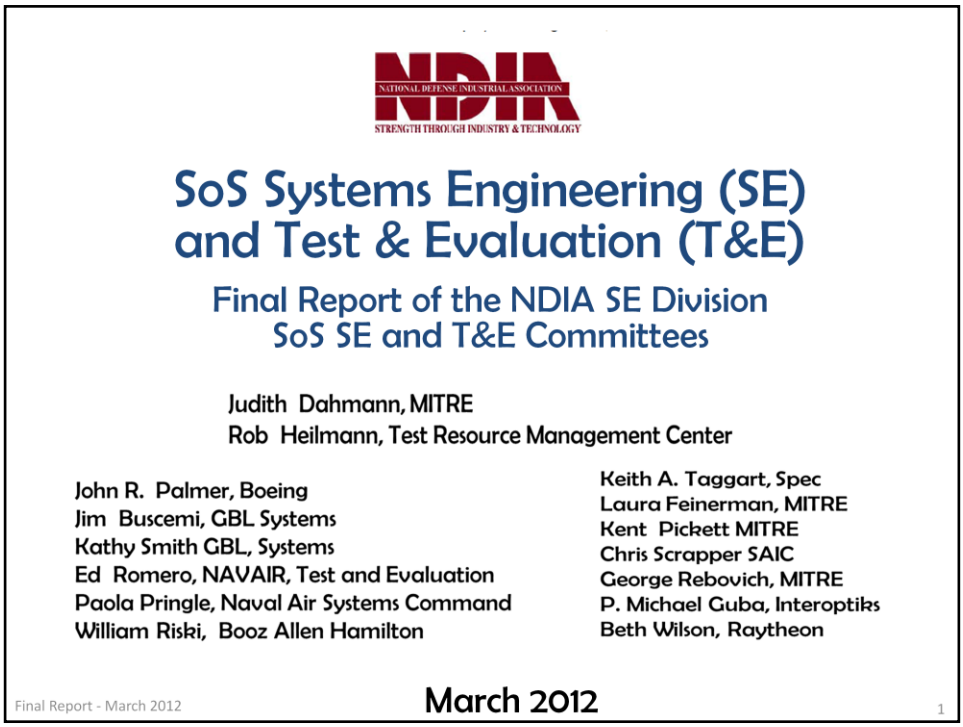


This presentation provides the results of an National Defense Industry Association (NDIA) Systems Engineering Division (SED) task implemented by members of the Systems of Systems and Test and Evaluation Committees.

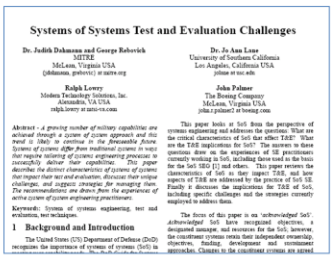
Abstract

This report presents an approach to integrated systems engineering (SE) and test and evaluation (T&E) for SoS based on work underway by the National Defense Industry Association Systems Engineering Division Systems of Systems and Developmental Test and Evaluation Committees. The report focuses on how to approach T&E for SoS given the challenges of large scale SoS development as a continuous improvement process that provides information on capabilities and limitations for end users and feedback to the SoS and system SE teams toward SoS evolution.

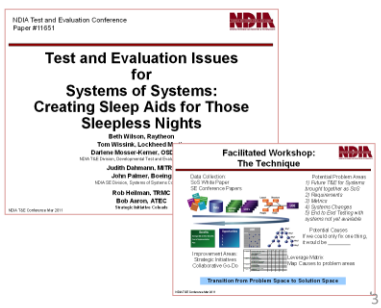
Task

- NDIA Strategic Initiative: Best Practices Model for SoS T&E
  - Product of one-day facilitated SoS and T&E Workshop sponsored by NDIA SoS SE and DTE committees, held August 17, 2010, MITRE, McLean VA
  - Adopted by NDIA SoS SE Committee to work with T&E Committee to address this as a 2011 action
  - Purpose: Outline the fundamentals of the model of SoS T&E as a:

"Continuous improvement process supporting capabilities and limitations information for end users and feedback to the SoS and system SE teams toward evolution of the SoS"


Systems of Systems Test and Evaluation Challenges

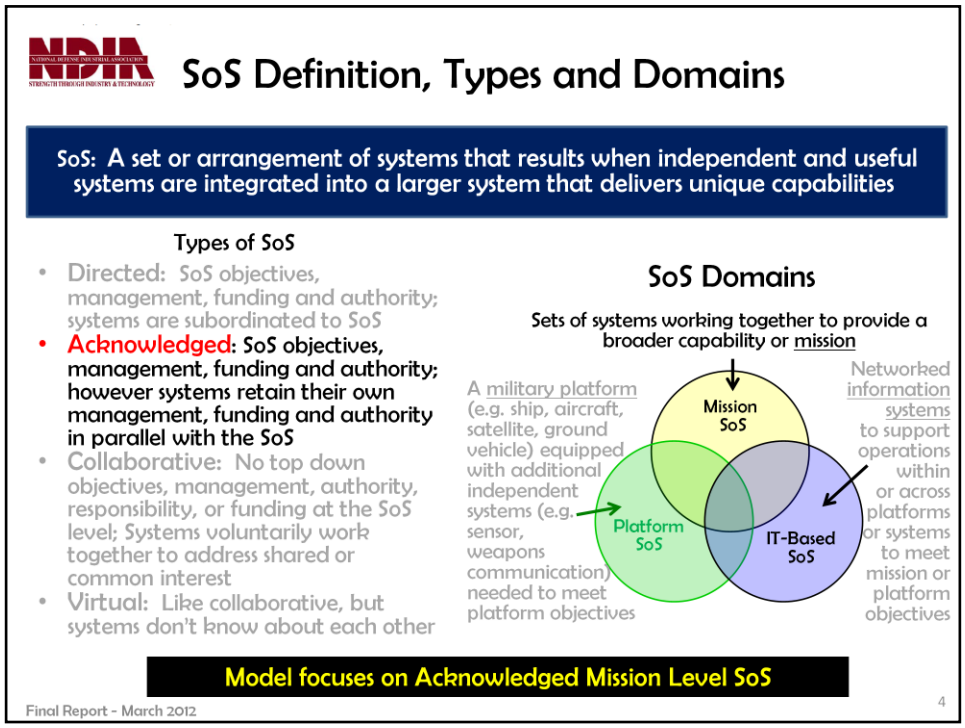
2010 IEEE SoSE Conference



Final Report - March 2012

From the initiation of the SoS committee of the NDIA SE Division in 2008, members identified SoS and T&E as an area of high interest, and the committee initially focused on understanding the challenges of SoS and T&E.

In August 2010, the SoS and Test Committees joined in a workshop to address these challenges. A recommendation from the workshop was to develop a 'best practices' model for T&E for SoS. A team was formed and, over the following year, work was undertaken to review the issues facing T&E of SoS given the driving characteristics of SoS, current guidance on SoS SE T&E, and experience with SoS and T&E. The initial results of this work is presented in this report.



