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Paper Session I-B - The Space Exploration Initiative and the Aero-Space Plane Launcher

Russel J. Hannigan
Visiting Research, Space and Hypersonics, CREST Ecole Polytechnique, Paris, France

David C. Webb
President, International Hypersonic Research Institute, Winter Springs, FL

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THE SPACE EXPLORATION INITIATIVE

AND

THE AERO-SPACE PLANE LAUNCHER

Russell J. Hannigan
Visiting Researcher, Space & Hypersonics
CREST Ecole Polytechnique
54, rue Boissonade,
75014 Paris, France

Dr. David C. Webb
President
International Hypersonic Research Institute
1213, Jaguar Court
Winter Springs, Florida 32708, USA
THE SPACE EXPLORATION INITIATIVE &
THE AERO-SPACE PLANE LAUNCHER
Russell J. Hannigan1 & Dr. David C. Webb2

ABSTRACT

Consideration is given to the critical operational issues associated with large-scale space programs, like the proposed Space Exploration Initiative (SEI), in order to demonstrate their intimate relationship with the Earth-to-orbit launch systems being used. These operational issues include failure resilience and continuous access. It is shown that scenarios using expendable, vertically launched Heavy-Lift Launch Vehicles (HLLVs) as the primary space launch means, may be difficult to accomplish. This is because the performance characteristics of such vehicles - most notably reliability and availability - contradict the identified critical operational requirements of SEI. An alternative strategy is outlined for the Lunar Base part of a future SEI program. This scenario uses a duel launch architecture consisting of the HLLV and the proposed fully reusable, winged Aero-Space Plane Launcher (ASPL). Relevant technical issues of the hardware elements are identified and discussed from the total program perspective. The rationale used to optimize the scenario is outlined, and the potential value of carefully matching payload types to the launcher performance is subsequently demonstrated.

1. INTRODUCTION

Regardless of the motivations, the establishment of a permanent base on the Moon followed by manned missions to Mars - referred to under the generic title as the Space Exploration Initiative - are unquestionably extraordinary endeavors. The political, organizational and economic challenges inherent in such enterprises are immense. However, it is the array of technical problems that poses the greatest hurdles and, in many respects, these problems drive the political and organizational issues, especially those relating to economics. Thus, the choice of technical solutions has a strong bearing on the chances of the program being funded and remaining funded.

The determination of the optimum technical solution for SEI is a complex process that must match system performance with the restrictions imposed by funding and technology. However, because of the large-scale and long-term nature of the program, the operational issues are likely to have the greatest impacts on the solution and, therefore, economics. Understanding precisely what is involved in supporting manned space programs like SEI is absolutely fundamental to determining the best overall solution. Two issues are pre-eminent. The first is the ability of a particular operational scenario to absorb failures, and the second is the need to maintain uninterrupted access to space and the systems in space.

Failure resilience: Regardless of the effort put into a program like SEI, failures - although "probabilistic" - are inevitable. Such failures can range from the loss of a major system, to the malfunctioning of individual components within a system. The more resilience or robustness that is built into the program from the beginning, the higher the probability that operations will be allowed to proceed despite such failures. Alternatives, where reasonable or needed to enhance safety, should always be available. Clearly, because of the requirement to maintain a continuous access for SEI operations, as described below, the need for resilience is a fundamental prerequisite.

Continuous access: Large scale manned spaceflight activities differ significantly from most other smaller-scale operations because each element has to depend upon one or more other elements functioning properly. This differs fundamentally from the more classical space programs, such as communications and science satellites, that must carry all the systems needed to support their entire mission. Continuous access is needed to supply the hardware elements (e.g. landers, habitats), logistics (e.g. food, water, air), spare parts for routine and unexpected maintenance (e.g. lights, valves etc.), the mission payloads (e.g. science instrumentation), and the crew. Supply of each will need to start with the first element launch and continue thereafter on a regular and reliable basis over the program life-time.

