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Verified Nuclear Warhead Dismantlement: An Analysis and Methodology for Facility Assessment

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ABSTRACT
Effective verification of nuclear warhead dismantlement is an endeavor for which a solution is widely sought, but also one which poses numerous challenges, such as protection of information and safety and security of warheads and components. Some or all of these challenges could be influenced by the nature of the hosting dismantlement facility. We have developed a systems engineering approach for use in assessing this aspect of the dismantlement verification problem. We have used the methodology to evaluate which of four broad classes of facilities would be most favorable for verified dismantlement of nuclear warheads: a nuclear warhead facility engaged in active stockpile work, a nuclear warhead facility not currently in use for active-stockpile work, a converted industrial facility, and a purpose-designed dedicated dismantlement facility. The analysis is based on the level of challenge involved in implementing verified dismantlement, with respect to five key areas: Verification, Confidentiality, Safety, Security, and Compatibility with the overall nuclear warhead reductions regime. Using our method we find the option of the existing nuclear warhead facility not currently in use for active-stockpile work to be most favorable. On initial consideration, a dedicated dismantlement facility turns out to be the least favorable. This outcome is related to Compatibility and depends on the importance of making a dedicated dismantlement facility available in the same time frame as an existing nuclear warhead facility. If this criterion is relaxed, the dedicated dismantlement facility instead becomes the most favorable option. Verification, Confidentiality and Security have less impact on the overall outcome.

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Introduction

Nuclear warhead reductions may be undertaken unilaterally by states possessing nuclear weapons. However, if reductions are undertaken in a bi- or multilateral context, detailed verification may be required.[1] If verification is

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a requirement, the multidimensional problem of verification of nuclear warhead dismantlement needs to be addressed. The analysis of the problem must consider the protection of information (both for reasons of nonproliferation and national security), safety and security of warheads and components, financial costs and environmental issues alongside complex technical processes. There have been several studies on the various technical processes required for verified dismantlement of nuclear warheads, though the challenges have by no means all been solved.[2]

One set of questions revolves around the impact of the environment on those challenges. Existing facilities for warhead assembly and disassembly are secure facilities designed for handling warheads and their components. Several studies have assumed dismantlement would take place in a single facility, often a facility currently in use for nuclear warhead-related purposes.[3] There are however reasons why assembly or maintenance areas may not necessarily be well suited for verified dismantlement. One significant difference between verified dismantlement and normal working activities is the possible presence of both foreign inspectors and a variety of equipment designed to increase the confidence of inspecting parties that actual dismantlement of real warheads is taking place. The assumption that dismantlement would take place in a facility in use for nuclear warhead-related purposes has been challenged with suggestions ranging from modifications to existing facilities, to the use of a new, dedicated dismantlement facility.[4] Alternatively, different safety philosophies or security sensitivities might give rise to quite different challenges for verification in the same type of facility implemented in different states. Which kind of facility is most favorable for the dismantlement of warheads in a verifiable way? What properties of possible facility alternatives are the most important, and how do they impact the level and types of verification challenges faced? What essential functions would be the hardest or the easiest to fulfill with different facility choices?

In this paper, we present a systems engineering method developed to explore this type of questions. The paper has been structured to adhere to the steps of the developed methodology. The analysis is based on the level of effort or "challenge" involved in implementing verified dismantlement, with respect to five key areas: Verification, Confidentiality,[5] Safety, Security, and Compatibility with an overall nuclear warhead reductions regime. It is important to note that the alternatives studied (i.e., facility types) cannot differ in the degree or quality of fulfilling these requirements, only in the level of effort that must be expended in order to fulfill them. We also present the results of a systematic study that implements the method to assess and compare the level and types of challenges that would be posed by verified dismantlement in four broad classes of possible

Table 1. Facility types considered in the analysis.

Facility type	Verified dismantlement option
I	Using, with necessary modifications, a nuclear warhead maintenance, assembly and disassembly facility engaged in active-stockpile work
II	Using, with necessary upgrades and modifications, a nuclear warhead maintenance, assembly, and disassembly facility that has been, but is not currently, in use for such activities
III	Converting an industrial facility not previously used for nuclear weapons related purposes but otherwise fulfilling some suitable requirements
IV	Designing, building, and commissioning a new, dedicated facility for nuclear warhead dismantlement under international verification

facilities used or constructed for different purposes, but all in the same state (i.e., operating within the same regulatory framework): a nuclear warhead maintenance, assembly and disassembly facility currently in use for activities related to the owner's nuclear arsenal; a similar facility that has been, but is not currently, in use for such activities; a converted industrial facility not previously used for nuclear weapons related purposes but otherwise fulfilling some suitable requirements; and a dedicated facility, designed, built, and commissioned for nuclear warhead dismantlement under international verification.

Several aspects often discussed in relation to verification of nuclear disarmament are not considered in the framework developed, notably the "initialization problem" (verifying that an object presented for dismantlement is in fact what it is declared to be), and final disposition of warhead components. Financial cost is also not discussed in this paper. Assessment of cost poses particular challenges in this context,[6] although broad estimates have been made.[7] The aim of this work is to produce an analysis method that can provide the "benefit" side of any future cost-benefit consideration and cost in itself does not constitute a "challenge" in the sense of the quantitative analysis presented.

The research group for this work comprised scientists from the Nuclear Weapons-related Issues unit of the Swedish Defence Research Agency (FOI) and the nuclear treaty verification team at the Atomic Weapons Establishment (AWE), United Kingdom. The group was well suited for the work, having experience in systems analysis as well as issues around nuclear weapons and treaty verification. Additional expertise in areas such as the operation of nuclear facilities, and safety and security was sought from the participating organizations when forming and scoring this framework to ensure all areas of the framework were able to be scored knowledgeably.

Facility types and key terms

Although the methodology developed is intended to be generally applicable, its presentation in the next section will be facilitated using examples from our specific study. Four broad classes of facilities were chosen for our analysis. These facility types were defined after listing different categories of facilities that might be suitable and available or made available for verified dismantlement, then grouping them according to defining attributes. The chosen facility types are labeled I to IV in Table 1.

For Facility types I–III, the options pre-suppose an existing facility that may be used after modification, upgrading or conversion. The actual availability of such a starting point is not part of the analysis. In other words, the a priori likelihood of finding a former nuclear warhead disassembly plant in a state is not assessed, nor the likelihood of finding a suitable industrial facility that may be converted. Facility type I would be expected to be present in any state with nuclear weapons, whereas the availability of a candidate for Facility type II would depend on state-specific circumstances. The likelihood of finding a suitable candidate for Facility type III is discussed below. For Facility type IV, design, construction and commissioning of a new nuclear weapons facility are part of this option, and the assessment of challenges will reflect this. Facility types III and IV, which represent a potentially much larger variety of facilities than types I and II, need some further specification for consistent evaluation.

Facility type III is an existing industrial facility not designed nor ever used for nuclear weapons related activities. It is assumed that specific features that facilitate the conversion to nuclear warhead dismantlement work are present. First, the location itself must be logistically suitable (e.g., shipment and receipt of dangerous goods). The site should offer the potential for installation of appropriate safety and security features and the facility should already be configured for housing processes involving hazardous substances (e.g., explosives). Structures should be of high standard, sturdy enough to mitigate accident consequences and protect against environmental hazards and external threats. By our definition, Facility type III is understood to be scarce in the sense that only a handful of suitable candidates might be found in a given state. It is not simply an arbitrarily configurable "empty shell" to be filled with the equivalent of a dedicated dismantlement facility. Conversion should involve only limited modifications to existing building features; the major effort required would be related to safe and secure storage and the installation of equipment specific to nuclear warhead dismantlement.

Facility type IV is a dedicated facility designed and built for verified dismantlement of nuclear warheads. A dedicated facility can be designed to optimize the efficiency and verifiability of a dismantlement process, giving less tension between Verification and other key areas, for example Confidentiality. In this respect, the dedicated dismantlement facility would be expected to compare favorably with the other facility types.

Table 2. Definitions of key terms used in this work.

Term	Definition
Chain of custody (CoC)	The procedures and documents for confirming the identity and integrity of an item by tracking its storage and handling from its entry into the verification or monitoring process to its exit from the process (adapted from IPNDV).
Containment and surveillance	Containment refers to structural features intended to prevent undetected access, movement or tampering with an item; surveillance provides instrumental or human observation to indicate or detect the same (adapted from IAEA nuclear safety glossary v1.3).
Continuity of knowledge (CoK)	The confidence provided by chain of custody and other measures to confirm the identity and integrity of an item during movement and periods between inspections, to allow inspectors to confirm that the item has not been diverted, modified, or otherwise subjected to tampering (IPNDV definition).
Dismantlement	The process of physical separation of essential components of a warhead from each other so that the warhead can no longer produce a nuclear yield, and the separated components can enter separate output streams (adapted from IPNDV).
Dismantlement area	The part of a dismantlement facility where a warhead is dismantled.
Essential components	Material and parts in a warhead (e.g., fissile material and high explosives), the separation of which renders the warhead incapable of producing a nuclear yield.
Dismantlement facility (Facility)	A location with adequate provisions, including safety and security, to allow the process of dismantlement of nuclear warheads.
Warhead	A generic term for an object containing fissile material and high explosives that is capable of producing a nuclear yield, a sudden release of energy instantaneously released from self-sustaining nuclear fission and/or fusion (adapted from P5 definition of "Nuclear weapon").

Definition of key terms

We define with the term facility a location with adequate provisions, including safety and security, for carrying out the dismantlement of a nuclear warhead. Several other terms (including dismantlement and warhead) related to the dismantlement process need further specification to avoid any ambiguities and allow for a systematic evaluation. Definitions of key terms used in this work are listed in Table 2. Several of the definitions are based on the P5 Glossary of Key Nuclear Terms,[8] the International Partnership for Nuclear Disarmament Verification (IPNDV) definitions,[9] or the IAEA Safeguards Glossary,[10] with some adaptations (marked by "adapted from … ") to suit the needs of this work. While some of the entries are not frequently used, they are still key terms when they occur.

Methodology

A methodology was devised to allow quantitative comparison between different facility types and their suitability for implementing verified dismantlement.[11] The methodology uses a systems engineering approach, first exploring the larger context of verified nuclear warhead reductions and then gradually narrowing down the wider system to a well-defined problem. The process yields a clear single statement of user need that all of the

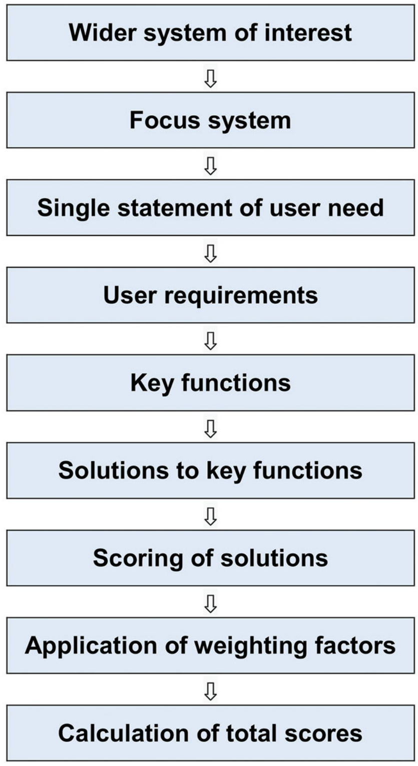

Figure 1. Flow chart summarizing the analysis methodology.

chosen facility types have to fulfill, taking into account both verification issues and challenges such as protection of information and safety and security of warheads. This single statement of user need is broken down into specific requirements and functions in a process that allows for a systematic evaluation and scoring of the facility types. Figure 1 gives an overview of the methodology and the corresponding steps are discussed in detail below.