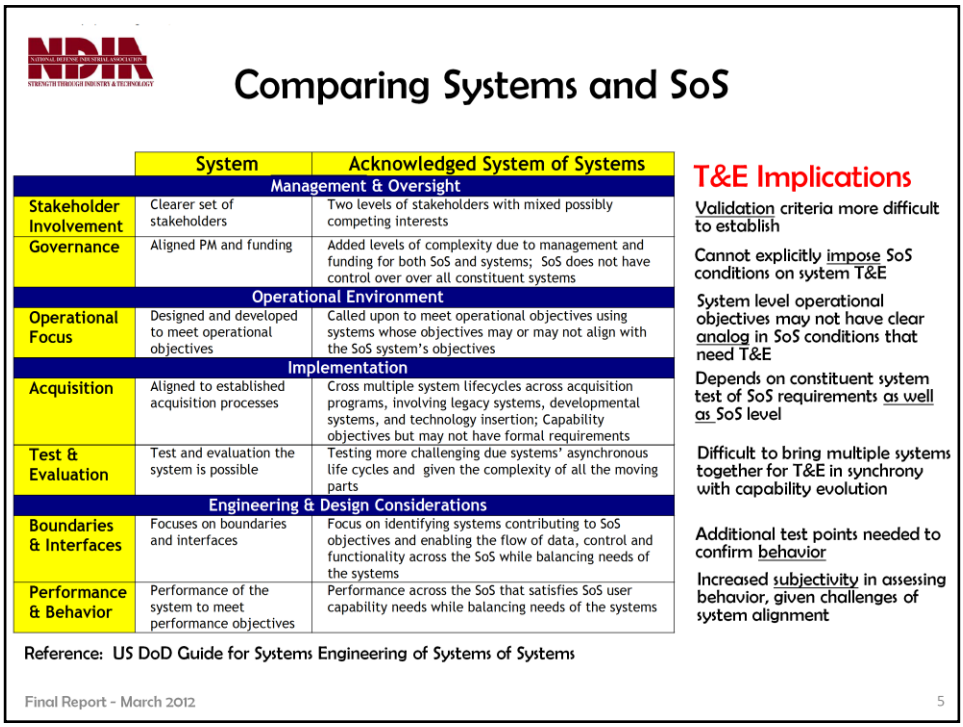
This slide provides basic definitions and scope for the task.

This task used the DoD definition of an SoS: "a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities"

The task focused on 'acknowledged' and 'mission-level' SoS. Acknowledged SoS have recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, development and sustainment approaches. 'Mission-level' SoS are those SoS where multiple platforms, information technology (IT) and other systems are brought together to meet larger mission level capability objectives.

Other SoS, such as platform-level SoS (integration of separately developed systems on a submarine for instance) and IT-based SoS (where information across an SoS is managed as an enterprise asset), share many of the issues addressed here, but they have their own specific considerations, as well. A potential next step in this research is to look more closely at how this approach applies to other SoS types and domains.

[1] DoD Defense Acquisition Guidebook, Chapter 4.



Comparing Systems and SoS

	System	Acknowledged System of Systems
Management & Oversight		
Stakeholder Involvement	Clearer set of stakeholders	Two levels of stakeholders with mixed possibly competing interests
Governance	Aligned PM and funding	Added levels of complexity due to management and funding for both SoS and systems; SoS does not have control over over all constituent systems
Operational Environment		
Operational Focus	Designed and developed to meet operational objectives	Called upon to meet operational objectives using systems whose objectives may or may not align with the SoS system's objectives
Implementation		
Acquisition	Aligned to established acquisition processes	Cross multiple system lifecycles across acquisition programs, involving legacy systems, developmental systems, and technology insertion; Capability objectives but may not have formal requirements
Test & Evaluation	Test and evaluation the system is possible	Testing more challenging due systems' asynchronous life cycles and given the complexity of all the moving parts
Engineering & Design Considerations		
Boundaries & Interfaces	Focuses on boundaries and interfaces	Focus on identifying systems contributing to SoS objectives and enabling the flow of data, control and functionality across the SoS while balancing needs of the systems
Performance & Behavior	Performance of the system to meet performance objectives	Performance across the SoS that satisfies SoS user capability needs while balancing needs of the systems

T&E Implications

Validation criteria more difficult to establish

Cannot explicitly impose SoS conditions on system T&E

System level operational objectives may not have clear analog in SoS conditions that need T&E

Depends on constituent system test of SoS requirements as well as SoS level

Difficult to bring multiple systems together for T&E in synchrony with capability evolution

Additional test points needed to confirm behavior

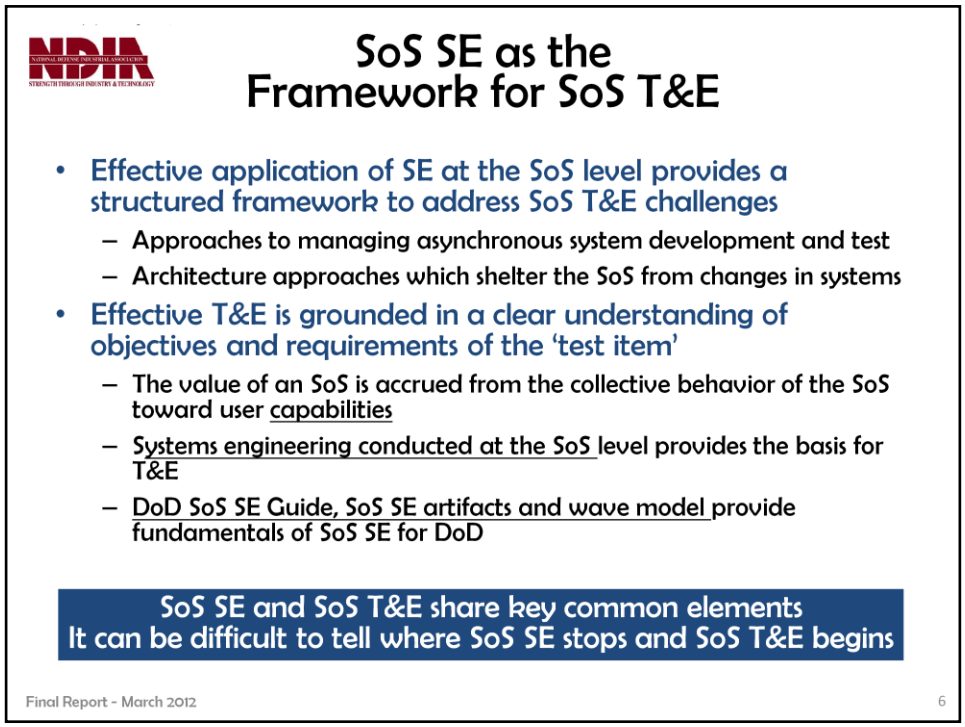
Increased subjectivity in assessing behavior, given challenges of system alignment

Reference: US DoD Guide for Systems Engineering of Systems of Systems

Final Report - March 2012 5

This chart shows the difference between systems and acknowledged SoS based on work presented in the DoD Guide to SE for SoS. The slide also highlights the implications of these differences for T&E for an SoS based on work done on the challenges of SoS for T&E [1].