Another potentially critical concern relating to continuous access is orbital testing. Developing subsystems, systems and operational procedures for space applications usually demands repeated testing to the "edge of the envelope." Failures that occur during traditional test campaigns are usually the only method of fully characterizing the performance of a particular piece of hardware or operational procedure. Indeed, hardware that is not rigorously tested may cover up inherent design flaws that could lead to later failures. Obviously, from an engineering standpoint, the most prudent method of verifying SEI hardware and procedures, especially complex systems like a lunar lander or assembly operations, is to repeatedly test them in orbit. Unfortunately, because of the current high cost of space operations, coupled with limited opportunities, such testing is minimized.

The single common factor having the greatest impact on the above issues is the Earth-to-orbit launch vehicle. Throughout the paper, discussion will focus on the impacts launch vehicles have on SEI-type activities, within the general context of those issues relating to failure resilience, continuous access and orbital testing.

2. THE HEAVY-LIFT LAUNCH VEHICLE

The utilization of heavy-lift launch vehicles (HLLV) seems almost synonymous with any SEI-type activity that is considered. Effectively, it is automatically assumed by many SEI planners that an HLLV is, firstly, a necessary
capability and, secondly, the primary launch system. Typically, HLLVs are expendable, vertically launched rockets such as the proposed Shuttle-C and ALS. It is true that, because of the considerable amount of mass that needs to be launched, some form of “bulk” launch system is needed, and therefore requiring an HLLV. However, by examining closely some of the technical problems inherent with SEI, as identified in Section 1, it is clear that more than just an HLLV-type launcher is required.

Limitations of HLLVs

The positive aspects of HLLVs are well understood, with the “low cost per pound” to orbit as the principal advantage (1). However, on the negative side, despite this the actual dedicated costs range anywhere from $100 million, as is targeted for the original ALS, to $300+ million for a Shuttle-derived vehicle. Even this is only a partial representation as it does not fully take into account what is actually being launched - i.e. the payload itself. If the payload was just an equally priced “lump of mass,” then low cost per pound would clearly have some meaning. For example, the propellant needed by each mission to the Moon (e.g. around 75 tonnes) can be described precisely in this way. However, for the remainder of the other payloads, it is somewhat less than fair to describe them on a mass only basis.

There are many “generic” reasons why expendable launchers like the HLLV would negatively impact the payloads being carried, as discussed below:

Reliability: Vertically launched expendable boosters are notoriously unreliable, compared with terrestrial transportation systems. Typically, boosters like the Atlas, Titan, Delta and Ariane have reliabilities that range from 90 to 98%. This is an inherent characteristic of such boosters, and it is clearly important to understand why this should be the case. As mentioned in Section 1, extensive testing is fundamental to increasing reliability. However, because of the demanding function they perform, launch systems tend to be very large, complex and highly integrated pieces of machinery. Thus, as a direct consequence, expendable launchers are expensive. The developer of an expendable booster is, as a result, in a “Catch-22” situation in that it drives the cost of the payloads up and reduces the rate at which they can be launched. Availability can be increased through mass production. However, mass production would not bring down the cost of the launch enough to generate more users and, in any case, critical line-items such as liquid rocket motors tend to inhibit higher production rates, as is the case with Ariane, Delta, Atlas and Titan. With the much larger and more complex HLLV, it is difficult to see how a high availability rate will be achieved - especially in view of the high value of the payload being carried.

Impacts of HLLV on SEI Activities

The use of the HLLV as the primary launch system for SEI adversely affects the critical failure resilience and continuous access operational requirements in a profound way, as discussed previously. The inevitable net consequence is that it drives the cost of the payloads up and reduces the rate at which they can be launched. If the reliability and availability are limited, then the HLLV flight rate must be minimized to avoid losses. Therefore, for the program to maximize their use, payloads will be designed to be as highly capable as possible, meaning they must also be highly integrated and lightweight. These are conflicting requirements which increase the cost of the payload and reduce the number built. This, in turn, places higher reliability demands on the launcher - thus increasing the HLLV costs and impacting the availability.

This vicious circle is further exasperated by the fact that SEI payloads will be critically dependent on payloads launched by other boosters in a continuous sequence. Thus, the loss of one payload would have a extreme economic and schedule impact on the total program. For example, in the NASA 90-day Study of Human Exploration of the Moon and Mars (2), 3 or 4 HLLVs are needed one after the other to assemble the hardware for just one lunar landing mission. At this rate, after only two or three sorties to the Moon, there would be a better than 50:50 chance of losing one of the next boosters.

