. Among other things, SESAME will be a powerful tool to cost-effectively improve nuclear security.

ACKNOWLEDGMENTS

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