Wider system of interest

To define the context of the analysis, the wider system of interest of verified nuclear warhead reductions was first sketched and explored as a rich picture (see Figure 2). The wider system of interest comprises all processes, constraints and considerations that constitute, surround or impact the verified dismantlement of nuclear warheads. It spans the full process: before, during and after dismantlement. The system also includes: a notional overarching treaty regarding nuclear warhead reductions including dismantlement, an associated inspection regime, and national regulations regarding safety and security of relevant materials. Unnecessary detail is avoided in order to maintain generality.

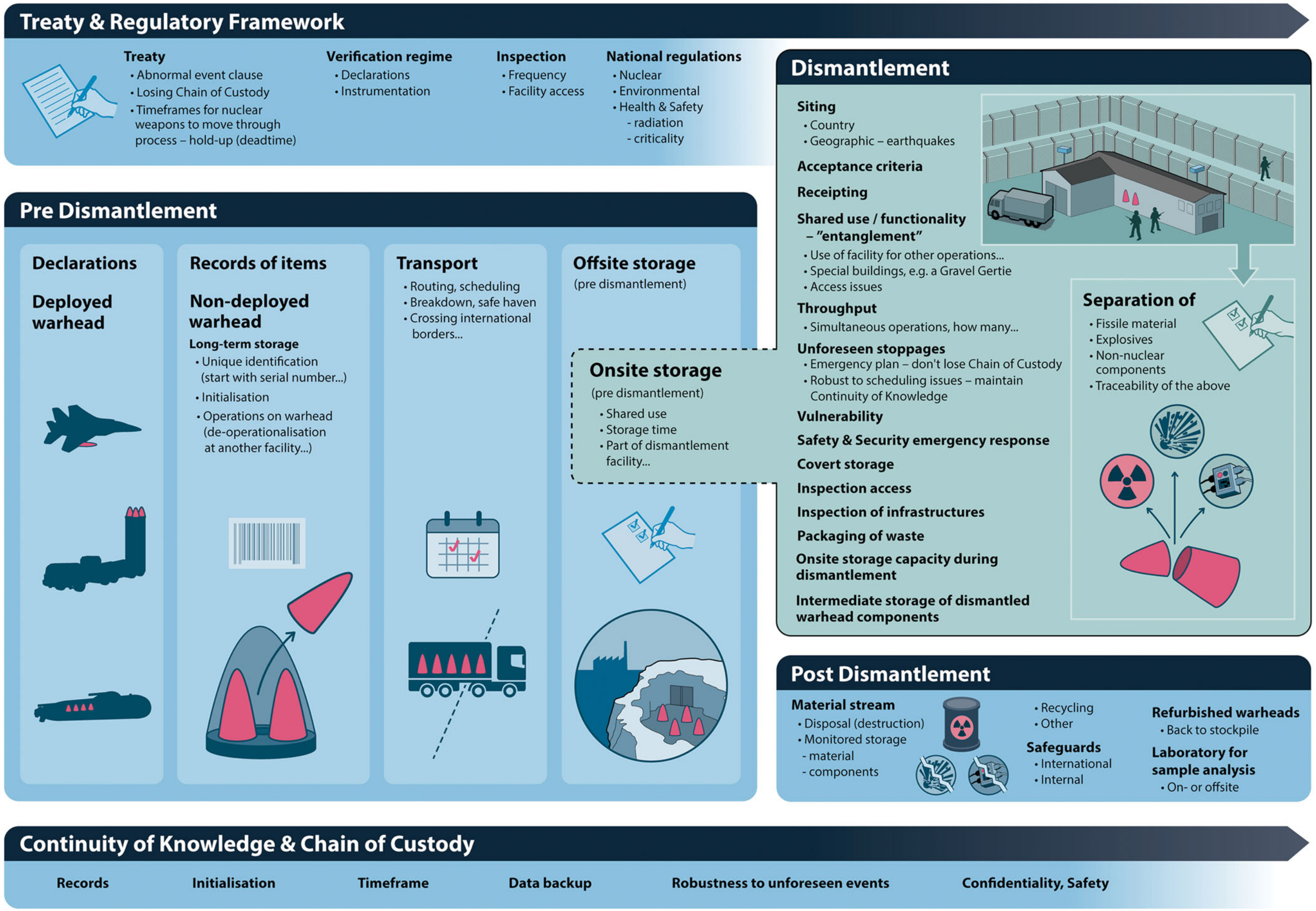

Figure 2. Illustration of the wider system of interest and the focus system within it (green area labeled "Dismantlement").

Table 3. Assumptions on which the present work is based.

Number	Assumption
1	All necessary requirements following from national and international regulations concerning environmental issues, radiation safety, explosives, security etc. should be fulfilled for any dismantlement facility. While this general formula would allow for a similar assessment to be made in any State or regulatory system, the regulatory and public policy environment governing nuclear facilities in Western Europe and the United States has been assumed in this study.
2	An overarching treaty including nuclear warhead dismantlement subject to verification is present.
3	The host has nonproliferation commitments comparable to those imposed by the NPT.[16]
4	The dismantlement facility is under host ownership and control and is situated on host soil.
5	The inspecting team may include citizens of nuclear and/or non-nuclear weapon states.
6	Initial identification of warheads on entry into the dismantlement system, often called initialization, is outside the scope of this study.
7	Everything within scope of the analysis is co-located at one site.
8	Warhead dismantlement takes place in only one area of a facility.
9	Most parts of the dismantlement process occur out of view of inspectors, in order to fulfill requirements regarding protection of information for reasons of nonproliferation and national security.
10	Dismantlement uses contemporary technologies, allowing for possibly extensive engineering development, but no new scientific breakthroughs.
11	One warhead is processed at a time and verified dismantlement is required to be repeatable. The process must support verified dismantlement of different warheads on several distinct occasions.
12	Dismantlement of different warhead types must be possible.
13	Dismantlement is required to be irreversible. This requirement is satisfied by the creation of waste streams which can be further managed down-stream.

The wider system of interest serves as a basis for formulating assumptions concerning the global external environment, necessary to define the scope of the study and maintain consistency in the analysis. These assumptions narrow the problem and define the impact of the wider system on the process of verified dismantlement in the facility types to be assessed. Table 3 lists the assumptions on which this work is based. They include areas such as the presence of treaties, safety regulations, and nonproliferation commitments, and broadly outline the dismantlement process. Assumptions of special importance for the analysis concern host control, i.e., that the dismantlement facility is under host ownership and control, and the process of dismantlement under outside verification.

Focus system

To bound the problem, a focus system was selected within the wider system of interest; see the green area labeled “Dismantlement” in Figure 2. The focus system includes the actual dismantlement process and the provisions necessary for the verification of this process. The focus system also includes temporary onsite storage. It does not include other pre and post dismantlement phases. Note that the selected focus system indeed falls under the definition of a dismantlement facility (see Table 2), but that it further specifies its properties. This is essential for a more exact description of the requirements and functions that a dismantlement facility has to fulfill.

Single statement of user need

The focus system needs to provide a well-defined function within the wider system of interest, and the essential elements of this function are expressed in the single statement of user need:

> A specified facility in which inspectors can verify the safe and secure dismantlement of multiple, uniquely identifiable nuclear warheads from receipt to dispatch, with due regard to confidentiality.

Four key areas can be explicitly identified: Verification, Safety, Security and Confidentiality. In this context, confidentiality includes both proliferation and national security-related concerns. In addition, by definition, the focus system must be generally compatible with the structure and workings of the overall nuclear warhead reductions regime. Hence, we have the fifth key area of Compatibility.

User requirements

The five key areas identified above are formulated as user requirements, each containing the related issues that must be fulfilled by any dismantlement facility:

- **Compatibility:** The facility must be able to accommodate the functions and needs of the nuclear warhead reductions process.

This user requirement reflects external constraints and demands on the functionality or properties of the dismantlement facility in the context of the wider system of interest, and external to that in the form of society at large. For example, the facility must be made available in a timely manner consistent with the implementation of the verification regime, and dismantlement operations at the facility should have minimal impact on the host party's wider requirements for strategic security.

- **Verification**: The facility must allow an adequate verification regime to be implemented.

This user requirement reflects the needs of the inspecting party to reach a suitable level of confidence that the process is being conducted as agreed.

- **Confidentiality**: The facility must enable the implementation of adequate procedures and measures to prevent the proliferation of knowledge, technology, and materials. Measures must also protect national security interests.

This user requirement reflects the needs of the host party (the owner and operator of the facility) to protect information that must not be revealed to inspectors, either because of nuclear nonproliferation obligations or because of legitimate (i.e., not in conflict with the terms of the agreed warhead reductions) national security interests.

- **Safety**: The facility must comply with the safety measures appropriate for nuclear warhead dismantlement.
- **Security**: The facility must allow for the inclusion of all measures appropriate for mitigating any malevolent acts against it.

It is important to note that facility types cannot differ in the degree or quality of fulfilling the user requirements. In this sense, none of the user requirements is more important than the others. While different states and verification regimes correspond to different standards for the user requirements, these standards would be reflected in the breakdown of the user requirements to key functions and solutions below.

Key functions

Each user requirement is broken down into a number of key functions to provide a more highly resolved analysis. The key functions provide clearly defined statements concerning the properties required for the facility. Since facility types cannot differ in the degree or quality of fulfilling the user requirements, all key functions within any user requirement are regarded as absolute in the sense that they must be fulfilled and fulfilled completely. Facility types can only differ in the level of effort that must be expended in order to fulfill the key functions.

The breakdown of user requirements into a chosen set of key functions can be tailored toward the ultimate purpose of a study, and to account for particular verification schemes and state-specific standards. For example, the interplay of verification and confidentiality interests might be more highly resolved by a detailed breakdown into a larger number of key functions for those particular user requirements.

For the present study of the four dismantlement facility types listed in Table 1, we have chosen a deliberately generic approach, staying on a fairly high level of abstraction. Still, a total of 77 key functions. Were identified for the five user requirements, see Appendix B. Table 4 shows three of the Verification key functions that were identified, along with corresponding solutions and subsequent scoring for each facility type. A solution is a particular way of addressing a specific key function and each solution is scored with respect to the degree of challenge of implementation, ranging from A "implicit" to F "unlikely to be feasible even with considerable effort" (see Table 5). Both solutions and scoring will be discussed further below.

Table 4. Examples of verification key functions, solutions, and scoring (excerpt from Appendix B).

