



Section 4F

Alternate Outpost Development Strategies

Appendix 4F – Alternate Outpost Deployment Strategies

This initial lunar surface outpost deployment strategy was developed as part of an overall lunar program strategy led by the ESAS team. The primary purpose of developing the outpost deployment strategy was to determine the order and manifest of the flights required to deploy a core set of lunar surface capabilities for sustained, concentrated lunar operations and provide for the evolution of the surface capabilities as the lunar program progresses. The core and evolved capabilities around which the strategy was developed were derived from a mixture of ESAS guidance and findings from studies recently conducted by NASA Headquarters' (HQ's) Exploration Systems Mission Directorate (ESMD).

Since this strategy was developed in the context of the ESAS team's lunar program strategy, a number of key mission parameters (e.g., crew size, mission duration, outpost location, etc.) were defined by the ESAS team and used as a starting point for outpost concept development. It is important to note that this outpost deployment strategy is a point design and highly dependent upon the ESAS team's initial assumptions. Furthermore, this strategy was developed in parallel with many of the key technology trades (e.g., outpost primary power supply); therefore, it is reflective of the initial set of assumptions and has not been revised to incorporate recent decisions.

4.3.8.3 Initial Outpost Deployment Strategy

4.3.8.3.1 First Outpost Deployment Flight

The first outpost deployment flight delivers the primary power supply, Power Management and Distribution (PMAD) assets, communications assets, navigation assets, and ISRU pilot equipment. For the purposes of this study, the PMAD and communications assets were combined into a PMAD/Communications Center. As described above, the initial choice for the primary power source was assumed to be a nuclear fission reactor, providing 50-100 kWe to the location of the outpost.

An early trade was performed in order to assess nuclear source-shielding mass versus PMAD-cable (connecting the PMAD/Communications Center to the power source) mass. The outcome of this trade determined that the power supply for initial estimating purposes should be separated from the rest of the outpost assets by approximately 2 km. The next major decision was whether the power source or the PMAD/Communications Center should be moved by a mobility unit in order to achieve the 2 km separation distance. It was deemed less complex and risky to move the PMAD/Communications Center rather than the power source, due in part to their relative masses. Another major consideration influencing this decision was the potential impact to the landing site where the habitat would eventually be deployed. It was assumed that the outpost will be located on an elevated feature at a polar region. This study assumed that a crater rim or hilltop served as this outpost deployment location. Therefore, due to the limited available land mass at such locations, it is extremely vital to take extra care that the "premium land" is reserved for the habitat where significant crew operations will take place. Thus, it would be highly undesirable to land the nuclear reactor near the location of the future habitat, but then have a failure associated with the mobility unit that is used to transport the reactor 2 km from the habitat site. It is much more preferable to land the reactor at a designated location and drive the PMAD/Communications Center into the vicinity of the future habitat. If a failure were to occur in the PMAD/Communications Center's mobility unit, a work-around could be found while posing no impact to the success of the future outpost.

Packaging volume was not seen as a distinguishing factor between the PMAD/Communications Center and the reactor/energy conversion unit/stowed radiators.

Based upon this rationale, the following strategy was developed. The first flight would land at a designated site on or near the chosen elevated polar feature. After landing, the descent stage would deploy a set of ramps, either autonomously or through a set of commands sent from Earth. Next, a mobility unit would transport the PMAD/Communications Center from the descent stage to the surface and then travel 2 km to the vicinity of the future habitat. Navigation assets (e.g., reflectors) would be placed upon the PMAD/Communications Center and the descent stage to facilitate relatively-precise landing accuracies for future flights. The lunar ISRU pilot equipment would also make this 2 km journey, either individually or in coordination with the PMAD/Communications Center. While it is possible that the PMAD/Communications Center and any other assets that must be mobile would draw power from the nuclear power source during the 2 km traverse, that is an issue for a future study, during which the impacts to the equipment will need to be assessed for operating in the proximity of an active nuclear source.

4.3.8.3.2 Second Outpost Deployment Flight

The second outpost deployment flight delivers the habitat to the lunar surface. Using the navigation assets deployed on the first outpost deployment flight and the DSN, it was assumed that the habitat mission (and all subsequent missions) could achieve a landing accuracy of ± 100 m. The habitat would be targeted to land as close to the PMAD/Communications Center as possible, taking into account all precautions and operational keep-out zones. Once landed, the habitat will require keep-alive power while it waits in a dormant mode for the crew's arrival. To obtain this power, a power cart will be lowered to the surface from the descent stage and traverse approximately 100–200 m to plug itself into the PMAD/Communications Center. The power cart operations may be controlled either autonomously or through a set of commands sent from Earth.