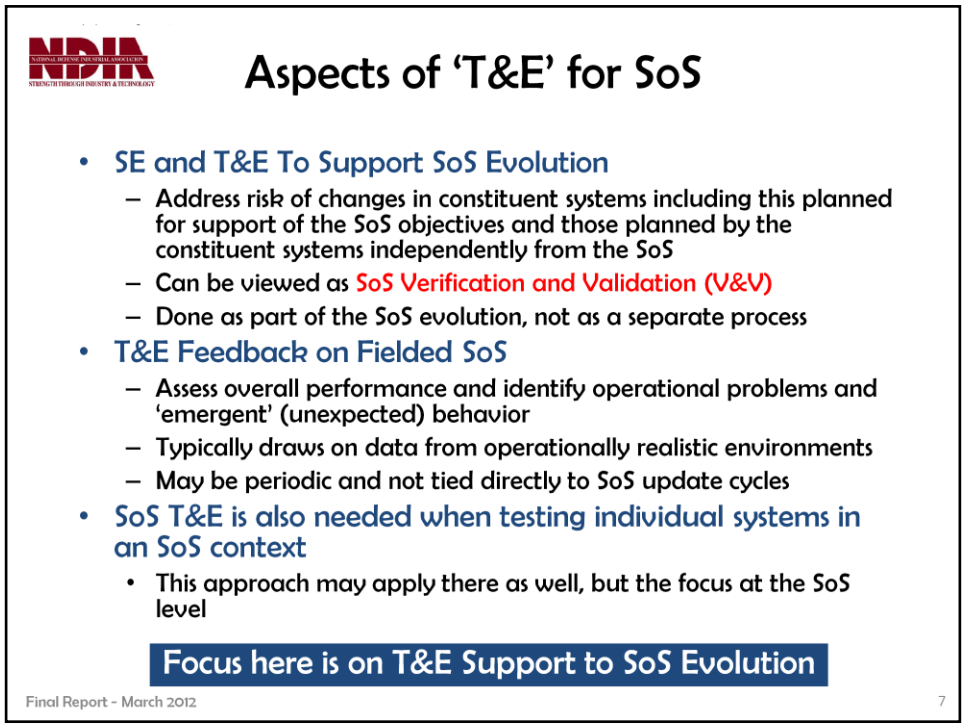
[1] Dahmann, J., G. Rebovich, J, Lane and R. Lowry. "Systems of systems test and evaluation challenges," Proceedings of Institute of Electrical and Electronics Engineers Systems of Systems Engineering Conference, May, Loughborough, UK, June 2010.]



SoS present challenges which also impact T&E. Most acknowledged mission SoS are comprised of multiple, existing systems which maintain managerial and operational independence and hence have their own development and upgrade cycles. SoS evolution is a product of changes in constituent systems which are typically implemented asynchronously across an SoS. Since the systems typically continue to support other users concurrently with their role in an SoS, there is natural resistance to delaying a system's deployment until other systems' developments have completed and an SoS test can be conducted. In addition, systems may be making changes independently from the SoS to meet other user needs.

Consequently, it can be very difficult to align changes in systems across an SoS and, in effect, there may be changes in a large SoS taking place fairly continuously. These are challenges which face SE of SoS in development of a sound SoS architecture and in implementing a disciplined approach to evolution of an SoS. Similarly, they affect the ability to conduct T&E as typically practiced in system acquisition where T&E is used to support acceptance and deployment decisions.

This discussion is grounded in the principle that applying effective T&E to an SoS is based on effective application of SE at the SoS level. As a result, SoS SE and SoS T&E share key common elements making it somewhat difficult to tell where SE stops and T&E begins. SoS objectives and metrics serve as the basis for requirements on constituent systems and for evaluating SoS objectives. As such SoS SE provides a starting framework to address SoS T&E challenges including approaches to accommodating asynchronous system development and test and to developing architecture approaches which shelter the SoS from changes in systems.



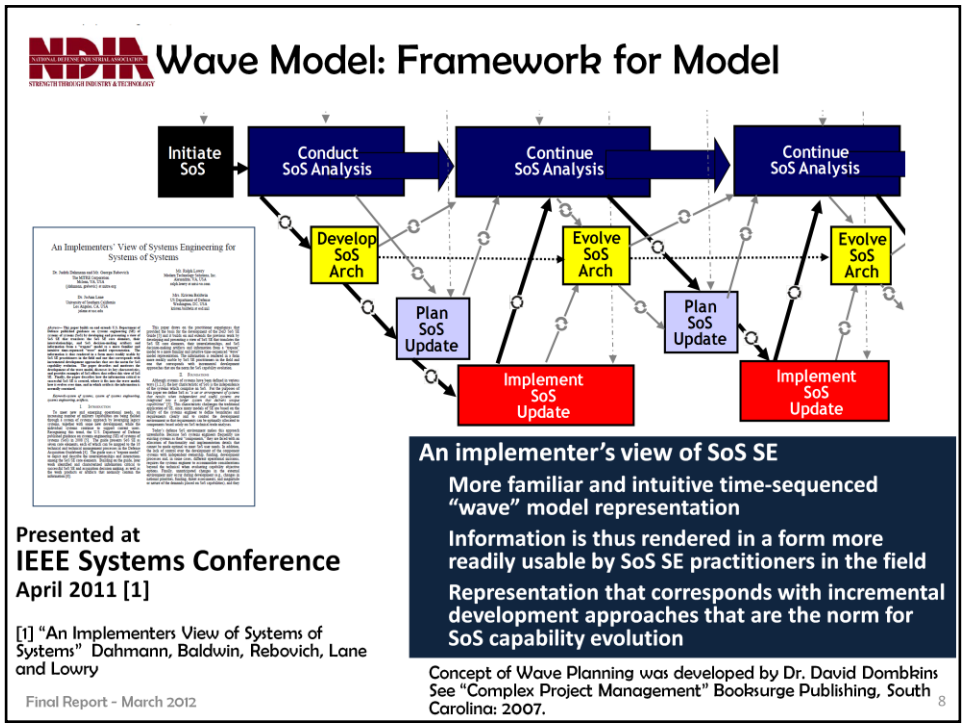
There are several perspectives one can take on T&E for SoS.

First, systems engineering and T&E can be focused on supporting the evolution of the SoS. This is the focus of this report. It looks at risks of changes in constituent systems to adversely impact either the SoS or other constituent systems. This includes changes made to respond to SoS needs or other changes made independently from the SoS to meet constituent systems needs. In many ways this is conceptually akin to V&V of the SoS, although the characteristics of SoS and their evolution mean that V&V of SoS may look different from what is done with individual system develops.

