

A Software Package for the Assessment of Proliferation Resistance of Nuclear Energy Systems

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Abstract: In order to better safeguard nuclear material from diversion by a malicious actor, it is important to search the input parameter space to gauge the attractiveness of various strategies that could be employed by such an actor. The ability to create and cluster a large number of scenarios based on similarity allows for a more complete and faster investigation of this parameter space. The software tool PRCALC was developed by the Brookhaven National Laboratory to estimate the various measures for covert diversion of nuclear material from a hypothetical fuel cycle system. The software package OSUPR (Ohio State University Proliferation Resistance) was written to extend PRCALC's abilities to allow for the creation of many scenarios at a time, as well as to take advantage of multiple processing threads in the computation of proliferation resistance measures. OSUPR also allows for clustering of the outputs of PRCALC using three methods: mean-shift, k -means, and adaptive mean-shift. The clustered results can yield insights to vulnerable aspects of the fuel system.

Keywords: PRCALC, Proliferation Resistance & Physical Protection, Clustering, Mean Shift, k -means.

1. INTRODUCTION

Since the Treaty on the Non-Proliferation of Nuclear Weapons took effect in 1970, efforts have been made to better identify and secure vulnerable parts of the nuclear fuel cycle. The treaty is primarily enforced through safeguards – methods by which diversion of material may be deterred or detected. A cornerstone of international safeguards is nuclear materials accountancy, complemented by containment and surveillance. One aspect of safeguards accountancy is to detect material unaccounted for (MUF), by comparing the mass of certain materials entering and exiting a process to the changes expected for the process. Other safeguards focus on consistent record-keeping, evidence of tampering, and surveillance of sensitive areas.

Due to the cost associated with changing an already-built nuclear fuel system, it is desirable to implement in the design of the system features to enhance proliferation resistance & physical protection (PR&PP) before construction. An effort by Brookhaven National Laboratory to model PR&PP of a Generation IV reactor and reprocessing system [1] had led to the development of the software tool PRCALC [2] towards such a purpose. This paper describes an extension of PRCALC that can create and process multiple material diversion scenarios, as well as cluster the results with a goal of identifying vulnerable areas of the system.

2. BACKGROUND AND MOTIVATION

2.1. PRCALC

One of the systems for which data are available in PRCALC is a hypothetical Example Sodium-cooled Fast-spectrum Reactor (ESFR) [3] and a hypothetical reprocessing plant. The reprocessing plant accepts both ESFR and light water reactor (LWR) spent fuel as inputs, and outputs ESFR fuel assemblies and various waste products. It is assumed that the facility is under International Atomic Energy Agency (IAEA) safeguards represented by 4 categories:

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1. Audit of various nuclear material accounting records or reports
2. Material verification such as physical inventory verification (PIV) of all nuclear material in a nuclear energy system
3. Surveillance and monitoring of spent fuel pool, reactor and reprocessing areas
4. Containment seals on reactor, shipping casks, and safeguards equipment

PRCALC represents the diversion from the fuel system as a Markov model as shown in Fig. 1, with each stage and stage element listed in Table 1. Each stage element is a potential target for material diversion by some malicious actor. Each diversion attempt may be detected, fail for technical reasons, or be successful. Once enough material is diverted, the actor converts it to weapons-usable material in a clandestine facility which is not subject to safeguards. Scenarios are created one at a time by varying targets, diversion rates, and safeguards in place. A scenario is a single PRCALC input file, with a unique set of input parameters. Multiple scenarios may be batched together and run all at once, so that the user does not have to manually load each scenario.

