6500m HOV Project
Stage 1: A-4500 HOV

Systems Engineering, Integration & Testing Plan

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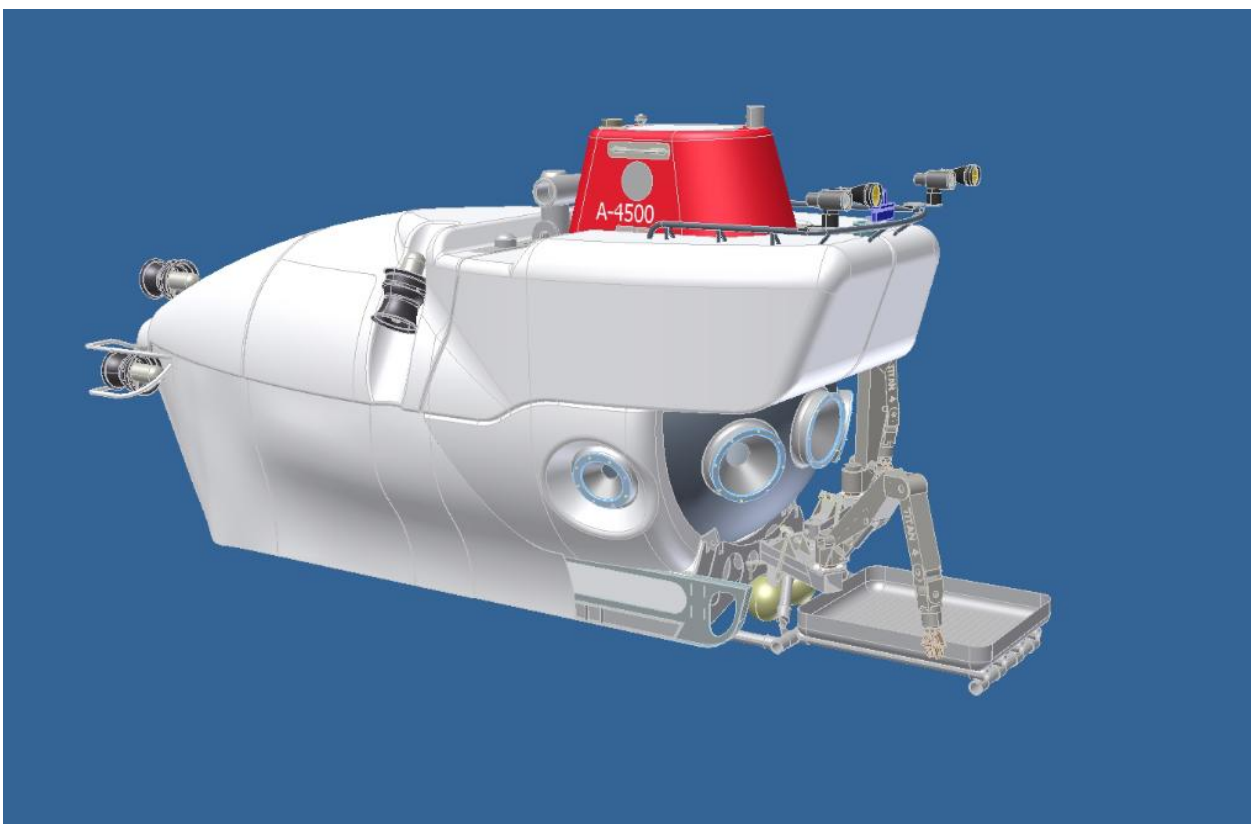

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1.0 Introduction

This document describes the Systems Engineering process by which the A-4500 HOV project team will move from requirements to features and design, and then track those requirements as designs change with increased knowledge and experience. This document also describes the process by which we will manage integration of subsystems into a complete submersible, ready for commissioning and transition to operations.