Second, it has been recognized that it can be difficult to 'create' a realistic environment for large SoS and hence there are advantages to gathering feedback from field implementation of SoS. This feedback can address both data on the performance of the SoS as well as on any operational issues or unexpected, emergent behavior. These environments may be field exercises or actual deployments. Because these are often opportunistic they may take place asynchronously from SoS development cycles. This aspect of SoS and T&E is not addressed in this report.

Finally, given that most systems support one or more SoS capabilities, there is increased interest on how to evaluate systems in terms of their contribution to SoS

capability objectives. The approach described in this report may contribute to this aspect of SoS and T&E, but it was not the focus of the study.



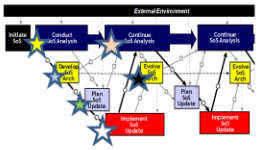
Most SoS development is evolutionary, with updates to the SoS accruing over time based on changes in constituent systems. A model of implementation of the evolution of an SoS – the 'wave model' -- shown this slide[1], is used as the framework for the task.

This 'wave model' for systems engineering of an SoS builds on Dombkins 'work on 'wave planning' for complex systems management [2].It is characterized by multiple overlapping iterations of evolution supported by ongoing analysis which provides an analytic basis for each iteration or wave of SoS evolution. Continuous monitoring of the external environment is key for SoS SE, since any manager or engineer of an SoS has control over only a small part of the environment that affects the SoS. Finally architecture evolution is also important. The architecture of an SoS provides a persistent framework for the SoS evolution over time, however the architecture is typically implemented incrementally and may itself evolve.

[1] J. Dahmann, G. Rebovich, J, Lane and R. Lowry. "Implementer's View of Systems Engineering for Systems of Systems," Proceedings of Institute of Electrical and Electronics Engineers Systems Conference, Vancouver, Canada. May 2011.

[2] D. Dombkins. Complex Project Management, Booksurge Publishing, South Carolina: 2007.

SoS SE and T&E Evolution at Each Step



- **Recognize SoS T&E constraints**
  - Full SoS T&E to address changes in constituent systems is not feasible given the size and complexity of many SoS and the dynamic nature of constituent systems
    - Includes conventional live testing and approaches using various forms of virtual and constructive simulation
- **Focus T&E specifically on areas of risk**
  - Begin with the changes which have been made in the SoS
  - Identify where changes could have adverse impacts on the user missions
  - Assess the risk using evidence from a range of sources including live test
    - Evidence can be based on activity at the SoS level, as well as roll-ups of system level activity and can be explicit verification testing, results of models and simulations, use of linked integration facilities, and results of system level operational test and evaluation
- **Results 'Continuous improvement' feedback to**
  - End users in the form of 'capabilities and limitations' rather than as test criteria for SoS 'deployment'
  - SE teams of both the SoS and systems on progress and issues

Final Report - March 2012 9

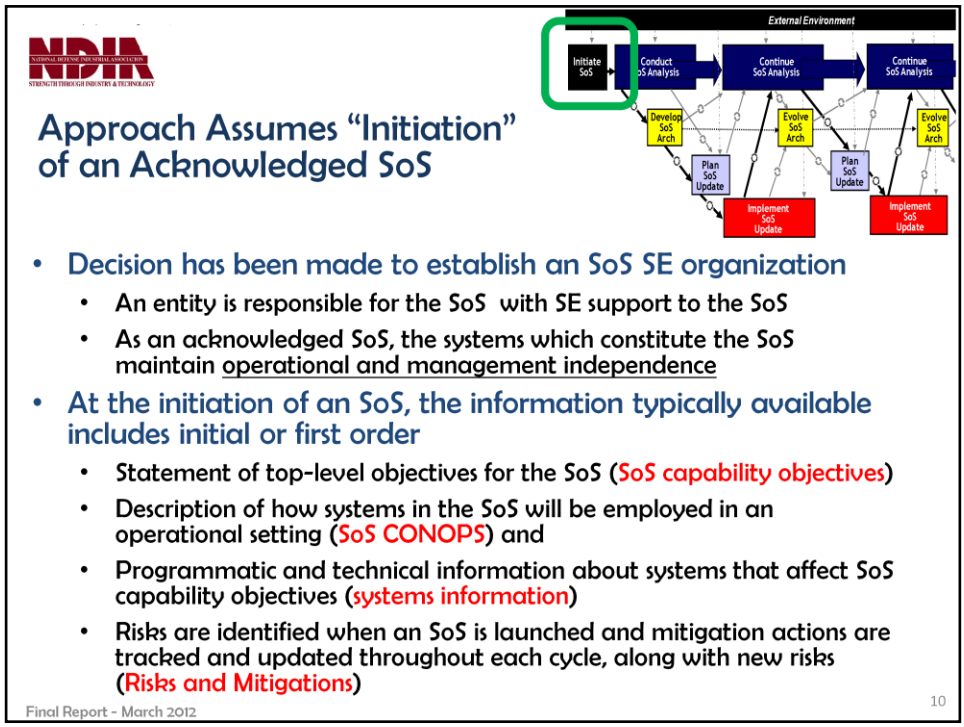
In this report we will examine the SoS SE and T&E at each step of the wave model.

The team's approach to T&E recognizes the inherent constraints on applying T&E to a large dynamic SoS with potentially large numbers of independent constituent systems in an SoS which may each be making changes on their own development, test and fielding schedules, Even with the advantages of modeling and simulation support, it is difficult and costly, if not impossible to test a full SoS each time change in constituent systems are made.