User requirement	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
Verification	V-1	Design of facility allows use of verification equipment	V-1A	Adequate space to install equipment, design attributes that prevent the use of verification equipment are avoided. Adequate infrastructure to install main and ancillary equipment (cables, power, communications equipment).	E	D	C	A	Somewhat easier in a facility with no ongoing weapons work. Difficult to completely deconvolve Confidentiality, Safety and Security issues from Verification in this case.
	V-2	Facility has the means to identify warhead and receive it into pre-dismantlement storage	V-2A	Identify using measurements	D	D	B	A	Possible nuclear forensics pose similar difficulties in Facility type I and II.
			V-2B	Use unbroken paperwork/records (envisions a relatively comprehensive audit of document trail)	E	E	E	E	It would be technically difficult to make this the only solution regardless of facility.
			V-2C	Use continuous inspector presence	D	C	B	B	The solution is not implicit in a dedicated facility as it would be no different to the converted industrial facility solution.
			V-2D	Use containment and surveillance measures	D	C	C	A	Issues to consider include: Would floor plans be needed? Doors that you cannot see behind?
	V-5	Facility should accommodate verification that no other warhead is present in dismantlement process area	V-5A	Material flow control using containment and surveillance measures (Ensure that no warhead or essential components have entered dismantlement process area without subsequent exit)	D	C	B	A	Benefits of containment and surveillance include: High degree of control over measures; Inspector access more easily managed; No human presence near hazards. Modifications may be more difficult to implement in older facilities.
			V-5B	Material flow control using inspector presence (Ensure that no warhead or essential components have entered dismantlement process area without subsequent exit)	E	D	C	B	Inspector presence can be challenging in-facility.

(*continued*)

Table 4. Continued.

					Facility type scoring				
User requirement	#	Key function	#	Solution	I	II	III	IV	Comment
			V-5C	Dismantlement process area can be swept for warheads and essential components prior to process start using visual inspection only	D	C	C	B	
			V-5D	Dismantlement process area can be swept for warheads and essential components prior to process start using measurements	E	D	C	C	Having inspectors and instruments in the dismantlement area presents both authentication and certification, and access challenges.

Table 5. Scores and labels for scoring of solutions with respect to degree of challenge of implementation.

Score	Label
Implicit	A
Straightforward	B
Minor challenges	C
Challenging but likely to be surmountable	D
Very difficult, considerable effort needed	E
Unlikely to be feasible even with considerable effort	F

Solutions to key functions

While each key function provides a clearly defined statement that the facility needs to obey, many of the key functions could conceivably be addressed in a number of ways. A particular way of addressing a specific key function is labeled a solution and one or more solutions were defined for each of the key functions. Solutions are regarded as independent, meaning that:

- Each solution should be sufficient to fully address its particular key function.
- Different solutions to one key function are not combined.

By enforcing independence of the solutions, the catchall "optimum combination of all applicable measures" is avoided. While some sort of "optimum combination" would normally be expected to be the best strategy when devising most complex systems, it provides little clarity if one wants to pinpoint which key functions and which category of solutions are most challenging for different facility types.

Since we have avoided specifying an overarching treaty or scenario in detail, solutions are intended to be as generic as possible, and technology agnostic wherever achievable.

For our four-facility study, a total of 128 solutions were defined for the 77 key functions, see Appendix B. For the Compatibility, Safety, and Security user requirements, key functions mainly have only one associated solution (typically along the lines of "implement regulatory requirements"), which will lead to somewhat limited variations in scoring. In the cases of Verification and Confidentiality, most key functions have multiple solutions associated with them, leading to wider variations in scoring. Among the solutions, there is one exception to the "no combination" rule. This concerns the verification of essential components after dismantlement, where one solution is a combination of two other solutions (see V-9, Appendix B). This solution is a combination of verification of the absence of undeclared components and verification of the presence of declared components. Such a solution is critical to any verification regime requiring detailed verification of the dismantlement step itself. A combination of both absence and presence measurements is likely to be made on essential components for confidence that the correct components are leaving via designated routes. Therefore, leaving out the combination of these methods is overly simplistic for this particular key function. On inspection, this exception will turn out to have no impact on the overall facility rankings and only a minor impact on the relative scores for each facility.

As an example of the hierarchical structure created, consider the Verification user requirement which was broken down into 14 key functions, three of which are shown in Table 4. Key function V-2 states that a facility should have the means to identify a warhead and receive it into pre-dismantlement storage. Four solutions were considered whereby this key function might be accomplished:

- Measurements (V-2A).
- Paperwork and records (V-2B).
- Continuous inspector presence (V-2C).
- Containment and surveillance (V-2D).

These solutions would in a real dismantlement verification scenario constitute components that could be used in a mutually reinforcing manner. However, the different character of these solutions would tend to make them more or less easily applied in the different facility types considered. For the purpose of this particular study, it is most interesting to highlight the latter differentiation, not the particular combinations that one might construct in any specific case.

Scoring of solutions

The basis for quantitative comparison between facility types is the degree of challenge in fulfilling each key function within the user requirements. The solutions to each key function are scored, considering the particular facility type and the details of the solution. Scoring of the degree of challenge is done with descriptors on a six-point scale ranging from "implicit" to "unlikely to be feasible even with considerable effort," see Table 5. The descriptors define each step in the scale and a corresponding label is assigned, with "A" the easiest and "F" the most challenging. Scoring with descriptors rather than numbers allows consistency over time and between collaborators.

For our four-facility study, decisions on scores were made by a team of relevant subject matter experts who discussed the relative merits of proposed solutions until consensus was reached. Scoring for all solutions was carried out by the same group of experts, including additional expertise when required, to maintain consistency. Discussions on scoring followed a consistent format, with regular comparisons to previously assigned scores. Scoring was carried out over a relatively short period in order to keep the experts "calibrated" to the six-point scale. The scoring process often included a pair-wise comparison to differentiate between the challenges each solution contained. While the solutions were intended to be generic, discussion of solutions did include the use of existing technologies in their implementation. As such, the analysis remains inherently subjective and will include bias based upon the experiences and knowledge of these experts. It is expected that if additional context were introduced (e.g., a specified host state, desired implementation timeframe …) that the analysis could be repeated with results significantly more relevant to the host state.

All key functions and their corresponding solutions were extensively reviewed in an iterative process, both before and during scoring. The iterations re-assessed scoring as well as reviewed how the scores had been applied to ensure a consistent approach. Independent external review was also undertaken to ensure that the method and results were consistent.

For a scoring example, consider the Verification key function V-2 in Table 4, and in particular the "Measurements" solution V-2A. We scored this solution with a "D" for Facility type I and II (the existing nuclear warhead facilities), a "B" for Facility type III (the converted industrial facility) and an "A" for Facility type IV (the dedicated dismantlement facility). One consideration in this scoring was the confidentiality issues that might occur for any measurement process applied in Facility type I or II. In particular, a discussion on nuclear forensics resulted in the same score applied to such facilities regardless of whether nuclear warhead related work would be currently ongoing or not. The difference between the other two types of facility has more to do with practical issues of implementing a given measurement scheme in a preexisting structure compared to one that is designed to accommodate such a scheme.

Our study contains one special case when applying the above six-point scale during scoring. One key function within the Compatibility user requirement states that the facility must be online, meaning up and running in a timely manner (see CP-8, Appendix B). This was scored on a relative scale. The score was assessed based on how difficult it would be to make the facility operational for verified dismantlement in the same time frame that it would be "very difficult" ("E") to do this for Facility type I (the nuclear warhead facility engaged in active-stockpile work). The scoring of this function will turn out to have a significant impact on the results.

Application of weighting factors

Scoring the degree of challenge of implementing each solution in a particular facility type provides a complete assessment of the facility. One could in

Table 6. Weighting schemes for calculating total numerical scores.

	Weighting scheme		
Score	standard	semi-linear	flattened central
A – Implicit	0	0	0
B – Straightforward	1	5	5
C – Minor challenges	2	20	5
D – Challenging but likely to be surmountable	5	50	5
E – Very difficult, considerable effort needed	20	100	20
F – Unlikely to be feasible even with considerable effort	500	500	500

principle stop at this point and analyze the results by simply counting the number of assigned scores for each step in the scale in Table 5, grouping score counts by facility type and user requirements. Additional insight can nevertheless be gained by applying weighting factors which turn the assigned degree of challenge into a numerical score, with higher numerical scores being more challenging. It is important to note that applying weighting factors does not change the actual scoring. It gives a measure of the difference in challenge between the different scores ("A" to "F"). Weighting factors can thus be used as a tool for both estimating the relative impact of different scores and probing how different "calibrations" of the descriptive scale would affect the results. Applying numerical weighting factors also makes it straightforward to aggregate total scores for each user requirement and facility type.

Table 6 shows the weighting schemes employed in the present analysis. In general, one would expect the difference in challenge between "unlikely to be feasible" and "very difficult" to be considerably wider than between "minor challenges" and "straightforward." For this reason, the weighting scheme adopted as standard is highly non-linear. This scheme also puts a severe penalty on the "unlikely to be feasible" "F" score compared to the less challenging scores.[12]

The semi-linear weighting scheme increases the difference in challenge between scores in the lower end of the scale and decreases it in the upper end, compared to the standard weighting scheme. This reduces the relative penalty of both "F" and "E" scores compared to the less challenging scores.

The flattened central weighting scheme consists of setting equal weights to the "B", "C", and "D" scores, in effect reducing the number of steps on the scale so that there is no longer any difference between "Straightforward," "Minor challenges," and "Challenging but likely to be surmountable." This scheme can be used as a tool for reducing possible arbitrariness in scoring at the lower end of the scale, and probe its potential impact on the results.

Calculation of total scores

After applying a weighting scheme, the final step in the analysis sums the numerical scores to yield aggregate scores for each facility type. The solution with the lowest degree of challenge is chosen for each key function, and the score of that solution enters the total for each user requirement. Total scores are divided by the number of key functions within each user requirement. This normalization makes sure the functional breakdown and level of detail considered for each user requirement will not in itself affect the final score. Analysis of scores for each facility, user requirement, and key function yields insight into what aspects of verified dismantlement present challenges for any given facility type.

Normalizing the total score of each user requirement is consistent with all user requirements being equally important in the sense that facility types cannot differ in the degree or quality of fulfilling them. As mentioned above, different standards arising from particular verification regimes or state-specific issues should be reflected in the scoring of solutions and possibly in the breakdown of the user requirements into key functions and solutions. For example, if a specific state places less emphasis on Safety, many solutions might be scored as less challenging under the Safety user requirement.

Reliability and stability of results

A potential problem with the above methodology is that solutions selected to address different key functions are not intrinsically guaranteed to be consistent with each other. Similarly, the particular scoring of a given solution and facility type may contain implicit assumptions that are inconsistent with ones made elsewhere. This type of risk was mitigated in our study by the iterative review mentioned above. It is also a reasonable expectation that with a large number of scores entering the sums, the totals should be reasonably robust to the effects of any remaining individual variations or inconsistencies.

The reliability and stability of the results were examined by using the different weighting schemes, exploring the impact of both unavoidable arbitrariness in scoring and different "calibrations" of the descriptive scale. The robustness of the conclusions was also assessed by considering second best scoring. This will be discussed further below.

