DOI: 10.13009/EUCASS2022-7251

An Overview of the EURASTROS Study

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Abstract

In the frame of a think tank initiative DLR research institutes and ArianeGroup GmbH formed a working group to study the needs and solutions for European human access to space towards LEO and to identify potential future commercial markets. High-Level Requirements for an astronautical space transportation mission to LEO have been defined in the very early phase of the study. A reference mission using Ariane 6 launcher trajectory was proposed. The existing huge data base of Apollo missions and heritage of the successful European flight demonstrator ARD were the key drivers for the choice of the Apollo shape of the capsule. The main challenge of the EURASTROS study was the definition and performance prediction of the atmospheric and exo-atmospheric abort systems.

Abbreviations

A62: Ariane 62 with two solid boosters
A64: Ariane 64 with four solid boosters
AGG: Ariane Group GmbH
ALM: Additive Layer Manufacturing
ATV: Automated Transfer Vehicle (of Ariane 5)
CAD: Computer Aided Design
CM: Crew Module
DOF: Degree of Freedom
DRL: Down-Range Landing site
ELA-4: Launch complex for Ariane 6 in Kourou
ELV: Expendable Launch Vehicle
ISS: International Space Station
LAS: Launch Abort System
LEO: Low Earth Orbit
LLC: Launch Control Centre
LLPM: Lower Liquid Propulsion Module
LPE: Launch Pad Escapen
LV: Launch Vehicle
Ma: Mach number
NCR: Non-recurring costs
p: Pressure
RC: Recurring costs
RLV: Reusable Launch Vehicle
RTLS: Return To Launch Site
SM: Service module
TPS: Thermal Protection System
TRL: Technology Readiness Level
TVC: Thrust Vector Control
ULPM: Upper Liquid Propulsion Module (of Ariane 6)
VTHL: Vertical Take-off and Horizontal Landing
VTVL: Vertical Take-off and Vertical Landing

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1. Introduction

Astronautical space transportation is a prerequisite for the construction and operation of near-earth and lunar infrastructures and thus for the future commercialization of space travel. Private US space companies such as SpaceX and Blue Origin therefore expect their commercial success primarily in astronautical space travel. SpaceX already generates a large part of its revenues from astronautical missions to the ISS and soon to the moon, while Europe's space industry is currently not providing astronautical transport services due to a lack of capabilities. Consequently, in contrast to the transport of payloads to different orbits, there is no independent European astronautical access to space. If Europe wants to participate in the future global commercial space market, it must be able to launch astronauts into space on its own as soon as possible. Based on the European expertise on operation of the Ariane 5 launcher system, which is also designed for astronautical space transportation, the new cost-efficient launcher Ariane 6 can be upgraded for astronautical space travel in an acceptable time period with acceptable resources.

For the identification of missing technologies and infrastructures for an independent European space transportation of astronauts to Low Earth Orbit (LEO) and prediction of corresponding costs, German Aerospace Center (DLR) and Ariane Group GmbH (AGG) initiated a study with the title European Astronautical Space Transportation (EURASTROS) [1]. The EURASTROS study was a joined activity between Ariane Group GmbH and several DLR institutes. Following the High-Level Requirements for an astronautical space transportation mission to LEO, which were defined in the very early phase of the study, a reference mission using Ariane 6 launcher trajectory was proposed. The European Ariane 6 launcher, with a maiden flight planned for 2022, was baselined as the reference launch vehicle [2]. The existing huge data base of Apollo missions and heritage of the successful European flight demonstrator ARD were the key drivers for the choice of the Apollo shape of the capsule [3].

The main challenge of the EURASTROS study was the definition and performance prediction of the atmospheric and exo-atmospheric abort systems [2][3][4]. There is a big technological gap to develop and fly such systems within the next five to seven years. In Europe, no matching service module is available. EURASTROS made use of the existing knowledge based on the ASTRIS kick-stage layout and its BERTA engine for the definition of a service module concept [2]. To enable the exo-atmospheric abort envelope, the number of engines was adapted accordingly to meet the required thrust. Another key activity carried out with significant effort was the cost analysis for recurring and non-recurring costs [5]. A development and qualification plan has been created with focus on module level instead of sub-system level to identify module weaknesses early and to accelerate the learning curve, which is expected to lead to cost efficiency.

