SPACE STATION DESIGN WORKSHOP 2010

FINAL REPORT

Universität Stuttgart

Space Station Design Workshop 2010

Final Report

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Foreword

Strong sentiments have recently emerged that there must be a clear destination and purpose for human spaceflight. We propose a global guide to space built on human needs, scientific knowledge, technological challenge, and the sense of discovery and progress that only space exploration can provide. Others recognize that space applications can provide vital knowledge to deal with life and death issues such as global warming, worldwide drought, and holes in the Ozone layer that could lead to genetic mutations which could ultimately endanger life on Earth. With a well-conceived international program of human exploration, space science, and space applications can advance discovery, understanding, and cooperation. It can lift our sights and fuel our dreams. Thus, it is time to develop a logical, systematic, and evolutionary architecture for human expansion into the solar system, with an approach leading ultimately to a human exploration of Mars and a permanent human presence in the solar system. Likewise it is time for international cooperation to use space to unlock new scientific knowledge and to use space technology to improve the human perspectives.

Within this framework, the mission statement of last year had been centered around the Moon and a small infrastructure on its surface. This year, the destination of Near-Earth Asteroids (NEAs) was chosen for the Space Station Design Workshop (SSDW), pushing the envelope of human space exploration further out. Manned missions to asteroids provide a unique opportunity to be the first human expedition to an interplanetary body not gravitationally bound to Earth. Such a mission statement is well in line with current discussions on international level as US president Barack Obama and his administration have set a new course for NASA. The goal is no longer to return to the Moon, but instead to advance beyond the Earth-Moon system, to interplanetary targets, primarily NEAs. At the same time, the United Nations together with the Association of Space Explorers represented by US astronaut Russel "Rusty" Schweickart presently take initiatives to determine the potential threat of asteroids and our ability to mitigate these threats. Accordingly, the relevance of the topic of human missions to NEAs was adopted.

Lectures on space stations, subsystems and its utilization have been given at the Institute of Space Systems at the University of Stuttgart for more than two decades. When it became clear in 1995 that many European countries would join the International Space Station project, the lectures were extended and supplemented by the so-called Space Station Design Workshop or "SSDW". Here students learn, as part of their regular studies, in a hands-on, interactive, team-centered environment to perform conceptual design studies of a complex human spaceflight system. They are supported by a concise methodology and by customized software tools enabling them to successfully tackle the challenging task. These methodology and tools were developed, constantly improved, and extended in recent years for near-Earth exploration missions in the frame of research projects mainly carried out by PhD students at the Institute of Space Systems. In order to enable the design of a complex mission to NEAs and its required spacecraft, the tools and methodologies had to be adapted and expanded. In this context, software tools for the selection of promising target asteroids based on celestial mechanics constraints and scientific criteria were successfully used.

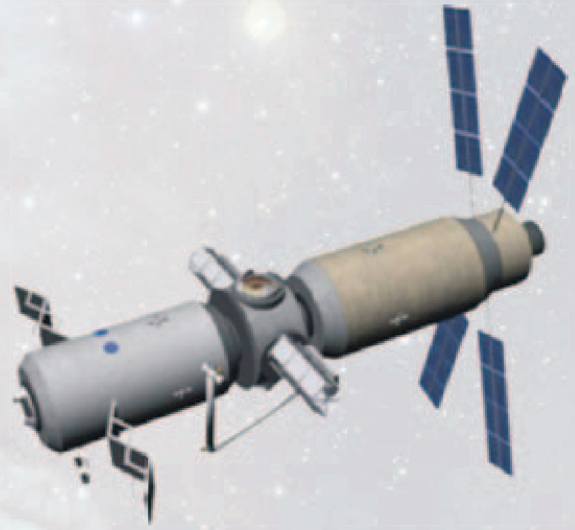
Reflecting the interdisciplinary working environment, the SSDW involves many disciplines and partner universities, and consequently was conducted with English as the working language. In many instances, the SSDW was also held at the partner universities' sites, e.g., in Toulouse, at the International Space University in Strasbourg, at the University of Sydney and at ESA's Space Research and Technology Centre ESTEC in the Netherlands.

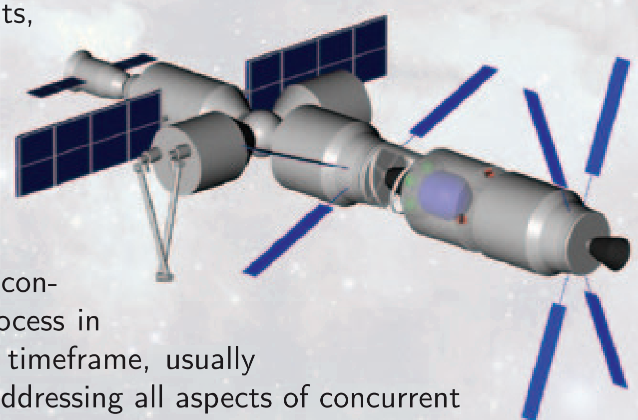
This time again at the University of Stuttgart, it was a pleasure for me to see the fresh design ideas, the enthusiasm emerging from working together with student teams and supported by equally motivated university staff. I wish to thank ESA for the support given again as in previous years, and the other sponsors, and all of the participants, including the students and the instructors for their contributions to making this Space Station Design Workshop 2010 such a valuable experience for all of us.