The design and implementation of the vehicle's many systems and parts are tightly related and interconnected. The various systems are being designed by multiple engineers and teams; hence, integrating the designs together successfully depends on the correctness and robustness of their requirements, and design and specification of the interface between them. This engineering process is driven primarily through a common understanding of the design, as facilitated by coordination meetings and face-to-face interactions. It is incumbent on the designers to ensure that requirements issues are considered and properly accommodated. This is, by nature, an iterative process. Figure 1 illustrates the paths by which designs are refined until the requirements are satisfied.

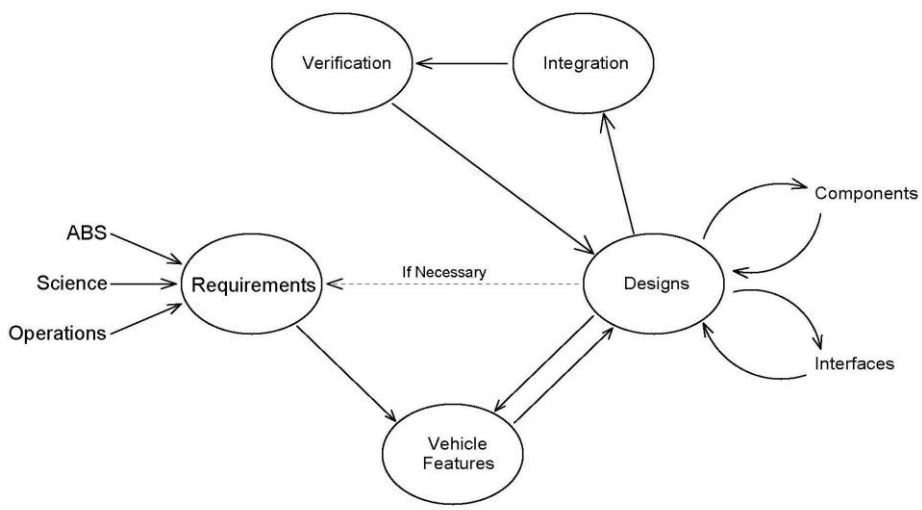

Figure 1. Systems Engineering Flowchart

As represented in Figure 1, the systems engineering process begins with planning activities represented by the collection of system requirements developed from science, ABS, and operations requirements. These map into features and designs, which the engineering team iteratively refines to satisfy these requirements. If necessary, there may be opportunities to negotiate or relax requirements to support the system features or designs. Once designs are complete, they are prototyped, constructed, integrated and tested. This is again an iterative process that further improves the design's quality. The arrows in Figure 1 show the time sequence of these activities.

2.0 Requirements

Identifying project requirements is fundamental to Systems Engineering and is integral to, or a prerequisite for, a meaningful Risk Management Plan, Project Execution Plan, Procurement Plan, and the identification and selection of design alternatives. Systems engineering practice requires that requirements are atomic, unambiguous, and testable. Requirements must be satisfied by either a test, a specific analysis, or by the development of one or more derived requirements, each of which can itself be satisfied. Requirements for complex projects are often managed using purpose-made software, such as the Dynamic Object-Oriented Requirements System (DOORS) package, but many projects can be managed using a database or spreadsheet. Requirements for this project are gathered, derived, documented, and tracked using multiple worksheets in an Excel workbook.

The A-4500 HOV requirements originate from several sources:

- **American Bureau of Shipping (ABS) Requirements**
  The classification authority for the new submersible is ABS. The ABS classification process dictates certain features and designs for the new submersible that must be considered as mandatory. Additionally, ABS imposes requirements (rules) on how work is performed, not just on the result. This is an important distinction between the ABS requirements and the Science and Operational Requirements.

- **Science Requirements**
  The deep submergence science community is the ultimate customer of the system. These are the requirements that this community has established as being important for the scientific success of the submersible. Although a serious attempt has been made to make these requirements as quantitative as possible, in some cases the result has been not entirely satisfactory since the users, the builders, and the operators of the submersible all understand that any submersible design is the result of a set of compromises between requirements. These requirements apply to the end result of the effort, not to the processes and procedures by which they are achieved.