Results of our study

Application of the chosen methodology to compare the four facilities listed in Table 1 identified 128 solutions for 77 key functions within the five user requirements (see Appendix B). The degree of challenge in implementing each solution in a specific facility type was scored using the descriptive scale, labeled A–F in Table 5. Corresponding numerical scores were then

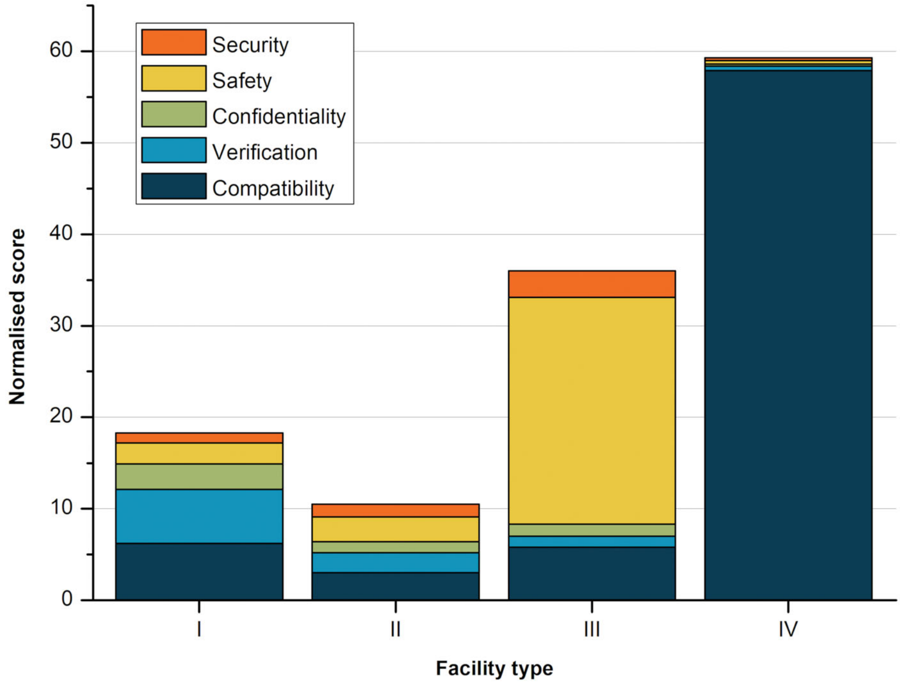

Figure 3. Total normalized score of best-case solutions for Facility type I to IV (standard weighting).

calculated using the weighting schemes in Table 6. These results were analyzed with respect to sums of "best," i.e., lowest scoring, solutions per facility and user requirement. Total scores were normalized by the number of key functions within each user requirement.

The total normalized score of best-case solutions for Facility type I to IV is shown in Figure 3 (see Appendix A for numerical values). Facility type II (the nuclear warhead facility not currently in use for active-stockpile work) is the favored facility. Facility type I (the nuclear warhead facility engaged in active-stockpile work) is ranked second, Facility type III (the converted industrial facility) is ranked third, and Facility type IV (the dedicated dismantlement facility) is scored as the least attractive alternative. The spread between the scores is significant on the scale implied by the distribution of scoring weights and the normalization applied, and they are robust to the perturbations in weighting described above.

Figure 4 shows the same normalized scores arranged by user requirement. Notably, the unfavorable score obtained for Facility type IV depends on a single "F" score within the Compatibility user requirement, present in the key function requiring the facility to be operational a timely manner (see CP-8, Appendix B). Without this particular choice of key function and scoring, the outcome for Facility type IV can be quite different. This will be discussed further below.

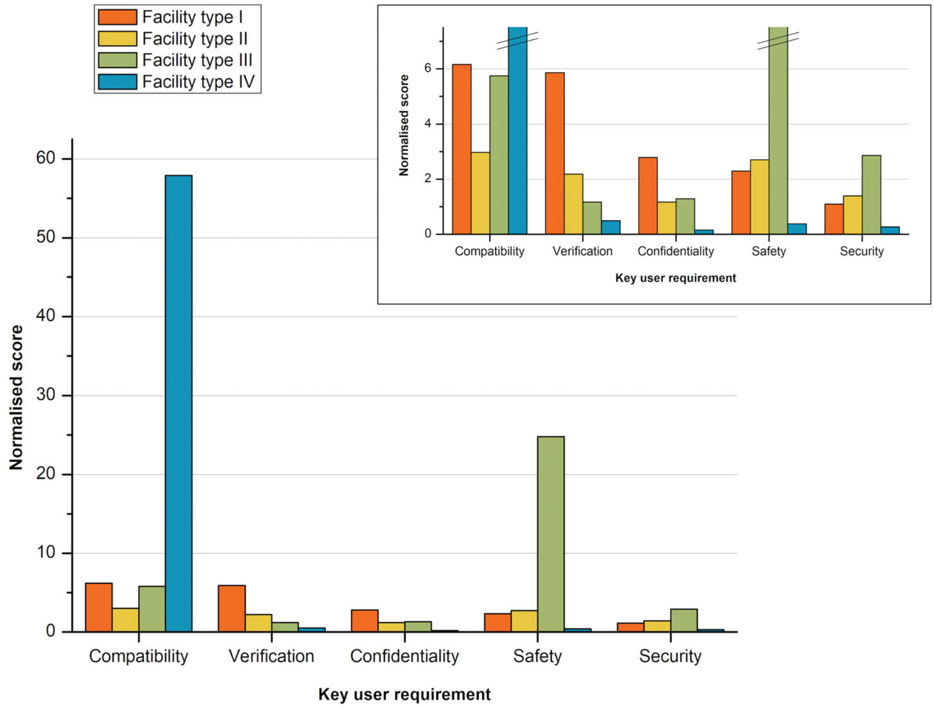

Figure 4. Normalized score of best-case solutions per user requirement for Facility type I to IV (standard weighting). The insert shows the same data but re-scaled to better display differences between the lower scores.

Table 7. Ranking of Facility types for differing weighting schemes.

	Facility type ranking by weighting scheme		
Rank	standard (0-1-2-5-20-500)	semi-linear (0-5-20-50-100-500)	flattened central (0-5-5-5-20-500)
1	II	IV	II
2	I	II	I
3	III	I	III
4	IV	III	IV

Numbers in parentheses represent weights applied (see Table 6). Rank 1 represents the lowest degree of challenge (lowest total score), whereas rank 4 represents the highest (highest total score).

Impact of weighting

The reliability and stability of the results were tested by applying different weighting schemes to the six-point descriptive scale. The high-level results, reflected in the relative ranking of the analyzed Facility types, are shown in Table 7. With semi-linear weighting, the relative penalty of both "F" and "E" scores are reduced compared to the less challenging scores. Accordingly, since the unfavorable ranking of Facility type IV with standard weighting is caused by a single "F" score, the high-level effect of semi-linear weighting is to shift Facility type IV from last place (least attractive) to first place (most attractive).

With flattened central weighting, the weights of “B”, “C”, and “D” scores are set equal, in effect reducing the number of degree of challenge steps on the scale. In our study, the outcome does not in fact change with respect to the standard weighting scheme, showing that possible arbitrariness in scoring at the lower end of the scale (“Straightforward,” “Minor challenges,” and “Challenging but likely to be surmountable”) does not affect the conclusions.

The “best to worst” mutual ranking order of II, I, III is consistent throughout the different weighting schemes. Several further variations of the weighting schemes were also applied during analysis. None of these

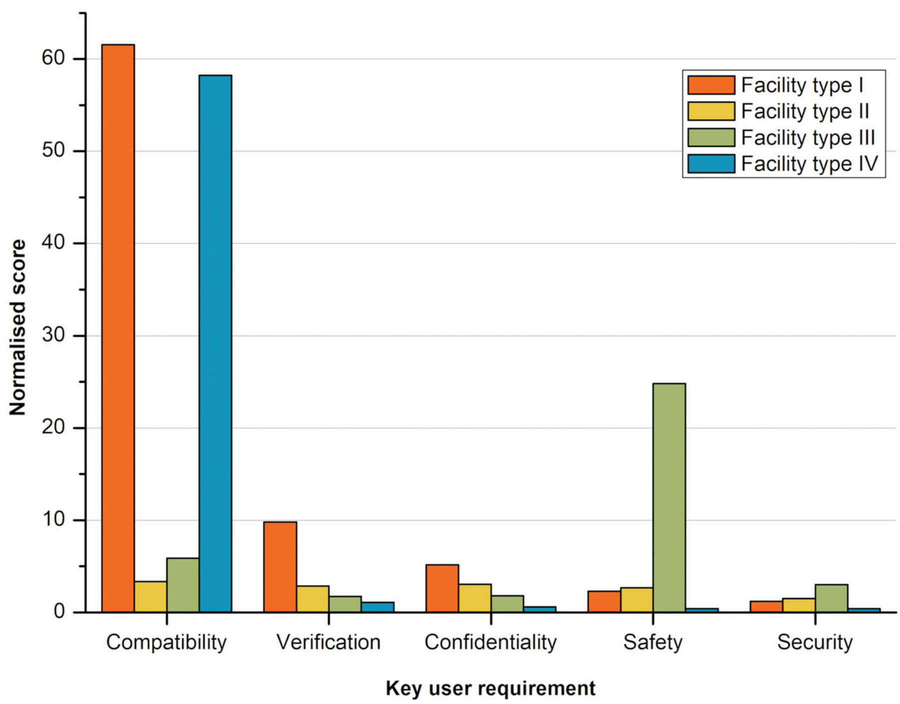

Figure 5. Normalized score of second-best scoring solutions per user requirement for Facility type I to IV (standard weighting).

Table 8. Ranking of Facility types – comparison of best-case solutions to second best scoring.

	Facility type ranking based on scoring	
Rank	Best case	Second best
1	II	II
2	I	III
3	III	IV
4	IV	I

Higher ranking for lower scores (less challenging).

revealed any additional information and results appear to be robust under most reasonable variations in weighting.

Second best solutions

In order to assess the reliability of the Facility type scoring for the best-case solutions, consideration was given to the second-best scoring, i.e., the combination of solutions with the second lowest degree of challenge (see Figure 5).

Table 8 compares the scores for the best-case solutions and the second-best scoring solutions, showing that Facility type I (the nuclear warhead facility engaged in active-stockpile work) is lowered from position 2 to position 4 in the rankings. This is a result of an "F" score in the second best solution for a key function within the Compatibility user requirement, requiring verification to be repeatable on additional warheads (see CP-2, Appendix B). The "F" score reflects the difficulties in tracking changes (e.g., material balance, design verification) in order to ensure continuity of knowledge in a nuclear warhead facility engaged in active-stockpile work. If a dedicated process line for dismantlement could be identified and isolated within Facility type I, this second-best score would drop to an "E" or better and the rankings would return to the same order as those based on the best-case solutions.

The relative total scores for Facility type II, III and IV show little variation between the scoring for the best-case solutions and the second-best scoring. As noted previously, this limited variation in scoring is due to that most key functions within the Compatibility, Safety and Security user requirements only have one associated solution (see Appendix B).

In summary, the second best scoring has few changes from the best-case solutions scoring. The one significant change can be clearly attributed to a single key function within the Compatibility user requirement, impacting the score for Facility type I, the nuclear warhead facility engaged in active-stockpile work.[13] This, together with the stable behavior under different weighting schemes, provides confidence in the scoring methodology and the reliability of the analysis used to identify the best-case solutions.