November 2010
Ernst Messerschmid

Introduction and History

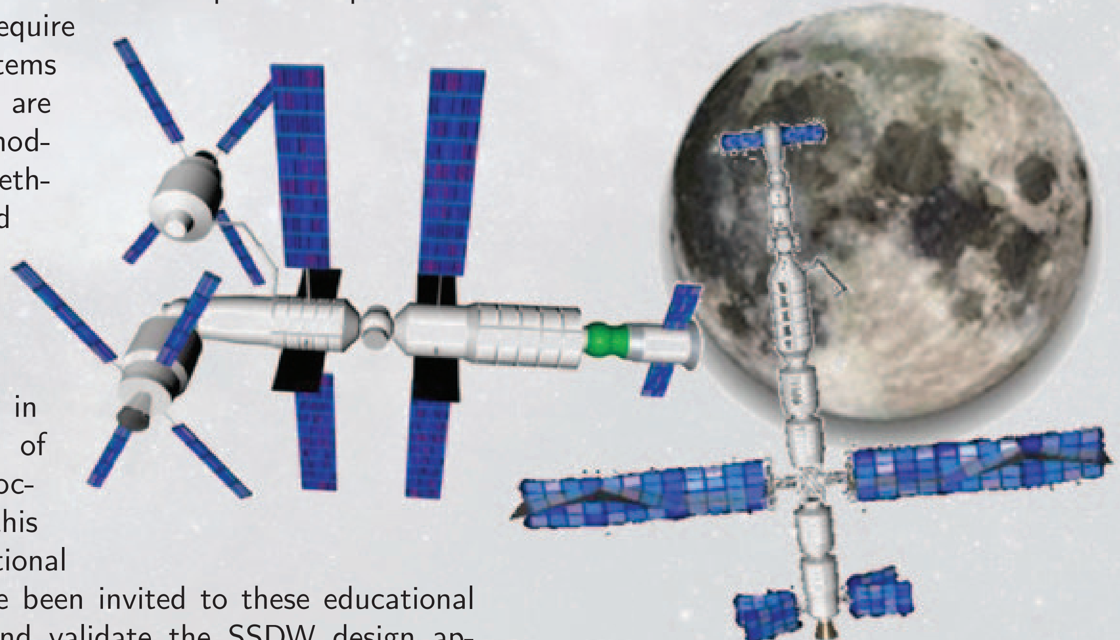
Being developed over more than ten years at the Institute of Space Systems (IRS) of the University of Stuttgart, the conceptual design environment of the Space Station Design Workshop (SSDW) offers exceptional capabilities for space systems engineering and human space mission design. Originally adopted for space station design (hence the name SSDW), the technical expertise at IRS as well as the environment, its methodology, and software tools have considerably evolved in recent years for exploration missions beyond low Earth orbit (LEO) to destinations such as libration points, near-Earth objects (NEOs), Moon, and Mars. It enables a small design team to run through a conceptual design process in a relatively short timeframe, usually one week, while addressing all aspects of concurrent and systems engineering of a complex human space exploration mission.



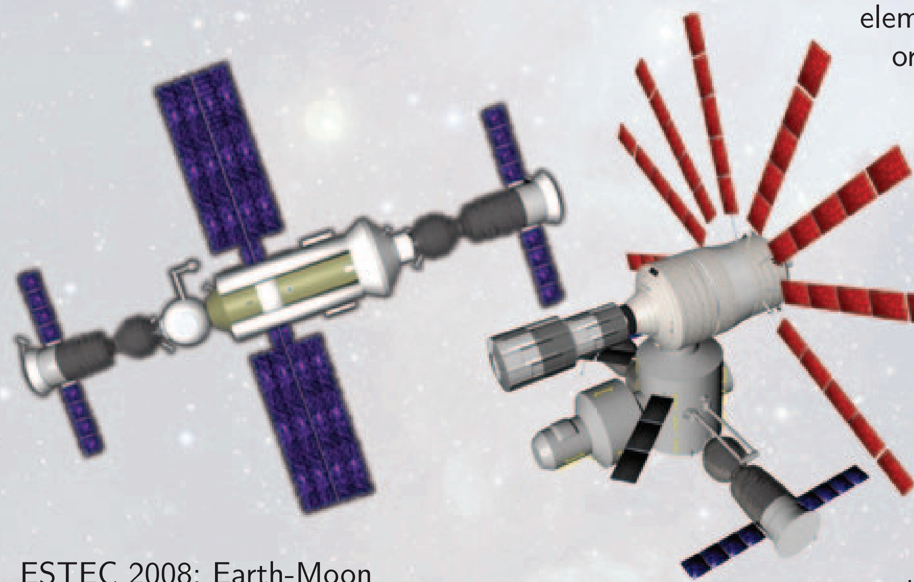


IRS 2006: Earth-Moon Libration Point 1

While the SSDW design environment allows professional assessment of new designs, existing infrastructures, and study plans, it also provides an exceptional opportunity for hands-on student education in the form of annual workshops. Conceptual design problems require well-trained systems engineers who are familiar with modern tools and methodologies and have gained sufficient hands-on experience at the universities or in their first years of professional preoccupation. In this context, international participants have been invited to these educational events to use and validate the SSDW design approach for exploration missions beyond LEO since 2006, with the definition of potential transportation elements, libration point, and lunar orbital infrastructures in support of Moon exploration, as well as planetary surface installations on the Moon. With the design of human missions to near-Earth asteroids, the SSDW 2010 opens a new chapter in the workshop history. For the first time the participants analyze the feasibility of missions to destinations that are not gravitationally bound to Earth. This step completes the capabilities of the design environment for orbital stations, planetary surface missions, and near-Earth as well as interplanetary transfers.