4.3.8.3.3 Third Outpost Deployment Flight

The third outpost deployment flight delivers a suite of utility vehicles (e.g., logistics module and unpressurized human transport rovers) and other ISRU/science payloads. Similar to the second outpost deployment flight, the assets contained on this deployment flight will require keep-alive power. Therefore, another power cart will undergo the same operations as the one used on the second outpost deployment flight.

It is not required that any of these assets (aside from the power cart) perform deployment operations prior to the arrival of the first outpost crew. However, it was felt that it would be desirable for the logistics module to be maneuvered into proximity of the habitat prior to the arrival of the crew in order to reduce the quantity of habitat start-up processes that must be performed by the first crew once they reach the lunar surface. If this were the case, the actual mating of the logistics module to the habitat (or any type of connections that will be made) would probably wait until the crew arrives and can oversee this operation. It is anticipated that the lunar terrain will be rough and it might be necessary for crew members to oversee this operation so as to ensure that damage to the interfaces does not occur.

The ISRU equipment carried on this flight, along with the pieces delivered on the first outpost deployment flight, compose the core "pilot" assets that will demonstrate habitat-scale ISRU consumables production.

4.3.8.3.4 Fourth Outpost Deployment Flight

The fourth outpost deployment flight delivers a fully-fueled LSAM ascent stage to the lunar surface. This ascent stage will be used by the first outpost crew to return to their CEV and the ascent stage that lands with the first outpost crew will be used by the second crew to return to their CEV, etc. Thus, pre-deploying this LSAM ascent stage sets up a strategy of providing all crew increments with one primary and one back-up vehicle to return to the CEV.

4.3.8.4.2 Payload Unloading

Methodologies for unloading payload from descent stages were viewed in this study as a key logistical issue, since this capability will be needed beginning with the very first outpost deployment flight and will continue to be required throughout the lunar program. However, an important distinction should be made between the early outpost deployment flights and those that follow after the first outpost crew has landed. As guided by the ESAS team, the strategy for outpost deployment was built upon the assumption that sortie missions are not incorporated as part of the outpost deployment strategy. Since there was a necessity for a few of the early payloads to be deployed prior to the arrival of the first crew (e.g., PMAD/Communications Center), there was a need to develop a payload unloading capability that could operate without the presence of crew members. All solutions that could provide this capability incur a mass and complexity “penalty” to the descent stages and/or the deployable payloads. Thus, while necessary for the initial flights, a different solution was found for the later flights, during which crew members could facilitate the required operations. A variety of options for unloading payloads from the early outpost deployment flights were considered. The down-selection process was based upon the desire to minimize the mass and complexity “penalties” that would be incurred during each flight. Figure 4F-1 shows the options that were considered during this study.

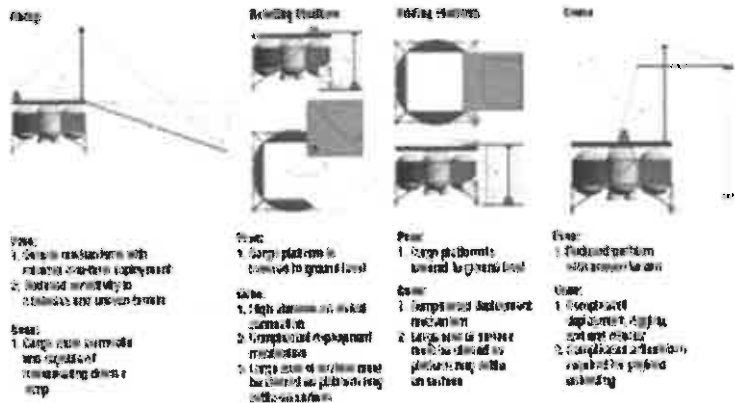


Figure 4F-1. Options Considered During ESAS

Alternate Outpost Deployment Strategies

The ESAS ultimately concluded that the outpost should be deployed by utilizing the excess cargo capability of a series of sortie missions. This “incremental build strategy” is discussed in detail in Section 4.2.5.1.4, **Outpost Deployment Strategies**.