The T&E approach for SoS is characterized by several core ideas

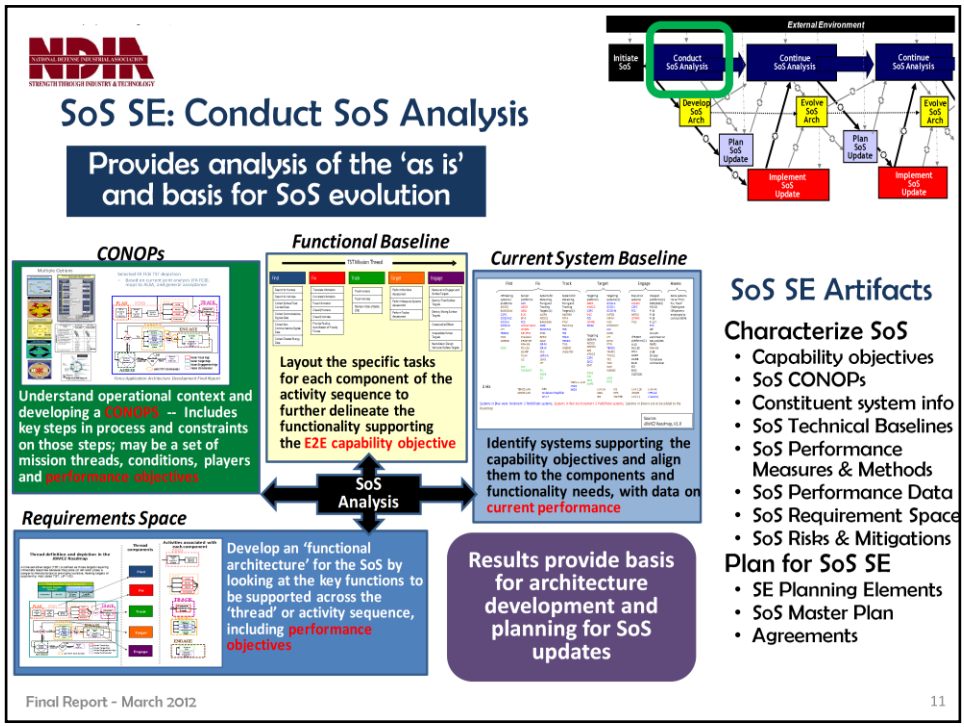
- Integrate T&E with SE throughout the evolution of an SoS;
- Focus T&E on risk, both in the planning of the SoS and in its implementation
- Employ a variety of sources of evidence including prior T&E results, data from analysis, and SoS test events as needed

The objective of the approach is to provide the data needed to achieve the goal of SoS within these constraints of large scale SoS.



This approach assumes that the '**Initiate SoS** step' in the wave model has taken place. This means that there is an organization responsible for the SoS and there is SoS SE support. However, as is the case with acknowledged SoS, the systems which support the SoS objectives maintain management and operational independence, and typically continue to support their original users.

Initiate SoS provides the foundational information to start the SoS SE process. This includes an understanding of top-level objectives for the SoS (SoS capability objectives), a description of how systems in the SoS will be employed in an operational setting (SoS CONOPS) and programmatic and technical information about systems that affect SoS capability objectives (systems information).

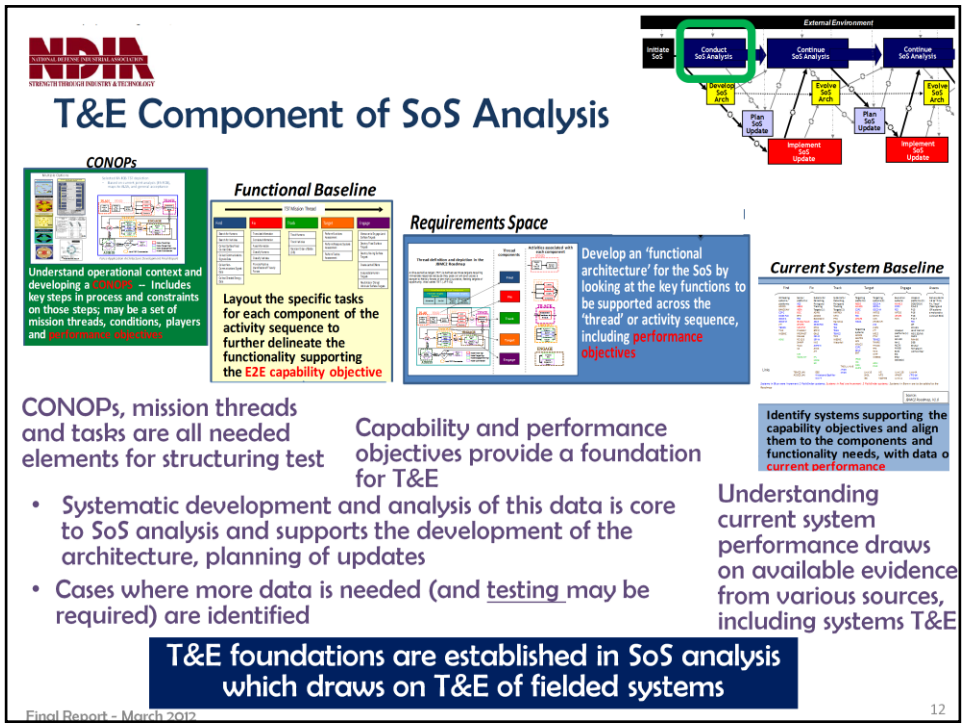


The next step in the SoS implementation is '**Conduct SoS Analysis'**

The SE activities in this step provide an analysis of the "as is" SoS and the basis for SoS evolution by establishing an initial SoS baseline and developing initial plans for the SoS engineering efforts. Artifacts important to this step are shown the slide. These are developed based on a set of SoS SE analysis activities focused on characterizing the SoS. These include

- Understand operational context and develop a **concept of operations** (CONOPS) which includes key steps in process and constraints on those steps. This provides some form of an activity sequence (business process model, set of mission threads, or use cases), including conditions, players and performance objectives
- Develop the **functional baseline** by defining the specific tasks for each component of the activity sequence to further delineate the functionality supporting the SoS capability objective
- Define the **current SoS system or product baseline** by identifying systems supporting the capability objectives and align them to the components and functionality needs, with data on current performance
- Develop a baseline **functional architecture** for the SoS by identifying the key functions to be supported across the activity sequence, including performance objectives

These together provide the basis for the development of the SoS architecture and planning for evoution of the SoS. They also provide the technical drivers for developing the systems engineering plans for the SoS.

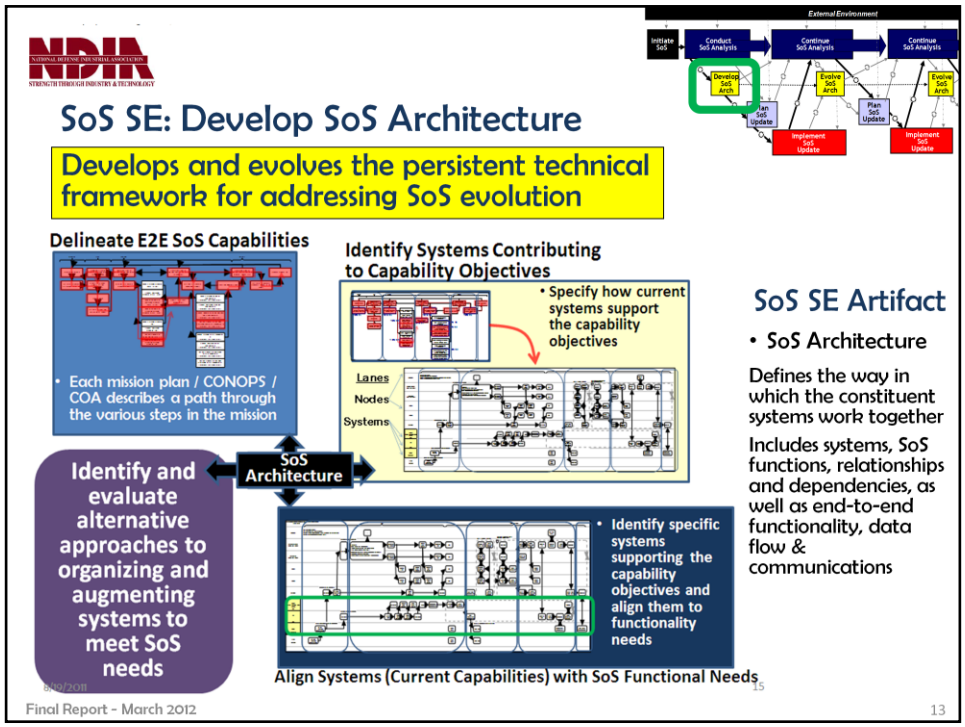


What is the relationship of these SoS activities and artifacts to T&E of the SoS?

