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ABSTRACT

The U.S. Department of Energy (DOE) is interested in developing tools and methods for potential U.S. use in designing and evaluating safeguards systems used in enrichment facilities. This research focuses on analyzing the effectiveness of the safeguards in protecting against the range of safeguards concerns for enrichment plants, including diversion of attractive material and unauthorized modes of use. We developed an Extend simulation model for a generic medium-sized centrifuge enrichment plant. We modeled the material flow in normal operation, plant operational upset modes, and selected diversion scenarios, for selected safeguards systems. Simulation modeling is used to analyze both authorized and unauthorized use of a plant and the flow of safeguards information. Simulation tracks the movement of materials and isotopes, identifies the signatures of unauthorized use, tracks the flow and compilation of safeguards data, and evaluates the effectiveness of the safeguards system in detecting misuse signatures. The simulation model developed could be of use to the International Atomic Energy Agency IAEA, enabling the IAEA to observe and draw conclusions that uranium enrichment facilities are being used only within authorized limits for peaceful uses of nuclear energy. It will evaluate improved approaches to nonproliferation concerns, facilitating deployment of enhanced and cost-effective safeguards systems for an important part of the nuclear power fuel cycle.

INTRODUCTION

The U.S. Department of Energy (DOE) is interested in developing tools and methods for potential U.S. use in designing and evaluating safeguards systems used in enrichment facilities [3]. The International Atomic Energy Agency is also continuing to review needs, capabilities, and efficiency in safeguarding enrichment plants. The IAEA hosted a technical meeting in Vienna on April 18-22, 2005 with the aim of further strengthening its inspection and verification approaches applied to uranium enrichment activities.

The present applied research focuses on analyzing the effectiveness of the safeguards in protecting against the range of safeguards concerns for gas centrifuge enrichment plants (GCEPs), including diversion of attractive material and unauthorized modes of use. It is part of a multi-laboratory DOE project, following on from an earlier examination of possible safeguards for natural uranium conversion plants [2, 4, 6].

Based on the earlier work, we have put together a tool suite for safeguards analysis, the Lawrence Livermore National Laboratory LLNL Integrated Safeguards System Analysis Tool (LISSAT) as outlined in Figure 1. It is a framework for performing systems analysis for evaluating the effectiveness of a safeguard system for a nuclear fuel cycle facility. LISSAT can be used to evaluate safeguards effectiveness for several nuclear fuel cycle facilities, as shown in Figure 2, like reactors [7], fuel fabrication plants, natural uranium conversion plants [2, 4, 6], nuclear fuel reprocessing facilities, enrichment facilities, spent fuel storage facilities, and Material tracking. In this paper we describe the application of LISSAT to evaluate the effectiveness of the safeguards for a generic enrichment facility. LISSAT is a suite of systems analysis tools including directed graphs and fault trees to structure the vulnerabilities, potential misuse actions, plant and safeguards configurations, and responses to observations. A second set of tools includes simulation modeling to analyze both authorized and unauthorized use of a plant and the flow of

safeguards information. We will analyze and simulate a generic medium-sized centrifuge enrichment plant's material flow in normal operation, plant operational upset modes, and selected diversion scenarios; for selected safeguards systems. We will evaluate the effectiveness of selected new instruments in the information flow of safeguards information for timely detection of undeclared operations or material.

The digraph-fault tree analysis is at the heart of the process. It structures possible diversion activities in a diversion scenario together with the safeguards measures and activities relevant to the diversion scenario. Then it incorporates possible failure modes of the safeguards measures and develops a fault tree for the safeguard system in this situation. Among the inputs to the fault tree are the analysis of the inspector's verification of the facility material declarations. Specifically these inputs are the probabilities of detection of various diversion activities meant to influence the facility's declared nuclear material balance. Outputs of the digraph-fault tree analysis are the probability of success, quantity, and value of the material removed in the