Figure 1: PRCALC Markov Model

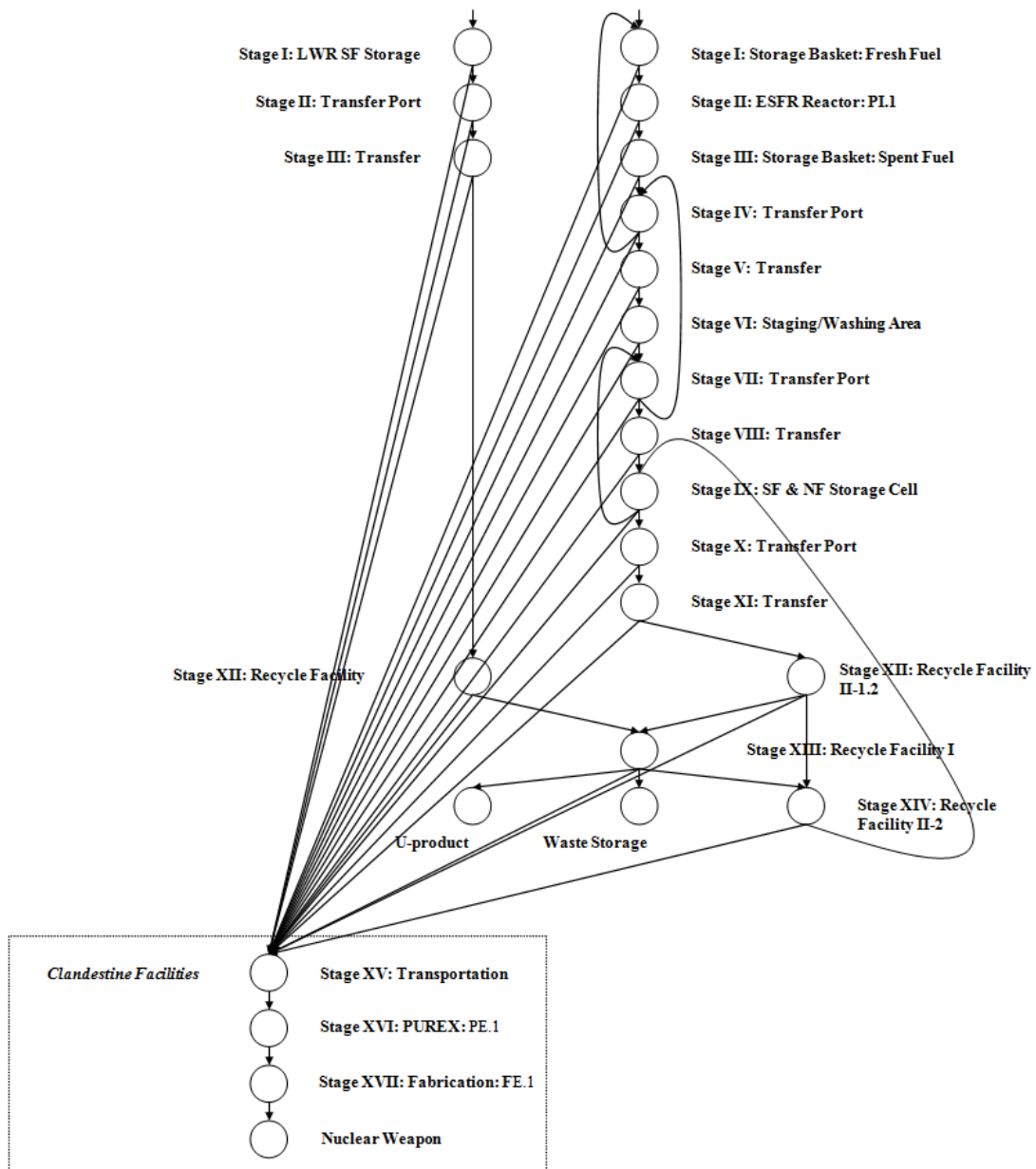


Table 1: PRCALC Stages & Elements

Stage I	LWR SF Storage
	Storage Basket: Fresh Fuel
Stage II	LWR Transfer Port
	ESFR Reactor
Stage III	LWR Transfer
	Storage Basket: Spent Fuel
Stage IV	ESFR Transfer Port
Stage V	ESFR Transfer
Stage VI	Staging/Washing Area
Stage VII	Staging/Washing Transfer Port
Stage VIII	Staging/Washing Transfer
Stage IX	SF & NF Storage Cell
Stage X	SF & NF Transfer Port
Stage XI	SF & NF Transfer
Stage XII	LWR SF Disassembly
	ESFR SF Disassembly
Stage XIII	Chopping
Stage XIV	Electro-refiner
Stage XV	U-product Processing
	TRU Extraction
Stage XVI	Product Preparation
Stage XVII	Pin Fabrication
Stage XVIII	Assembly
Stage XIX	Clandestine Transportation
Stage XX	Clandestine Chemical Conversion
Stage XXI	Clandestine Chemical Separation

Diversion rates are inputs to the PRCALC analysis. Thus, if the proliferators are able to overcome technical challenges and avoid detection, the time to achieve a goal quantity of material is determined by input. For each type of safeguards activity there is a characteristic time to detect an anomaly, and a time to confirm that the anomaly was caused by diversion and is not a false alarm. The detection rate is given by

$$r_i = \sum_{j=1}^n \frac{1}{T_{D(i,j)}} \quad (1)$$

where r_i is the total detection rate for stage i , n is the number of safeguards approaches for stage i , and $T_{D(i,j)}$ is the total detection time for safeguard j on stage i . This greatly simplifies the Markov model, as opposed to including a detection state and transition rate associated with confirmation of detection for each safeguard approach at each stage of the fuel cycle. The total technical failure rate for each stage is handled in a similar fashion, being a combination of multiple technical failure mechanisms.

PRCALC provides five outputs relating to proliferation resistance. Probability of Detection (DP) is the likelihood that a diversion attempt will be detected by safeguards and subsequently halted by outside intervention. Probability of Failure (PF) is the likelihood that a proliferation attempt will fail either in obtaining material or in converting it to weapons-usable material because of failure to overcome

technical barriers. For example, the material could be too hot, thermally or radioactively, for the actor to move it in a manner that would not be detected. The actor also may lack the expertise or equipment to reliably convert the material once obtained. Probability of Success (PS) is the likelihood that the proliferation attempt will succeed, and is equal to $1-(DP+PF)$. Proliferation Time (PT) is measured in weeks and is the time that would be required to obtain and convert the material without intervention or technical difficulties. Finally, the Material Type index (MT) reflects the average attractiveness of diverted material. This is based on the effort that would be required to convert the material to weapons-usable plutonium. For example, reactor-grade plutonium has an MT of 0.95 while LWR spent fuel has an MT of 0.50.