First, looking at the SE activities, it is clear that many of these are key for SE and they also are critical elements of T&E. Capability and performance objectives and methods provide a foundation for T&E. CONOPs, mission threads and tasks are all needed elements for structuring T&E activities.

Second, recognizing that most acknowledged SoS are comprised of existing, fielded systems, understanding current system performance requires an understanding and assessment of available evidence from various sources, including systems' T&E results. Systematic development and analysis of this data is core to SoS analysis. Further, since SoS typically brings systems together in new ways, there may not be data available to understand key aspects of current performance of the SoS. In cases where more data is needed, addition testing may be required to support the SoS analysis.

T&E activities during SoS analysis establish T&E foundations for the SoS. Further, T&E feedback from constituent systems is an important input to the SoS analysis.

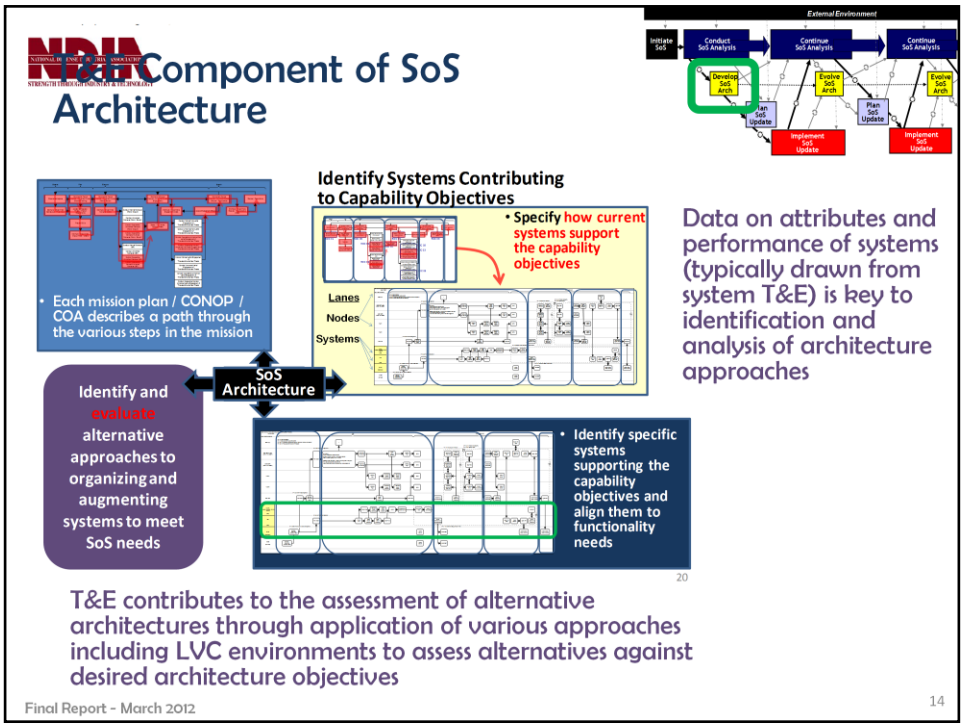


The next step is to develop the SoS Architecture, which includes systems, key SoS functions, relationships and dependencies, as well as end-to-end functionality, data flow and communications protocols. It is used to address possible changes in functionality, performance or interfaces. The architecture defines how constituent systems work together and may lead to with changes needed in system interfaces and functionality when key to cross-cutting SoS issues

Architecture development and evolution is conducted based on a set of activities:

- Delineate end to end SoS capabilities
- Identify how current systems support the capability objectives
- Align systems with SoS functional needs by identifying how specific systems support the capability objectives and align to functionality needs
- Identify and evaluate alternative approaches to organizing and augmenting systems to meet SoS needs building on knowledge gained through SoS analysis

The evaluation of architecture alternatives is a based on a set of considerations which include support for SoS functional and performance objectives, impact on constituent systems, costs of implementation and sustainment and risks. The products are the selection of architecture and plans for implementation, including changes needed in constituent systems.

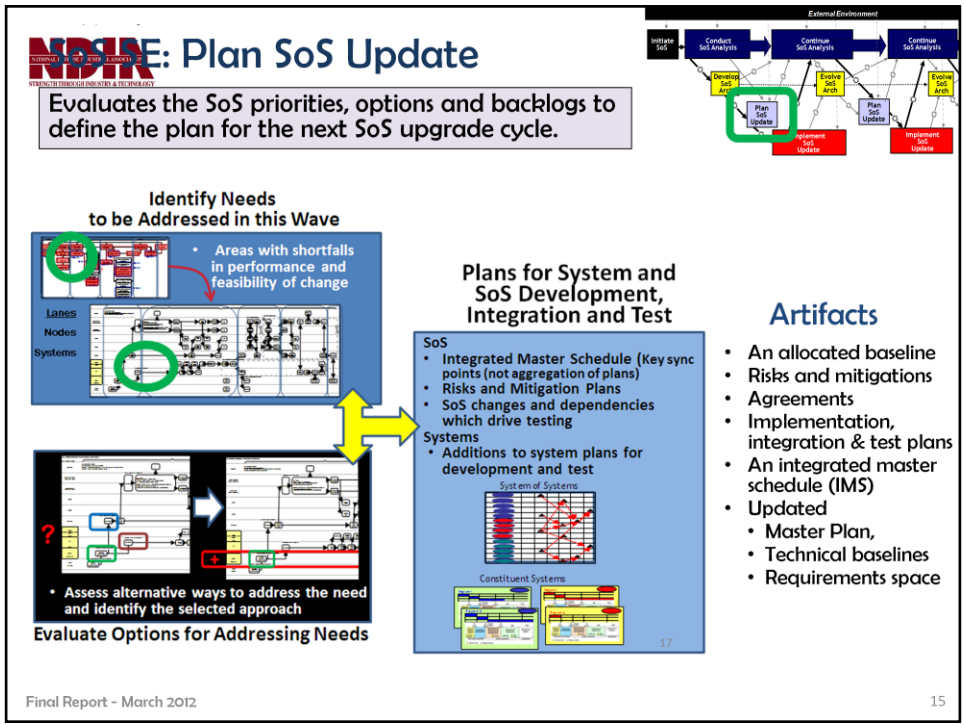


What is the role of T&E in SoS architecture development and evolution?