Option 1 – Dividing a Habitat for Delivery on a 15-mT Cargo Lander

It is assumed that the maximum payload mass delivered to the surface by the descent stage is

15 mT. This poses a challenge for the habitat module. Previous ESMD design efforts found that the mass of a four-crew member, 90-day lunar habitat is approximately 22 mT. While this should be viewed as an extremely rough estimate due to the very limited time that was spent on the habitat design, it is roughly comparable to estimates generated during previous design efforts when surface duration and habitat volume are taken into account.

The 15 mT limit imposed the necessity for a two-step approach: delivery of the habitat to the lunar surface, followed by later outfitting by the crew on the lunar surface. This strategy is shown in Figure 4F-2.

As can be seen in Figure 4F-2, a pressurized cargo volume was included in the logistics module concept in order to deliver the remainder of the habitat outfitting supplies. This incurs a mass and complexity “penalty” to the deployment strategy of the habitat, but will undoubtedly be a useful feature since the logistics module will be permanently docked to the habitat (or swapped out for other logistics modules).

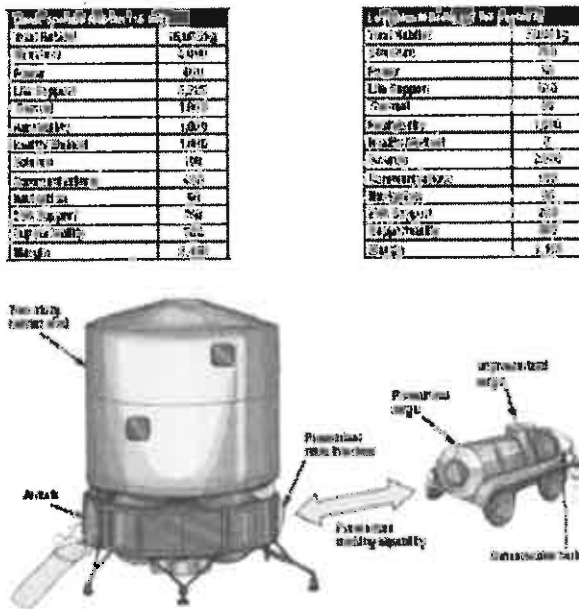


Figure 4F-2. Logistics Module Concept

Option 2 – Salvaging Hardware from Spent Descent Stages

Consideration was given to whether components or consumables from spent LSAM descent stages could be used as part of the outpost deployment strategy. Airlocks, batteries/fuel cells/solar arrays, descent propellant tanks, and residual propellants were among the items that were considered for salvaging.

Airlocks

Salvaging airlocks from the descent stages only begins to become feasible if the nominal lifetime of the habitat’s airlock is less than that of the outpost itself (e.g., it may be found that airlocks have short lifetimes due to the effects of lunar dust on seals). If this were the case, it would become necessary to remove and replace the habitat airlock(s) multiple times throughout the habitat’s lifetime. In this situation, two options arise. First, a habitat-specific airlock

could be delivered to the lunar surface as a payload by an LSAM. Secondly, the LSAMs could be designed to leave their airlocks behind on the lunar surface and these airlocks could have an appropriate design so as to be able to be removed from the LSAM descent stage and connected to the habitat.

Ideally, it will prove to be feasible to design the habitat's airlock with a lifetime equal to that of the habitat itself. If not, this poses significant design challenges. First, the habitat/airlock interface will need to be designed such that the two components can be separated. If an unsolvable failure were to occur in the attachment of a new airlock, the crew would either need to depressurize the habitat to regain access to their living quarters or return to the LSAM (possibly abandoning the lunar surface) until a work-around could be found. Secondly, assuming a strategy of reusable LSAM airlocks for habitat purposes, if the habitat's airlock only requires infrequent replacement, the inefficiencies associated with the added capability to repurpose the airlocks would be absorbed into each LSAM vehicle. Finally, this strategy would require extra surface infrastructure to aid in removing the airlock from the LSAM, transporting the airlock across the lunar surface, and installing the airlock onto the habitat. This would most likely prove to be a significant task and require sophisticated surface assets.