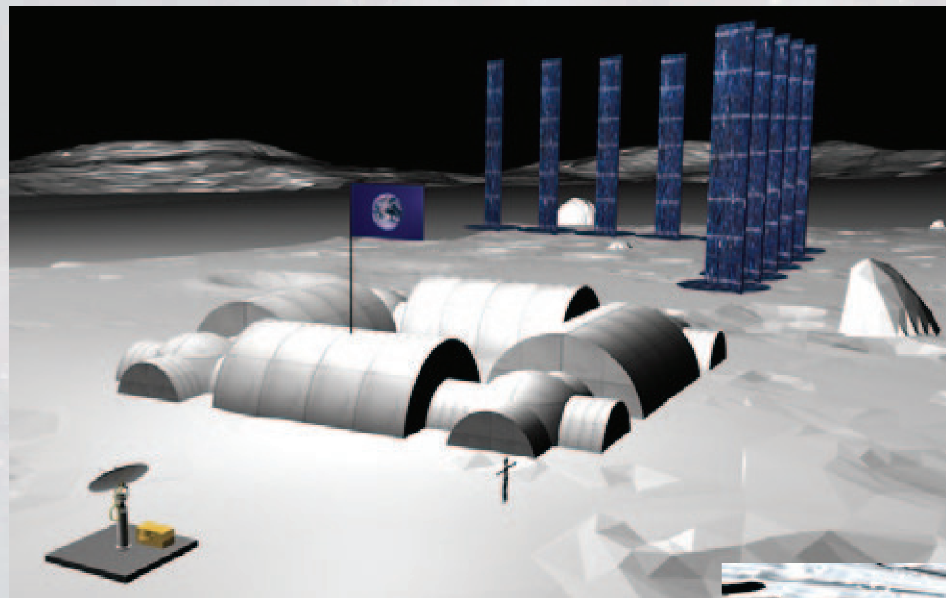


University of Sydney 2007: Low Lunar Orbit

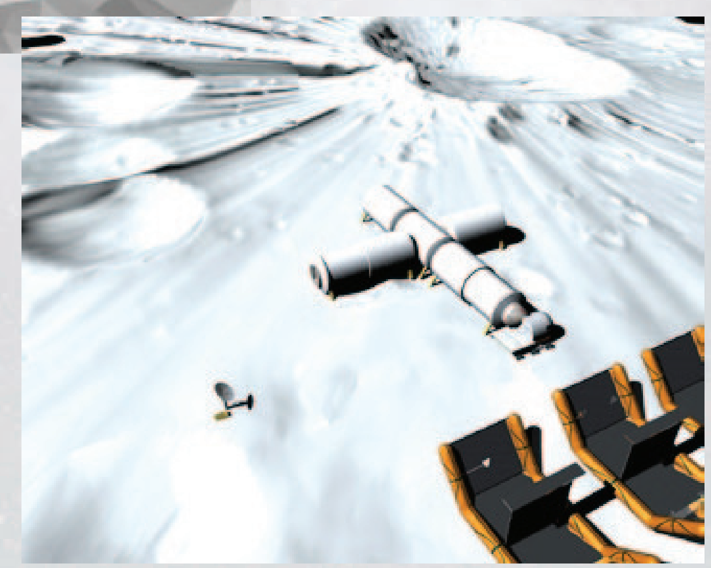


ESTEC 2008: Earth-Moon Libration Point 2

This report describes the SSDW methodology and tools for conceptual mission design, including the typical complexity of a human space project and the solutions to support, stimulate, and accelerate the early design phase. While discussing the general concept of the design first, it provides detailed insight into the organizational efforts, the task, and the resulting concept solutions of the SSDW 2010, analyzing two human missions to near-Earth asteroids and their respective spacecraft.



IRS 2009: Lunar Surface



Conceptual Human Space Mission Design

The Conceptual Design Problem

In the beginning of designing a space mission or system, a mission statement lists the objectives of the customer. Politicians, economists, and scientists have their specific expectations in mind to formulate these objectives. Therefore, from the engineering point of view, the given mission and system requirements have to be translated into primary and secondary objectives, defining technological requirements as well as political and economical constraints. The understanding and verification of the customer's expectations and needs is crucial for project success. This early phase of a space project is referred to as the conceptual design phase.