First, as in SoS analysis, system T&E is a rich source of data on system, data needed to support SoS architecture development.

Second, because most SoS include existing systems, T&E methods and tools can contribute to the assessment of alternative architectures through application of various approaches including live, virtual and constructive environments to assess alternatives against desired architecture objectives.

Finally, T&E considerations may suggest important architecture characteristics. For example, if elements of the SoS are known to have long lead time test and certification requirements (e.g. airborne platforms) and there is a need for rapid improvements in the SoS performance, an architecture which shelters these constituent systems from changes would be a consideration. Similarly, if some systems are known to be very dynamic, an objective of the architecture may be to isolate changes in those systems from impact on other systems in the SoS. The robustness of the architecture maintains continued support for SoS objectives in the context of change in these systems, and limits risk of impacts on the SoS. It may also facilitate more efficient T&E.



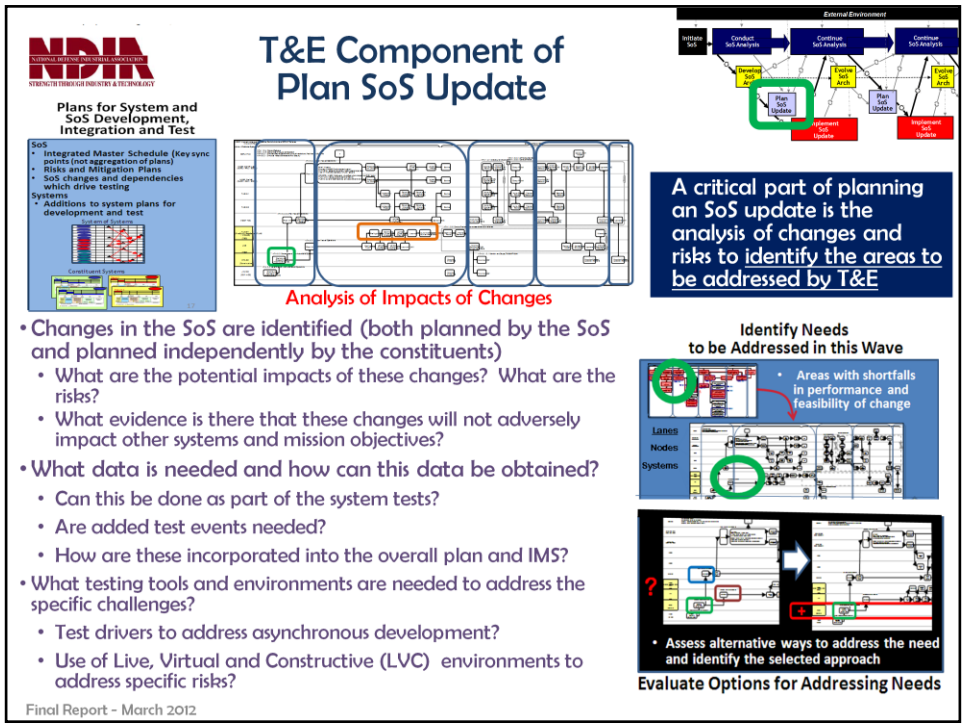
The next step in process is planning updates to the SoS.

In **Plan SoS Update** the SoS priority needs are reviewed and options for addressing these are identified and assed, largely based on the plans and characteristics and constraints of the constituent systems.

SE activities in this step include

- Identify areas to be addressed in the next iteration, based both on areas with shortfalls in performance and the feasibility of making changes in the associated systems, given their development plans etc.
- Evaluate options for addressing needs, working with the relevant systems to identify and assess alternative ways to address the needs and identify the selected approach
- Develop plans for system and SoS development, integration and test; this includes the SoS level Integrated Master Schedule (IMS) which focuses on key synchronization points among system level plans and additions to system plans for development and test, not on aggregation of system-level plans at the system level,
- Identify and address risks and mitigations, which include systems changes and their potential impacts

The result is a plan for the next SoS upgrade cycle. The artifacts generated during this step, listed on the slide, provide the technical plans for the next increment of SoS evolution and the supporting schedules and agreements.



What is the role of T&E in planning an SoS update?

First, as both the activities and artifacts indicate, T&E planning is a core part of the planning for the update. Second, this step is critical in identifying areas of risk which warrant T&E attention.

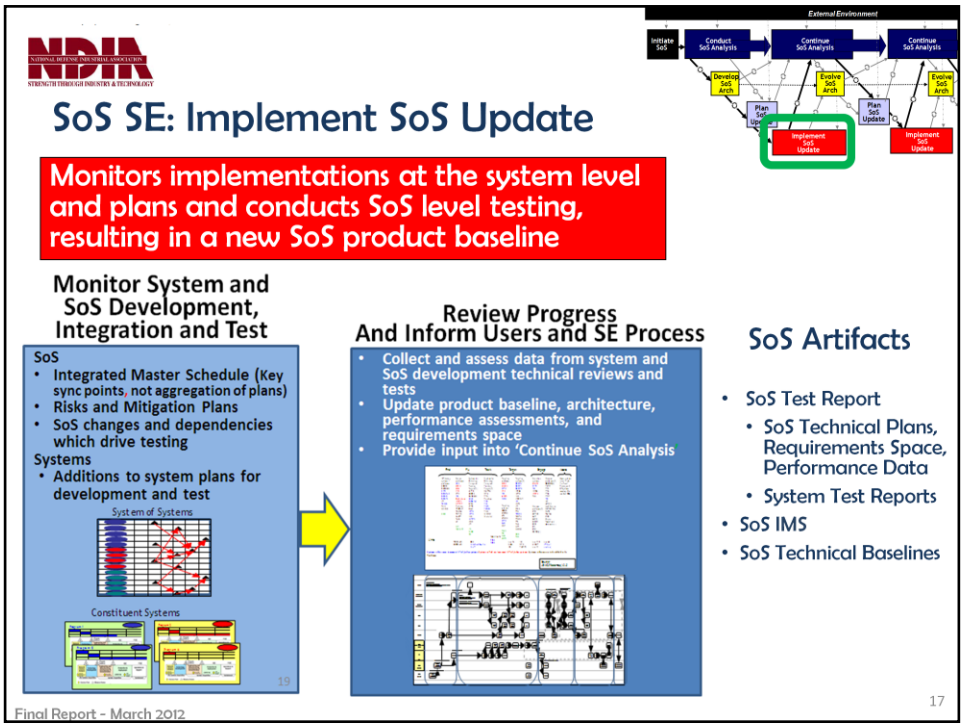
- Changes in systems are identified. This includes both changes planned as part of the SoS as well as changes planned by the system for other reasons.
- Using the architecture as the technical framework, the potential impact of these changes can be assessed. How does a planned change affect other systems in the SoS given the CONOPS and system dependencies? Where will these changes be experienced? Are other components of the SoS equipped to handle the changes? Where are the risks and how can these be assessed? How can they be mitigated?