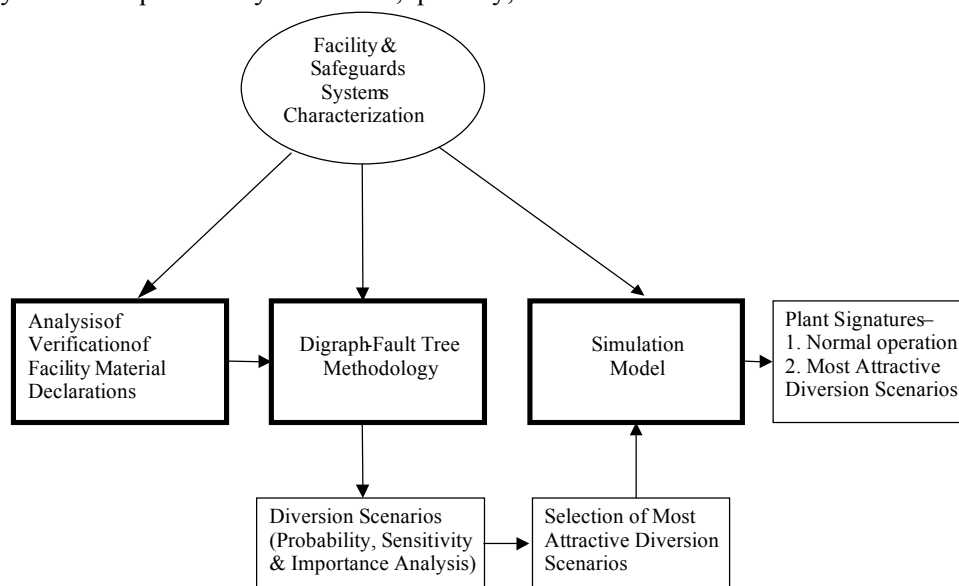


Figure 1. LLNL Integrated Safeguards System Analysis Tool LISSAT for evaluating the effectiveness of a safeguard system for a nuclear fuel cycle facility

diversion scenarios. The most attractive diversion scenarios are selected for time-domain simulation. The simulations track the uranium flow through the facility. The simulations include normal operation, intermediate storage, normal variations of input flow, and diversion scenarios. Simulation outputs are the time series of material outputs, which illustrate the data signatures of normal operation and diversion schemes. The simulation model can be used as an inspection tool. The model can be stored on the laptops of inspectors while inspection of the plant is occurring. The simulation model can be run to conduct “what if” scenarios and can be helpful in identifying data signatures that are indicative of diversion.

Several important results are generated when LISSAT is used. First, the directed graph/ fault tree analysis provides a structured systematic approach to incorporate all root causes for each diversion scenario including operator misdeclarations. Second, it helps quantify the change in the probability of diversion due to the introduction or use of material accounting, surveillance cameras, detectors, new safeguard measures/tools, new technology, and changes in plant design.

Third, the simulation modeling helps identify plant signatures (normal versus abnormal) that might assist IAEA inspectors as indicators of diversion. Fourth, it helps identify the ideal location

