

Galaxy Serpent: A Web-Based Table-Top Exercise for National Nuclear Forensics Libraries

J.D. Borgardt^a, F.M.G. Wong^b

^aOffice of Weapons of Mass Destruction Terrorism,
U.S. Department Of State
Washington, DC, 20520, USA
(on detail from Juniata College, Huntingdon, PA, 16652, USA)

^bDomestic Nuclear Detection Office
U.S. Department Of Homeland Security
Washington, DC, 20005, USA
(on detail from Lawrence Livermore National Laboratory, Livermore CA, 94550, USA)

Abstract. *Galaxy Serpent* is a first-of-a-kind, virtual, web-based international table-top exercise, where teams of scientists from various countries 1) used provided public domain spent fuel compositions to formulate their own model national nuclear forensics library (NNFL), and 2) determined if hypothetically seized spent nuclear fuel is or is not consistent with their national nuclear forensics library. This table-top exercise is conducted under the auspices of the Nuclear Forensics International Technical Working Group (ITWG) and involved approximately 24 teams of scientists. *Galaxy Serpent* aimed to promote “best practices” through providing a vehicle for participants to gather key technical expertise to create a NNFL using guidelines in IAEA documents and to illustrate the potential probative benefits offered by creating such a library. During the play of *Galaxy Serpent*, many teams quickly saw the need to involve other areas of expertise such as nuclear reactor engineers and fuel experts. The involvement of such additional experts helps to mature the expertise of the nuclear forensics international community. Teams also noted that different technical approaches yielded similar analytical conclusions. In addition, some of *Galaxy Serpent* teams have used this table-top exercise experience to inform their efforts at home to develop their own NNFLs.

1. Introduction

Nuclear forensic science, often referred to as simply “nuclear forensics”, is defined as “*the examination of nuclear or other radioactive material, or of other evidence that is contaminated with radioactive material, in the context of legal proceedings, including national or international law or nuclear security.*”[1] Nuclear forensics (NF) is an essential component of national and international nuclear security response plans to events involving nuclear or other radioactive (RN) material out of regulatory control. The ability to collect and preserve seized RN material as evidence and conduct NF analysis may provide information about the history and origin of material, point of diversion, and identity of the perpetrators. NF is a technical capability that will also inform the investigatory process. [1] A national nuclear forensics library (NNFL) augments these capabilities by providing an organized set of data possibly supported by a sample archive that allow comparison of illicitly trafficked material to national holdings to help determine if seized material originated in a particular country. Nuclear forensics has become an important tool to aid in identifying where loss of regulatory control may have occurred, as well as potentially excluding specific sites as a point of origin.

The *Galaxy Serpent* exercise was conducted under the auspices of the National Nuclear Forensics Libraries Task Group of the Nuclear Forensics International Technical Working Group (ITWG) and funded and organized by the U.S. Department of State with technical expertise provided by the U.S. Department of Homeland Security. The ITWG is a multinational, informal association of official practitioners of nuclear forensics - laboratory scientists, law enforcement personnel, and regulatory officials - who share a common task in responding to nuclear security events involving nuclear or other radioactive materials out of regulatory control. The ITWG conducts its work through a combination of annual meetings, task group activities, and special exercises. Participation in the ITWG is voluntary and open to competent and qualified Government participants from States having, or wishing to have, a nuclear forensics capability. [2]

2. Galaxy Serpent

Galaxy Serpent was designed with the goal of raising awareness about the technical aspects of creating and using national nuclear forensics libraries via a cost-effective, wholly web-based, platform. It also sought to increase appreciation among policymakers regarding the critical insights that can be gained by having a NNFL, even a basic one, in place prior to any investigation involving RN material. A virtual exercise afforded a means of exercising national capabilities for analyzing complex data and rendering conclusions regarding these data without having to secure and ship RN material, or perform material characterization in a laboratory. Such considerations motivated the development of a wholly web-based, technical, table-top exercise using public domain nuclear material data which would focus on developing a national nuclear forensics library without requiring laboratory measurements and would also engage a broader diversity of teams and technical experts while maturing the concept of NNFLs and illustrating their potential efficacy.

The table top exercise (TTX) involved observers and participants from 24 States, including teams from 18 States who have actively participated in the five rounds of the exercise as of April 2014. These rounds occurred between January 2013 and April 2014, noted in table 1. Further details on the exercise as well as technical articles by nine teams that participated in the early rounds of the exercise and reported their experiences, findings, and lessons learned are published in a special issue of the Journal of Nuclear Materials Management (JNMM). [3] Table I lists the teams involved in each round, provides specific timeframes for individual rounds, and also identifies those teams who contributed articles for the JNMM special issue. Each round was composed of 3-4 teams, conducted over approximately 8-10 weeks, and was identical in exercise structure and tasks posed.

