US NAVY SUBMARINE LOGISTICS AS AN ANALOGY FOR INTERPLANETARY SUPPLY CHAIN MANAGEMENT

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ABSTRACT

This study explores submarine operations and supply chain management as an analogy for interplanetary exploration to identify supply chain lessons. This is not the first time submarines were used as an analogy for space travel. In 1969, NASA conducted experiments aboard the PX-15 deep sea submarine to study the impacts on human behavior [6]. This research evaluates two case studies: the Trident submarine, and the Navy Research – 1 (NR-1) for logistics lessons that may apply to space travel. Space travel is unique due to the distances, durations and lack of support. Submarines as an analogy cannot account for the uniqueness of space travel, but offers lessons in developing supportable vehicles and identifies design considerations for volume/weight tradeoffs and propulsion choices.

MISSION ANALOGY

Duration and Environment

In terms of operations, mission duration and environmental impacts are considered. Mission duration for US Navy submarines varies depending on the type of boat and its mission. Typically, for designated missions they remain submerged for a maximum of two months only surfacing in extremis such as a major break or critical medical evacuation (MEDEVAC) [9]. The Trident's typical cruise is scheduled for 70-days [1, p. 1]. During the 70-day cruise, the Trident typically will not surface in order to remain hidden from potential adversaries and perform its mission. In addition to mission duration, long term survival at extreme depths requires a vessel which provides an environment that can support human life. The Trident can perform its mission at an 800-foot operating depth, allowing it to have sufficient volume to house its crew and all necessary equipment and supplies [10, p. 180]. In comparison, The NR-1 was designed to conduct a wide variety of missions to include: underwater search and recovery, oceanographic research and installation and maintenance of underwater equipment [17]. With its standard crew and two scientists it can operate submerged at 3000 feet for up to 30 days, limited only by its food storage capacity and air supply [12, p. 5-7].

Two mission categories to be considered for the purposes of this study are exploration of the Moon and Mars [7]. The characteristics and challenges of these two missions are very different for developing and maintaining an effective supply chain. The first difference is accessibility of the target body. The Moon, offers more frequent launch windows than Mars which is only accessible every 2.13 years [14, p. 619]. The second difference is time. A standard Apollo mission was 10 to 14 days with in-transit time being approximately 3-5 days each way [15, p. 12]. The implication for the supply chain is that if a Lunar mission experiences a problem requiring logistical support the supply chain may have the accessibility and time to ensure mission success. Mars missions may not have the luxury of accessibility or time.

LOGISTICS ANALOGY

There are two primary questions regarding logistic support for the submarine supply chain: what to allocate as on-board spares and how to handle requirements for non-stocked items. Routine spares are kept on hand but, due to space limitations, spares for parts that rarely break must be obtained through an external supply chain. On-board spares requirements are calculated by the Navy's Readiness-Based Spares (RBS) model which considers provisioning data (price, quantity), system data (configuration, reliability), and ship data (design information) to determine the optimal spares stock levels that meet the required readiness level at the least cost. This approach balances the reliability of components, redundancies in the system, cost, available stowage and mission duration to optimize the boat's capabilities and ensure the required operational availability [13]. The considerations for both submarine and spacecraft are similar: weight, volume, criticality, reliability and redundancy. The RBS model's basic construct, inputs and outputs should fit into a spares model for interplanetary missions.

While Tridents maintain enough supplies and spares for 90-days of autonomous operations as calculated by the RBS model, the typical at-sea duration is 70 days [9, 15]. The baseline operations cycle was planned for nine years of continuous 95-day patrol/in-port cycle. The 95-day cycle is broken into 70-day patrols followed by an 18-day repair period and a 7-day patrol preparation and sea trial period before its next 70-day patrol. Every nine years the boat is brought into the shipyard for a one-year overhaul. The maintenance strategy and logistics concepts for Trident were designed to minimize repair and overhaul time and logistics delays to meet the operational availability requirements [1, p. 1]. The strategy includes a rotatable equipment pool (spares) to eliminate the need for the submarine to be present for longer duration repairs and inspections [1, p. 3]. The equipment pool is simply spares available to put into the boat during its 18-day repair cycle, leaving the piece needing repair in-port while the boat continues. In the case of an unplanned spares requirement, the Navy's Priority Materials Office (PMO) delivers materials to the port nearest the submarine, a predetermined port, or to the nearest fleet using commercial and military delivery resources [2].

The NR-1 logistics requirements differ significantly from the Trident. Though it can operate submerged for 30-days, the boat requires a dedicated support ship to tow it to and from its operating area, as well as for logistical support beyond thirty days [12, p. 5-7]. Though the NR-1 is capable of operating at depths and for durations few, if any other vessel can, it must leave the underwater environment to obtain logistical support and extend its mission beyond 30-days.

In terms of mission duration, with operating times on the order of days, typically 70 days for the Trident and 30 days maximum for the NR-1, the submarine analogy can apply to lunar missions. The supply chain for submarines is designed to support mission durations comparable to lunar exploration. However, the accessibility and duration issues related to a Mars mission changes the supply chain calculation, reducing the application of the submarine analogy.

DESIGN ANALOGY

Hull

An integrated operations and logistics approach to submarine design is important in three areas: hull design, propulsion system choice and the environmental control system. Hull design is a function of operational requirements and technological capabilities. The depths required to perform a mission directly impacts the volume and weight allowances in the design. Volume and weight impact the vessel's buoyancy while operational requirements push the submarine to greater depths that further constrain available volume for equipment, supplies, spares and crew. The Trident's size (560 feet long and 42 wide) allows stowage for spares and supplies to maintain the boat for at least 70 days. The Trident hull is designed to operate at a relatively shallow depth because of the extremely large volume required to house the necessary equipment, supplies and personnel [11, p. 180]. The design goals for the NR-1 resulted in a hull capable of going to much greater depths, but with only a fraction of the crew size, equipment capabilities and available stowage space, translating to shorter endurance and the requirement to have a dedicated support vessel.