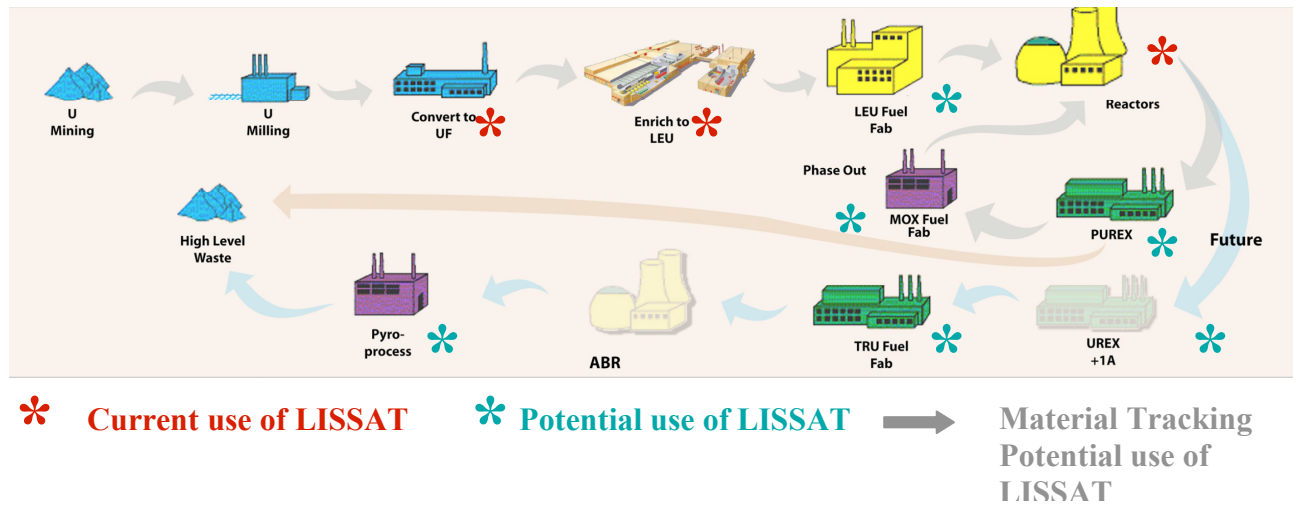


Fig. 2. Current & Potential use of LISSAT in Nuclear Fuel Cycle Safeguards

of detectors, surveillance cameras, and inspection points.

In this paper we present the simulation model of the plant and example results. The statistical and digraph-fault tree analysis are currently ongoing.

FACILITY & SAFEGUARDS SYSTEM CHARACTERIZATION

The facility analyzed in this paper is a medium sized generic enrichment facility based on Ref. [5]. It has a separative capacity of 500,000 SWU/yr. It has 50 cascades, each with 250 centrifuges, and each enriching to the same value of 3.5% enrichment. The feed to the plant is 900,000 kgU/yr in the form of UF₆. The product is 115,000 kgU/yr in the form of UF₆ enriched to 3.5%.

The block diagram for this generic facility is shown in Figure 3. It consists of nine modules. There are two material balance areas (MBAs), the storage area and the operations area. The more detailed block diagram for the Cascade Hall is shown in Figure 4.