2.2. Motivation

The goal of this work is to develop a methodology for PR&PP analysis of proposed fuel systems that involves analyzing a large number of scenarios for common factors. Each scenario is a unique strategy that an actor might use to obtain nuclear material. The product is OSUPR (Ohio State University Proliferation Resistance), with a MATLAB graphical user interface (GUI). PRCALC was chosen as the basis of the methodology and used as a module of OSUPR due to its ease of use and expandability. Because PRCALC was originally written to create one scenario at a time, a method was developed to create a large number of scenarios with little input from the user. By using multiple processing threads it was found possible to greatly reduce the time required to process the large data sets that were produced. Finally, clustering of a data set can be accomplished using different methods (Section 3), allowing the user to inspect the data in diverse ways.

3. OSUPR

OSUPR is shown schematically in Fig. 2. It comprises two interfaces that each accept user input and output data to MATLAB-compatible files. The Scenario Creation interface is shown as Fig. 3, and has 11 steps which are listed in Table 2. The number of scenarios created is estimated (Step 5) using Eq. (2), where r is the number of diversion rates (set in Step 2), N_{SG} is the number of safeguards conditions to be considered (Step 3), and N_{stage} is the number of targets selected (Step 4). In Step 6 the folder for the scenario creation data is chosen, and Step 7 creates the scenario files. Each PRCALC scenario is one file. To simplify data collection, a single file (referred to as data set in the rest of the paper) is kept for the set with all relevant information as noted in Table 3. It first includes scenario creation data, and is later grown to include PRCALC outputs and clustering results. Step 8 informs the user of the number of processing threads available. Step 9 selects the number of equal-sized batches to create, typically the same as the number of processing threads listed in Step 8. Step 10 creates the batch files. Finally, scenarios are run through PRCALC using Step 11. If a set of scenarios has been previously created, there is also an option to load the Information File to run through PRCALC.

$$N_{scen} = r^{N_{stage}} * N_{SG} \quad (2)$$

Once a set of scenarios has been run through the PRCALC engine, the Information File is updated and may be examined immediately or clustered (see Fig.2). The general structure of the Information File is shown in Table 3. The BatchAssign, Batches, and ConfirmFile fields are used for multithread processing. PRResults contains both the raw output of PRCALC, and the outputs normalized so that each output varies from 0 to 1 over the set. Finally, each clustering algorithm information field contains the parameters used, the number of clusters, cluster centroid locations, and cluster assignment

for each scenario. The cluster centroid for a certain dimension is the average value of the scenarios in that cluster along that dimension.