2. Objectives and Work Logic

As mentioned before the main objective of the study is identification of missing technologies and infrastructures for an independent European space transportation of astronauts to Low Earth Orbit (LEO) and prediction of corresponding costs. The study was carried out in the following steps:

- Definition of High-Level Requirements for an astronautical space transportation mission to LEO
- Mission definition and preliminary ascent trajectory analysis to create technical input for other work packages
- Discussion on Ariane 6 interfaces and necessary modifications for the crew rated configuration
- Definition of capsule shape based on aerodynamic stability, volumetric efficiency and existing heritage in Europe
- Analysis of aerothermal loads on capsule during re-entry for different flight conditions
- Structural and thermal design of the capsule and creation of mass budget
- Definition of the payload module with focus on propulsion unit
- Concept development for the launch and flight abort systems
- Detailed design of the launch and flight abort systems including performance prediction of different propulsion unit configurations
- Description of tools for future flight dynamic analysis of abort systems
- Creation of a development and demonstration plan
- Study of needs and definition of necessary updates of ground infrastructure and operation
- Development of a cost model for the complete system
- Detailed cost prediction at system and sub-system level
- Presentation of study results to the space community and documentation of the study contents and achievements.

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3. High Level Requirements

Following high level requirements are defined for the development of an independent European astronautical access to space:

#	1
Title	**Time to market**
Description	The European Astronautical Transportation System shall have the first mission within seven years.

#	2
Title	**Mission to LEO**
Description	The European Astronautical Transportation System shall be able to take up to 3 astronauts to LEO and back to Earth. The first mission shall be headed to the ISS.

#	3
Title	**Probability of Loss of Crew (LOC)**
Description	The European Astronautical Transportation System shall safely execute its objectives with a mean value of the Loss of Crew (LOC) probability distribution for the combined ascent and entry phases of an ISS mission no greater than 1 in 200.

#	4
Title	**Probability of Loss of Mission (LOM)**
Description	The European Astronautical Transportation System Loss of Mission (LOM) probability distribution for an ISS mission shall have a mean value of no greater than 1 in 55.

#	5
Title	**Non-recurring costs**
Description	The European Astronautical Transportation Launch System shall be developed so as to minimise non-recurring costs as far as possible and shall not in any case cost more than 5000 M€, including, but not limited to, development, qualification, procurement of jigs and tools, adaptation of facilities and ground segment.

#	6
Title	**Recurring costs**
Description	The European Astronautical Transportation System shall have recurring costs comparable to actual market prices for transport to ISS and back.

#	7
Title	**Human I/F**
Description	The European Astronautical Transportation System shall provide a user- friendly and efficient human interface to allow for: a. Maximum possible autonomous flight with the option of manual override, b. Controlling the spacecraft, c. Communications between ground and flight segment, d. Communications between flight segment and ISS in any way necessary for the execution of the mission.

#	8
Title	**Accommodate humans**
Description	The European Astronautical Transportation System shall provide an accommodation suitable for the astronauts on-board. That includes, but is not limited to: a. Cleaning and provision of air, b. provision of drinkable water, c. body waste management, d. thermal control,

	e. ambient pressure control, f. limitation of translational accelerations, g. limitation of rotational rates and accelerations, h. limitation of noise level This requirement applies to the full mission including in particular launch and re-entry phases.

#	**9**
Title	**Adaptation of existing Ariane 6 launcher**
Description	The European Astronautical Transportation Launch System shall be based on the Ariane 6 launcher. It shall complement the existing A6 launch system, limiting its modifications as far as possible. As such, the maximum mass of the upper part (all structures above the upper stage) shall be: a. 10 metric tons for an A62 configuration b. 20 metric tons for an A64 configuration For placing the upper part on the following orbit: Za = 250 km, Zp = 250 km, inclination = 51.6°

#	**10**
Title	**Accompanying cargo transport**
Description	The European Astronautical Transportation Launch System shall be capable of transporting accompanying cargo. The first test flight shall be a cargo mission.

#	**11**
Title	**Mission duration**
Description	The spacecraft has to allow a minimum free flight duration of 4 days and minimum docked mission duration of 210 days.
Rationale	

#	**12**
Title	**Docking with the ISS**
Description	The European Astronautical Transportation System shall provide for a docking/berthing capability with the ISS, allowing astronauts pass into the ISS through the docking hatch.

#	**13**
Title	**Abort and rescue system**
Description	The spacecraft shall provide continuous autonomous launch abort capability from lift-off through orbital insertion in the event of a loss of thrust or loss of attitude control.