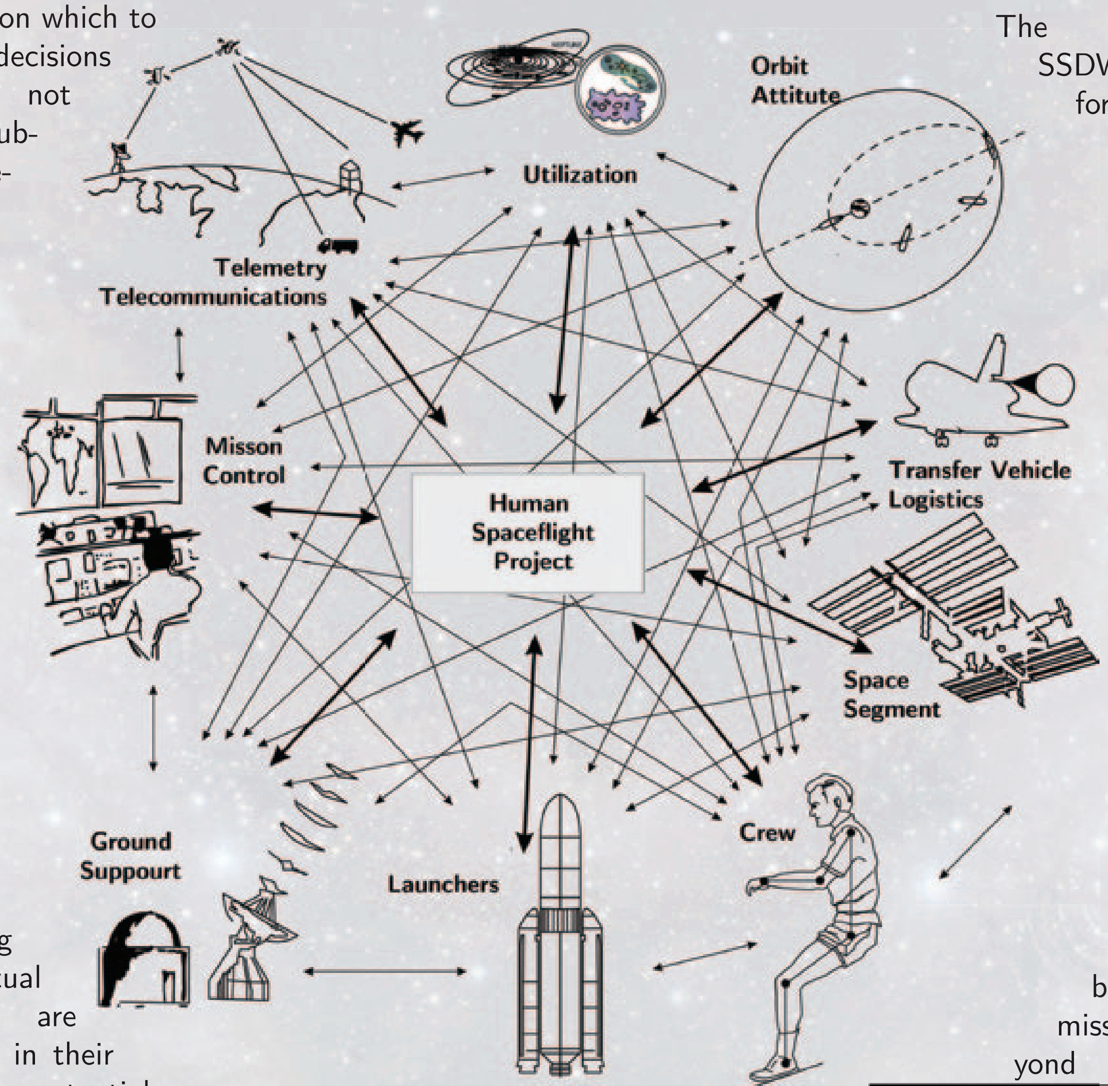
All mission and system elements of a human spaceflight project are strongly interdependent. Changes to one element impose direct or indirect changes to largely every other element. All local interferences can yield significant consequences to the entire system. Therefore, within this early project phase of conceptual design of the overall mission and the systems, all the mission elements must be considered simultaneously down to a high subsystem requirement level. Conflicting requirements must be dispelled and fundamental mission and system parameters have to be concretized, optimized, and fixed in a baseline concept following an iterative process.

The designers of complex space systems are faced with a set of challenges:

- Fuzzy problem formulation:
  Objectives and boundary conditions are initially vague. The mission must be developed in detail together with the space system.

- Strong interdependencies between system elements: The complexity of designing a space system stems from the network of links among its elements. These preclude the separate, sequential definition of individual elements.

- Adverse relationship between available information and consequenes of conceptual design decisions:
  By defining system elements during the conceptual design stage, central decisions about mission performance, system architecture, technical risk, developmental effort, cost, and organizational structure are made. However, sufficient information on which to base these decisions is usually not available. Subsequent design phases provide more information, but design decisions that are made then have to stay within the envelope defined during the conceptual phase and are thus limited in their mitigative potential.



- Extreme boundary conditions:
  Compared to other systems of comparable technological complexity, space systems are subject to much tighter technological boundary conditions. They have to operate in the harsh space environment (temperature, vacuum, radiation, microgravity, debris) as well as withstand high g-loads during launch. They must be designed for minimum weight and must be maintainable under difficult access conditions. Complete testing can only be achieved during the first space flight of the system.

- Crew:
  Designing a crewed space station adds the complications of life support requirements, increases demands on safety, reliability, and crew integration, as well as the degree of public scrutiny in a highly politicized design environment.

Methodology

The interdisciplinary SSDW methodology for conceptual design of human space systems and missions has been developed at the Institute of Space Systems. Initially dedicated to space station design, the systems and concurrent engineering approach have been extended to mission design beyond LEO, including destinations such as near-Earth libration points, Moon, near-Earth asteroids and Mars.

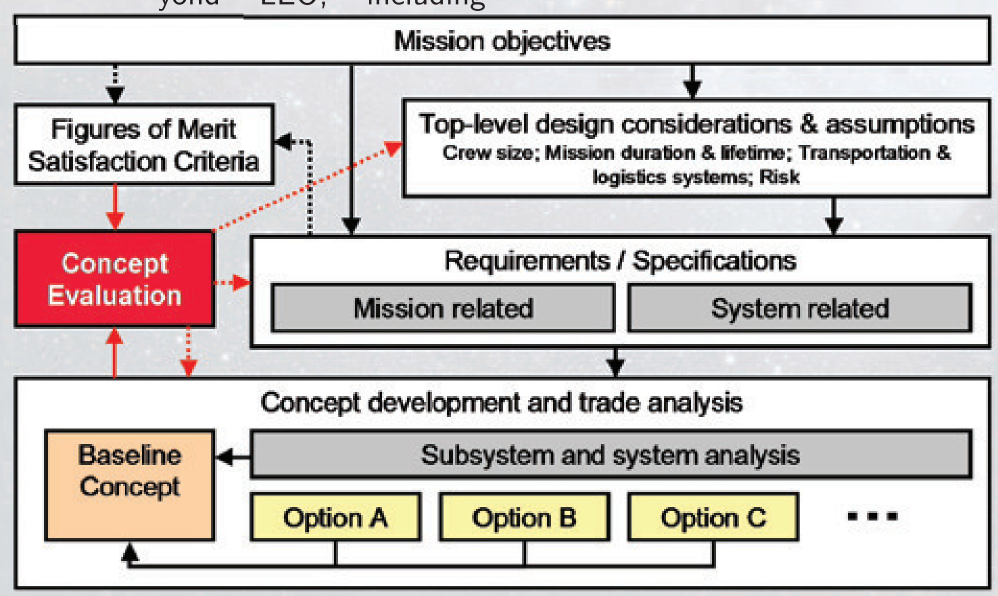
It combines guidelines in the technical areas of engineering, physics, system architecture development with the art of systems engineering, pointing to the soft skills such as project design flow, team management exploiting individual expertise and experience, conflict resolution, and customer presentation.