Table I: Summary of Teams Participating by Round

Round 1 (Feb-Apr 2013)	Round 2 (May-July 2013)	Round 3 (Aug-Oct 2013)	Round 4 (Feb-Apr 2014)	Round 5 (Feb-Apr 2014)
Australia/ANSTO	<i>Japan^a</i>	<i>Hungary</i>	Team 13	<i>JRC/ITU^b</i>
Brazil	South Africa/NECSA	Sweden	<i>Team 14</i>	Team 17
<i>Canada</i>	UK/AWE	Team 11	Team 15	Team 18
Team 4	Team 8	Team 12		

^aItalicized text indicates the team in each round which was assigned the reactor that was the source of the hypothetical seizure.

^bJRC/ITU is the European Commission Joint Research Centre Institute for Transuranium Elements

The objectives of the *Galaxy Serpent* TTX are to have participants organize a model national nuclear forensics library (NNFL) using provided spent fuel characteristics from three nuclear reactors (“Phase 1”) and then determine if data from a hypothetical seizure of spent fuel is or is not consistent with a reactor in their model NNFL (“Phase 2”). In Phase 1 of the exercise, teams were provided existing, public domain, data sets from Spent Fuel Isotopic Composition (SFCOMPO), a database of isotopic measurements of spent fuel. [4]. SFCOMPO is data collected from public domain, published literature of isotopic compositions of spent nuclear fuels (SNF) obtained through post-irradiation experiments (PIE), which are used in the validation of burn-up credit methodologies. SFCOMPO consists of SNF isotopic compositions for 14 commercial nuclear reactors in four countries (Germany, Italy, Japan, and the US). It includes spent fuel data exclusively from light water reactors, which use low-enriched uranium (LEU) as fuel – seven pressurized water reactors (PWR) and seven boiling water reactors (BWR). SFCOMPO was initially developed by the Japan Atomic Energy Research Institute (JAERI), and in 2002 the database was transferred to the Organization for Cooperation and Economic Development / Nuclear Energy Agency (OECD/NEA) [4].

3. Exercise Assumptions

SFCOMPO datasets had been used in a previous effort to explore the use of statistical methods to reveal patterns and associations in SNF data that had been re-purposed for nuclear forensic applications. The success of this effort demonstrated that this modified version of SFCOMPO could be used as the foundation for a table-top exercise that focused on class association involving an “unknown” SNF sample with finite, known families of isotopes. There are two specific modifications to the SFCOMPO datasets that enabled their use in *Galaxy Serpent*. First, uncertainty values for the data points needed to be determined. Since SFCOMPO data did not include measurement uncertainties, it was necessary to generate a robust set of uncertainty values. The uncertainties were a pre-requisite both to generating the set of problems, namely data sets for each of the hypothetical seizures, and to performing any forensic evaluations of the problems. Since measurements made on a sample of interest would not exactly match any one particular set of reactor fuel data, without explicit data uncertainties it would be impossible to determine if the measurements for any one fuel would fall within the limits of a single reactor fuel. Determining and assigning uncertainty values to the PIE measurements in SFCOMPO proved to be a significant task and involved including uncertainties from published references associated with SFCOMPO data or the use of “best judgment” based on traditional analytical methods for the determination of uncertainties in similar fuel matrices [5].

Secondly, based on the premise that the spent nuclear fuel isotopic compositions in the SFCOMPO database represent the entire universe of SNF for *Galaxy Serpent*, five forensics problems had been created based on actual SFCOMPO data. SFCOMPO data for a particular fuel pin measured at various positions (and burnup) were used to model the variation of the isotopic compositions as a function of fuel burn-up. This mathematical model was then used to derive (i.e., to interpolate or extrapolate) isotopic compositions at other positions or different burnup values – simulating measurements obtained on samples at different times in the irradiation history of the fuel pin. Finally, a random adjustment was applied to these values representative of measurement noise, and these adjustments were consistent with the measurement uncertainties for the corresponding SFCOMPO data [5]. While the exercise was designed using a single class of RN material, in practice any State seeking to develop or enhance a NNFL would need to consider the range materials to be included in a library.