#	**14**
Title	**Landing system**
Description	The European Astronautical Transportation System shall use a new deceleration/landing system, which allows keeping the maximum loads of the ground impact within human tolerable limits. The landing shall be performed on water.

#	**15**
Title	**Ground infrastructure for human spaceflight**
Description	The European Astronautical Transportation Launch System's ground segment shall be capable of support all human spaceflight related functions, including, but not limited to: a. Astronaut preparation for launch b. Astronaut installation in the launch vehicle c. Astronaut rescue in case of abort to back to ground, including medical team d. Astronaut recovery after landing, including medical team e. Health-Monitoring for Astronauts f. Adapting launch pad for astronautical space transport g. Communication

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4. Main Achievements

The main activities of EURASTROS comprised the conception of an atmospheric abort system & exo-atmospheric launch abort scenarios, the capsule concept and re-entry profiles and the service module conception. In order to develop an astronautical space transportation system within an acceptable time and cost frame, Ariane 6 launcher is used as the baseline launcher. Modifications to the launcher was kept at a minimum level. The A64 version with four strap-on boosters has been selected as baseline for an astronaut carrier to provide sufficient performance margin for all intended missions. The architecture intends to keep all existing main stages, the P120C, the LLPM and the ULPM modules untouched as far as possible. The main difference is related to the forward payload section which is to be replaced by astronaut capsule, service module and emergency escape system protected by a new faring system dependent on the selected Launch Abort System architecture. The overall A64 concepts with an integrated and an abort tower system are visualized in Figure 1 [6].

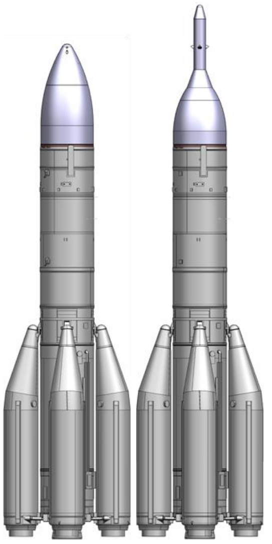

Figure 1: Sketch of A64 concept adapted for human space flight equipped with an integrated Launch Abort System (left) and a Launch Abort Tower System (right) [6].

A major activity of the study was the conceptual work on the end to end safety chain including the launch abort system with focus on technical trade-offs and trajectory optimizations. It was identified that the pad abort scenario from ELA-4 is critical due to huge distance to water for splashdown. Furthermore, the active control of the abort system was identified to be critical for the development.

A launch abort system (LAS) is the key technology to ensure Astronaut’s safety in the case of system malfunctions. Within the EURASTROS study on human spaceflight the abort safety chain has been interpreted as the full chain from faulty parameter sensing to escape maneuver execution. The LAS refers to a high-energetic propulsive system to accelerate the crew out of a critical zone after critical events as launcher failure detection within an atmospheric mission phase. An end-to-end abort capability has been envisaged and its feasibility proven. Besides several studies on crewed vehicles (HERMES, ARV, BERT and many more) within the last decades, no deep understanding for launch abort system was elaborated in Europe yet. Consequently, within EURASTROS a full trade off analysis on the identification of the best fit solutions has been carried out. Major objective was to realize a LAS with European, quickly accessible and lowest cost technology.

To achieve this goal a broad spectrum on potential solutions has been identified and rated regarding major study objectives. Three concepts were followed in more detail: (1) a hybrid motor driven solution, (2) a solid driven integrated solution and (3) a solid abort tower solution. All three concepts were conceptualized and pre-dimensioned in terms of mass, propulsion, aerodynamics and the escape trajectory. The fundamental feasibility could be proven for all concepts, whereas the hybrid solution was considered to be most uncertain in terms of thrust build up duration. Hence, further analysis focused on the escape trajectory of the two different solid motor driven systems. It was shown, that a thrust level below 1000 kN for a burn duration around 3s is sufficient to achieve a safe crew escape for all atmospheric flight phases

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Finally, a solid-motor based tower abort system was selected to guarantee the compliance to end-to-end abort chain with very low risk using motors available in Europe (Figure 2). Its functionality is proven by heritage on previous applications as on the Apollo and Soyuz spacecrafts.