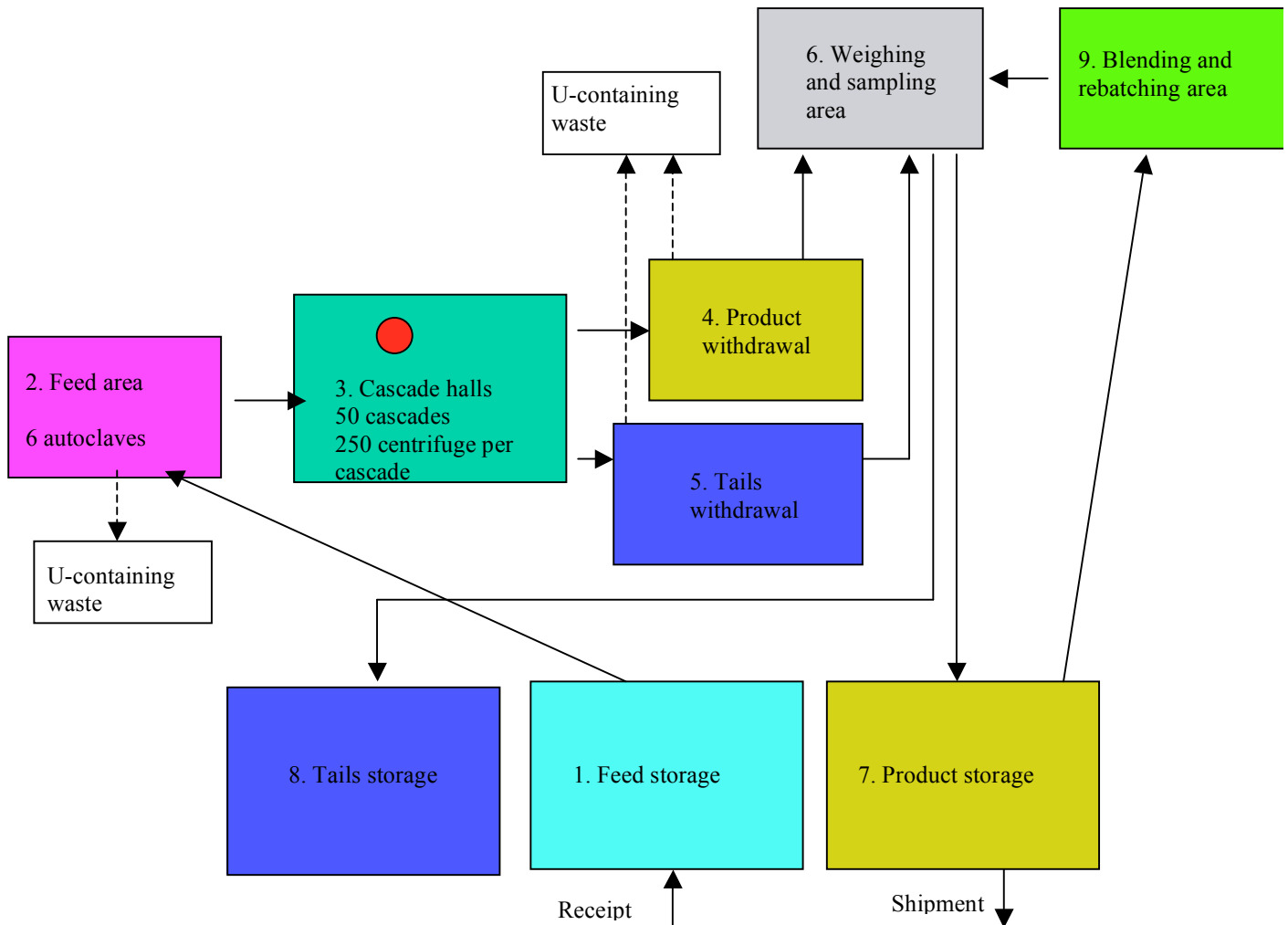


Fig. 3. Block diagram for generic enrichment facility

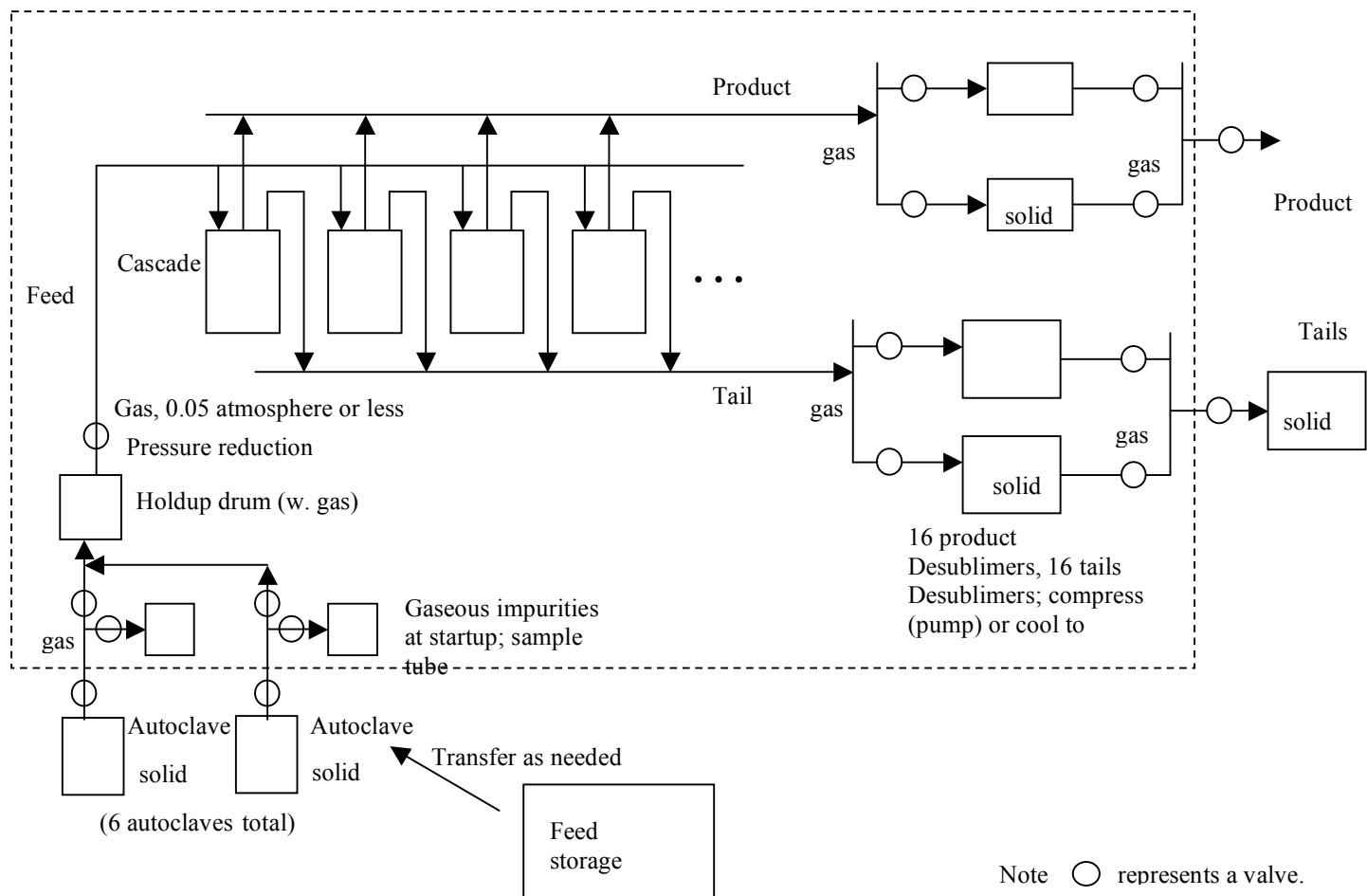


Fig. 4. Block diagram for Cascade Hall, autoclaves & product & tail withdrawal

DIVERSION SCENARIO

There are several safeguards concerns regarding GCEPs, including diversion of low-enriched uranium (LEU), excess production of LEU, and reconfiguration of part of the plant to produce HEU. As an example diversion scenario, we examine the steady skimming of 2% of the product (the product of one cascade) over a year, to divert 2000 kg of LEU, containing 70 kg of ^{235}U . This is near the IAEA significant quantity of LEU, which is LEU containing 75 kg of ^{235}U .

SIMULATION MODEL

An Extend simulation model was developed for this generic enrichment facility to model the flow of material throughout the facility. The model represents a continuous process. The simulation model consists of nine modules, each representing part of the enrichment process, from receipt of material at the feed storage to the enriched uranium at the product storage. The Product Withdrawal module is shown in Figure 5. It consists of iconic-blocks representing what is being modeled, the Desublimers, valves, and charts to monitor the flow of material at every stage. Input parameters to the simulation model were sized to match plant throughput. The simulation was run for one year with a time step of one hour. Figure 6 shows the plant signature when 2000Kg of LEU was diverted by skimming from one cascade throughout the year, it also shows the total amount of LEU produced throughout the year as well as the number of cylinders used.