For *Galaxy Serpent*, SFCOMPO data was adapted for a nuclear forensic application, which involved families of isotopic correlations for specified reactors. As a result, it is important to realize there is no need to average any of the PIE values from samples pertaining to the reactors. For this forensic application, the PIE data from the samples are typically treated as discrete samples from a “smeared” reactor core “entity” for each of the 14 reactors. Therefore, the geometric position data and information included in SFCOMPO for each sample is not relevant when creating the isotopic correlations that may distinguish among reactors or reactor classes. The correlations assume that the samples are representative of the isotopic compositions contained in a “smeared” reactor core as a function of exposure (i.e. neutron fluence). Actual reactor names in the SFCOMPO database were masked, re-naming each after a moon of Saturn.

4. Exercise Play

The *Galaxy Serpent* international virtual table-top exercise was designed to enable teams to use public domain data, have ample time to work on Phase 1 and 2 tasks, and reach out to appropriate expertise as needed. To enable these factors during exercise play, a web-based approach was used because it provides easy accessibility for all teams, does not involve travel or material transport costs, does not involve analytical measurements, and enables teams to engage experts that may not usually be involved in ITWG activities. An in-person table-top exercise format would not have been practical for *Galaxy Serpent*, because the Phase 1 and 2 tasks were usually not completed within hours or days, nor would the teams have been able to incorporate relevant expertise as needs arose during the exercise. Use of provided, published, public domain SNF data and information eliminated any sensitivities regarding teams from different States using their own materials data. As a result, teams only used

their expertise during the exercise, and the exercise was explicitly designed not to require the use of materials data from any participating State. It is recognized that when developing an NNFL, much of the materials information exists and may have likely been collected for other purposes. By using provided data in *Galaxy Serpent*, teams directly experienced organizing a small, model NNFL from existing data and information. Additionally, constraining the “universe” of nuclear reactors to those in the SFCOMPO database helped bound the problem so that the teams would formulate results in a finite amount of time. The exercise microcosm provided a model environment where ideas, concepts, and frameworks pertaining to NNFLs could be discussed and tested, allowing teams to effectively consider the process of creating an NNFL, while also applying it to a hypothetical seizure to see the potential value of an NNFL as an investigative tool. At the conclusion of the exercise, practical ideas and lessons from this *Galaxy Serpent* microcosm could be scaled up to include lessons learned and address issues of creating or managing actual NNFLs.