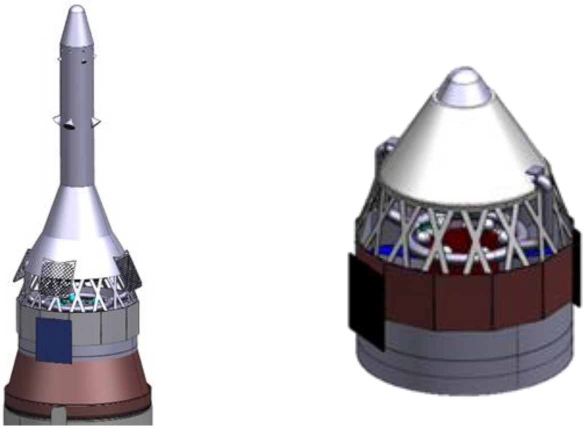

Figure 2: EURASTROS Launch Abort System (left) and capsule integrated on top of the service module (right).

The service module is another criticall part of the astronautical space transportation system. The principal functionalities of a service module are

- To provide structural continuity between the launcher & orbital system
- To provide thrust after upper stage/launch vehicle separation
- To provide electrical power
- To regulate heat for the life support & avionics equipment
- To store and provide other crew life relevant fluids (e.g. water, oxygen)

The already existing European expertise with the service module of the Automated Transfer Vehicle (ATV) and the European Service Module (ESM) for the Orion spacecraft of the NASA’s Artemis program was used to define the EURASTROS service module. It is noticed that the thrust level and size of the ATV service module is not compatible with the requirements of EURASTROS. The ESM system is equipped with motors, which are ITAR regulated and therefore cannot be applied to a pure European space transportation system. Finally, it was decided to use a vehicle-concept based on the ASTRIS Kick Stage and its main storable engine BERTA. The starting point for the conceptual design was the dimensioning the maximal required thrust level based on preliminary mass data. Within the next step the available ASTRIS architecture was extended in terms of required thrust performance and some critical elements as avionics or attitude control. Furthermore, all specific human spaceflight related equipment was added and an additional outer shell for equipment packaging was implemented. To carry the additional equipment, the mass of the primary structures needed to be scaled up accordingly. On top, the typical human spaceflight safety factor of 1.4 was implemented into the mass scaling. Having fixed the principal dry mass, the propellant sizing to achieve the required deltaV including margins was performed. The resulting propellant mass is well in line to the ASTRIS propulsive mass spectrum.

The shape of the capsule is derived from the Apollo capsule, i.e., it has a spherical nose and a truncated conical back shell. To accommodate at least two astronauts, an outer diameter of 3.5 m is chosen which results in a volume of 11.6 m^3 or about 72% of the Apollo capsule volume. A third astronaut can be accommodated as an option. The dry mass of the capsule is estimated slightly above 5600 kg incl. ISS docking adapter. The outer dimensions of the capsule are shown in Figure 2. The center of gravity of the capsule is offset from the axis to obtain a hypersonic trim angle of 25° which results in a L/D ratio of approx. 0.35. The resulting re-entry trajectories of the capsule have been analyzed for nominal as well as for off-nominal atmospheric re-entry. Controlled and uncontrolled/ballistic trajectories were considered for ISS return and for launch abort cases. The aerothermal and mechanical loads have been analyzed along the nominal and off-nominal re-entry trajectories. For this, approximative techniques and high-resolution aerothermal simulations with the CFD code TAU were used.

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The points of maximum heat flux and maximum dynamic pressure were analyzed in detail to provide a basis for the TPS and structural design. An example of the pressure distribution at the point of maximum dynamic pressure for a ballistic re-entry after launch abort at high altitude is shown in Figure 3 (right). The pressurized compartment of the capsule is designed as a 2.6 m diameter cylinder-cone section with outer orthogrid stiffening. The pressure vessel is designed for an internal pressure of 1 bar. To protect the structure from the aerothermal loads, the front and back shell is equipped with classic ablator type TPS. As the baseline material for the TPS investigations, the low-density ablator material ZURAM® of DLR was selected based on previous development experience and experimental test campaigns [3]. ZURAM® is a lightweight ablator based on a commercially available rigid carbon fiber preform which is infiltrated with a nano-porous phenolic resin. The production process has been developed over several years and a very stable level of material quality has been established. The material is fully characterized and a large data base from testing in arc-heated wind tunnels was established. In terms of performance, the material is comparable to competitor materials as ASTERM or PICA, so it is quite representative to select this material for the pre-development investigations presented here