Simple and clearly defined steps introduce the team to the design process and guide through

1. review of mission statement and identification of objectives, requirements, and constraints
2. development of alternative systems concepts and selection of a baseline,
3. characterization of system elements and preparation of system and subsystem budgets, and
4. evaluation and documentation of results.

The top-level guidance is supported by specific system and subsystem instruction, recommendations, background information, and software tools to facilitate design maturation and iterations. Extensive heuristics on human integration, crew composition, and operational aspects emphasize the human-specific issues in the design problem and contribute to the optimization with respect to habitability and crew performance.

Design teams usually consist of people of different cultural backgrounds and various disciplines, mirroring the heterogeneous environment of space business. While the workshop is highly goal-oriented from the perspective of the participants, it is also highly process-oriented, where team building, identification of individual expertise, and coordination of the process flow become equally important.

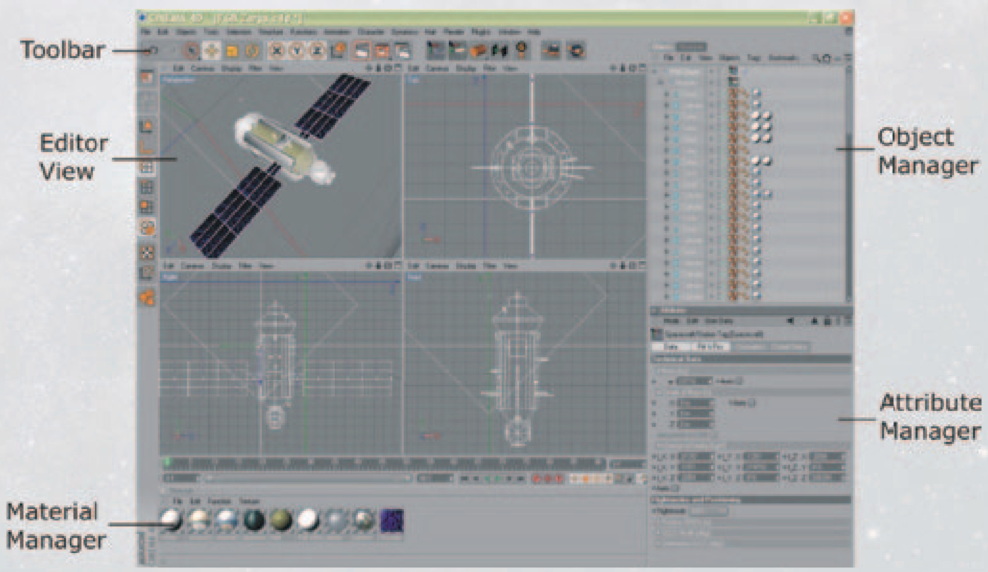


Design Tools

1. COMET

COMET stands for "Configuration Modeling and Editing Tool". It is a proprietary add-on to the commercially available 3D graphics software Cinema4D and it was developed to create virtual 3D models of space stations, vehicles, and modules. It provides an intuitive graphical user interface for generating and managing three-dimensional objects as well as renderings and short movie clips. COMET also provides a convenient output filter to export vehicle configuration data which can be used directly for orbit simulations and analysis. This enables quick-turnaround space vehicle design iterations.

COMET is an object-oriented software. It uses three types of object classes: "spacecraft", "module" and "primitive", which are ordered hierarchically. Primitives make up modules, and modules make up a space station or a deep-space vessel. Every object and its sub-objects can be saved separately to an object library, in which predefined modules and other elements of the International Space Station (ISS) are also readily accessible. An impression of the COMET main user interface is shown below.