Batteries/Fuel Cells/Solar Arrays

Batteries/fuel cells/solar arrays salvaged from spent LSAM descent stages are a possible way to collect spares for small-scale miscellaneous applications, develop an auxiliary power source for contingencies, or perhaps develop a capability to augment primary power sources during nominal operations (e.g., during lunar night or high-load periods). To enable these possibilities, the batteries/fuel cells/solar arrays used throughout the lunar surface architecture would need to be common, modular, removable, and replaceable. The two latter uses would require a significant number of flights to build up enough batteries/fuel cells/solar arrays to be useful.

Propellant Tank

Propellant tanks salvaged from spent LSAM descent stages could be used to store consumables, propellants, and fuel cell reactants. During the course of developing the outpost deployment strategy, the idea of reusing the descent propellant tanks as holding tanks for ISRU products was contemplated. This would reduce or eliminate the need to deploy separate holding tanks solely for the purpose of ISRU product storage. This would also add requirements to the propellant tanks and their plumbing in order to assure that interfaces are readily accessible and are designed for repeated loading/unloading of consumables. It is likely that the fluids that were originally stored in the tanks might limit the types of fluids that can be stored in the tanks for future purposes (e.g., contamination from previous contents or tank designs).

Option 3 – Reconnaissance and Pre-deployment of Assets at Outpost Site

In examining ways in which to leverage sortie missions for the eventual deployment of an outpost, operational strategies should also be considered. Due to the level, type, and duration of activities that will occur at the site of the outpost, it would be extremely beneficial to obtain a precise understanding of the local terrain, lighting conditions, regolith properties, and quantity of available resources. One of the most efficient ways of gathering such data is to send robotic probes and humans on reconnaissance missions to the site of interest. Such data would help mission planners and engineers to plan the layout of the outpost and design systems that accommodate the local environment.

Early sortie missions could also deploy assets at the site of the future outpost. For example, the deployment of the outpost will most likely require cargo missions that will need to perform

autonomous precision landing. To aid this, sortie missions could be used to deploy navigational aids that would allow the early outpost deployment flights to obtain precise landing accuracies. Another pre-deployment example might be to deliver an asset, such as an unpressurized rover, for the use of a future outpost crew. This would potentially shift the manifest of the unpressurized rovers in the outpost deployment strategy to an earlier date, thus freeing mass allotments during later flights. However, this type of strategy would carry with it requirements that increase the lifetime of the pre-deployed elements.

Option 4 – Infuse ISRU at a Moderated Pace

ISRU-related elements account for five out of the 17 (29 percent) major elements in the current outpost deployment strategy. Additionally, demonstration units are planned for the sortie mission flights. After examining the rate of ISRU-element deployment and dependencies between the ISRU-elements, it was felt that ISRU endeavors would benefit from implementing a more moderated pace of infusion. The current plan requires each element Design, Development, Test, and Engineering (DDT&E) cycle to occur within approximately 2 years. Since ISRU processes will be new to the types of activities undertaken by NASA, it was felt that 2-year DDT&E cycles would be extremely ambitious and, therefore, would perhaps endanger the success of incorporation of ISRU into the program. Furthermore, the purpose of delivering demonstration units to the lunar surface during sortie missions is to prove some of the key processes associated with lunar regolith manipulation and processing. However, given the current pace of the program plans for deploying “pilot” elements that incorporate lessons learned from the demonstration units and expand upon their capabilities, the pilot elements would already need to be entering Phase B project activities before the demonstration units are even flown. This provides little opportunity to incorporate into the pilot units any knowledge gained by the successes or challenges faced by the demonstration units. To examine the impacts of adopting a more moderated pace on program plans, a revised ISRU-infusion schedule was created. Figure 4F-3 shows the original plan outlined in the outpost deployment strategy next to the revised schedule. As can be seen, notional 4-year DDT&E schedules were adopted. Also, a 6- to 9-month learning period was incorporated for developing lessons learned from the demonstration units, which then led into Phase A of the pilot units.