Discussion

The methodology developed allows a balanced assessment of alternatives for verified dismantlement of nuclear warheads on a systems level. Quite different, but equally relevant aspects are considered (in the form of the identified user requirements) and comparison of their relative impact is facilitated. Particularly prominent challenges inherent in a given alternative may be identified, and further investigated through examination of the detailed breakdown into key functions and their solutions. The results of our study, comparing four particular facility types, may be seen as an example of employing the method as well as being of interest in their own right.

Selecting the most attractive option for verified dismantlement

The most attractive facility option for verified dismantlement of nuclear warheads in terms of lowest overall degree of challenge is Facility type II, the nuclear warhead facility not currently in use for active-stockpile work. Facility type IV, the dedicated dismantlement facility, is in fact the least attractive option of the alternatives assessed. However, the outcome for Facility type IV depends critically on a single "F" score, for a key function within the Compatibility user requirement stating that a facility must be operational in a timely manner (see CP-8, Appendix B). As mentioned in the Methodology section, "in a timely manner" is defined using a relative timescale on which there by definition is considerable effort required (very difficult, "E") to implement verified dismantlement in the nuclear warhead facility engaged in active-stockpile work, Facility type I. Considering time-consuming factors and processes that would likely surround the siting, design, construction, and commissioning of a completely new nuclear warhead handling facility, we believe there is good reason to mark timeliness as an even more difficult challenge for the dedicated dismantlement facility, giving it an "F". Nevertheless, the criterion is constructed in a particular way, and it should be noted that this score would certainly change if "plenty of time" would always be assumed available.

If the "F" score for "timeliness" of the dedicated dismantlement facility is improved by changing the assumptions behind the score, Facility type IV becomes the most attractive option, followed by Facility type II, the nuclear warhead facility not currently in use for active-stockpile work. The result regarding Facility IV is the same if "F" scores are given less penalty compared to the other scores, as in the semi-linear weighting scheme. Facility type II is consistently in the top two ranks regardless of the weighting scheme.

The converted industrial facility, Facility type III, is assigned an "F" score on the accident consequence mitigation key function within the Safety user requirement (see SF-12, Appendix B). The basis for this scoring is that for any facility, complying with regulatory expectations for the ability to mitigate accident consequences would constitute a major constraint on the entire project. Even the existing nuclear warhead facilities, Facility type I and II, are assigned "E" scores, in order to allow for the possibility that either facility has never handled a particular type of warhead, or the possibility that the regulatory framework has evolved. Only the dedicated dismantlement facility is assigned a low score, since it would by definition be sited, designed, and built to current regulatory expectations.

Facility type III consistently scores among the worst two alternatives. Furthermore, weighting or scoring variations that cause the final ranking for the dedicated dismantlement facility, Facility type IV, to improve do not have the corresponding effect on the ranking of Facility type III. The reason is that the pattern of other scores is very different for the two facility types. The majority (77%) of the scores for the dedicated dismantlement facility are "A"s ("implicit"), most of the rest (17%) are "B"s ("Straightforward") and none are "D"s ("challenging but likely surmountable"). The freedom to address issues at the design stage matters. In contrast, the converted industrial facility has no "A"s and over 20% "D"s. It also has four "E"s ("very difficult") compared to only one "E" for the dedicated dismantlement facility. Therefore, even if the impact of either or both "F" scores were challenged as too harsh, the rest of the scoring structure will enforce the unfavorable final evaluation of Facility type III.

Facility types and user requirements

Examining each facility in detail yields a greater understanding of the results. Turning first to Facility type I, the nuclear warhead facility engaged

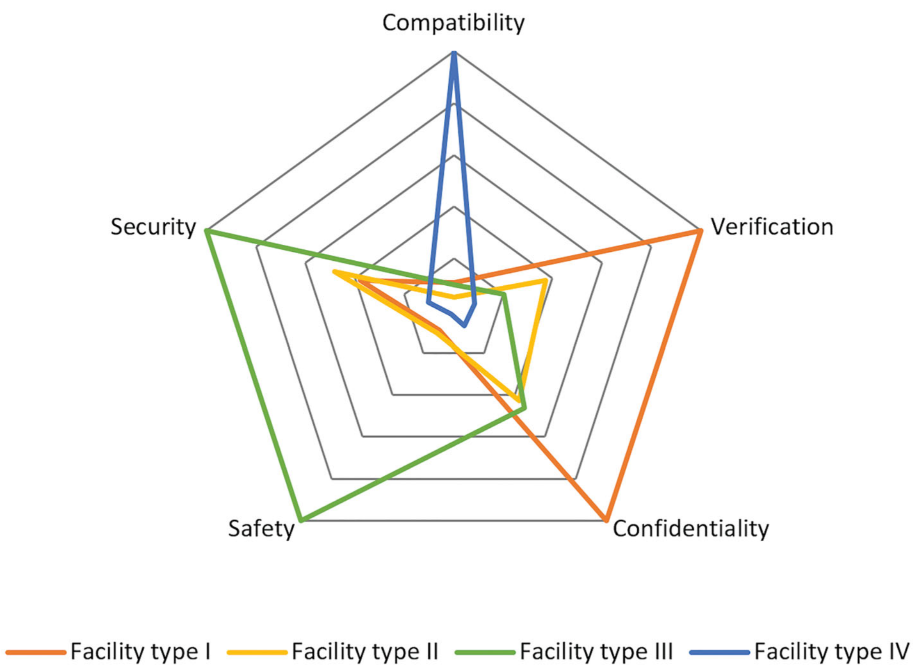

Figure 6. Radar chart of scores for the five user requirements for each Facility type. Scores within each individual user requirement are normalized to the highest score for that particular user requirement.

in active-stockpile work, Figure 4 shows the normalized sum of scores (with standard weighting) for each user requirement. Clearly, this facility option presents on average manageable problems in the areas of Confidentiality, Safety and Security, but more serious difficulties concerning Compatibility and Verification.

Comparing the scores for Facility type I with those for Facility type II, the nuclear warhead facility not currently in use for active-stockpile work, we see similar scores for Safety and Security. However, Facility type II scores considerably better for Compatibility, Verification and Confidentiality. This is due to lower impact on active-stockpile work and less sensitive information to protect than in a facility still engaged in such work.

Figure 6 shows a radar chart of the five user requirements for the four Facility types. In this diagram, the scores within each individual user requirement have been normalized to the highest score for that particular user requirement.

While the diagram in itself does not carry any new information, the patterns visualized may provide some further insight. As discussed above, Facility types I and II follow a similar pattern regarding Compatibility, Safety and Security while Facility type I is considerably less attractive regarding Confidentiality and Verification, due to active-stockpile work.

Facility type III, the converted industrial facility not previously used for nuclear weapons related purposes, shows a completely different pattern with considerable issues regarding Safety and Security, while Compatibility, Confidentiality and Verification are closer to those of Facility types I and II. Figure 4 also shows that Facility type III presents the greatest challenges in the area of Safety. This score represents an accumulation of challenging solutions to a number of key functions in the Safety area.

The highly unfavorable scoring for Compatibility of Facility type IV stands out while the otherwise favorable scores for this facility type are clearly evident.

It is also illuminating to follow the profiles of facility scores for each user requirement separately. Examining first the trend within the user requirement of Compatibility (leftmost group of columns in Figure 4), we again notice the impact of the “timeliness” key function for Facility type IV (see CP-8, Appendix B). If the impact of this key function is reduced by changing the score from an “F” to an “E”, the normalized total Compatibility score for Facility type IV drops significantly,[14] becoming second best after Facility type II and leaving Facility type I with the worst Compatibility total, closely followed by Facility type III. The latter result is mainly due to Facility type I scoring considerably worse than type IV on key functions related to the interference of any enduring nuclear weapons program on the verified dismantlement program. The scoring for Facility type III mainly reflects challenges related to the siting of the facility.

Turning to the Verification user requirement, Facility type I stands out somewhat. This is in large part due to challenges with accepting verification equipment and maintaining continuity of knowledge on essential components during warhead disassembly, where access restrictions are severe and verification was not an initial design requirement. Facility type II, while much better than Facility type I, is considerably less attractive than Facility type III which is in turn somewhat less attractive than Facility type IV, designed to facilitate verified dismantlement.

For the Confidentiality user requirement, the trend is much the same as for Verification. Several key functions present severe problems for the nuclear warhead facility engaged in active-stockpile work, such as hosting foreign inspectors and allowing the operation of a separate IT system for inspectors. These can be addressed with no or minor challenges (at least from a technical point of view), if considered at the facility design stage. This is reflected in the results for Facility type IV. Facility type III is more attractive in this respect than Facility types I and II, mainly due to the fact that it does not carry legacy information that might introduce issues regarding nuclear proliferation or national security.

The Safety user requirement is the main factor in the poor ranking of Facility type III, the converted industrial facility. Facility type I and II, the existing nuclear warhead facilities, have similar scores for the Safety user requirement, with Facility type II tending to score somewhat worse. This is generally due to the possibility that the regulatory environment might have changed over time so that the currently inactive facility no longer fulfills safety requirements by default. Facility type IV is designed to fulfill current safety regulations.

Finally, for the Security user requirement the trend is the same as for Safety. In general, the solutions to key functions within Security are scored in the "implicit" to "challenging but surmountable" region. Fulfilling Security thus appears less demanding than other user requirements. Key functions related to prevention of theft of material and maintaining security under adverse site conditions are of interest; the converted industrial facility receives unfavorable scores because it is not designed with these requirements in mind.

Facility type II

The consistently attractive ranking of Facility type II, the nuclear warhead facility not currently in use for active stockpile work, raises the question of how this Facility type might be realized. Several avenues could be imagined, depending on the structure of the stockpile support program in a given nuclear weapon state:

- An inactive but not decommissioned nuclear warhead facility could be re-activated for the purpose of verified dismantlement. To be considered as a Facility type II, this would mean a permanently closed-down state awaiting decommissioning.
- An existing and operating nuclear warhead facility with multiple process lines could be subdivided so that one line, fully sufficient for all verified dismantlement activities, is segregated from those parts still engaged in work on the active stockpile. In order to qualify as a Facility type II, this segregation would have to be complete. The hosting of inspection processes and verification equipment in the segregated line must not pose any problems for the protection of information about current active-stockpile activities in the rest of the facility. Furthermore, the capacity segregated to create a Facility type II should be surplus to the requirements of the current active-stockpile program.
- A decommissioned or partly decommissioned former nuclear warhead facility could be refurbished and re-activated. To represent a Facility type II rather than something more resembling a converted industrial facility (Facility type III), or even a dedicated dismantlement facility if actually re-built from scratch (Facility type IV), certain defining elements would have to still be in place, e.g. mitigating the consequences of accidents.

Conclusions

The early stages of this work began by looking at a new dedicated dismantlement facility as probably the most attractive option for verified nuclear disarmament. A dedicated dismantlement facility has also been suggested elsewhere in the literature.[15] However, after developing and applying a methodology that takes a full systems perspective into account, we find that the most favorable Facility type would be an existing nuclear warhead facility not currently in use for active-stockpile work.