Figure 1 attempts to show the relationship between flight rate, loss rate and down-time as a function of reliability as generated by a Monte Carlo simulator. As a reference point,
nominally it takes about 4 years to build up to the maximum flight rate of 10 per year, achieving a total of 88 flights in the 10-year span. However, even at 98% when 2 losses occur, it takes 7 or 8 years before about 10 flights per year are achieved and, perhaps more importantly, only 78 mission are flown. This reduction is brought about by the "knock-on effects" of down-time.

A further problem relates to orbital testing. The Space Shuttle is, as yet, the only vehicle capable of returning payloads for inspection after test. However, the limitations placed on its flight rate will effectively eliminate consideration of its regular use for SEI-type test activities. The alternative use of an HLLV, or any other large ELV, for such operations will do little to help the situation for many of the same reasons outlined above.

The use of the HLLV for SEI can be compared with the following terrestrial analogy: Consider what the status of inter-continental trade and development would be like today without the invention of the aircraft, and if it had to rely on ocean going vessels. Especially if such vessels could not be tested first, if they could not be recalled to port if a problem arose, if these ships had to be discarded after only one voyage and if the users had to pay the full production costs of the vessels. Although it is dangerous to make this sort of direct comparison, primarily because space launching is significantly more difficult than terrestrial transportation, it does help to highlight the intimate relationship of the transportation system with the role it fulfills.

3. THE AERO-SPACE PLANE LAUNCHER

The aero-space plane launcher (ASPL) is one concept for a space transportation system which is radically different than existing systems. Essentially, it is a fully resusable, highly maintainable, one or two-staged winged vehicle capable of taking-off and landing horizontally. Many studies have shown that this type of configuration is critical to significantly reducing dedicated launch costs (3). Achieving such a capability is an immensely difficult task, as is well understood within the aerospace community. But, in general, all indications are that this will be a realisable goal within the next 10-15 years. Assuming it is indeed achievable, the impacts on reliability and availability could be as follows:

Reliability: The most significant advantage positively impacting reliability is that the ASPL can be recovered. During the testing phase, it should be possible to incrementally expand the envelope so that eventually after many flights, and with the same vehicle, orbital flight is achieved. Thus, gradually over a campaign of many flights, the individual characteristics of the test vehicles can be evaluated. This is clearly critical to enhancing reliability. During the operational phase, ASPL-like vehicles should be able to return to Earth following an abort and, thereby, providing a means to recover the payload and make another launch attempt at a later date. Although ASPL-specific failures are possible, it is interesting to note that if the ASPL experienced the same "type" of failures as suffered by the ELVs in recent years, the ASPL and payload would probably have been recovered.

Availability: Once operational vehicles have been introduced, availability is enhanced compared with ELVs because a new vehicle does not have to be manufactured and verified for each mission. Problems associated with maintaining the large infrastructures needed to support the construction of ELVs, together with the large ground crews needed to integrate the various stages, are avoided. In addition, ASPLs also provide the potential to containerize the payloads in a manner that completely standardizes the interfaces between the payload and launcher (4). This may allow the satellite-to-launcher integration process to be reduced to hours, compared with the current days or weeks. Thus, because the ground operations are minimized, greater opportunities are provided for higher flight rates and significantly reduced dedicated launch costs.

To summarize, an ASPL-like capability could provide a much more "user-friendly" means of accessing space. The ability to launch payloads significantly more frequently reliably, when demanded, and at a much lower costs than existing launchers, is expected to have a profound impact on the current space operations including SEI (5).
A number of ASPL programs exist today with the most notable being the NASP, HOTOL and Sänger Programs. For background, the key features of each are summarized.

**NASP & NDVs**

Since 1986, the US Government and the industrial contractors have spent nearly $2 billion on the National Aero-Space Plane Program which intends to develop an experimental aircraft - the X-30 (Figure 2) - capable of reaching orbit with a single-stage. NASP is generally regarded as one of the most technically challenging projects ever initiated, and the program is well known within the aerospace community for its research in the areas of advanced materials, supersonic combustion ramjets, computational fluid dynamics and systems integration.