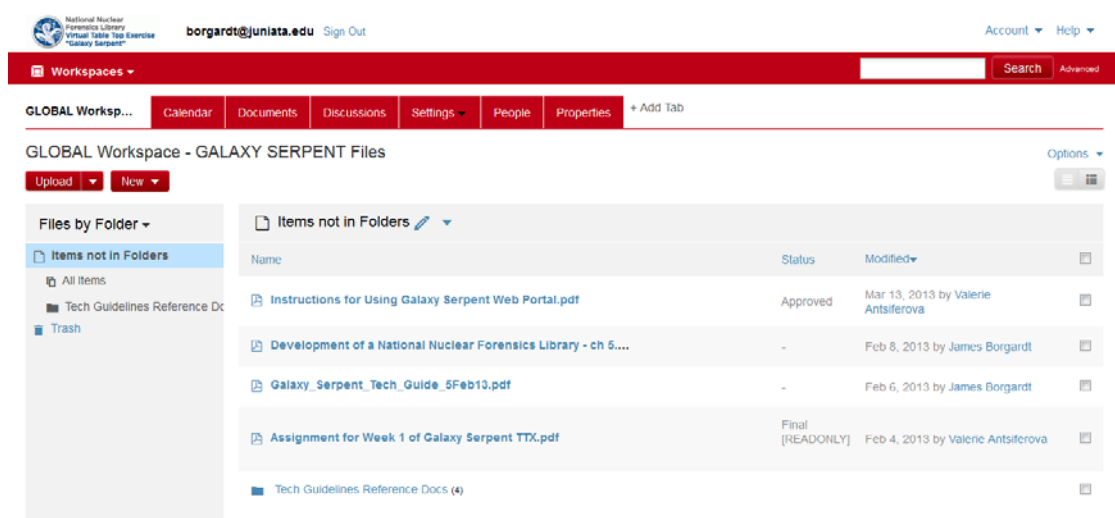


FIGURE 1: Galaxy Serpent Web Portal Workspace Example

Teams were provided with reference materials on nuclear forensics and NNFLs, including guidance documents drafted by the IAEA and the NNFL Terms of Reference from ITWG [6], but not instructions on how to construct a NNFL. Each of the 3-4 teams participating in a given round was provided, through the dedicated web portal, data sets for three different reactors. This required the use of adjusted datasets for 12 of the 14 possible SFCOMPO reactors. The reactors assigned to teams were scrambled for each round. The sole requirement was that each team be given a combination of PWR and BWR reactors. As noted, the team and reactor identities were masked: Teams were named after galaxies and the reactors named after moons of Saturn (Table 2). The web portal was designed to have two workspace levels: one public and accessible to participants and observers, and one private and accessible only by members of a given team. This was arranged so that teams, if desired, could communicate anonymously through a public discussion forum (shown in Figure 1) to exchange challenges encountered, methodologies, access reference material, and the like. The private forum served to allow teams to discreetly communicate with exercise organizers, access provided data sets, and upload progress reports. The summary of the assignment of SFCOMPO reactors used in *Galaxy Serpent*, along with their aliases is shown in Table II and III. Table II links reactor pseudonyms with their identity in the SFCOMPO database, and gives the class and number of data points for each reactor. Table III provides the pseudonym for the seizure dataset used in each round, and identifies the specific reactor of origin and the team which had this reactor as part of its model NNFL. For instance, in round 1 the Clio seizure originated from the Iapetus reactor which was assigned to the Zwicky galaxy (Canada). The two Siarnaq reactor seizures listed are distinct seizure data sets derived from the same reactor.

Table II: Summary of SFCOMPO Nuclear Reactors and Exercise Pseudonyms (moons of Saturn)

	Reactor	Data Points	Reactor Type	Pseudonym
1	Calvert Cliffs No. 1	447	PWR	Anthe
2	Cooper	294	BWR	Atlas
3	Fukushima Daiichi-3	506	BWR	Enceladus
4	Fukushima Daini-2	1437	BWR	Daphnis
5	Genkai-1	123	PWR	Ijiraq
6	Gundremmingen	663	BWR	Hyperion
7	H.B. Robinson Unit 2	257	PWR	Iapetus
8	JPDR	1098	BWR	Janus
9	Mihama3	700	PWR	Mimas
10	Monticello	480	BWR	Pandora
11	Obrigheim	1035	PWR	Prometheus
12	Trino-Vercellese	1684	PWR	Siarnaq
13	Takahama-3	1227	PWR	Tethys
14	Tsuruga-1	270	BWR	Titan

Table III: Summary of Team and Seizure Pseudonyms, and Seizure Origins

Round	Galaxy Name	Team	Seizure	Origin of Seizure
1	Draco	Brazil		
1	Virgo	Australia	Clio	Iapetus
1	Zwicky	Canada		
1	Cygnus	Team 4		
2	Ursa	Japan		Siarnaq-1
2	Tucana	South Africa	Erato	
2	Sculptor	UK/AWE		
2	Hydra	Team 8		
3	Andromeda	Sweden		
3	Keenan	Hungary	Melpomene	Daphnis-1
3	Shapley	Team 11		
3	Carina	Team 12		
4	Pisces	Team 13		
4	Aquarius	Team 14	Thalia	Daphnis-2
4	Seyfert	Team 15		
5	Centaurus	JRC/ITU		Siarnaq-2
5	Pegasus	Team 17	Terpsichore	
5	Sagittarius	Team 18		

After being provided data sets, teams were given 3-4 weeks for Phase 1 in which to develop their model NNFL and were encouraged to share approaches or methodologies, as needed or desired. Some teams completed Phase 1 within one week, while others required additional time beyond the allocated time for a variety of reasons. In Phase 2, a hypothetical seizure, named after one of the Muses, was announced, and its associated data provided. In a given round, all teams were provided identical seizure data, which originated from one of the 9 (in Rounds 4 and 5) or 12 (in Rounds 1-3) reactors in play during that round. Each of the five created seizure datasets discussed earlier was used in one of the rounds. Teams used their model NNFL developed in Phase 1 to determine whether the seized

material was or was not consistent with material in their model NNFL using an established system of confidence levels. [7]

5. Exercise Assessment

Teams successfully reported identification of the likely reactor from which the hypothetical seized SNF may have originated, as well as an evaluated set of “possibles.” These evaluated problem solutions, obtained using conventional “isotope correlation techniques” (ICT), illustrate a clear, understandable and defensible forensics capability for SNF. At least for this set of problem solutions, teams have demonstrated that the ability to identify the unknown materials from within the population of known samples is directly dependent upon the uncertainties in the data values and upon the gaps in the data values. Based on the assumptions made herein, in all cases, teams showed it was possible to downscale to a small number (to one, in some cases) of “possibles”. [5]

Roughly 75% of the participant teams reported findings that were consistent with the origin of the hypothetical seizure. The remaining teams did not report inconsistent results, but rather did not complete the exercise, for various reasons. Thus, all teams completing the exercise used their model NNFL to correctly evaluate, with various levels of confidence, whether the hypothetical seizure originated from their set of reactors.