2. ELISSA

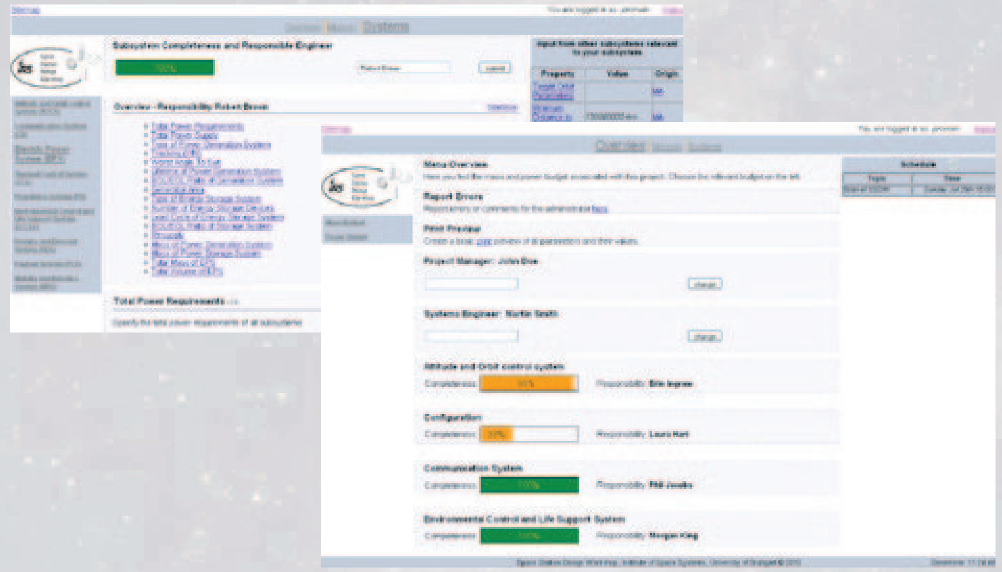
The Environment for Life Support systems Simulation and Analysis (ELISSA), implemented in the laboratory software LabVIEW, provides convenient graphical modeling of interlinked subsystems and interactive simulation of dynamic problems. Predefined component models provide

simulation features for life support systems as well as for the power supply and attitude/ orbit control subsystems. Using drag-and-drop techniques, the user models the subsystem to be analyzed before starting simulation runs. Simulation results comprise:

- mass budgets
- power budgets
- thermal budgets

3. COSMICS

The Concurrent System and Mission Conceptualization Software (COSMICS) features an approach to facilitating the complex conceptual design process as well as the system analysis. As a top-level systems engineering tool, it integrates subsystems and their interdependencies, accounting for all critical subsystem parameters required for the preliminary design phase. By controlling the process flow and collecting the overall concept budgets, COSMICS maps design progress and maturity. Through intelligent management of reading and writing authorization, this web-based software supports simultaneous multi-user inputs into one mission and system parameter database. It distributes parameters between subsystems, implements changes made to one subsystem and notifies all other subsystems affected by the change, which greatly facilitates documentation and communication among subsystem engineers.



4. Support Tools

Commercially available software suites such as Microsoft Office (Word, Excel, PowerPoint) are extensively used for concept analysis and documentation. Customized recipes guide through the design process and additional reference material is provided in the form of selected literature. Further information is widely available through the use of internet resources.

SSDW 2010 in Stuttgart

Drawing from the experiences of past workshops abroad, the SSDW 2010 was held at the local premises of the IRS in Stuttgart, Germany. 32 students and young professionals from 12 nations and with diverse backgrounds in physics, engineering, and economics were selected from a large applicant pool and invited to the University of Stuttgart from 25 to 30 July 2010 for a truly international and multidisciplinary challenge. The participants formed two competing design teams, tagged "RED" and "BLUE", and faced an intense one-week program.

1. Organization

Through the support of various sponsors and partners as well as experienced local staff, the SSDW 2010 was well-prepared in terms of infrastructure, time planning, and technical contents. Without knowing the original task that was awaiting them during the week in Stuttgart, the participants were introduced to human space mission design aspects already two months prior to the SSDW. Depending on their backgrounds and preference, they received pre-workshop assignments including reference literature and deliverables in order to engage them in thorough preparation and to level out expertise within the design teams.

Once in Stuttgart, local accommodation and transportation had been arranged for the international participants to enable a flawless execution of the intense workshop program. The infrastructure included a dedicated lecture hall and staff room as well as two well-equipped team rooms. Each of the latter featured a full set of networked computers with pre-installed software, projector, flipcharts, and selected reference material. Furthermore, every participant received a folder with all relevant organizational information as well as dedicated guidelines, instructions, and recommendations. These so-called "recipes" include information about process milestones and associated deadlines, but also cover various aspects of space systems development.