![Figure 2](image)

**THE NATIONAL AERO-SPACE PLANE**

The primary purpose of the NASP Program is to develop the technologies, systems and techniques needed for the eventual production of an operational fleet of aero-space plane launch vehicles, the NASP-Derived Vehicles. Presently, the “reference” NDV is designed as a highly maintainable vehicle capable of being turned around in a few days or hours, and able to place in Space Station Freedom orbit payloads of about 10 tonnes, at a cost of between $5-20 million per launch. Launch rates could be around 50 mission per year with a loss reliability of better than 99.5%. (Note: The recent OTA report (6) estimated that the worst case operational cost per launch, with facilities and other fixed annual costs amortized in, would be about $12m, with the best case being $2m.)

The NASP Program is midway through Phase 2, with funding running at $258m this year, and a decision in March 1993 is scheduled to be made to develop the first two experimental vehicles. After this, it is estimated that an operational NDV could gradually replace the Space Shuttle before the end of the next decade.

**HOTOL**

The HOTOL Launcher was conceived as a vehicle optimized solely for the purpose of significantly reducing operational launch costs. HOTOL, which was started in 1984 as a joint project between British Aerospace and Rolls Royce, uses a much more conservative design approach and more available technologies than NASP in order to reduce the development risk uncertainties. For example, air-breathing only occurs up to Mach 5.5, and in-coming air is slowed down to subsonic speeds prior to combustion. In addition, the original classified RB-545 engine was designed to allow full testing of individual sections first, allowing the engine performance to be fully characterized on the ground before installation on the vehicle. This is different to the NASP Program which must build and fly a full-up aircraft to test the engine.

The HOTOL Program was slowed when the UK Government decided to discontinue funding and BAe were asked to look for international support. Unfortunately, these efforts were thwarted by the UK Government refusal to declassify the RB-545. In September 1990, BAe announced an agreement with the Soviet Ministry of Aviation Industry for joint studies of a pure rocket version - the so-called “Interim HOTOL” - launched off the back of the Antonov-225 aircraft. This study is presently progressing. This, and the original version of HOTOL, are primarily unmanned - though “manable” - vehicles designed to place around 7-10 tonnes in low Earth orbit for a cost of about $5m per launch, or about $15m if development and production cost recovery is amortized.

**Sänger**

Contrary to the NASP and HOTOL Programs, Germany believes that the technologies for single-stage-to-orbit will not be available until at least 2010 or later. Therefore, they have embarked on the two-stage-to-orbit design known as Sänger, which is currently the reference vehicle configuration in the German National Hypersonic Research Program, and is funded at $250m over five years. Preparations are underway in an effort to “Europeanize” the program for development within ESA. It is hoped that a prototype will fly in the early part of the next decade, with an operational system available by about 2010.

Sänger consists of a first stage that carries the Horus upperstage up to a speed of about Mach 7, at which point the upperstage is separated. Horus comes in two configurations: the Horus-M for manned missions (plus 3 tonnes of payload to a Freedom orbit) and the Horus-C for unmanned cargo missions with a payload capability of about 7.5 tonnes to an equatorial orbit. The estimated launch cost is about $25m per mission.

4. SCENARIO DESCRIPTION

This section outlines an in orbit space transportation architecture based around the availability of an ASPL and an HLLV booster as defined earlier. For demonstration purposes, the scenario is specifically scoped for supporting a sustainable and long-term (>10 yrs) human presence on
the Moon. Mars is not directly discussed. The intention is
to demonstrate the practicality of such a scenario and
highlight some of the critical technical, programmatic and
infrastructure-related issues that are raised.

Guidelines

The following is a list of some of the general "guidelines**
used in developing scenario:

- establish a permanent and expandable lunar base
- optimize the utilization of both launchers
- optimize reusable versus expendable hardware
- minimize other infrastructure elements as practical
- ensure that consequences of failures are "tolerable"
- ensure a crew return capability to the Earth
- develop strategies for "rapid** contingency missions.