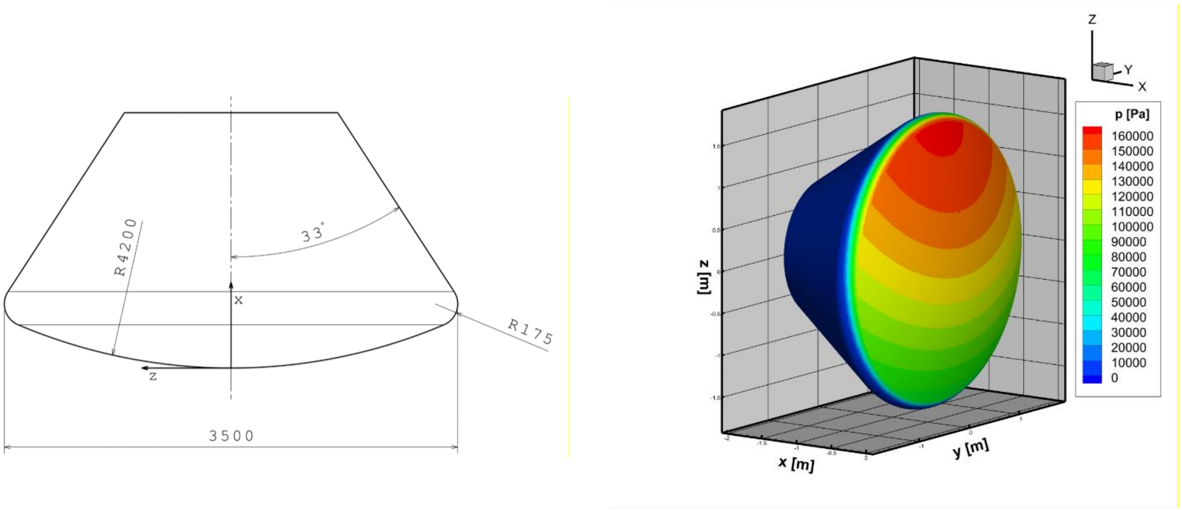

Figure 3: Preliminary shape of capsule with its major dimensions (left) and Pressure distribution for ballistic re-entry after launch abort (H=27.5 km,Ma=8.6,α=25°).

An initial performance assessment was performed in order to gain a first glimpse of attainable performances for the Ariane 6 launcher. To this end, the DLR in-house launcher model of A62 and A64 was used for a parametric study sweeping through a range of orbit altitudes at which the crew capsule will be released [4]. The performance of LAS was cross-evaluated against three escape scenarios: Escape from launch pad (LPE), escaping the LV facing maximum aerodynamic forces (maxQ) and during maximum acceleration (maxA). Defined requirements for successful escape were:

- All cases: Establish a clearance to LV of 200 m in 3.5 seconds after separation
- LPE only: Apogee of escape trajectory exceeding 1.5 km
- LPE only: Down range of ballistic landing area to separation point exceeding 3 km

It was found that the minimum thrust required to fulfil the escape requirements in all scenarios is 950 kN. This minimum thrust was derived mainly from the LPE scenario for which this minimum level was required in order to fulfill the requirements regarding apogee altitude and down range. Predicted mass distribution of major sub-systems is given in Table 1.

Table 1: Mass distribution of main components

EURASTROS system (w/o ULPM adapter)		
CrewModule		5016kg
ServiceModule		6389kg
	Orbital Mass	**11405kg**
LaunchAbortSystem		5276kg
	Total Mass	**16681kg**