- **Operational Requirements**
  These are the criteria that the designers and operators of the submersible consider necessary. Some are driven by safety considerations, others by the need to make the new submersible as reliable, flexible, and maintainable as the current *Alvin*. Paramount above all for a Human

Occupied Vehicle (HOV) is for the submersible to be safe and have operational flexibility. These requirements apply to the end product of the effort, and it can be difficult to develop measurement criteria.

Through a systems engineering approach, the project requirements will be regularly reviewed to ensure that they are all either addressed or adequately dispositioned.

2.1 ABS Requirements

ABS rules are defined in the *ABS Rules for Building and Classing Underwater Vehicles, Systems and Hyperbaric Facilities, 2002* (UWVS), with additional requirements in *Steel Vessels 2009*. Compliance with these rules, or an approved alternate arrangement, is mandatory for successful vehicle classing. WHOI has engaged a naval architect firm familiar with ABS classing to ensure that this occurs successfully. The *A-4500 HOV ABS Classification Plan* maps ABS rules into vehicle requirements, and then to technical solutions and designs.

2.2 Science Requirements

A poll conducted among science community users beginning in 1999 (Summary of Deep Submergence Community Questionnaire on Improved Submersible Capabilities) set the baseline for future use, needs and ideal capabilities of an HOV (http://www.unols.org/committees/dessc/replacement_HOV/replacement_hov.html). From this, a set of Functional Science Mission Requirements for the new system was developed and mapped to a set of "Vehicle Characteristics Requirements", both Operational and Scientific. These are described in Section 2.0 of the *A-4500 HOV Project Execution Plan* (PEP).

WHOI engineering staff have translated these scientific requirements into a set of technical solutions and system design requirements. This process is documented in the Science Requirements Traceability Matrix in Appendix B of the *A-4500 HOV Project Execution Plan*.

2.3 Operational Requirements

Operational Requirements originate with the vehicle operators and engineers. Many are baseline requirements that are essential to the safe and efficient operation of the vehicle system; some are desired system improvements. These will be recorded, tracked and implemented by the individual engineering efforts after consideration of impacts on budgets and schedules. Design and fabrication issues that affect Operational Requirements are addressed at coordination meetings between the Technical Director and the System Engineering Leads.

It is worth noting that under these requirements distinctions, going to 4500 meters is a Science Requirement, but coming back is an Operational Requirement, and building a vehicle appropriate for doing this is an ABS Requirement.

3. Design Development and Requirement Tracking

At this point in the A-4500 HOV project, the preliminary requirements have been identified in the *ABS Classification Plan*, Science Requirements Traceability Matrix, and by the individual System Engineers. Each of these has a mechanism to describe the part or parts of the design that satisfy each requirement. The requirements are further derived, documented, and tracked using the requirements workbook. This process will allocate the system requirements to subsystems and components, a step that will become important during the testing and integration phases of the development process.

After the Preliminary Design Phase of the effort is completed, and up to the Final Design Review (FDR) phase, testing of assumptions and development of confidence that the designs continue to support the requirements as they evolve, will be refined. Coordination meetings between the Technical Director and the System Engineering Leads, as well as individual System Engineering Lead meetings, will address the design evolution, multi-systems integration and its fulfillment of the requirements using the traceability mechanisms. If a design does not satisfy the requirements, then either the design must be changed, or the requirement relaxed, removed, or modified. These will be addressed and approved by the Change Control Board (described in the *A-4500 HOV Configuration Management Plan*).

In support of the Procurement Plan, the Program Management Team will ensure that the prime construction personnel, component manufacturers, and subcontractors comply with the project requirements. This activity entails:

- Assisting the Contracting Officer in evaluation and selection of bidders based on the bidders' past performance.
- Ensuring that the requirements flow down to the vendors and subcontractors by establishing purchase specifications, OQE requirements and acceptance criteria.
- Establishing procedures to detect and prevent quality problems.
- Reviewing and approving the contractors' Quality Assurance Plan.
- Verifying and accepting the end product.