Changes with no impact on other parts of the SoS (.e.g. improved quality of sensor feeds but no change in format, interfaces, volume, etc.) may not need SoS attention beyond T&E at the system level. Changes with potential impact, and hence risk to other systems and the SoS, will require SoS T&E attention.

This identification of risk based on unintended or adverse impacts of the planned changes on the SoS or other systems is an area of shared equity for SoS SE and T&E. In SoS SE update planning, an important factor is determining what changes will be made in an iteration is ensuring that once these changes are made, the SoS (and the constituent systems) will continue to perform as well as before or better. At a minimum, these should operate within an acceptable level of performance. Depending on the SoS architecture, changes in one system (added capacity for example) could affect systems downstream if they don't have the ability to handle the impact of the change (an increased load). In addition, a change in an interface or functionality to support the SoS, could impact other systems which depend on the current features.

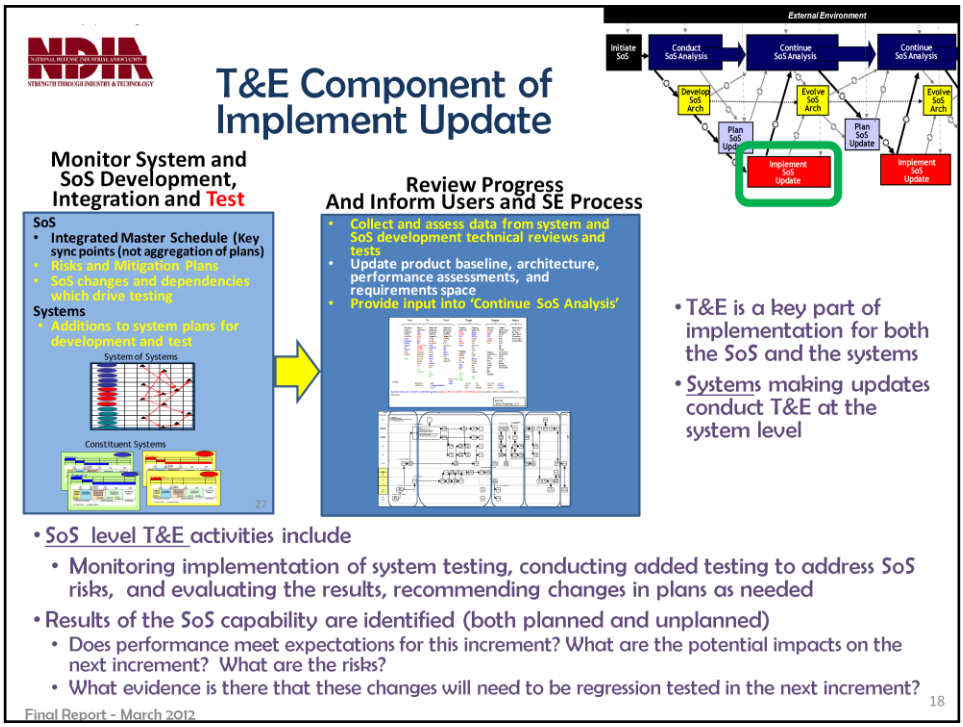
Even in areas where the results suggests that the changes will have no impact on other parts of the SoS, additions to systems testing may be needed to verify that the implementation does not include unanticipated changes beyond what was specified in the plans and which could increase the risk of undesirable impacts. For those areas where there is confidence of success but manageable risks, then the focus is on T&E during implementation.

In sum, a critical part of planning an SoS update is the analysis of changes and risks to identify the areas to be addressed by T&E.



The next step is implementation.

Implement SoS Update involves actions by both the systems and SoS. The systems implement and test changes while the SoS team monitors progress and conducts SoS integration and testing, resulting in a new SoS product baseline.



T&E is a key part of implementation on the parts of both the systems and the SoS.

Constituent systems conduct T&E of changes made to support SoS needs as part of their system level testing.

SoS T&E includes monitoring the implementation of the system testing, conducting added testing to address SoS risks, evaluating the results, and recommending changes in plans as needed.

Results in terms of SoS capability are identified (both planned and unplanned). Does performance meet expectations for this increment? What are the potential impacts on the next increment? What are the risks? What evidence is there that these changes will need to be regression tested in the next increment?

These results are the basis for capabilities and limitations information provided to end users and as feedback to the SE and T&E teams for the SoS and systems toward evolution of the SoS.

Summary and Next Steps

- Key elements of the approach to SoS SE and T&E
  - Addresses the key challenges facing T&E in an SoS environment – complexity, system independence and asynchronous development
  - Integrates T&E with SE throughout the evolution of an SoS based on the SoS 'wave model' – T&E contributes to all steps in the evolution
  - Focuses T&E on risks to systems and SoS – recognizing full end to end testing with each system change is intractable
  - Emphasizes use range of information types to address these risks
- Presentation is the product of the 2011 joint task of the NDIA SoS SE and T&E committees
  - Represents initial product in this area
  - Open areas and considerations for next steps

This presentation is the report of the 2011 work of a team from the NDIA SED SoS and T&E committees. It is the first step in an ongoing effort to examine ways to achieve the goals of T&E given the challenges of large acknowledged SoS

The report presents an approach to T&E for acknowledged, mission level SoS recognizing key challenges facing T&E in this environment. Full SoS T&E to address impact on the SoS of all changes in constituent systems is typically not feasible given the size of many SoS (including the number of different constituent systems) and the dynamic nature of constituent systems and their independent, asynchronous development schedules.

It integrates T&E with SE at each step in the evolution of an SoS using the SoS 'wave mode' as the framework and focuses T&E specifically on areas of risk critical to SoS and constituent system success. It begins with an examination of the changes which have been made in the SoS, and identifies areas critical to SoS success and places where changes could have adverse impacts. Risk is assessed using evidence from a range of sources including live test where the risks warrant it. Evidence can be based either on activity at the SoS level, or roll-ups of system level activities. T&E actions can be explicit verification testing, application of models and simulations, use of linked integration facilities, and analysis of results of system level operational test and evaluation. T&E results provide 'continuous improvement' feedback to end users in the form of 'capabilities and limitations' rather than as test criteria for SoS 'deployment' and to SE teams of both the SoS and systems on progress and issues.

The work leaves open a number of important questions and opportunities for future work. First, what are the implications of this approach for SoS analysis and architecture methods and tools? The approach calls for a foundational understanding of the constituent systems and their relationships and the ability to assess impacts of changes. Second, how applicable is this approach to other SoS types or domains? What are the differences in these types and domains and what do these mean for extending this approach for these other problem areas? Third, what has been the experience with use of the critical aspects of this approach by current SoS efforts? How can this experience be used to assess, adapt and mature the approach?