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At larger altitudes, i.e., above approx. 90 km, when the LAS is jettisoned, the service module (SM) takes over the abort operation. In case of a malfunction, the launcher engine is cut off and the SM separates from the launcher and ignites its engines to carry the capsule to a safe distance within a given timeframe. After using the SM to reach safe re-entry trajectories if needed, the capsule and the service module separate and the capsule reenters the atmosphere to safely carry the astronauts to the ground. Several requirements must be fulfilled to guarantee a successful rescue along the entire ascent. At any time, an abort must be possible without exceeding human tolerable g loads. This must be guaranteed for controlled re-entry as well as for uncontrolled/ballistic re-entry, where the loads are significantly higher. The launch profile of the A64 requires maneuvers with the SM engines at some points along the launch trajectory to meet this criterion. Launch abort at high altitude can lead to a very steep re-entry, and hence, very high g-loads, when a ballistic descent is performed. Nevertheless, the SM is designed to supply sufficient thrust to decrease the re-entry angle and ensure a successful re-entry even for a ballistic re-entry. In addition, the capsule must splash down on water for all abort scenarios. Since the ULPM provides relatively low acceleration, the launcher covers a relatively long distance before orbit insertion. As a consequence, the capsule would impact on land when an abort is necessary in the late phase of the launch. Therefore, the SM engines are used for a breaking maneuver for aborts shortly before orbit insertion. Additionally, a ballistic re-entry is conducted. This drastically reduces the landing downrange of the capsule to ensure a splashdown on water. At the point, where a breaking maneuver would not be sufficient anymore to ensure a water landing, the SM can provide enough change in velocity to reach an emergency orbit, i.e. an abort-to-orbit maneuver is performed. The dimensioning of the emergency escapes needs a careful consideration of the launch trajectory, the SM thrust and fuel, and the re-entry performance of the capsule. With the right balance, a successful abort is possible from launch pad to orbit for safe transportation of astronauts to space.

Figure 4Figure 4 shows the loads for the worst-case re-entry with and without the SM maneuver, a nominal ISS return for comparison, and the corresponding limits defined by NASA for the commercial crew program [7] . While the peak g-load with the maneuver of 19.5 g is still very high, the maximum g-load is acting short enough on the astronauts such that the re-entry can be considered acceptable in emergency situations [3][4]. Note that this worst-case scenario only occurs in the rare event that, in addition to a launch failure in a certain timespan, also the guidance and navigation system fails such that the ballistic fallback mode must be used. If a lifting re-entry is flown, the g-loads are much lower and just barely exceed the NASA limits for a nominal return.

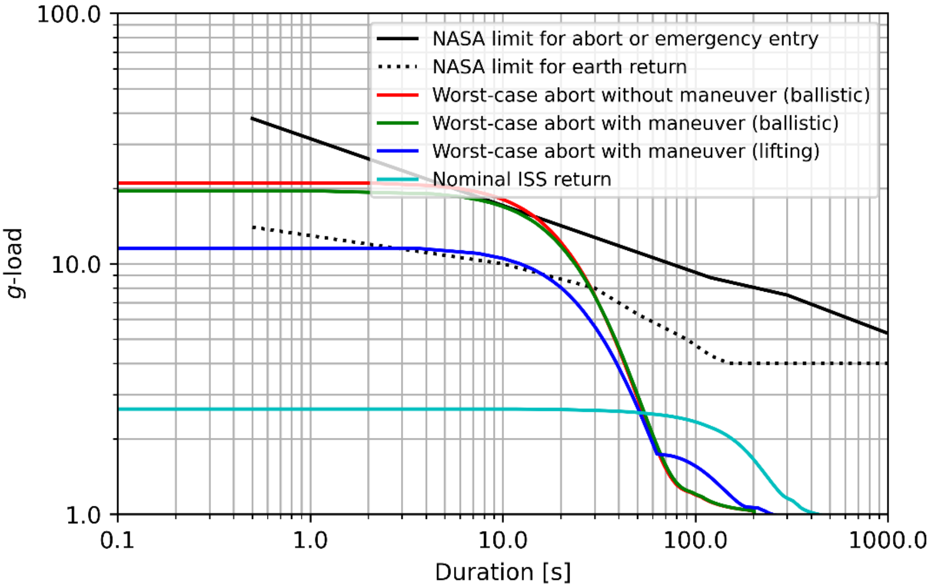

Figure 4: Worst-case g-load and load duration for ballistic re-entry after abort with and without maneuver, lifting re-entry with maneuver, and for nominal return from ISS.

In order to comply the ambitious top-level schedule, only low-risk systems were considered for the EURASTROS system. Furthermore, development activities were focused on module level instead of sub-system level to identify module weaknesses in early development status. This approach leads to a high risk of demonstration failures on module level but accelerates the learning curve and consequently reduces the costs. Following this logic, a first orbital demo flight was set 5 years after full scale development launch and a first crewed flight to LEO around two years later.