Figure 2: OSUPR Schematic

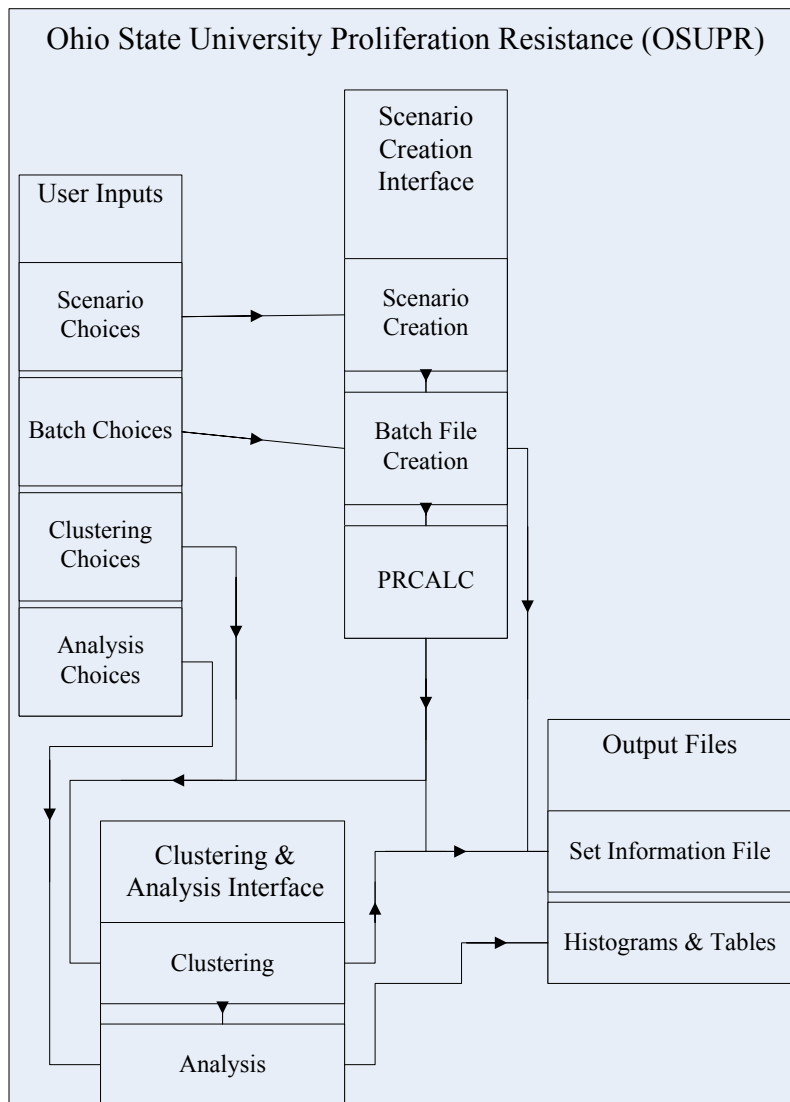


Table 2: OSUPR Scenario Creation Interface (see Fig.3) Steps

Step #	Description
1	Series Name
2	Diversion Rate Selection
3	Safeguards Condition Selection
4	Target Selection
5	Set Size Estimation
6	Folder Selection
7	Scenario Creation
8	Processing Core Availability
9	Batch Number Selection
10	Batch File Creation
11	PRCALC Operation

Figure 3: OSUPR Scenario Creation Interface

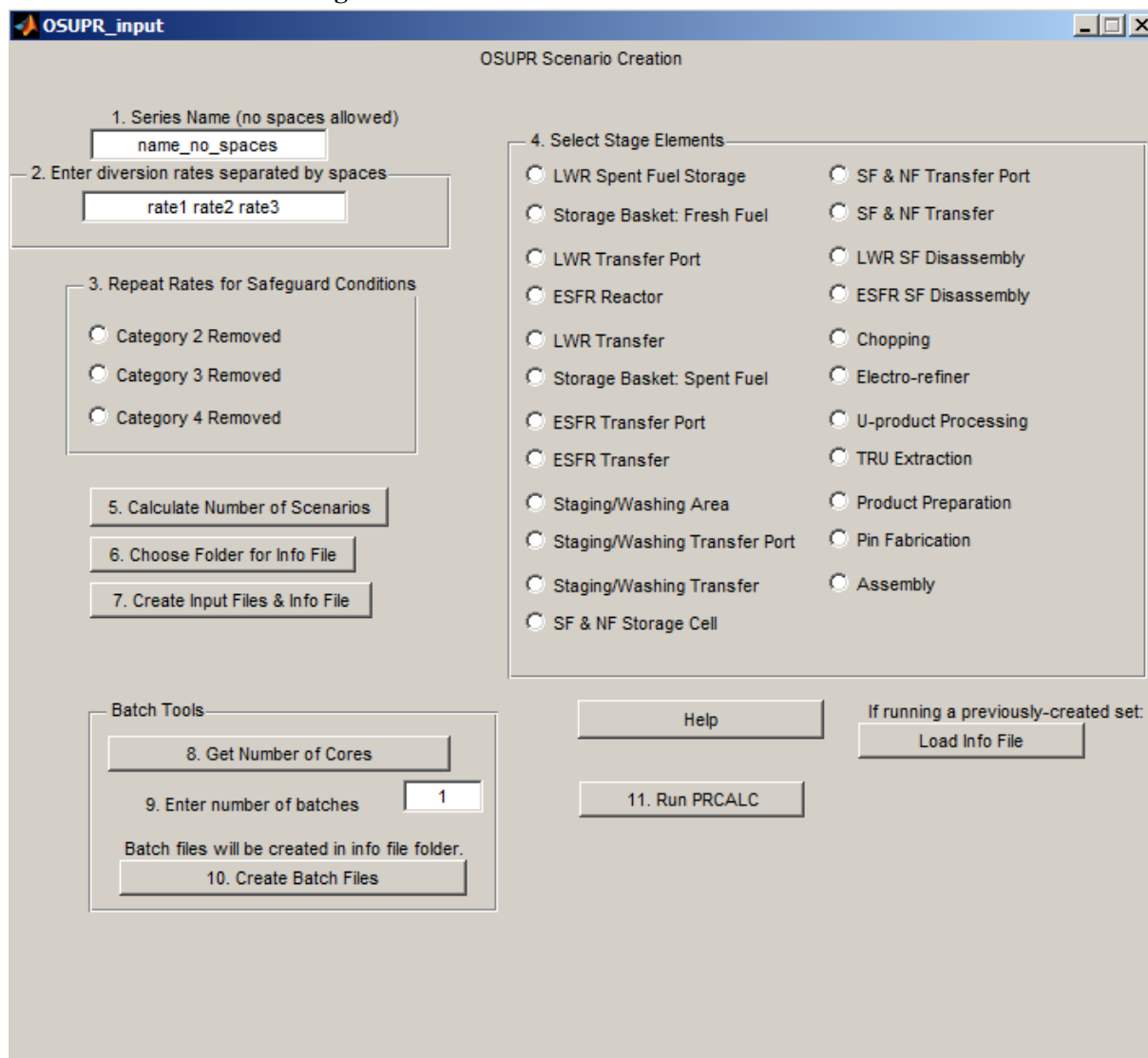


Table 3: OSUPR Information File Contents

Field	Description
Names	The name of each scenario file
Rates	Diversion rates associated with each scenario
BatchAssign	Assignment of each scenario to a batch
Batches	Batch file names and locations
ConfirmFile	The name of a small file used to confirm that a thread is finished
PRResults	PRCALC outputs, both raw and normalized
FOM	A rudimentary figure of merit for each scenario
KmeansInfo	Cluster assignment and statistics for <i>k</i> -means
MeanShiftInfo	Cluster assignment and statistics for mean-shift
FAMInfo	Cluster assignment and statistics for adaptive mean-shift