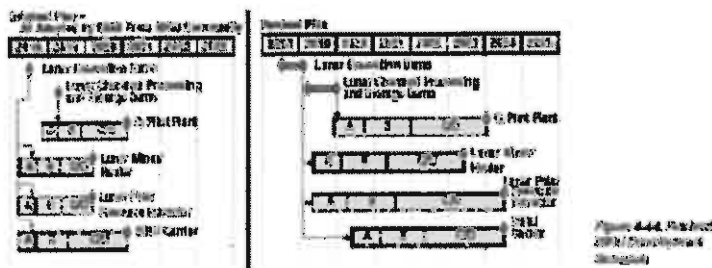


Figure 4F-3. Outpost Development Strategy Original Plan

Option 5 – Delay Delivery of Pressurized Rovers

The original lunar program timeline developed by the ESAS team included a pressurized rover, manifested in 2023. The team performed some rough calculations to assess whether deploying a pressurized rover early in the program was necessary. A maximum of four Extra Vehicular Activities (EVAs) per week was used as a starting point for the level of EVA that can

be expected in the early lunar program. Additionally, the NASA JSC EVA Project Office provided general guidance on the following EVA traverse radii:

- Within 3 km of outpost: No rovers needed, but would be useful;
- Between 3 km to 15 km of outpost: At least one un-pressurized rover needed – crew members are within walk-back range;
- Between 15 km to 30 km of outpost: At least two un-pressurized rovers needed with the performance required to transport all crew members back to the outpost – crew members are outside of walk-back range; and
- Beyond 30 km of outpost: Pressurized rovers are needed.

The team also made a few additional assumptions:

- Three of the four EVAs per week are used for exploration purposes (one is reserved for outpost maintenance or miscellaneous tasks);
- The crew will explore approximately 25 percent of the nearby land mass (similarities in the lunar terrain will negate the necessity to explore the entirety of the surface);
- The crew will re-visit 25 percent of the sites that they originally explore;
- At a site of interest, the EVA crew will explore a 100 m (0.1 km) radius around their rover; and
- Along their traverse route during the trip to/from the site of interest, the crew will be able to adequately explore a 40 m (0.04 km) path.

Given these assumptions, the team was able to perform some calculations regarding the number of EVAs required to explore the available land mass associated with the various radii defined by the EVA Project Office. It was determined that the lunar program could operate for approximately 6 years prior to requiring a pressurized rover to explore beyond 30 km from the outpost. Therefore, if the crewed operations at the outpost begin in 2022, the crews can continuously explore new areas until ~2028 without a pressurized rover.

Option 6 – Limit Operations to “Communications-Friendly” Outpost and Sortie Sites

The final major option for reducing mission complexity and cost is to limit the surface operations to sites that have a continuous view of Earth, have a view of Earth during the time of the mission, or can be provided with communications through a simplified constellation by timing the occurrence and duration of the mission. Currently, it is assumed that there will be a requirement to maintain constant communications between Earth and the lunar surface crew. Additionally, it is assumed that there will be a requirement to maintain constant communications between the crew members on the lunar surface, especially during EVA periods. Recent analysis shows that a 6-2 communications constellation would be required to provide these capabilities. Either limiting the outpost and sortie mission sites to communications-friendly sites (with respect to either Earth-viewing or a minimal constellation) or relaxing the requirements for constant communications would decrease the complexity of the constellation that must support such operations.

Alternate Outpost Deployment Recommended Strategy

The ESAS team recommends that all of these options be considered in future studies as alternatives to the baseline monolithically-deployed outpost. Incremental deployment of the outpost using both cargo and habitable elements delivered by repeated visits of sortie-class missions could result in increased capabilities with each subsequent sortie mission.



Section 4I

Lunar Robotic Precursor Missions

Appendix 4I – Lunar Robotic Precursor Missions

Robotic Precursor Missions

Robotic missions to the Moon should be undertaken prior to human return to the Moon for several reasons. Robotic missions can collect strategic knowledge that permits safer and more productive human missions. Such data includes information on lunar topography, geodetic control, surface environment, and deposits of largely unknown character, such as those of the polar regions. This information can be collected by a variety of spacecraft, including orbiters and soft landers.

In addition to collecting important precursor data, robotic missions can deliver important elements of the surface infrastructure to the eventual outpost site. Such deliveries include exploration equipment (i.e., rovers) and scientific instrumentation (i.e., telescopes). Additionally, since the extraction of resources will be an important activity of humans on the Moon, robotic precursors can deliver elements of the resource processing infrastructure, including digging, hauling, and extraction equipment. It is likely that NASA will want to experiment with various processing techniques and methods of extraction, and robotic missions can demonstrate process techniques at small scales in advance of the requirement to put large amounts of infrastructure on the lunar surface.