Size, configuration and location of hull hatches directly impact logistical support. Containers and equipment must be able to fit through the hatches and into the boat, or costly measures are required to conduct maintenance on internal systems. The Trident is fitted with three six-foot hatches positioned to allow access to the reactor, turbine, and command and control sections. All components are sized to fit through these hatches and be removed sequentially. The Trident's hatch design, coupled with features such as quick disconnect fittings, improves deck strength for transport and handling procedures and equipment and allows crews to replace any component within 12-18 hours [1, p. 3][4, p. 20].

Due to its operational requirements, building in features such as the Trident's large hatches and sized components to enable logistics was unrealistic; instead the NR-1's hallmark is reliability. All systems external to the hull were built and tested to withstand operating pressures associated with 20,000-feet, well beyond its normal operating depth, for up to 40 years [4, p. 191]. The NR-1 model includes extreme reliability with dedicated support. The same reliability concepts applied to these systems to allow operation at extreme depths for extended periods should be applied to any interplanetary spacecraft.

For interplanetary exploration, the constraints on useable volume within the hull of the spacecraft, the size of its crew and available stowage space are important factors to determine the appropriate supply chain design. Taking a lesson from the Trident program, the spacecraft and the supply chain strategy should be developed with an integrated approach to ensure the spacecraft's design and the supporting supply chain are complementary and optimized for success and maximum operational availability.

Propulsion

The choice of a propulsion system for a submarine is another critical design consideration born of operational requirements impacting the level of logistical support. WWII submarines were powered by diesel fuel and batteries requiring refueling or large fuel stores for extended operations [3, p. 126-7]. Nuclear submarines have no fueling concerns during normal operations enabling longer duration submerged operations [8, p. 134]. The Trident uses a reactor with an expected core life of nine years. Over the life-cycle of the boat, the reactor saves an estimated seven million barrels of oil [5, p. 26]. NR-1 is equipped with a reactor approximately the size of an office desk, adapted from components of larger reactors. The minimalist reactor design has powered the NR-1 for over 40-years [16, p. 54]. Both boats gain operational and logistical advantages from improved endurance and elimination of refueling.

Spacecraft propulsion options today are generally limited to chemical rockets, though other options are available. Assuming that chemical rockets will be used for future interplanetary missions, the choice of propulsion system will be a determinant for the volume within the hull and the maximum available weight for supplies within the spacecraft. The stowage volume and weight will determine supply chain requirements for how often resupply is required and which items are required.

Environmental Control Systems

Oxygen and carbon dioxide levels are maintained by environmental control systems (ECS). Boats with sufficient electrical power and proper systems can maintain acceptable levels indefinitely. Otherwise, the boat has limited systems needing resupply increasing the support requirements. The Trident uses an ECS that provides oxygen and removes CO_2 with few demands on the supply chain. Due to its size, the NR-1 uses an "oxygen candle" and CO_2 canister system resupplied every 30-days. For lunar missions, the NR-1 model may be an effective option, but the preferred technology for a Mars mission should provide the same long duration, low maintenance and minimal supply chain support as the Trident ECS.

STRENGTHS AND LIMITATIONS OF THE ANALOGY

Just as the Trident design addressed both operational and logistical issues to provide the greatest operational availability, space vehicle design also benefits from an integrated approach. Disconnecting operations and logistics in the design phase will result in longer periods when the spacecraft is unavailable, resulting in a greater number of spacecraft required to achieve the same fleet availability.

Additional propulsion and hull volume design considerations are other strengths of the analogy. The design constraints put on submarines for volume and weight, are similar to the constraints for spacecraft. Submarines must adhere to volume and weight limitations based on the intended operation depth. A spacecraft is limited in volume and weight based on lift and in-transit propulsion options. Intended operating depth for submarines is analogous to distance and required ΔV (ΔV is the velocity change to acquire the desired orbital trajectory) for a spacecraft. The submarine's operational depth becomes more restricting on the hull volume as the depth increases. For spacecraft, the available fuel to provide the required ΔV constrains the weight of the spacecraft. In turn, heavier Heavier spacecraft require a larger ΔV to obtain the desired orbit. Volume is constrained by the available weight based on limits on the amount of material used to build the spacecraft.

Limitations of the analogy exist in the areas of mission duration and accessibility. While lunar mission planners may be able to draw valuable lessons from the submarine mission duration analogy, submarine missions are simply too short to accurately simulate the logistical implications of traveling to Mars. Supply chain accessibility is another limitation to the analogy. The PMO delivers parts worldwide using established Defense Logistics Agency and commercial shipping. Barring catastrophic failure, if the submarine can surface it can be resupplied. Surfacing in this case is analogous to returning to Earth or to an orbiting base. Again, lunar missions may be able to use the analogy, but a Mars mission does not have the option to return to Earth should a critical part break with no spare on-board.

CONCLUSION

This study provides an overview of logistics lessons to apply when planning for interplanetary travel. Analysis of submarine operations, logistics support and related design issues reveal strengths and limitations of the analogy, and areas for further study. Applying the lessons from the Trident to design a spacecraft where required in-flight maintenance can be accomplished quickly will be important to maximize the scientific value of the mission by minimizing time spent on repairs. This will also increase operational availability in a multi-craft fleet. Maximizing the volume of the spacecraft within the design limitations based on weight and propulsion capabilities, just as submarine designers must balance weight, volume and propulsion against the mission, will allow greater stowage area for required supplies and spares to maintain the crew and spacecraft during the mission.

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