Currently OSUPR runs on a HP xw6400 workstation with 2 quad-core processors, which appear as eight processing threads under Microsoft Windows 7. Using Step 11 each batch is run in a separate instance of OSUPR, and the operating system automatically allocates the work efficiently across the

available threads. Table 4 shows the performance of OSUPR using multiple threads for a set of 6,558 scenarios. Time is kept from when scenarios are sent to PRCALC to when all batched outputs are assembled into a single file. It can be seen that the wall clock time required to run a set almost halves with each doubling of threads used. Perfect scaling would result in 8 threads requiring 12.5% of the time for 1 thread, while in the experiment it required 15.1%. This deviation is likely due to the overhead of re-uniting the outputs after all batches are finished running. It was expected that PRCALC would benefit from parallelization, as the scenario are independent of each other.

Table 4: OSUPR Multithreading Performance

Threads	Time (s)	vs previous	vs 1 thread
1	80460	N/A	100%
2	43848	55%	55%
4	22761	52%	28%
8	12111	53%	15%

In its default form, PRCALC displays a progress bar and a plot of outputs for each scenario. Some minor cosmetic changes were required for its use as a component of OSUPR. The progress bar in PRCALC, which tracks only the current scenario, was removed and replaced with a progress bar that tracks the entire set. The output plot was completely removed because opening a new MATLAB plot window for each scenario in a large set would tie up computer resources and overwhelm the user.

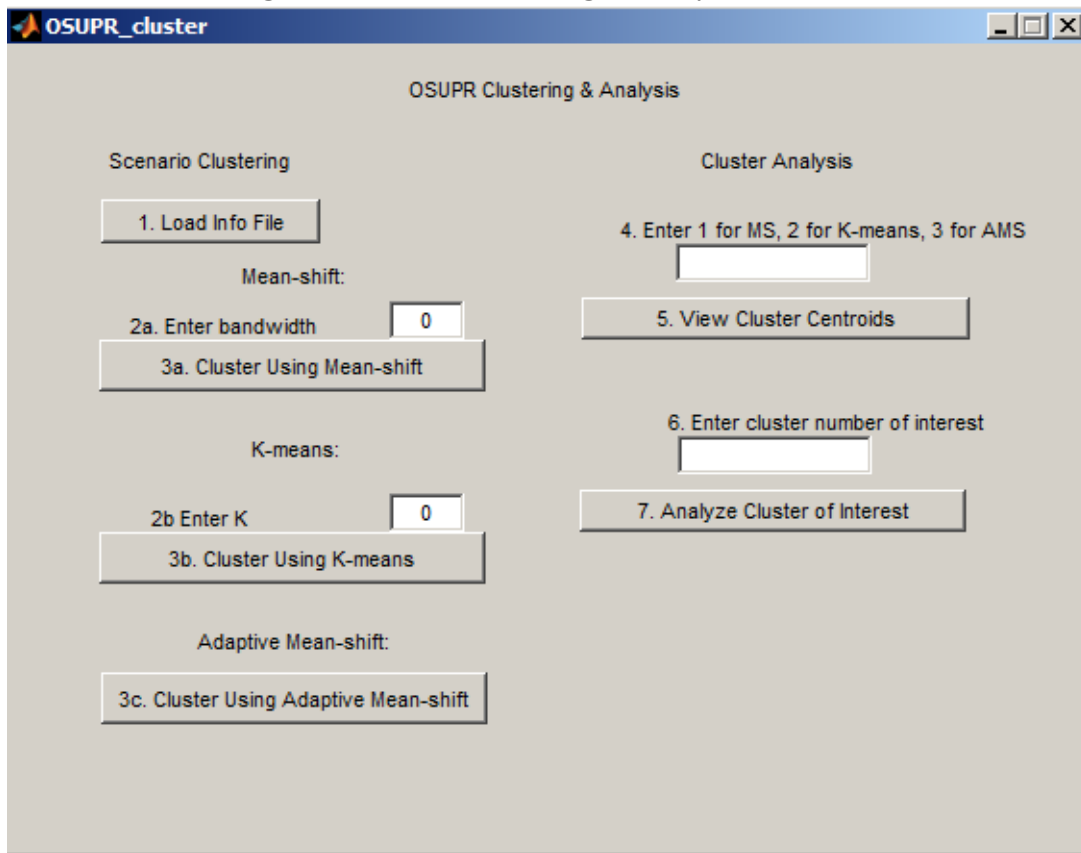
The Clustering & Analysis interface in Fig.2 is shown in more detail in Fig. 4, and its 7 steps are listed in Table 5. In Step 1 of the clustering process, an Information File (from the scenario creation interface) is loaded. Each scenario is a data point, to be clustered on the dimensions DP, PS, and PT. The user may choose between three algorithms (mean-shift, adaptive mean-shift and k -means), which are more fully described for this application in [4]. Mean-shift algorithm requires the user to specify a bandwidth, or neighborhood size, for each cluster. The algorithm iteratively searches for the highest data density within the neighborhood. If cluster centroids meet, they are merged into one cluster. Adaptive mean-shift is a variation on mean-shift in which the user does not need to specify a parameter. This is especially valuable if little is known about the nature of the data set. The bandwidth is varied for each point based on a pilot run including, by default, 10% of scenarios chosen at random. K -means requires the parameter k , which is the number of clusters desired. k cluster centers are randomly placed in the data space, and scenarios are assigned to the cluster with the nearest center. The center location of each cluster is then updated to the centroid of the data points assigned to it. This continues iteratively until the cluster assignment of points is stable. In Step 2 the user specifies a clustering parameter if necessary, and Step 3a, 3b, or 3c runs the chosen clustering algorithm.