Assessment of facility types

On initial consideration, the dedicated dismantlement facility is the least favorable option. This ranking however depends critically on the assessed importance of making such a facility available in the same time frame as an existing and operating nuclear warhead facility. If this criterion is relaxed, then in most circumstances the dedicated dismantlement facility instead becomes the most favorable. A converted industrial facility, even if assumed to be carefully selected, is unlikely to present the most attractive option for verified nuclear warhead dismantlement. Key findings for each facility type are:

Facility type I—A nuclear warhead maintenance, assembly and disassembly facility engaged in active-stockpile work presents numerous challenges associated with having ongoing nuclear warhead work, mainly due either to competition for capacity with dismantlement work or to national security concerns with verification measures.

Facility type II—A nuclear warhead maintenance, assembly and disassembly facility that has been, but is not currently in use is the most favorable option. It has most of the required properties in place for dismantlement, and presents fewer of the challenges associated with an active facility. Naturally, the availability of this type of facility may be limited, but there may be circumstances under which such a facility could be made available.

Facility type III—A converted industrial facility not previously used for nuclear weapons related purposes is the least favorable option, even if many quite demanding (but non-nuclear warhead related) industrial properties are assumed already in place. The difficulties are mainly in respect to safety, especially accident consequence mitigation.

Facility type IV—A dedicated facility, designed, built, and commissioned for nuclear warhead dismantlement under international verification is under certain circumstances highly favorable, especially from a verification standpoint. However, there are significant challenges concerning the lead time to becoming operational. If this requirement is relaxed, this facility becomes the most favorable.

Impact of user requirements

Two user requirements have a significantly larger bearing on the outcome of the analysis. In the Compatibility user requirement, the "timeliness" key function has the most variability in scoring (see CP-8, Appendix B). It summarizes the different degrees of challenge in terms of siting, licensing, building/modifying, and commissioning a facility. The Safety user requirement strongly affects overall conclusions, especially for the converted industrial facility not previously used for nuclear weapons related purposes. In particular, the key function of accident mitigation would pose challenges unlikely to be surmountable for a facility not originally sited or designed for it (see SF-12, Appendix B).

Verification, Confidentiality and Security have smaller bearing on the outcome; they would not be the primary determinants for facility choice.

Regarding Verification, the dedicated dismantlement facility faces the least challenge and the nuclear warhead facility engaged in active-stockpile work the greatest. Many challenges have little dependence on the type of facility and no insurmountable challenges were found. Confidentiality is strongly linked to Verification as the two user requirements have opposing drivers. This results in similar trends with regard to challenges. That Verification does not come out as a primary determinant may seem surprising, but one should bear in mind that:

- While the siting and facility layout can make some of the challenges more or less severe, ultimately the challenges presented stem to a large degree from the intended process itself (detailed monitoring of relevant aspects of the dismantlement of a nuclear warhead).
- The scope of this analysis is restricted to the dismantlement facility itself. In particular, the "initialization problem" has been defined as out of scope.

Remarks on the methodology

The methodology developed and employed for the study of verified dismantlement facility alternatives yields robust results. The results are stable under most reasonable variations in both scoring and weighting of the scores. In general, this systems engineering approach may prove fruitful for the analysis of other aspects of the problem of verified nuclear warhead reductions, described by the wider system of interest in Figure 2. Possible directions for future work, suggested by the results of the study presented here may be an investigation of areas shown by the scoring to have the greatest negative impact. It could also be useful to take the analysis beyond the deliberately generic approach used here and consider specific countries to host the facility, and perhaps even specific facilities. State-specific factors would change the analysis and could affect scoring in a multitude of ways, as would greater specificity on the Facility types (reflecting real facilities). Greater granularity could also be achieved, particularly in the Verification and Confidentiality areas to reflect the properties and constraints of existing facilities. This could help explore questions related to potential future use of existing facilities, such as a proposal to shut down a nuclear warhead facility that could function as a Type II facility, or the management of an industrial facility that could be converted to a Type III facility.

Disclaimer

The views expressed in this document are those of the author and do not necessarily represent those of AWE, the Ministry of Defence, or the Government of the United Kingdom.

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Notes and References

1. K. W. Abbott, "Trust but Verify: The Production of Information in Arms Control Treaties and Other International Agreements," Cornell International Law Journal 26(Winter 1993): 1–58; A. Woolf, "Monitoring and Verification in Arms Control," *Congressional Research Service*, 7-5700(2011), https://fas.org/sgp/crs/nuke/R41201.pdf.
2. Z. M. Koenig, J. B. Carlson, D. Clark, T. B. Gosnell, "Plutonium Gamma-Ray Measurements for Mutual Reciprocal Inspections of Dismantled Nuclear Weapons," Lawrence Livermore National Laboratory, U. S. Dept. of Energy, UCRL-JC-121105 (1995). Presented at the Institute of Nuclear Materials Management 36th Annual Meeting, 9–12 July 1995, Palm Desert, California, https://www.osti.gov/servlets/purl/102365; C. Paine and T. Cochran, "So Little Time, So Many Weapons, So Much To Do," *Bulletin of the Atomic Scientists*, (Jan 1992), 3–16; United Kingdom – Norway Initiative, "Trust in Verification Technology – A Case Study: The U.K.-Norway Information Barrier" (non-paper), 2015 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), United Nations, New York, 27 April to 22 May 2015, https://ukni.info/mdocs-posts/revcon2015-ibnon_paper__trust_in_verification_technology/; T. Taylor, "Dismantlement and Fissile-Material Disposal," in Frank Von Hippel and Roald Z. Sagdeev (eds), *Reversing the Arms Race: How to Achieve and Verify Deep Reductions in The Nuclear Arsenals* (New York: Gordon and Breach Science Publishers, 1990); T. Taylor, "Verified Elimination of Nuclear Warheads," *Science and Global Security* 1 (1989), 1–26.
3. O. Bukharin and K. Luongo, "US-Russian Warhead Dismantlement Transparency: The Status, Problems and Proposals," PU/CEES 314 (Center for Energy and Environmental Studies) Princeton University, Princeton, N.J. (Apr. 1999); A. Shaper, "Verifying Nuclear arms Control and Disarmament," *Verification Yearbook* (London: VERTIC, 2000), 58, http://www.vertic.org/media/Archived_Publications/Yearbooks/2000/VY00_Schaper.pdf.
4. Bukharin and K. Luongo, "US-Russian Warhead Dismantlement Transparency: The Status, Problems and Proposals;" R. Joseph, "Dismantlement of Warheads and Disposition of Fissile Material, Confronting the Challenges of the 21st Century," Proceedings of the 49th Pugwash Conference on Science and World Affairs, Rustenburg, South Africa, September 1999, 167; T. Milne and H. Wilson, "Verifying the Transition from Low Levels of Nuclear Weapons to A Nuclear Weapon-Free World," Vertic Research Report No. 2 (1999), 22, http://www.vertic.org/media/Archived_Publications/Research_Reports/Research_Report_2_Milne_Wilson.pdf;
SIPRI, Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions (Oxford University Press: 2003), ch. 9; J. Fuller, "Verification on The

Road to Zero: Issues for Nuclear Warhead Dismantlement," *Arms Control Today* 40 (2010): 19–27.

5. Including both proliferation and national security-related issues.
6. J. Alger and T. Findlay, "The Costs of Nuclear Disarmament," International commission on nuclear non-proliferation and disarmament, 2009, http://www.icnnd.org/Documents/Alger_Findlay_Cost_of_Disarmament.pdf.
7. G. Perkovich and J.M. Acton, *Abolishing Nuclear Weapons: A Debate* (Washington, DC: Carnegie Endowment for International Peace, 2009), http://www.carnegieendowment.org/files/abolishing_nuclear_weapons_debate.pdf; S. Nunn and R. E. Ebel (CSIS), "Managing the Global Nuclear Materials Threat: Policy Recommendations," *Journal of Energy Literature* 6 (2000), 101.
8. The P5 Working Group on the Glossary of Key Nuclear Terms, *P5 Glossary of Key Nuclear Terms* (Beijing: China Atomic Energy Press, 2015), https://2009-2017.state.gov/documents/organization/243293.pdf.
9. Working Group 1: Monitoring and Verification Objectives, "Deliverable 1: Framework Document with Definitions, Principles, and Good Practices," International Partnership for Nuclear Disarmament Verification (2017), http://ipndv.org/wp-content/uploads/2017/11/WG1-Deliverable-One-Final-.pdf.
10. IAEA, *IAEA Safeguards Glossary* (Vienna: International Atomic Energy Agency, 2001), www.iaea.org/sites/default/files/iaea_safeguards_glossary.pdf.
11. The term "quantitative" is used in the sense of a structured evaluation through application of numerical scores according to pre-defined rules. This allows traceable analysis in terms of comparison between alternatives, but the method is not fully quantitative in the sense that an absolute numerical value in itself carries sufficient information for conclusions to be drawn.
12. The actual number assigned to a particular weighting factor is of course irrelevant, it is the relation between the weighting factors in a particular scheme that carries the information. Given descriptors ordered with an increasing degree of challenge, the only restriction from a logical point of view is that the weighting factor should not decrease when going to a more challenging descriptor.
13. This is indeed also true for the worst-case solution, i.e. when the least favourable solutions for each key function are chosen. Again, the significant change mainly depends on the same key function within the *Compatibility* user requirement (see CP-2, Appendix B).
14. From 57.9 to 4.6, see Appendix A for a table with normalized scores of best-case solutions per user requirement.
15. T. Milne and H. Wilson, Verifying the transition from low levels of nuclear weapons to a nuclear weapon-free world; SIPRI, Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions; Fuller, "Verification on the Road to Zero: Issues for Nuclear Warhead Dismantlement."
16. "Treaty on the Non-Proliferation of Nuclear Weapons," Treaty Series: Treaties and International Agreements Registered or Filed and Recorded with the Secretariat of the United Nations 729, no. 10485 (1974): 172.

Appendix A.

Normalized scores per user requirement

Table A.1. Normalized scores of best-case solutions per user requirement for Facility type I to IV (standard weighting).

	Normalized score per user requirement				
Facility type	Compatibility	Verification	Confidentiality	Safety	Security
I	6,2	5,9	2,8	2,3	1,1
II	3,0	2,2	1,2	2,7	1,4
III	5,8	1,2	1,3	24,8	2,9
IV	57,9	0,5	0,2	0,4	0,3

Appendix B.
key functions, solutions, and scoring

Table B.1. User requirements with full set of corresponding key functions, solutions, and scoring for each facility type.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
Compatibility (CP)	CP-1	In-facility storage of multiple warheads prior to dismantlement (warheads can be received at higher rate than verified dismantlement rate).	CP-1A	Facility can store multiple warheads, pre-dismantlement.	C	B	C	A	
	CP-2	Verified dismantlement is repeatable on additional warheads.	CP-2A	Initial state of the dismantlement area and supporting process areas is reestablished (re-verified) before each dismantlement operation.	D	D	B	A	A type I facility would probably be harder than a type II facility, but not enough to justify an "E".
			CP-2B	Initial state (as above) established once, then maintain CoK (CoC, material balance, design verification, etc.).	F	C	C	B	A type I facility score would change from "F" to "C" if a dismantlement process line could be segregated for dedicated treaty use.
	CP-3	Facility must be sited at a location compatible with public safety.	CP-3A	Implement.	A	D	C	A	Public safety impact of a type II facility may have changed over time.
	CP-4	Ability /effort required to acquire site for a dismantlement facility.	CP-4A	Implement.	C	B	E	E	
	CP-5	Facility able to support multi-day operation, with overnight shutdown of operations.	CP-5A	Always maintain host and inspector presence in relevant areas.	D	C	C	C	
			CP-5B	Provisions for maintaining CoK on verification equipment and data, as well as secure storage of warheads, components, tooling and sensitive documents or recorded data.	C	C	C	A	

(*continued*)

Table B.1. Continued.