Finally, there is no fundamental reason why the in-space
transportation elements must be large. Indeed, for the
reasons outlined in section 2, it has been the incorporation
of H.L.L.V.s as the primary launch system in a number of
previous studies that has driven the large size of the
elements. It is considered that for cost and operational
reasons there are many positive advantages to remaining
modestly sized where appropriate, at least during the first
few years of operations.

Elements

The basic transportation elements consist of the:

- **Space Transfer Vehicle (STV)**
- **Manned Lunar Lander (MLL)**
- **Cargo Lunar Lander (CLL)**
- **Trans-Lunar Injection Stage (TLIS)**

Each of these elements and their functional requirements are
described as follows:

**Space Transfer Vehicle** : The STV (Figure 3) is fully
reusable and its primary functional requirements are to place
the MLL in lunar orbit, and then later return the Lunar Base
crew and their lander to Earth orbit. This concept is similar
to that proposed by British Aerospace (7) and utilizes an
umbrella-like system for deploying a 200 m2 aerobrake
made from a high temperature cloth similar to that used by
the Shuttle Orbiter. The value of this approach is that it
could allow the compact stowage of the complete STV
within one ASPL, allowing deployment without the need
for on-orbit assembly. (If such a design proved unfeasible,
an alternative approach could utilize an aero-brake
consisting of several solid "petals" that unfold following
launch. This "solid" aerobrake could be left on-orbit, for
example, while the core of the vehicle can be launched and
returned independently.) The STV central thrust structure is
surrounded by two hydrogen tanks and two oxygen tanks.
The four tanks are the same length, but the oxygen tanks
are thinner to reflect the higher density. The STV is
launched without cryogenic propellants.

**Manned Lunar Lander** : The MLL (Figure 4) is fully
reusable and is sized to place a crew of 3 or 4 on the Moon.
The central structure is composed of two frustrums joined
together by a short cylindrical insert, and is based on that of
the STV, except that the MLL insert is shorter. Similarly,
the propellant tanks of the MLL have the same hemispherical ends and interfaces as those on the STV, but
the cylindrical center section is shorter. The avionics, power
and other subsystems would also be similar where
appropriate. At this level of definition it is difficult to say
whether the commonality between the components would
lead to significant production cost savings, as only a few
STVs and MLLs would, at least initially, be built.
However, using a commonality approach reduces the
number of unique systems that have to be designed,
characterized and qualified, thereby, enhancing reliability and
reduces the spare parts burden. The crew cabin is around
3.5m in diameter and is equipped with a Freedom standard
docking hatch. The MLL, like the STV, is launched
without propellant and also without the crew on a single
ASPL mission.
MANNED LUNAR LANDER (MLL)

Figure 4

Cargo Lunar Lander: The CLL (Figure 5) is based on the MLL except that the propellant tanks and central structure are somewhat longer for more optimum performance. The manned cabin and crew related systems also have been removed. The CLL is conceived as an expendable vehicle able to land from 10 to as much as 15 tonnes of cargo on the Moon per mission such as, for example, modules, rovers etc. The CLL is, at least in the early operations, conceived as being expendable. From a total cost perspective, it is probably cheaper to use each lander once than to recover it, since twice as many missions are required to land the same mass using a reusable lander as compared with an expendable version. In addition, the STV is not needed for the cargo missions, simplifying orbital operations and lessening the burden on the STV, essentially reserving it for the manned missions where reliability is rather more critical. The CLL is also launched dry on one ASPL mission. The payload would be launched separately.

CARGO LUNAR LANDER (CLL)

Figure 5

Trans-Lunar Injection Stage: The expendable TLIS (Figure 6) is launched on a single HLLV booster and uses as many components of the launcher as possible (e.g. tanks, engines etc). The TLIS, which has a mass of 60 - 90 tonnes at launch, performs the trans-lunar injection burn and carries all the propellant needed by the TLIS as well as the STV, MLL or CLL. This avoids ever needing to bring large quantities of propellant near the Space Station (see the next subsection). The TLIS is conceived as being essentially a "dumb" stage and is equipped only with sufficient avionics to keep it pointing in a fixed direction following orbital insertion. This is necessary to allow the STV/MLL or CLL to dock with it. All other control and monitoring equipment is provided by the MLL or CLL.