Clustering algorithms may only be run one at a time, but each algorithm can be run and the results recorded to the Information File for a given set of scenarios. This allows the user to compare the outputs of each algorithm. The user is notified when clustering is complete, but no progress bar is available due to the nature of clustering. Based on experience a set of approximately 50,000 scenarios on the same computer requires roughly a second for k -means, an hour for adaptive mean-shift, and tens of hours for mean-shift. The adaptive mean-shift program currently used is in the form of a Windows executable file, and has not been tested with other operating systems.

Table 5: OSUPR Clustering & Analysis Interface (see Fig. 4) Steps

Step #	Description
1	Load Information File
2	Enter Clustering Parameter
3	Run Clustering Algorithm
4	Choose Algorithm for Analysis
5	View Cluster Centroids
6	Choose Cluster of Interest
7	Analyze Cluster of Interest

Figure 4: OSUPR Clustering & Analysis Interface



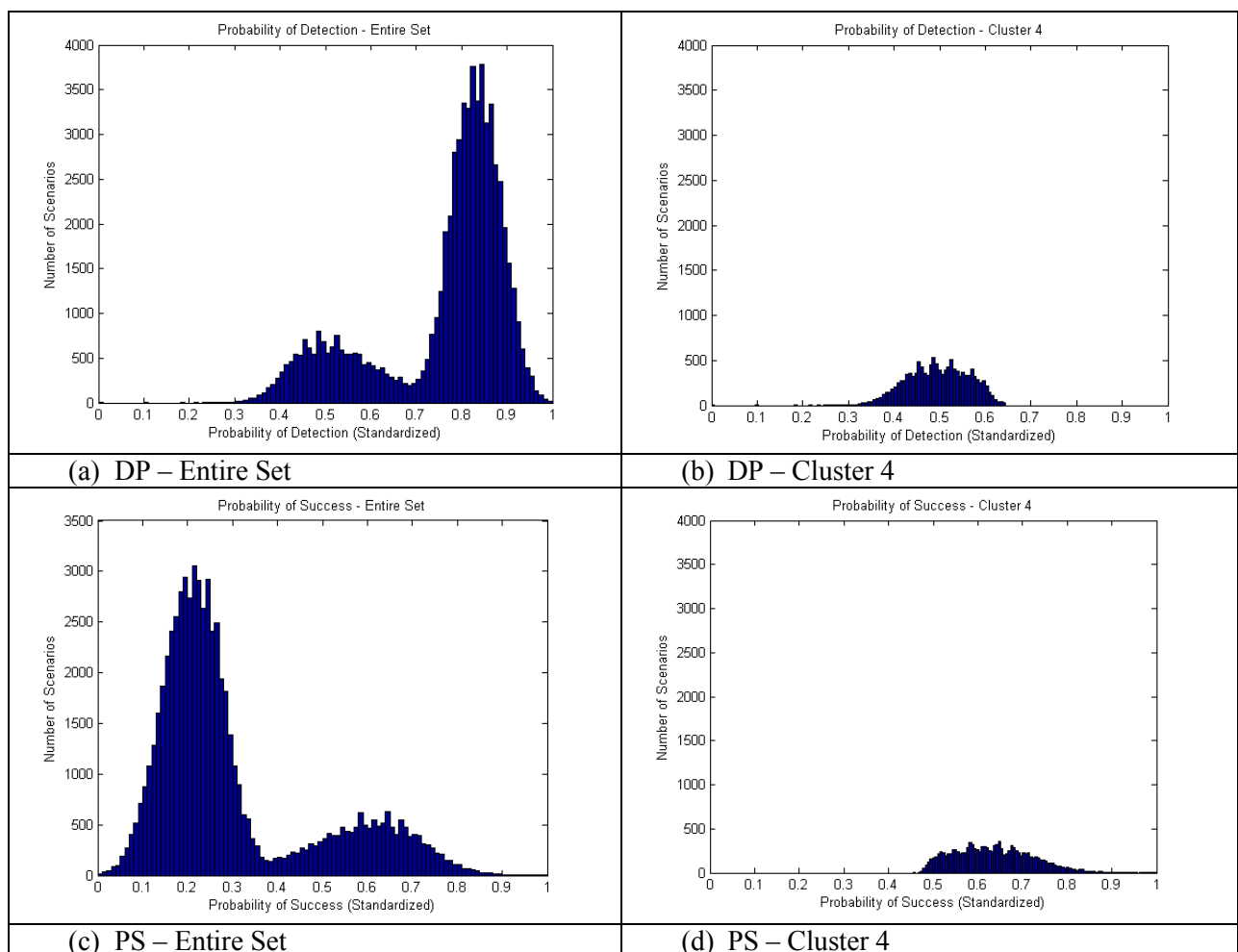
For the user to analyze the results of a particular clustering algorithm, the algorithm must be chosen in Step 4. The analysis of a single cluster is demonstrated more fully in [5]. Step 5 presents the cluster centroids, as demonstrated in Table 6. This set of scenarios was created using 4 diversion rates, 7 potential targets, and 4 safeguards conditions. The use of Eq. 2 returns 65,536 scenarios. Four scenarios were created with diversion rates of 0 at every target, and these were removed for a total of 65,532 scenarios. This allows the user to choose a cluster that is of interest for further examination. In this example the scenarios in Cluster 4 have on average the lowest probability of detection, the shortest time requirement, and the highest probability of success. These properties may cause these scenarios to be of interest to a would-be proliferator, and therefore also to a safeguards analyst. The cluster of interest is chosen in Step 6 of the clustering & analysis interface.