					Facility type scoring				
User require-ment	#	Key function	#	Solution	I	II	III	IV	Comment
	CP-6	Facility must be accessible for transport of warheads (input) and components (output).	CP-6A	Implement.	A	D	C	A	Accessibility of a type II facility may have changed over time.
	CP-7	Facility design should limit delays to the dismantlement process, and therefore credibility or financial or other damage.	CP-7A	Ensure extra resources (mainly space) available as required to buffer delays and disturbances.	E	D	C	A	The type I facility score of "E" reflects the risk that treaty dismantlement work could be negatively affected by other work.
	CP-8	Facility must be made operational in a timely manner.	CP-8A	Implement.	E	D	E	F	Normalized to a timescale on which there is considerable effort required (very difficult, "E") to implement verified dismantlement in a type I facility. Consider factors such as impact on host's national deterrent program and political, administrative and legislative processes.
	CP-9	Dismantlement operations at facility should have minimal impact on host's wider national deterrent program.	CP-9A	Implement.	D	B	B	B	
Verification (V)	V-1	Design of facility allows use of verification equipment.	V-1A	Adequate space to install equipment. Design attributes that prevent the use of verification equipment are avoided. Adequate infrastructure to install main and ancillary equipment (cables, power, communications equipment).	E	D	C	A	Somewhat easier in a facility with no ongoing weapons work. Difficult to completely deconvolve Confidentiality, Safety and Security issues from Verification in this case.

(*continued*)

Table B.1. Continued.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
	V-2	Facility has the means to identify warhead and receive it into pre-dismantlement storage.	V-2A	Identify using measurements.	D	D	B	A	Possible nuclear forensics pose similar difficulties in Facility type I and II.
			V-2B	Use unbroken paperwork/ records (envisions a relatively comprehensive audit of document trail)	E	E	E	E	It would be technically difficult to make this the only solution regardless of facility.
			V-2C	Use continuous inspector presence.	D	C	B	B	The solution is not implicit in a dedicated facility as it would be no different to the converted industrial facility solution.
			V-2D	Use containment and surveillance measures.	D	C	C	A	Issues considered include: Would floor plans be needed? Doors that you cannot see behind?
	V-3	Pre-dismantlement storage can accept measures needed to maintain CoK over items stored.	V-3A	Use continuous inspector presence.	E	C	B	B	V-2 and V-3 may be similar, but V-2 is the initial process and V-3 is the continuing state. This difference may result in different scores.
			V-3B	Use containment and surveillance measures.	D	C	B	A	The type I facility is consistently marked as more difficult due to the possibility of "traffic" in the storage area.
	V-4	Facility has the means to allow CoK to be maintained through the process of warhead identification and checkout from pre-dismantlement storage.	V-4A	Identify using measurements.	D	D	B	A	
			V-4B	Use unbroken paperwork/records.	D	D	D	D	
			V-4C	Use continuous inspector presence.	D	C	B	A	
			V-4D	Use containment and surveillance measures.	D	C	C	A	
	V-5	Facility should accommodate verification that no other warhead is present in dismantlement process area.	V-5A	Material flow control using containment and surveillance measures (Ensure that no warhead or essential components have	D	C	B	A	

(*continued*)

Table B.1. Continued.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
				entered dismantlement process area without subsequent exit)					
			V-5B	Material flow control using inspector presence (Ensure that no warhead or essential components have entered dismantlement process area without subsequent exit)	E	D	C	B	
			V-5C	Dismantlement process area can be swept for warheads and essential components prior to process start using visual inspection only.	D	C	C	B	
			V-5D	Dismantlement process area can be swept for warheads and essential components prior to process start using measurements.	E	D	C	C	
	V-6	Facility has the means to allow verification that specific checked-out warhead enters dismantlement process.	V-6A	Identify using measurements.	D	D	B	A	
			V-6B	Use unbroken paperwork/records.	D	D	D	D	
			V-6C	Use continuous inspector presence.	D	C	B	A	
			V-6D	Use containment and surveillance measures.	D	C	C	A	
	V-7	Facility has the means to allow inspector detection of attempts to remove entire warhead or essential components.	V-7A	Control dismantlement area perimeter and inspect dismantlement area after completion of process.	D	C	B	A	
			V-7B	Continuous surveillance of relevant aspects of	E	D	C	B	

(*continued*)

Table B.1. Continued.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
				dismantlement process (i.e., diversion of warhead or essential components).					
	V-8	Facility has the means to allow detection of attempts to introduce another warhead or essential components to dismantlement process.	V-8A	Control dismantlement area perimeter during dismantlement process.	D	C	C	B	
			V-8B	Continuous surveillance of relevant aspects of dismantlement process (i.e., insertion of warheads or essential components).	E	D	C	B	
	V-9	Facility has the means to allow verification of essential components after dismantlement.	V-9A	Verify absence of essential components in inappropriate separate containers.	D	D	C	C	
			V-9B	Verify presence of essential components in appropriate separate containers.	E	E	D	D	
			V-9C	Combination of V-9A and V-9B.	C	C	B	B	This is the one exception to the "no-combination" rule; discussed in the section titled "Solutions to key functions".
	V-10	Facility has the means to allow inspectors to verify the correctness of the dismantlement process by maintaining CoK on essential components during dismantlement (warhead disassembly stage).	V-10A	Confirm using measurements.	E	D	D	D	Scoring very dependent on measurement scenario. Before/after measurements; installed equipment covering process (e.g., scale(s), portal monitor(s)); gamma camera templating; IB technology.
			V-10B	Use continuous inspector presence.	E	E	E	E	Mostly process-driven rather than determined by facility.
			V-10C	Use containment and surveillance measures.	E	D	C	C	Process area perimeter control for inspectors harder in type I facility; appropriate measures easier to accomplish by design.

(*continued*)

Table B.1. Continued.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
	V-11	Facility has the means to allow inspectors and hosts to ensure integrity of data that is used as basis for verification conclusions.	V-11A	Store data in facility under joint seal.	B	B	B	B	
			V-11B	Store records/agreed joint conclusions in facility under joint seal (no underpinning data stored).	B	B	B	B	
	V-12	Facility has the means to allow inspectors to ensure the correct functionality of any mobile verification measurement equipment.	V-12A	Initial verification that equipment complies with specifications, then store under joint seal.	C	B	B	B	
			V-12B	Repeatable verification that equipment complies with specifications.	D	B	B	B	Potential additional constraints from other ongoing work on the possibilities of validation.
	V-13	Facility has the means to allow inspectors to ensure correct functionality of any installed verification measurement equipment.	V-13A	Initial verification that equipment complies with specifications, then store under joint seal.	C	C	B	B	
			V-13B	Repeatable verification that equipment complies with specifications.	D	C	C	C	
	V-14	Facility provides office/analysis space for inspection team.	V-14A	Implement.	B	B	B	A	
Confidentiality (CF)	CF-1	Facility allows protection of proliferative aspects of warheads pre-dismantlement.	CF-1A	Secure storage and handling of warheads designed to restrict access to proliferative information.	B	B	B	A	
			CF-1B	Managed access procedures (e.g., shrouding, walkways and restricted views).	C	C	B	A	
	CF-2	Facility allows protection of proliferative aspects of warheads during dismantlement.	CF-2A	Entire dismantlement/ proliferation-sensitive aspect occurs in presence of host staff only.	A	A	B	A	

(*continued*)

Table B.1. Continued.

					Facility type scoring				
User require-ment	#	Key function	#	Solution	I	II	III	IV	Comment
			CF-2B	Managed access procedures (e.g., shrouding, walkways and restricted views.)	D	D	C	A	Facility type III appears better than existing nuclear warhead facilities; redesign of the facility interior is easier.
	CF-3	Facility allows protection of proliferative aspects of essential components.	CF-3A	Secure handling of essential components designed to restrict access to proliferative information.	C	C	B	A	
			CF-3B	Managed access procedures (e.g., shrouding, walkways and restricted views).	D	D	C	A	
			CF-3C	Facility can accommodate process for removal of proliferative properties of essential components (e.g., shape change).	E	E	D	C	
	CF-4	Facility allows protection of proliferative documentation.	CF-4A	Secure storage and handling of documentation.	B	B	B	B	
			CF-4B	Managed access procedures (e.g., shrouding, walkways and restricted views).	D	D	C	A	
	CF-5	Facility allows protection of proliferative aspects of tooling.	CF-5A	Secure storage of tooling pre and post dismantlement.	B	B	B	A	
			CF-5B	Managed access procedures (e.g., shrouding, walkways and restricted views).	D	D	C	A	
	CF-6	Facility allows protection of national security aspects of warheads pre-dismantlement.	CF-6A	Secure storage and handling of warheads designed to restrict access to national-security sensitive information.	D	B	B	A	
			CF-6B	Managed access procedures (e.g., shrouding, walkways and restricted views).	D	C	C	A	

(*continued*)

Table B.1. Continued.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
	CF-7	Facility allows protection of national security aspects of warheads during dismantlement.	CF-7A	Entire dismantlement/national-security sensitive aspect occurs in presence of host staff only.	A	A	B	A	
			CF-7B	Managed access procedures (e.g., shrouding, walkways and restricted views).	D	D	C	A	
	CF-8	Facility allows protection of national security aspects of essential components.	CF-8A	Secure handling of essential components designed to restrict access to national-security sensitive information.	C	C	B	A	
			CF-8B	Managed access procedures (e.g., shrouding, walkways and restricted views).	D	D	C	A	
			CF-8C	Facility can accommodate process for removal of national-security sensitive properties of essential components (e.g., shape change).	E	E	D	D	
	CF-9	Facility allows protection of national-security sensitive documentation and operational information.	CF-9A	Secure storage and handling of documentation.	D	B	B	B	
			CF-9B	Managed access procedures (e.g., shrouding, walkways and restricted views).	D	D	C	A	
	CF-10	Facility allows protection of national-security sensitive aspects of tooling.	CF-10A	Secure storage of tooling pre and post dismantlement.	C	B	B	A	
			CF-10B	Managed access procedures (e.g., shrouding, walkways and restricted views.	D	D	C	A	
	CF-11	Ability to install/allow operation of separate IT systems for inspectors.	CF-11A	Prior to construction/ installation of any equipment,	E	D	C	C	

(*continued*)