In performing these duties, the Project Manager will track the progress and performance and take corrective actions where appropriate.

It is also important that interfaces are identified, specified, designed and documented. Note that while interfaces themselves do not satisfy requirements, their quality is important in integration of systems and components, which do. Interfaces themselves can be analyzed, prototyped, tested and controlled. Once verified in this way, it is important for interfaces to be controlled for the verification to remain valid. If changes are required at this point, an appropriate level of analysis and acceptance testing must be repeated. This has the added benefit that once the interface is fully specified and verified, design and some test effort on both sides of that interface can continue with greater independence.

- Consider the example of a computer-controlled device. Without this approach, the software developers would need to have an example of the equipment, and the hardware developers would need to have executing software. As changes are made to either of these developments, additional testing is required to ensure that the combination still works properly: a software change may cause the device to behave improperly, or a hardware change may prevent it from accepting commands.

  Alternatively, the interface to the device can be defined early on. This would describe the type of signaling used to communicate with the device, and the commands and responses that are available.[1] Once so defined, an emulator for the interface can be built and provided to both the software and hardware developers. Now, both development teams can continue with their design and testing, with good likelihood that their design has not unknowingly changed.

- The sphere mock-up is being used to verify the physical interfaces between in-hull equipment. Once the sphere interface (primarily its diameter and viewport locations) was controlled, the mock-up can be readily used to design and fit in-hull equipment, with good assurance that it will properly fit into the sphere. If the sphere interface were to change (its diameter, for example), a certain amount of that fit-up would have to also be changed.

- CAD simulation has been used for the purpose of developing the workspace design, involving lighting, manipulator and basket location. Rather than build a mock-up of these items, a software simulation has been used.

[1] For example, see: Abrams, L., “Lanecon – Functions and Command Protocol,” March 13, 2009.

4.0 Systems Integration

Once FDR is completed, these procedures will have allocated requirements to subsystems and components. Requirements can be verified or tested upon component receipt, as portions of a subsystem or component design reach completion, or as part of an overall system acceptance test. Deficiencies in meeting the requirement are identified at this point and addressed through either a design change, a repair, or a requirement change. In cases where either a design or requirements change is required, these will be addressed and approved by the Change Control Board.

5.0 Testing & Acceptance

WHOI will verify that the design solution satisfies the requirements. The team will provide evidence that their design solution adequately addresses each requirement. A minimal degree of evidence will be provided that will depend on the priority of the requirement (perhaps based on SSC Grade), certification or governmental criteria or constraint, and the novelty of the design solution. Data showing that the proposed solution has satisfied similar requirements on past projects will also be used as a basis for verifying that the requirements are met and form the basis for vehicle acceptance.

WHOI engineers and Team Leads will develop maintenance, testing and acceptance criteria during the design and development phases of new systems. Some of these tests will require ABS acceptance and approval that they meet the requirements of classification, and will require that an ABS inspector witness such tests. Where new systems are designed, new tests will have to be developed along with the equipment. In cases where existing submersible systems are to be incorporated into the A-4500 HOV, the existing *Alvin* maintenance and testing procedures currently in place will be acceptable. However, additional testing may be required to validate that the existing systems are appropriate and adequate with the new vehicle's interfaces.

For example, as components and subsystems become available, they will be tested as fully as possible. Component and system testing must verify functionality, performance, and satisfaction of the requirements. Similarly, as design-adjacent components and systems become available, their interactions will also be tested. (Note that physically adjacent components and systems must also be checked for interference, another type of interaction.) Interface testing must verify all of the normal and fault interactions, and also proper behavior across the complete range of correct and error results. By doing this testing early, errors and anomalies can be found and more easily repaired. Where interface emulators have been used (as described above), real equipment can be installed in place of the emulator to test actual performance.