TRANS-LUNAR INJECTION STAGE (TLIS)

MANNED & CARGO CONFIGURATIONS

Figure 6

Space Station Node Facilities

The value of on-orbit servicing of the transportation elements is the subject of intense debate. However, in an ASPL era it can be expected that the on-orbit facilities will be considerably more extensive than those planned for Freedom, simply because of the available, reliable and affordable capabilities of the new launcher system. Therefore, the trade-off may favor on-orbit servicing because access to the facilities is possible. Conversely, even in the ASPL era it may still be more cost effective to return the MLL or STV after every mission for precisely the same reasons.

Ultimately, the transition to on-orbit servicing practises will arise once the flight rate to Moon increases to the point where it is more cost effective to leave the hardware on-orbit. For example, it might be cheaper to invest in orbital facilities to support servicing operations, rather than pushing the ASPL to steadily increasing flight rates, especially since the total cost of an ASPL loss would probably be comparable to that of the servicing facilities. It is possible to envisage a situation during initial
operations where the MLL and STV is brought back to Earth and, as more experience is gained with the launch system and the behaviour of the lunar transportation elements has been more thoroughly characterized, a gradual transition to servicing facilities would be realizable. It is also important to note that in the intervening period before orbital servicing is possible, the unique capabilities of the ASPL would allow the testing out of servicing-type operations in space, again because frequent access to space is more practical. Such a situation does not exist today, and will not until a vehicle with ASPL-like capabilities is introduced.

Assuming such a scenario, a conceptual design for a servicing facility is shown as part of Figure 7. The design assumed the use of Freedom in its present (Jan. 1991) configuration purely as a means to demonstrate what might be practical. The concept does not require the use of the Freedom truss structure, but instead uses two pairs of pressurized modules, arranged in a "L", docked to the middle nodes (3 and 4). The lower end of the outer module is equipped to accept either an MLL or STV. In addition, these modules are equipped with a conical skirt that is draped around the docked MLL or STV to provide an isothermal environment and protection against meteoroids.

Thus, the concept shown in Figure 7 allows direct pressurized access to the MLL and STV, thus reserving any hazardous EVA activity to only those off-nominal situations where EVA is the only alternative, such as the repair of loose thermal insulation. In the case of the MLL, this arrangement is particularly attractive as it ensures continuous access to all of the internal systems, allowing systems checks and simulations to be performed. In the case of the STV, it is possible to envisage a design where all the critical systems are located in a pressurized section just below the STV/MLL interface so as to allow routine pressurized servicing. Other docking ports are provided for the CLL and its payload.

As an important side effect, this type of servicing concept would probably have less disruptive impact on other Freedom operations compared with a servicing concept that uses the upper and lower booms (2). Overall, the reason why such a concept could be practical is because the transportation components are of manageable size, i.e. they are small.

Operational Philosophy

Assuming the availability of an on-orbit servicing facility, the operational philosophy is conceived as follows:

- Manned Missions

In a manned scenario (Figure 7), the MLL and its STV would be serviced at the station as required. Then the Station manipulator system would grapple the STV and place it on the back end of the MLL. Once docked, the crew can enter the MLL and perform verification checks between both vehicles. When the mated STV/MLL had been cleared for flight, an HLLV would launch the TLIS. If this HLLV fails to reach orbit, the STV and MLL would remain safely at the Station until the next TLIS launch can be attempted.

Once the TLIS had been placed in a safe orbit, the STV/MLL would rendezvous with the TLIS and dock. Propellants from the stage would then be pumped into the STV/MLL tanks. The composite would then be fully checked out before the TLIS main propulsion system is ignited to place the STV/MLL into trans-lunar injection. The remainder of the mission trajectory (Figure 8) follows a classic Apollo-style Lunar Orbit Rendezvous strategy, with the STV performing the Lunar orbit insertion manoeuvre before the MLL separates and to the surface. Meanwhile, the STV remains in Lunar orbit with its aero-brake facing the Sun to minimize propellant boil-off. After the MLL has ascended from the Moon and redocks with the STV, the STV performs an Earth orbit injection burn, and the aero-brake is then used to place the STV/MLL in Earth orbit following a final burn of the STV engine.
It should be noted that the scenario outlined above always returns the MLL to Earth orbit after every mission, as opposed to leaving the descent section in Lunar orbit as suggested by many previous studies. Thus, it eliminates the need to perform propellant or propellant tank transfer. In addition, and perhaps much more critically, it allows the MLL to be fully checked out before the next crew boards. This is particularly important during the first few years of operations because of safety uncertainties relating to the performance of vehicles like lunar landers. It should be appreciated that the ability to return the MLL arises by virtue of its small size.