In Step 6, the cluster of interest is compared to the full set of scenarios. One type of comparison that is output is a histogram for each clustering dimension, as demonstrated for DP and PS in Fig. 5. The same set of data is used as in Table 6. A bimodal distribution is seen on both outputs across the set, with the cluster of interest containing the “best” scenarios from the point of view of a proliferator. The group of scenarios centered around a DP value of 0.5 for Fig.5(a) are nearly all in Cluster 4 in Fig.5(b). Similarly for PS, much of the group of scenarios seen in c centered around 0.65 are present in Fig.5(d), in Cluster 4. These histograms are output as image files in the same folder as the Information File, specified in Step 6 in Fig. 3.

Table 6: Sample Cluster Centroid Output
(DP: Detection Probability, PT: Proliferation Time, PS: Probability of Success)

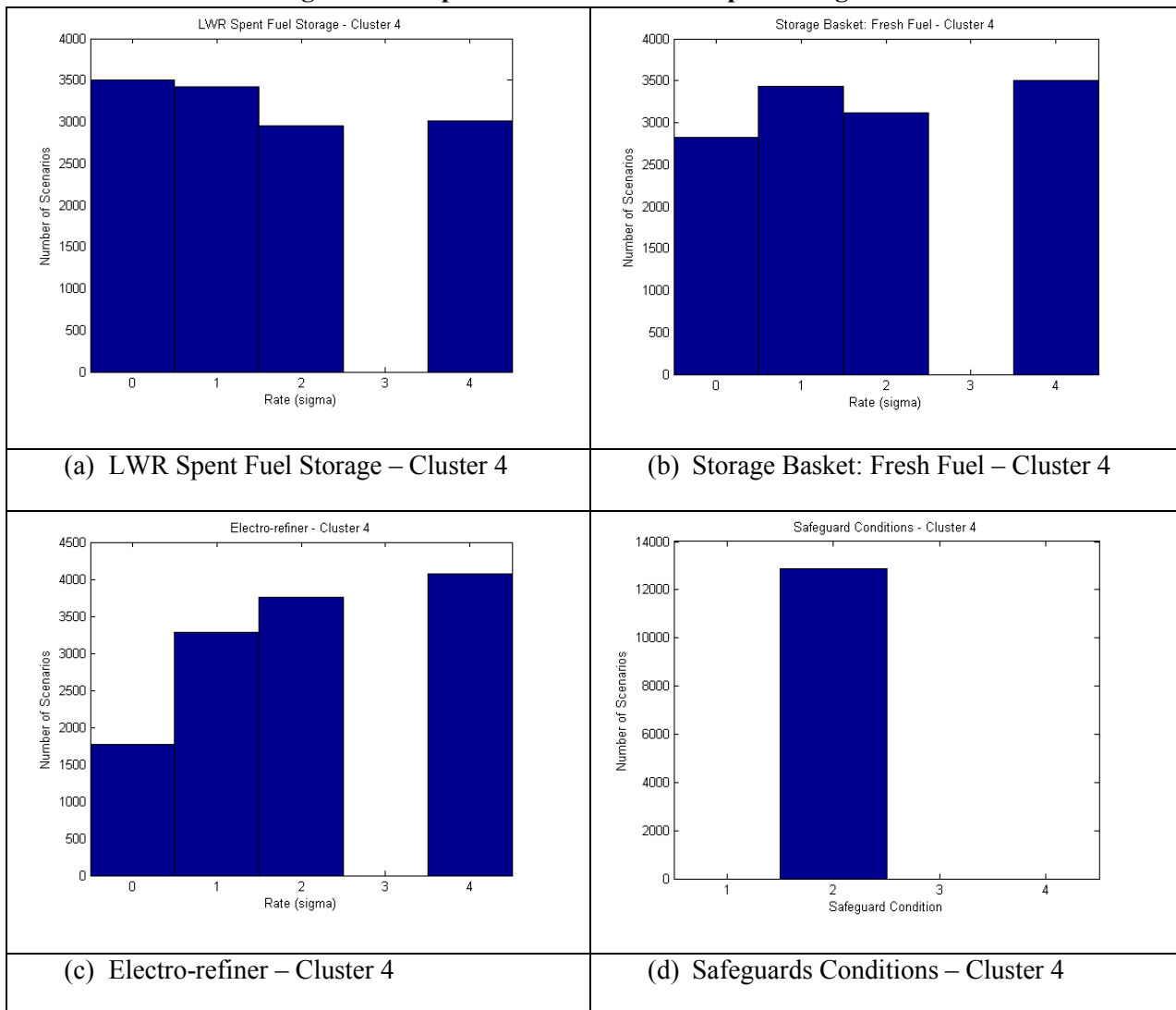
Cluster	DP	PT (weeks)	PS
1	0.980	756.159	0.002
2	0.984	390.579	0.002
3	0.818	32.706	0.034
4	0.493	31.067	0.096