Strategic Knowledge Requirements

Before humans can successfully return to the Moon, gaps in our knowledge of the surface, environment, and nature must be filled. Robotic missions provide a way to cost-effectively answer these questions; but, in addition, offer the opportunity for early accomplishment, asset emplacement, and long-term risk reduction.

Strategic knowledge consists of those facts about the Moon and its environment that can affect the design and operation of systems that will ultimately make up the lunar outpost. For the Moon, this consists of its physical environment and nature of its deposits at a variety of scales. The latter qualification means that both orbital and landed robotic missions are required to provide the information needed to let humans safely return and then effectively operate on the Moon.

Because one of the principal objects in lunar return is to learn how to use space resources, much strategic knowledge revolves around the nature of lunar materials, especially materials from environments and areas on the Moon for which we have little or no data. This includes the vexing problem of water ice at the lunar poles, an issue whose resolution should come as soon as possible in a program to return humans to the Moon. Thus, much of the discussion below deals with this problem. However, the types of measurements done and equipment delivered to the Moon as described below are applicable to a landing at any site on the Moon, although the strategic knowledge requirements vary depending upon which sites are chosen for consideration as the outpost site (Table 4I-1).

A General Robotic Strategy

The ESAS team identified a general strategy that systematically fills in the most pressing knowledge gaps first, but is flexible enough to adapt to changing circumstances in the

different processing methods. Thus, a likely set of payloads that could follow the initial mapping and prospecting lander might include a variety of bench-scale experiments designed to evaluate the relative efficacy of water production methods. Such experiments would allow us to test various processing schemes prior to the landing of people. The needs of such experiments need to be defined; at a minimum, they will involve collecting regolith feedstock, grading the feedstock to eliminate rocks and other non-useful components, processing the ore to extract the product, and transferring and storing the extracted water.

The payloads and missions of future landers need to be defined after the basic data collected from these missions has been evaluated. They may contain additional resource processing experiments and equipment, specialized resource and outpost civil engineering experiments, scientific packages (e.g., demonstration telescopes and small geologic rovers), and other pieces of outpost infrastructure. The definition of such payloads should be deferred until more information on their requirements has been collected.

Table 4I-1 Strategic Knowledge Requirements as a Function of Type of Outpost Site

Sites	NavCom	Precision topography and local terrain	Surface deposit characterization	Site environment
Equatorial and low latitude sites	No	Probably not	No	No
Limb sites	Yes	Yes	No	No
Polar sites	Yes	Yes	Yes	Yes

Table 4I-2. Summary of Proposed Robotic Mission Campaign

Mission	Type	Information	Duration	Other/Comments
LRO	Orbiter	Lunar geodetic model, polar deposit characterization, radiation of near-Moon environment	1 year mapping; 4 years extended	Needs communications relay capability
NavCom system	Multiple Orbiters	Enable near-Moon navigation for precision landing (within 100 m); comm. relay for far side and limb landings	3-5 years	Can be implemented with 4-6 microsats in a variety of orbits
Lander 1	Soft lander	Characterize polar environment and deposits; rove to cold traps to make in situ measurements; conduct other site characterization as required	2 years	Emplace long-lived beacon and demonstrate key subsystems for human return; demonstrate precision landing and other spacecraft systems that are extensible to human landers
Lander 2	Soft Lander	ISRU experiments, bench-scale water production, map mining prospect	1-2 years	Demonstrate reproducibility of lander design
Lander 3	Soft Lander	Additional ISRU experiments, scientific packages, outpost infrastructure	Indefinite	Material and information as needed to build up outpost (e.g., power systems)

Table X-3 Robotic precursors and human lunar return

Key knowledge needed for human safety and mission success

Detailed topography, physical environment, polar deposit states and compositions, terrain, geotechnical properties

Technology demonstrations

Precision landing, propulsion, ISRU demonstration experiments

Infrastructure elements for eventual human benefit

Landing beacons, communications relays, cislunar and surface navigation and geodetic control, earth-moving equipment, paving machines, diggers, thermal processing, power system deployment

Scientific information to guide human exploration

Remote sensing data of site, pre-outpost sampling traverses, demonstration experiments (e.g., robotic telescope), geophysical package deployment