o Cargo Missions

Lunar cargo missions are much simpler than manned missions because the hardware is expendable. A typical cargo mission would involve the launch of the CLL and cargo on separate ASPL flights, and subsequently integrating them at the station. Once completed, the TLIS would be launched and the mated CLL/cargo would autonomously rendezvous with the TLIS and dock. After the TLIS is launched, the CLL/cargo would either insert into lunar orbit or descend directly to the surface.

Future Expansion

If, in the future, a Lunar oxygen production facility is set up, it is possible to envisage a situation where the CLL on the Moon would be partially refuelled, loaded with excess liquid oxygen and returned to Earth. The main problem would be that the CLL must trade payload for the extra hydrogen fuel needed for the return. Nevertheless, potentially several tonnes of liquid oxygen could be returned to the Earth. Whether sufficient oxygen could be returned economically to refuel a fully reusable TLIS, has not been estimated at this stage. However, a future scenario that eliminates the HLLV is clearly advantageous, but only if at least two different types of ASPLs are available.

5. SCENARIO OPTIMIZATION

The scenario described in Section 4 is intended to demonstrate a level optimization that could be possible if a launch architecture consisting of the ASPL-type launcher and a HLLV booster is available. The rationale and approach for the scenario is driven by consideration of the actual payloads, and the requirements they place on the launch system, as seen from the critical perspective of their operational needs. Of particular importance, the optimization process develops a scenario which takes advantage of the best characteristics of the ASPL and HLLV, while minimizing the burden on each.

HLLV Utilization

An HLLV is needed within SEI scenarios because of the large mass-to-orbit requirements. However, by its very nature, the HLLV is expected to exhibit relatively low reliability and availability, as discussed in Section 3. Therefore, it seems reasonable to reserve the HLLV for those "cheap" payloads which can be launched in bulk, and as infrequently as possible to minimize the HLLV flight rates and, therefore, HLLV loss rates. In addition, such payloads should not be critical to servicing and maintenance-type activities in order to minimize availability concerns. Because propellant makes up the majority of the mass, this is an ideal payload for the HLLV.

Once a decision has been made to use the HLLV in this manner, it seems reasonable to configure the propellant tank to also be an expendable lower stage (TLIS), and use, where possible, suitable components from the HLLV such as engines, structure and avionics. This might be a sensible approach because these components would already be manufactured on a production line and, therefore, the additional cost impact might be relatively "minor." It should be noted that an alternative approach of launching a reusable stage might seem initially to be attractive when considered independently. However, because of the additional operational complexities involved in maintaining such a large stage in-orbit, combined with the need to refuel it with propellant (e.g. tank exchange), when considered from an overall system standpoint it appears somewhat less attractive.

Finally, launching inexpensive and mass produced payloads makes a significant contribution towards reducing the down-time after an HLLV failure. This should be compared with the alternative of using an HLLV as the primary launcher for all the STV, MLL and other critical hardware elements. Since such payloads are more expensive, and only a few are produced, more care and time will be taken to ensure that the HLLV will not fail again immediately after an initial failure. Therefore, it is considered likely that higher risk levels are more tolerable if the payload being launched is inexpensive and built in numbers, especially in a contingency situation. (Note : This is essentially the strategy used by the USSR Space Program.)