Figure 5: Sample Cluster of Interest Output Histograms
(DP: Detection Probability, PS: Probability of Success)



Another set of histograms is created to show the inputs that led to a scenario being in the cluster of interest. This is most closely tied to the goal of the work, which is to identify vulnerabilities in a fuel system. Sample outputs are shown in Fig. 6 for the same set as in Table 6. The diversion rates used in this set were 0, 1, 2, and 4. Safeguards Condition 1 has all default safeguards (see Section 2.1) in place. Conditions 2-4 have Categories 2, 3, or 4 removed. This represents a successful attempt by the proliferator to circumvent various safeguards in the interest of material diversion. Because scenarios are created using every combination of the input rates and targets with equal likelihood, the histograms shown in Fig. 6 would be flat across the entire set of scenarios. Thus, a deviation from level in one cluster may indicate that a strategy is more or less attractive to a proliferator. It must be noted that this analysis is for a hypothetical fuel system, and is only to demonstrate the methodology that has been developed.

Figure 6: Sample Cluster of Interest Input Histograms



In Fig. 6(a), LWR Spent Fuel Storage, increased diversion seems to lead to a decrease in attractiveness. It may be that increased diversion at this target contributes highly to detectability while contributing little to speeding up diversion. Fig. 6(b) shows that for Storage Basket: Fresh Fuel, which represents the storage of new ESFR fuel, no advantage is evident for high or low diversion rates. For part Fig. 6(c), scenarios with a high diversion rate are well-represented in the cluster of interest. This indicates that an increase in diversion from the Electro-refiner would be attractive to a proliferator.

Finally, Fig. 6(d) shows the Safeguards Conditions present in Cluster 4. Only scenarios with Physical Inventory Verification safeguards removed are in the cluster of interest, indicating that the integrity of these safeguards is important in the fuel system under consideration.

4. CONCLUSIONS

The analysis of a large number of scenarios may yield insights into proliferation resistance for future and current nuclear fuel systems. A mechanized process of defining scenarios, estimating PR-related outputs, clustering the outputs and presenting meaningful results to a user is developed and built into an easy-to-use graphical user interface.

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References

- [1] R. Nishimura, R. Bari, P. Peterson, J. Roglans-Ribas, D. Kalenchuk, "Development of a Methodology to Assess Proliferation Resistance and Physical Protection for Generation IV Systems," *America's Nuclear Energy Symposium – ANES 2004*, Miami Beach, FL, October 3-6 (2004).
- [2] M. Yue, L. Cheng, R. Bari, "Quantitative Assessment of Probabilistic Measures for Proliferation Resistance", *American Nuclear Society 2005 Winter Meeting*, Washington, DC, November 13-17 (2005).
- [3] "PR&PP Evaluation: ESFR Full System Case Study Final Report," http://www.gen-4.org/Technology/horizontal/documents/PRPP_CSReport_and_Appendices_2009_10-29.pdf (2009).
- [4] Z. Jankovsky, D. Zamalieva, R. Denning, A. Yilmaz, T. Aldemir, "A Comparison of Various Clustering Schemes for Proliferation Resistance Measures," *2013 American Nuclear Society Winter Meeting*, Washington, DC, November 10-14 (2013).
- [5] Z. Jankovsky, D. Zamalieva, A. Yilmaz, R. Denning, T. Aldemir, "A Clustering Analysis of Probabilistic Proliferation Resistance Measures in an Example Nuclear Fuel System," *2013 International Topical Meeting on Probabilistic Safety Analysis*, Columbia, SC, September 22-26 (2013).