4. PRODUCT WITHDRAWAL

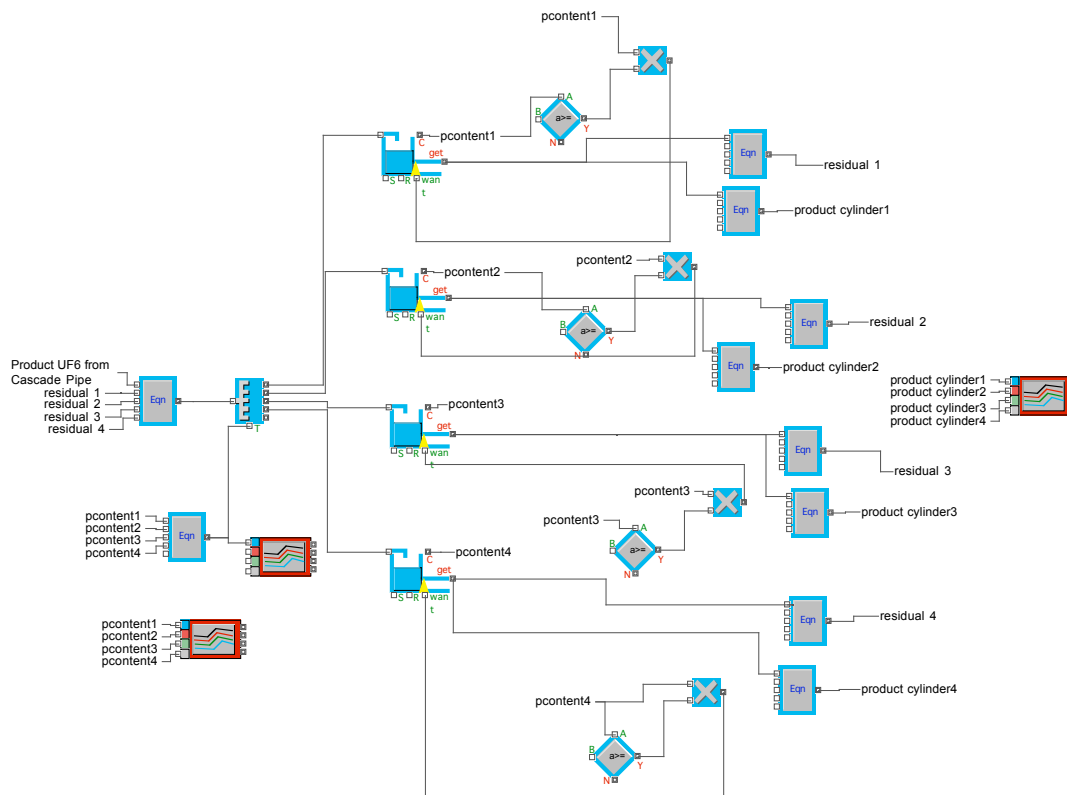


Fig. 5. Product Withdrawal Module in Extend Simulation Model

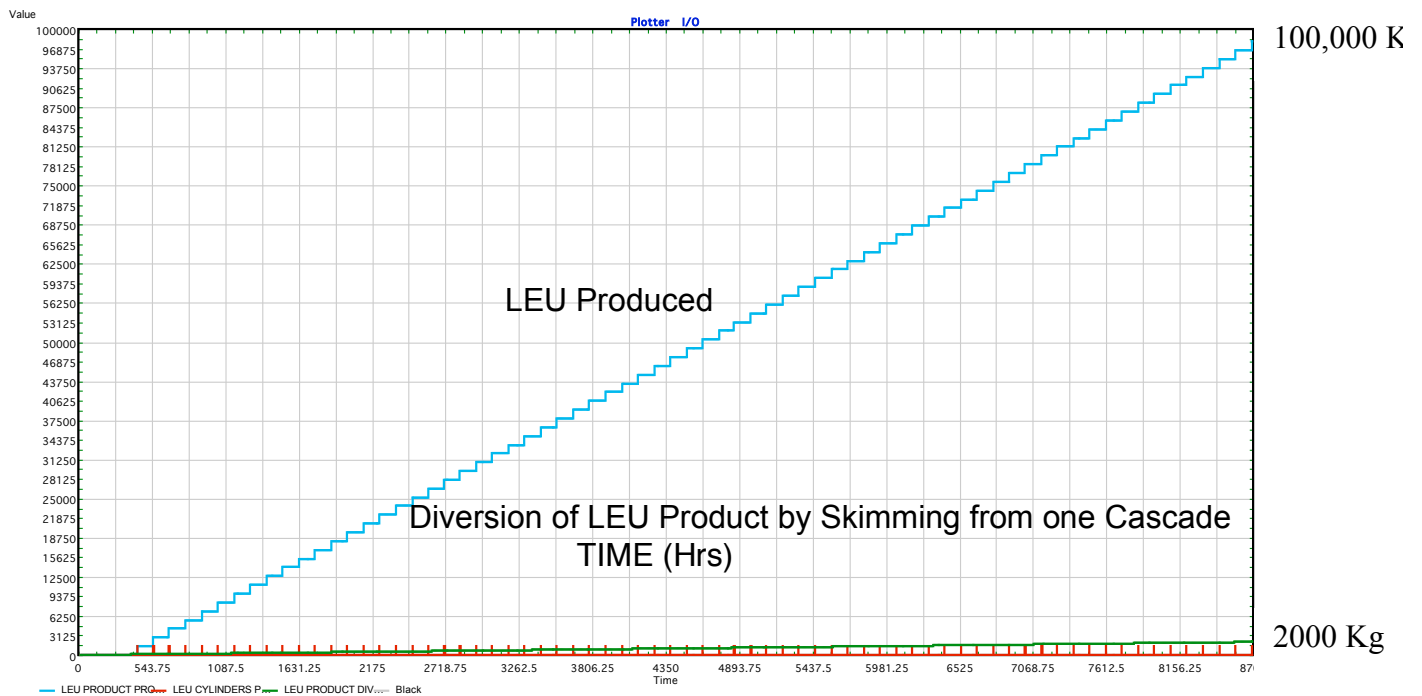


Fig. 6. Simulated Total Production of LEU (100,000 kg) & Diversion of 2000 kg of LEU by Skimming from One Cascade Throughout the Year