Table B.1. Continued.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
				appropriate host accreditor to approve IT infrastructure.					
	CF-12	Ability to restrict different people to different facility areas.	CF-12A	Pass-based electronic access system for each defined area. Individuals are assigned to groups within this system.	B	B	B	B	
			CF-12B	Key-based mechanically lockable access system for each defined area.	C	C	C	C	
			CF-12C	Available areas for guards at entryways.	C	C	C	A	
	CF-13	All entryways should have the ability to be monitored for personnel movement	CF-13A	Pass-based electronic access system for each defined area. Individuals are assigned to groups within this system.	B	B	B	A	
			CF-13B	Available areas for guards at entryways	C	C	C	A	
			CF-13C	CCTV.	B	B	B	A	
	CF-14	Facility designed with consideration of need to search vehicles and personnel on entry/exit from site	CF-14A	Areas to perform searches required, limited number of entrances to site/facility. Separate for deliveries (lorries) and staff vehicles.	A	A	C	A	
			CF-14B	Automated search mechanism (unspecified, but e.g., portal monitor).	B	B	C	A	
	CF-15	Designed with consideration of lines of sight from external to site to inside facility buildings	CF-15A	Shrouds, Blinds, Mirrored windows.	A	B	C	A	
			CF-15B	No windows.	A	A	C	A	
			CF-15C	Large perimeter wall.	A	B	C	A	
			CF-15D	No area containing sensitive items or processes at the	A	A	D	A	

(*continued*)

Table B.1. Continued.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
				building perimeter (at least one room separation).					
	CF-16	Facility able to receive inspectors without compromise to nonproliferation.	CF-16A	Application of managed access measures as appropriate (e.g., shrouding and covering of sensitive items and signage, aid where possible in the restriction of covert nuclear forensics, removal of items, image and sound recording, emplacement of items or devices).	D	C	C	B	Facility type IV can be designed to more easily accommodate host's requirement to control inspectors' actions (covert sampling, information gathering etc.).
			CF-16B	No proliferative information or source of information is present in areas of facility visited by inspectors.	D	C	C	C	
	CF-17	Facility able to receive inspectors without compromise to national security.	CF-17A	Application of managed access measures as appropriate (e.g., shrouding and covering of sensitive items and signage, aid where possible in the restriction of covert; nuclear forensics, removal of items, image and sound recording, emplacement of items or devices).	D	C	C	B	Facility type IV) can be designed to more easily accommodate host's requirement to control inspectors' actions (covert sampling, information gathering etc.).
			CF-17B	No information or source of information compromising national security is present in areas of facility visited by inspectors.	E	B	B	B	

(*continued*)

Table B.1. Continued.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
	CF-18	Facility able to support multi-day operation without compromise to nonproliferation through overnight shutdown of operations.	CF-18A	Always have host presence in relevant areas.	C	C	C	C	
			CF-18B	Provisions for housing/storing verification equipment and data on site without compromise to nonproliferation, as well as secure storage of warheads, components, tooling and sensitive documents or recorded data.	C	C	C	A	This requirement and solution is worded similarly to CP-5, but has different driving concerns: Nonproliferation as opposed to multi-day verified dismantlement operations in general.
	CF-19	Facility able to support multi-day operation without compromise to national security through overnight shutdown of operations.	CF-19A	Always have host presence in relevant areas.	C	C	C	C	
			CF-19B	Provisions for housing/storing verification equipment and data on site without compromise to national security, as well as secure storage of warheads, components, tooling and sensitive documents or recorded data.	D	C	C	A	This requirement and solution is worded similarly to CP-5, but has different driving concerns: National security as opposed to multi-day verified dismantlement operations in general.
Safety (SF)	SF-1	Ability to monitor all entryways for contraband materials (e.g., radioactive materials, fissile material, explosives, electrical equipment, igniters).	SF-1A	Space and infrastructure for installation of appropriate monitoring equipment and procedures as required.	B	B	C	A	
	SF-2	Compliance with a set of Ionizing radiation regulations agreed by participating nations (includes storage of	SF-2A	Implement agreed ionizing radiation regulations.	A	B	B	A	

(*continued*)

Table B.1. Continued.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
		separated radioactive materials post dismantlement.)							
	SF-3	Compliance with a set of high explosives regulations agreed by participating nations (includes storage of separated explosive materials post dismantlement.)	SF-3A	Implement agreed explosives regulations.	C	C	E	A	Includes storage of ammunition / guns for security personnel (ordinance).
	SF-4	All host permanent equipment and installations will be appropriate for operation around a nuclear weapon.	SF-4A	Permanent equipment and installations are assessed and tested prior to inclusion in designated dismantlement areas as required.	B	D	D	A	Supporting infrastructure. For a type II facility, extensive adaptations may be required.
	SF-5	Comply with directives for Special Nuclear Material (SNM) handling storage.	SF-5A	Implement agreed SNM regulations.	B	D	E	A	
	SF-6	Facility must be able to accommodate both host and inspector staff simultaneously while complying with modern standard health and safety regulations.	SF-6A	Implement Building regulations, Fire regulations, and occupancy numbers for rooms must be sufficient.	B	B	B	B	Explosives regulations are likely to be the most restrictive factor determining the number of people allowed in an area.
	SF-7	Facility must be able to safely store warheads in access-restricted area prior to dismantlement.	SF-7A	Provide separate area where access is physically restricted and controlled.	B	B	D	A	
	SF-8	Facility must be able to safely store warhead components and disassembly output (excepting radioactive or explosive components) in access-restricted area following dismantlement.	SF-8A	Provide separate area where access is physically restricted and controlled.	C	C	C	B	Type IV facility will still not score "A" as unforeseen demands may arise that cannot be considered at design.

(*continued*)

Table B.1. Continued.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
	SF-9	Facility must be able to safely store process-enabling substances and materials.	SF-9A	Provide separate area where access is physically restricted and controlled.	C	C	C	B	Type IV facility will still not score "A" as unforeseen demands may arise that cannot be considered at design.
	SF-10	Facility must allow for movement of large, heavy objects.	SF-10A	Facility should provide adequate access to buildings and transfer corridors between areas, floor loading must be adequate for predicted mass, space must be available for any lifting equipment required.	C	C	C	A	This may include the changing of corridors to allow for bigger packages. Would age of facility have a positive or negative effect here?
	SF-11	Access to areas where safety procedures or equipment are required should be restricted to those who understand these measures.	SF-11A	Pass-based electronic access system for each defined area. Individuals are assigned to groups within this system.	B	B	B	A	Much of this is covered by regulations cited above, however the access aspects are considered of particular importance.
			SF-11B	Key-based mechanically lockable access system for each defined area.	B	B	B	A	
			SF-11C	Available areas for guards at entryways.	C	C	C	A	
	SF-12	Facility should help mitigate, to regulatory expectations, against accident consequences.	SF-12A	Implement.	E	E	F	A	This will be a major design influence on the facility. Cost is expected to be high. Assumption made that a warhead type being brought for dismantlement was not previously handled in the facility.
	SF-13	Location of facility should avoid, or be defensible against, flood.	SF-13A	Avoid location in flood plain; carefully assess future potential for flood risk or coastal erosion.	C	C	D	C	Facility types I and II may not necessarily be in the best location in relation to current standards, despite mitigating actions to make situation adequate. A new facility might need to be relocated rather than use engineering controls.

(*continued*)

Table B.1. Continued.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
	SF-14	Location of facility should avoid or be designed to withstand earthquakes.	SF-14A	Assess and implement appropriate planning and design measures.	C	C	D	C	The consequences of these environmental scenarios may vary in their difficulty of mitigation. In addition, older buildings may have outdated regulations, which were good at the time of building but in the advent of major works may have to be re-visited.
	SF-15	Location of facility should avoid or be designed to withstand tsunami.	SF-15A	Assess and implement appropriate planning and design measures.	C	C	D	C	
	SF-16	Buildings containing warhead related activities should be resistant to storm damage.	SF-16A	Assess and implement appropriate planning and design measures.	C	C	D	A	
	SF-17	Buildings containing warhead related activities should be resistant to lightning strike.	SF-17A	Assess and implement appropriate planning and design measures.	B	B	C	A	
	SF-18	Buildings containing warhead related activities should be resistant to static charge build-up.	SF-18A	Assess and implement appropriate planning and design measures.	B	C	D	A	
	SF-19	Buildings containing warhead related activities should be resistant to snow loading.	SF-19A	Assess and implement appropriate planning and design measures.	C	C	D	A	Highly dependent on building age.
	SF-20	Buildings containing warhead related activities should be resistant to ice build-up.	SF-20A	Assess and implement appropriate planning and design measures.	C	C	D	A	
	SF-21	Facility should have good temperature regulation in buildings containing warhead related activities.	SF-21A	Assess and implement appropriate planning and design measures.	B	B	C	A	
	SF-22	Facility should have backup in the event of power failure.	SF-22A		C	C	D	A	

(*continued*)

Table B.1. Continued.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
				Assess and implement appropriate planning and design measures.					
	SF-23	High voltage should be limited in buildings containing warhead related activities.	SF-23A	Assess and implement appropriate planning and design measures.	C	C	D	A	
	SF-24	Facility should have exit routes from site to road that are safe, i.e., no challenging road junctions.	SF-24A	Assess and implement appropriate planning and design measures.	C	C	D	A	
	SF-25	Facility should comply with requirements related to safety of local populations.	SF-25A	Assess and implement appropriate planning and design measures.	C	C	D	B	
Security (SC)	SC-1	The facility must be defensible against external unauthorized ingress (persons, road, tunneling).	SC-1A	Perimeter security (layered, fence, wall and signage, unauthorized entrance detection), regulated perimeter entrance (guards, pass).	B	B	C	B	Site dependent.
	SC-2	There must be suitable routes into/out of the site to transport warheads without unnecessary risk.	SC-2A	More than one possible route.	C	C	C	B	
			SC-2B	One route heavily guarded.	B	B	B	A	
	SC-3	Theft of physical material should be hindered by facility design (e.g., theft of warhead).	SC-3A	Follow best practices for multi-layered site security.	B	C	D	A	
	SC-4	Security personnel and equipment must be accommodated in the facility design.	SC-4A	Provision of area for security personnel and equipment.	B	B	B	A	
	SC-5	The facility must be able to withstand damage from internal or external hostile	SC-5A	All dismantlement process behind at least one layer of security.	C	C	D	C	Similar to seismic issues – facilities are built to withstand the threat at the time of construction.

(*continued*)

Table B.1. Continued.

User require-ment	#	Key function	#	Solution	Facility type scoring I	II	III	IV	Comment
		physical action and still continue to function.							
	SC-6	The facility must be able to withstand damage from internal or external hostile cyber action and still continue to function.	SC-6A	Separate systems from the internet or pen (e.g., paper) solution.	C	C	C	A	Assumption that facility is built with verification in mind for new facility.
	SC-7	Facility should be able to maintain security processes during adverse weather conditions.	SC-7A	Assess and implement appropriate planning and design measures.	B	B	D	A	Analogue to safety.
	SC-8	Facility should be able to maintain security processes in the event of fire.	SC-8A	Assess and implement appropriate planning and design measures.	B	B	D	A	Analogue to safety.
	SC-9	Facility should be able to maintain security processes in the event of power failure.	SC-9A	Assess and implement appropriate planning and design measures.	B	C	C	A	Analogue to safety.
	SC-10	Facility must have location for secure storage of security staff (police) equipment e.g., guns and ammunition.	SC-10A	Secure location for security staff equipment available.	A	B	B	A	