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The analysis shows that the final EURASTROS configuration is capable to provide enough thrust to be able to always land on water or alternatively perform an abort to orbit. The following decision points along the launch trajectory were identified that ensure a safe abort. After t+815 s, a fully lifting re-entry would lead to impact on land. Hence, the capsule must gradually reduce its lift by performing bank reversals to reduce the down range. From t+861 s, even a ballistic descent would not be sufficient anymore to splashdown on water. Therefore, the SM engines must be used for a breaking maneuver to further ensure a safe water landing. After t+912 s, the SM can provide enough change in velocity to reach an emergency orbit, i.e. an abort-to-orbit maneuver is performed instead of a breaking maneuver [4]. To be able to reach orbit, the SM must be equipped with sufficiently high thrust. The analysis showed, that the abort-to-orbit scenario defines the minimum thrust of the SM of 16 kN since all other considered cases, i.e. nominal mission, escape from launcher, maneuver to reduce re-entry loads, require less thrust.

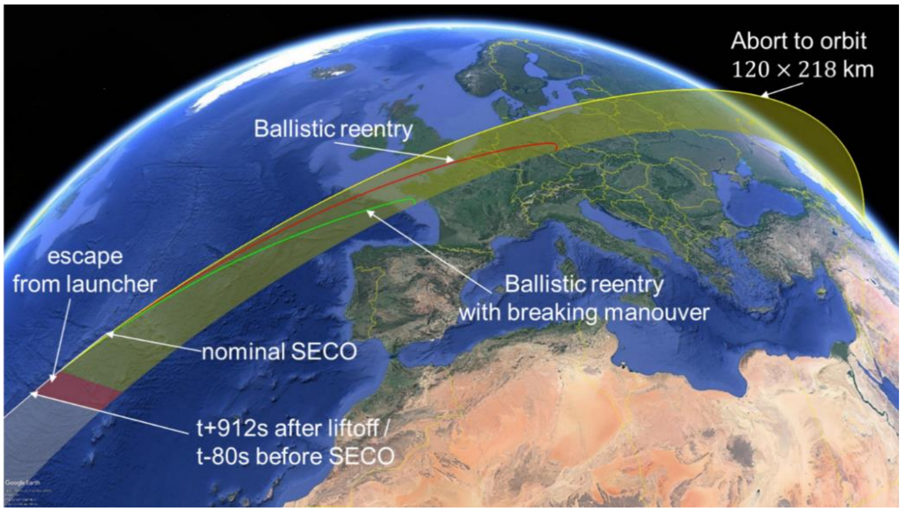

Figure 5: Launch abort scenarios at t-80s before second-stage engine cutoff (SECO): Breaking manouver with splashdown or abort to orbit. (altitude is exaggerated by factor of [4].

Another key activity carried out with significant effort was the cost analysis for recurring and non-recurring costs. This required a development and qualification plan, which has been created with an analysis at module level instead of sub-system level to identify module weaknesses early enough and to accelerate the learning curve, which should lead to cost reduction. The EURASTROS cost estimate is broken down into the three segments: Space, Launch and Ground Segment. Furthermore, it is divided into non-recurring cost (NRC) cost for design and development, and recurring cost (RC) for production and operation [5]. The recurring cost strongly depend e.g. on the mission frequency (i.e. number of launches per year), learning effects, supplier contract conditions and if modifications are planned or necessary throughout the program duration. However, rough order of magnitude assessments are made regarding the expected average recurring cost per segment. The major contributor of the NRC are the test flights, which make up to 40% of the costs. Following this logic, a first orbital demo flight is set 5 years after full scale development launch and a first crewed flight to LEO around two years later. Clearly, the major contributor among those branches is the space segment with 2000 M€-3000M€ with the crew module being the major driver. The ground segment was estimated to cost around 400M€ and the A6 adaptations around 800M€. Altogether an NRC range of 3000 M€-4000M€ was estimated to bring the system into commercial service 7 years after Kick-off. In the analyzed setting RCs of around 400M€ were computed w/o re-usability.

5. Concluding remarks

The main objective of the EURASTROS study was to identify technological needs for a quickly available, cost effective and technologically robust Human Spaceflight service in Europe and to propose solutions for key technologies including cost prediction. Special effort is necessary to develop atmospheric abort systems and exo-atmospheric abort strategies. The EURASTROS study showed that from a technological point of view an independent European astronautical space transportation mission can be carried out in a time frame of seven years. It is recommended to elaborate more details on the commercial aspects of such a service and to consider the influence of re-usability and number of astronauts on its business model.

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