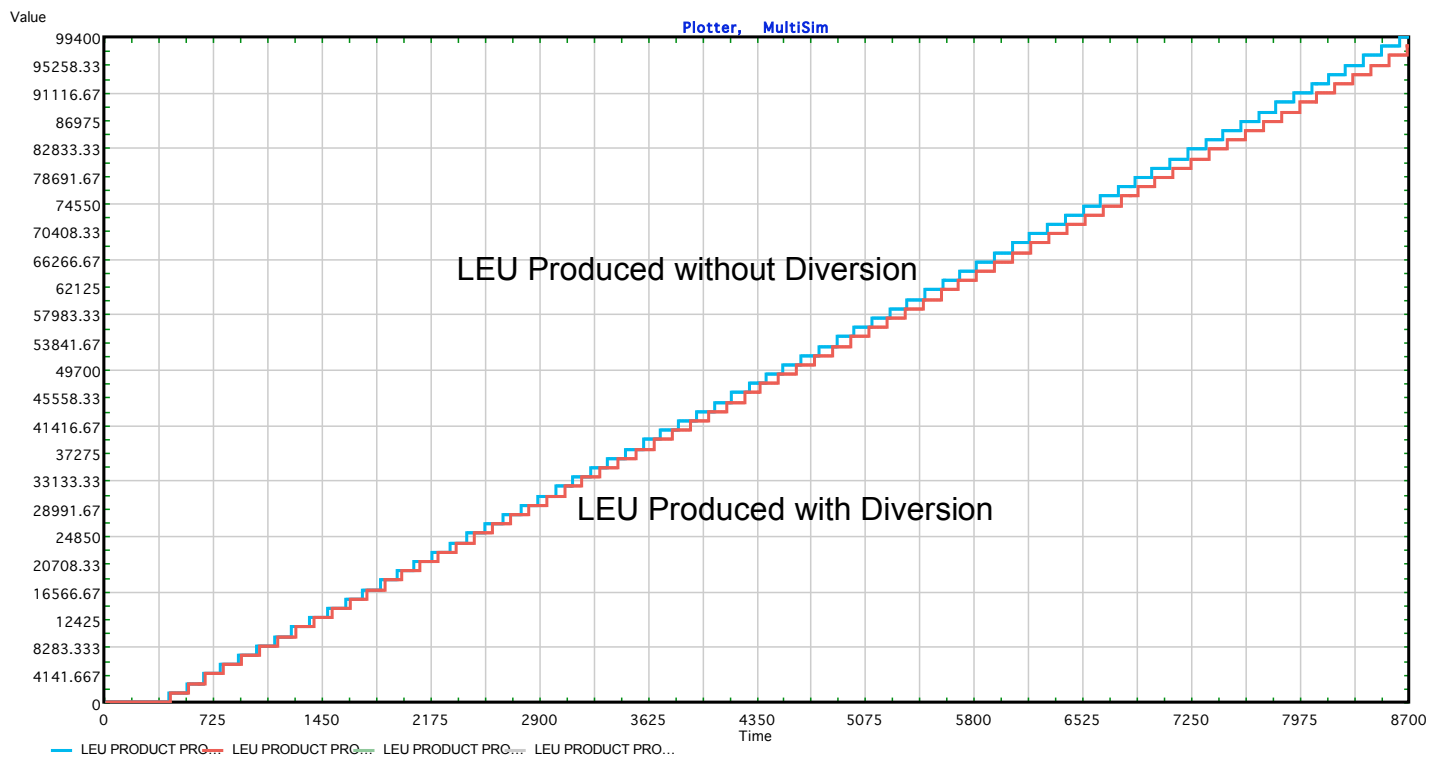


Fig. 7. Simulated Total Declared Production of LEU (100,000 kg) Under Normal Plant Operation Versus under Diversion of 2000 kg of LEU by Means of Skimming

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