Time	Sunday, 25.07.	Monday, 26.07.	Tuesday, 27.07.	Wednesday, 28.07.	Thursday, 29.07.	Friday, 30.07.	Time
Topic	Welcome Introduction	Subsystems Lectures and Requirements Engineering	Requirements and Systems Engineering	Systems and Subsystems Engineering	Subsystems Engineering, Documentation	Evaluation, Final Presentation	
08:30		Mission Statement *A. Zimmer (IRS)*	Q&A Session	Hayabusa Mission I *P. Abell (NASA)*	Q&A Session	Final Report Delivery	08:30
08:45						Introduction to Evaluation	08:45
09:00		Near-Earth Objects *P. Abell (NASA)*	Life Support Systems *B. Ganzer (IRS)*		Workshop Session III: Subsystems Engineering		**09:00**
09:15				Hayabusa Mission II *P. Abell (NASA)*		Coffee Break	09:15
09:30		Human Factors *E. Messerschmid (IRS)* *S. Lizy-Destrez (ISAE)*				Workshop Session IV: Design Results Evaluation	09:30
09:45							09:45
10:00			(EPS / TCS) *S. Belz (IRS)*	Coffee Break			**10:00**
10:15				Workshop Session III: Systems and Subsystems Engineering			10:15
10:30		Coffee Break					10:30
10:45		Transportation Architecture *F. Renk (ESOC)*			Coffee Break		10:45
11:00			Coffee Break		Workshop Session III (continued)		**11:00**
11:15			Workshop Session II: Initial Systems Engineering				11:15
11:30		Team Introduction & Organization					11:30
11:45							11:45
12:00							**12:00**
12:15							12:15
12:30						Lunch Break	12:30
12:45							12:45
13:00	Welcome Reception	Lunch Break	Lunch Break	Lunch Break	Lunch Break		**13:00**
13:15							13:15
13:30	Welcome to IRS *E. Messerschmid (IRS)*						13:30
13:45							13:45
14:00	Intro to SSDW *A. Zimmer(IRS)*	Workshop Session I: Requirements Engineering (continued)	Workshop Session II: Initial Systems Engineering (continued)	Workshop Session III: Systems and Subsystems Engineering (continued)	Workshop Session III (continued)	Public Presentations and Graduation (V27.02)	**14:00**
14:15							14:15
14:30	Human Space Exploration *E. Messerschmid (IRS)*						14:30
14:45							14:45
15:00					Preparation of Design Team Presentations		**15:00**
15:15							15:15
15:30	Coffee Break						15:30
15:45							15:45
16:00	Systems & Concurrent Engineering *J. Noll (IRS)*	Coffee Break	Coffee Break	Coffee Break	Coffee Break	Reception (V27 Foyer)	**16:00**
16:15		Workshop Session I (continued)	System Concepts Review BLUE	Workshop Session III (continued)	Preliminary Design Review (PDR) (Design Results)		16:15
16:30							16:30
16:45			System Concepts Review RED				16:45
17:00	Team Building						**17:00**
17:15			Workshop Session II (cont'd)				17:15
17:30						Feedback & Wrap-Up	17:30
17:45							17:45
18:00		Preliminary Req. Review (PRR)					**18:00**
18:15			Planetarium Stuttgart				18:15
18:30							18:30
18:45					Workshop Session III (continued)		18:45
19:00	Welcome Dinner (Sophies Brauhaus)	Social Event (Karlshöhe) (Backup: Movie)				Get Together	**19:00**
19:15			Social Event (Schloßgarten)				19:15
19:30							19:30
19:45							19:45
20:00							**20:00**
20:15							20:15

Lectures V27.01	Groupwork Team Design Rooms	Other (Location in brackets)

After the welcome and introduction, the first three days included half-day lectures addressing critical aspects of human space mission design, while the participants already engaged in workshop sessions during the afternoons. This hands-on team work is started early in the timeline and grows in importance throughout the workshop, where full days are dedicated to systems and subsystems engineering, modeling, simulation, and concept refinement.

Although densely packed with project work, the SSDW also encouraged team building and socializing between the participants and featured cultural activities on most evenings.

2. Mission Statement

The SSDW 2010 task assumes continued interest and effort in human space exploration on an international level with the ultimate goal of landing humans on the Martian surface. As such, continued operation of ISS for preparation and technology maturation and the manned activities of the US, Russia, and China would be complemented by European and Japanese assets for transportation of cargo and potentially crew at a later stage.

Public awareness of the risk of an asteroid impacting the Earth is on the rise. As such an impact could possibly bear disastrous consequences for the entire population, Near-Earth Asteroids (NEAs) attract attention from space programs worldwide and call for international collaboration in the investigation of Potentially Hazardous Objects (PHOs). In general, asteroids are of particular interest for the fundamental understanding of the solar system. As these last existing planetesimals are composed of pristine material unaltered since the dawn of the solar system, their exploration can shed light on the formation of the inner planets. Investigation of composition, gravitational field, trajectory, and origin can yield insight into their potential usefulness as well as the threat they pose to Earth.

In this context, the mission statement asks the participants to "outline a comprehensive study of a sustainable international exploration concept to address all interest humankind currently takes in NEAs. The missions shall allow for extensive manned and robotic exploration, enabling new insights into NEAs, the solar system, and its development. In addition, they shall serve the purpose of technology demonstration and maturation for future human activities on the way to Mars and deflection missions for potentially hazardous NEAs. The architecture as well as the concept spacecraft shall exhibit growth potential and extendibility towards further manned space exploration." This mission statement is well in line with current discussions at international level and thus provides relevance to exploration activities. Technically, the objective of the study is to define a flexible, sustainable, and extendable mission architecture and to develop a conceptual design of a spacecraft in an international human NEA mission scenario.

In particular, the spacecraft shall:

- enable human missions to several NEAs between 2020 and 2040;
- safely accommodate a crew of astronauts and exhibit extensive EVA capabilities;
- offer the possibility to conduct technology demonstration and research on asteroid properties and human aspects for long-duration deep-space missions;
- enable human exploration of asteroid 1999 AO10 in 2025/2026;
- allow for a human precursor mission to Apophis in 2028/29 delivering scientific payload to Apophis' surface, e.g., for compositional and structural analysis;
- encourage international cooperation and outline a significant contribution and visibility of Europe in the international program.

The two design teams looked at various options within the specified frame of the mission statement, both at systems and subsystems level. Two different approaches are chosen for detailed assessment, labeled Concept BLUE and Concept RED.

3. Team BLUE Design Results

- **Mission Targets & Launch Windows**

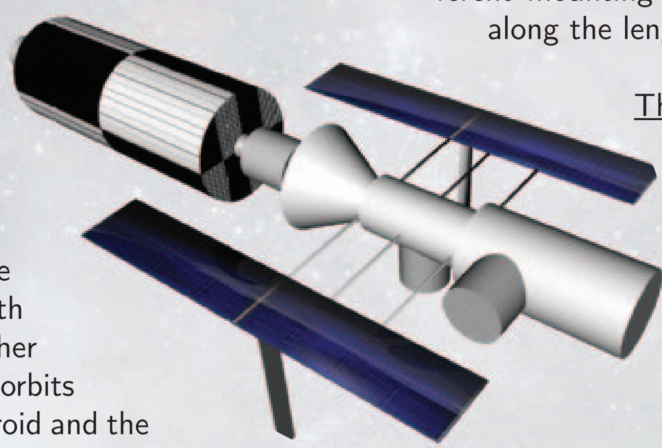
Asteroid Designation	Departure Date	Total Δv [km/s]	Mission Duration [days]	Stay Duration [days]
1999 AO10	11.08.2025	6.579	139	11
2004 MN4	01.05.2028	5.277	348	11
2007 UY1	29.08.2032	5.813	365	24
2008 TP	03.05.2035	5.695	352	18
2009 UY19	23.10.2038	6.461	183	20