The exercise has been successful in a number of areas. Developing a NNFL containing nuclear data potentially has both national security and proprietary commercial sensitivities. The use of published, public domain data removes many of these concerns. *Galaxy Serpent* has also expanded the pool of experts aware of the use and potential efficacy of NNFLs, including reactor engineers, fuel experts, and statisticians. The web-based approach allowed a cost-effective method to advance the goals of the exercise, and also provided ITWG members with more opportunities to interact throughout a year, rather than limiting contact to ITWG annual meetings or reviewing of ITWG draft documents. A number of teams pursued parallel paths, such as statistical methods and isotopic correlation techniques, which yielded corroborating results.

While teams may have exhibited various levels of expertise and detail in working through the exercise, they were able to obtain useful and probative findings. Similar conclusions apply to the complexity of the developed model libraries; increased sophistication often facilitated greater resolution in assessing whether the seizure was or was not consistent with reactors in the model NNFL. However, it is absolutely critical to note that even a basic library proved valuable in providing critical insights as to the origin of the seizure.

The advantages and disadvantages, discussed earlier, associated with the re-purposed SFCOMPO data did impact participants ascribing confidence levels to their findings. In an actual event, the analytical and investigate work would not occur dissociated from other communities, such as first responders, law enforcement, legal representatives and policy makers. While the constrained universe, comprised of only LEU reactors, may have limited the range of sources teams had to consider, many note in their articles that the limited (in number of reactors, and samples within a reactor) and incomplete (in the variety of provided parameters) datasets presented challenges in assigning a confidence level. Nevertheless, despite these artificialities, all teams noted that the ability to compare data from a hypothetical seizure with a pre-established NNFL was essential in reaching conclusions.

6. Conclusions

The virtual, web-based *Galaxy Serpent* table-top exercise demonstrated the efficacy of NNFLs in drawing inferences about the origins of a hypothetical seizure of spent nuclear fuel. It also showed that, however useful NNFLs proved, they would be even more effective when used in conjunction with an investigative effort involving many communities within a State. A number of teams reached out to expertise outside their discipline for assistance, or in order to independently pursue multiple

technical approaches. The collaborative option built into the exercise, via communication in the global workspace of the web-portal, was used by some teams to exchange methodologies and questions regarding interpretation of data sets, but was in general an underused facet of the exercise. This seemed to largely be due to the weeks-long timeframe of each phase allowing teams to progress at different paces, but may have also involved inherent sensitivities over the nature of the exercise. Several participants also preferred to communicate directly with exercise organizers to have such questions answered.

The universe of data sets were intentionally constrained to LEU reactors, which helped bound the problem for this exercise. The basic model NNFLs, composed of just three reactors, as well as their limited datasets, represented additional artificialities. Nevertheless, this exercise experience provides practical lessons as to the utility NNFLs can have, and how nuclear forensics may provide a powerful probative tool to help “rule in” or “rule out” data or information relevant to an investigation. Comparisons of the data from the hypothetical seizure with NNFLs helped each team quickly, in relation to a full-fledged inquiry, determine if the hypothetical seized SNF is or is not consistent with their holdings. Several teams also demonstrated that independently applied analytical methodologies confirmed findings. In an actual nuclear security event, the question “Is it ours?” may likely be one of the first questions asked by senior officials, and in the context of this exercise NNFLs proved to have high efficacy in addressing this key concern.

The exercise was successful in expanding the community of experts aware of nuclear forensics, and NNFLs. The web-based format also allowed an international collaboration of scientists representing, all told, over 20 States. Participants found the exercise beneficial, instructive and insightful, and many requested a follow-on “*Galaxy Serpent 2.0*” exercise based upon a different class of nuclear material. Despite noted artificialities, the exercise proved valuable in engaging and expanding the existing nuclear forensics community of experts, and advanced the concept of national nuclear forensics libraries. Finally, and most notably, the *Galaxy Serpent* exercise demonstrated that having even a basic NNFL established may provide critical and probative insights in the course of an investigation involving RN material, and in particular, answering the question “Is this material ours?”

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