As more systems become available, they will be integrated and tested as promptly as possible, until the entire vehicle is complete. Overall and final vehicle testing will be performed as described in the *A-4500 HOV Construction Plan* and the *A-4500 HOV Transition to Operations Plan*.

Appendix 1. Systems Engineering Glossary

Alternate Arrangement

A design that does not fully satisfy the ABS rules, but does satisfy the intent of the rule. This is made by application to, and acceptance and approval by, ABS.

Assessment

For engineering applications, the process of estimating the value of something using authoritative expert judgment based upon observations of representative cases and rough calculations, rather than determining the exact value based upon comprehensive and detailed examinations, and precise and rigorous complete calculations.

Change Control Board

As defined in the *A-4500 HOV Configuration Management Plan,* the body responsible for approval of changes to requirements and designs. It is made up of the Project Management Team, with additional members and guests as appropriate.

Cognizant System Engineer

The engineer assigned technical responsibility for a particular system, who coordinates technical activities related to the assigned system. The Cognizant System Engineer has technical understanding of the system requirements design, operation, testing and maintenance. The Cognizant System Engineer ensures that relevant documents, such as system design descriptions, technical drawings, diagrams, lists, and procedures for surveillance, testing and maintenance are complete, accurate, and up to date. The Cognizant System Engineer may also keep vendor technical information and appropriate files concerning system history of repairs, modifications, operational problems, and other unique conditions or circumstances. Equivalent terms include: cognizant engineer, system engineer, system specialist, lead engineer and subject matter expert.

Configuration

The combination of the physical, functional, and operational characteristics of the HOV and HOV Support Systems.

Configuration Baseline

All approved documents that represent the definition of the project at a specific point in time.

Coordination meeting

A meeting between the Technical Director and the System Engineering Leads for the purposes of forming a common understanding of the design, rectifying mismatches between design components, and solving design problems.

Design authority
The person responsible for establishing the design requirements and ensuring that design documents appropriately and accurately reflect the design basis. The design authority is responsible for design control and ultimate technical adequacy of the engineering design process.

Design basis
The design's inputs, constraints, and analysis and calculations. The design basis explains why a design requirement has been specified in a particular manner or as a particular value.

Design documents
Design documents define either the design requirements or the design basis of the project. Design documents include design specifications, design change packages, design drawings, design analysis, calculations, summary design documents, correspondence with others that provides design commitments, and other documents that define the project design.

Design requirements
Those engineering requirements reflected in design documents (such as drawings and specifications) that define the functions, capabilities, capacities, physical sizes and dimensions, limits, etc. specified by design engineering for a structure, system, and component. The design requirements provide the results of the design process.

Objective Quality Evidence (OQE)
Any documented statement of fact, quantitative or qualitative, pertaining to the quality of a product or service, based on observations, measurements or tests, which can be verified. Evidence is expressed in terms of specific quality requirements or characteristics. These characteristics are identified in drawings, in specifications, and in other documents that describe the item, process or procedure.

SSC grade
A measure of the importance of SSCs within the project based on the most important design requirements applicable to the SSC that can be used to determine priorities and proper levels of attention and resource allocations. An example of SSC grades and associated priorities is: (1) safety, (2) environmental, (3) mission, and (4) others.

Structures, systems, and components (SSCs)
Structures are elements that provide support or enclosure systems and components from the sea pressure such as the sphere, tabs, component foundations or pressure housings. Systems are collections of components assembled to perform a function such as seawater piping; electrical distribution cables, hydraulic systems or life support systems. Components are items of

equipment such as pumps, valves, relays, or elements of a larger array such as computer software, lengths of pipe, elbows, or reducers.

System Design Description (SDD)

An SDD describes the requirements and features of a system. It identifies the requirements of structures, systems, and components, explains the bases for the requirements, and describes the features of the system that are designed to meet those requirements.

Technical Review

The interdisciplinary process to confirm or substantiate the technical adequacy of a proposed change and ensure that it does not substantially degrade safety margins.