ASPL Utilization

In an SEI scenario, the value of a launcher exhibiting ASPL-type performance characteristics is its ability to launch reliably and frequently. Therefore, its performance should be reserved for those payloads and missions it best serves. Specifically, expensive, operational and maintenance critical elements. If possible, operational elements like the STV, MLL, CLL and lunar base elements should be launched individually, because there is a higher chance of reaching orbit, or recovered after an abort, compared with the HLLV. The ASPL also offers the potential to return elements for ground refurbishment - something impossible with HLLVs. For orbital maintenance-type missions, the quick reaction capability of the ASPL allows rapid access - particularly in a contingency situation. As discussed earlier, the need for a responsive "sortie" capability in large-scale space operations should not be underestimated.
In addition, during the development of SEI hardware, the ability to test each element thoroughly in orbit first, could be useful for the reasons highlighted in Section 1. The availability of ASPL-type capabilities would be critical here because of the ability to launch at the kind of high flight rates needed to support multiple test flights over a relatively short time-scale. The modest payload size, recovery capability and low dedicated operational launch costs would also contribute significantly to its utilization in this role. These characteristics are directly opposite to those offered by the HLLV.

It should also be noted that although the ASPL could conceivably launch propellant, this would not seem to be a suitable use of the vehicle as up to 10 flights per year mission could be needed. Although the total launch cost would be about the same, there might be a danger in pushing the ASPL unnecessarily to higher flight rates, and thereby increasing the probability of failure, especially while low on the ASPL learning curve. Also, the added complexities of significantly increased orbital operations in exchanging up to 10 propellant tanks, could be prohibitive. Launching propellant does not seem to be the best use for an ASPL.

Architecture Resiliency

A critical feature of the optimization process is the launch failure resilience, that is, the response to failure of one of the launch systems. Scenarios involving the failure of either the ASPL or HLLV are described below:

**ASPL Failure**: After the initiation of lunar base operations, if an ASPL fails and the fleet is grounded - a situation that is likely to occur during the early operational phase of the ASPL - access to the Moon would still be possible through use of the HLLV, albeit at a degraded level until the ASPL is available. For example, in a scenario where Freedom is used as a node, the STV and MLL will already be in orbit. Therefore, for a manned mission, one or two HLLV flights would be needed: one for the TLIS launch, and the other for the crew and logistics, assuming a Personnel Launch System-type capsule. If Freedom was not being used, then it may also be necessary to launch an already stacked STV and MLL on the crowded HLLV flight and dock it to Freedom until the TLIS can be launched. A similar scenario for cargo missions can be envisaged. Consideration of this type of scenario should be an important factor in understanding the need for a LEOS, as it could reduce the dependence and burden on the launch system.

**HLLV Failure**: Alternatively, if an HLLV fails, access to the moon would have to be halted for as long as it takes to renovate the HLLV. However, for the reasons outlined earlier in this section, this stand-down time is likely to be significantly less than that experienced if an ASPL failed. This is because the cost of an ASPL and its payload is so much higher, and only a few of each are built, compared with the much cheaper replacement cost of the mass-produced HLLV and mass-produced TLIS stage. In an extreme scenario, if access to the lunar base was absolutely necessary, then it is possible to envisage a situation where another TLIS is launched immediately, even if the problems of the previous HLLV failure had not been resolved.

### 6. CONCLUSIONS

There appears to be rational arguments to suggest that it may be difficult or impractical to support long-term lunar operations using expendable, vertically launched heavy-lift type vehicles as the primary launch system because of their low reliability and low flight rates. The reasons are based on the operational requirements to maintain a level of failure resilience and to ensure that continuous access to the orbital hardware is always possible. Such requirements are indicative of large-scale space activities just as they are for any terrestrial activity. For converse reasons, the proposed aero-space plane launcher would not be able to support lunar activities on its own. However, a combined architecture consisting of an ASPL fleet and HLLVs seems ideally suited for SEI-type applications, provided careful optimization is performed so that payloads are properly matched to each launcher. Such an optimization leads to scenarios that attempt to ensure continuous access to space, while simultaneously being able to minimize the highly disruptive impacts of a launch failure and subsequent stand-down period.

It is clear that the scenario is critically dependent on the development of a vehicle exhibiting ASPL-type performance characteristics. Although it is not certain that such a vehicle is technically feasible, the variety of national programs presently underway seems to indicate that the outcome will be positive. The potential high value to all space operations of ASPL-type launchers should provide further motivation to encourage their development.

### REFERENCES