Team BLUE selects five asteroids as mission targets, see the table above. Missions to the two asteroids 1999 AO10 and 2004 MN4, also called Apophis, are demanded in the mission statement and can be reached by Concept BLUE. The launch windows associated with all target asteroids are approximately equally spaced with nearly one mission every three years. All of these missions require a low total Δv. Total mission and stay durations at the asteroid vary significantly.

- **Configuration & Assembly**

The space vehicle of Concept BLUE consists of three main components with six own standing modules. The three components are the Exploration Vehicle (EV) for docking with the NEA, the Mother Vehicle (MV) which orbits or stays close to asteroid and the Propulsion Stages (PS). The following configuration is selected as a result of iterations and modifications in order to decrease the mass of the whole system while still meeting the boundary conditions given by human factors. The assumption is made that this mission is clearly an exploration mission and the comfort level of the astronauts needs to be downgraded in order to make the mission affordable. The total habitat volume inside the space exploration vehicle is assumed to be 71 m^3 (50 m^3 for the habitation area and 21 m^3 for the laboratory area). The habitat volume is split between the Exploration Vehicle (43 m^3), the Node (13 m^3) and the Orion capsule (15 m^3).

The figure below shows the conceptual design of the spacecraft. The element to the right is the Exploration Vehicle (EV). The EV is docked to a node; this node serves the purpose to connect the asteroid explorer to the rest of the spacecraft structure and the solar arrays. To the left of the node is the re-entry vehicle Orion. Two propulsion elements follow the space capsule on the left. The structure also accommodates different mounting points for the robotic arm along the length of the spacecraft.



The Exploration Vehicle

The Exploration Vehicle is the main habitat and lab module of the entire spacecraft. The EV allows descent to the surface (or at least close to the surface of the asteroid) in order to fulfill the main objectives of the mission. The EV also accommodates the scientific payload and docking devices for the rendezvous with the asteroid. In order to perform spacewalks on the asteroid, the EV is equipped with an inflatable suit lock. In order to shield the astronauts from radiation, 0.45 m diameter storage tanks are added around the outer structure. The water, oxygen and hydrogen in the storage units may also serve as an additional radiation shield.

For the part of the structure where two of the tanks are aligned close to each other, an aluminum wall thickness of the cylindrical structure of 60 mm is assumed; otherwise the thickness is chosen to be 10 mm.

Node

The node connects the EV to the Orion capsule, the solar panels, and the Soyuz. The Russian ISS node module PIRS served as a basis for the node in this spacecraft design.

Orion Capsule

The Orion space capsule is selected since the design of a new re-entry vehicle can be assumed as very time consuming and would probably exceed 10 years. The Orion space capsule is designed for re-entry from deep space which is advantageous in comparison to the Soyuz capsule, which is only able to re-enter the Earth's atmosphere from LEO.

Soyuz Spacecraft

Due to the non-availability of a human-rated launcher for the Orion space capsule at the moment, the astronauts are taken to the LEO assembly site with the Russian Soyuz. The Soyuz spacecraft docks to the docking port underneath the node of the Exploration Vehicle and is then sent back to Earth before the mission departs from LEO.

Propulsion Stages

The propulsion section consists of two propulsion stages with different sections. The units are attached to the back of the Orion capsule by a truss structure.

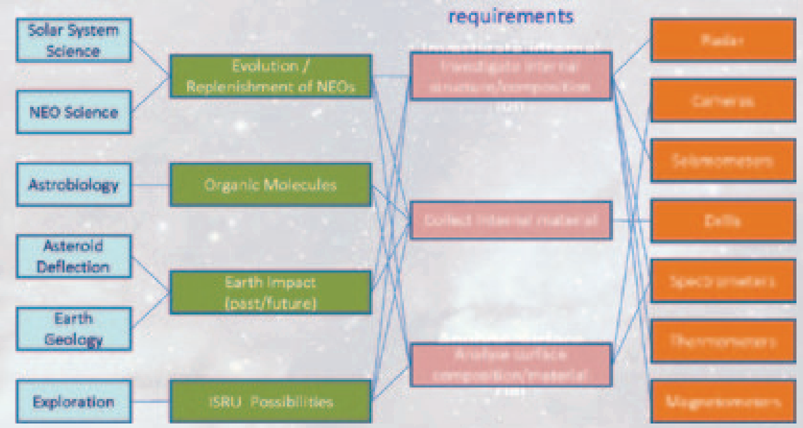
Airlock

For redundancy purposes and in order to prevent a single point failure, the vehicle is equipped with two airlocks, a suit lock at the EV and an emergency airlock. In case that the EV airlock (suit lock) fails or an emergency EVA is required when the EV is on the surface of the asteroid, the Orion capsule can be sealed from the Node, depressurized, and the hatch of the Orion space capsule can be used as an emergency airlock.

Solar Arrays

On each side of the Node there is a solar array with an area of 18 m by 3 m at a distance of 4.5 m from the Node. On each side two radiators are attached perpendicular under the solar arrays.

- **Payload & Operations**



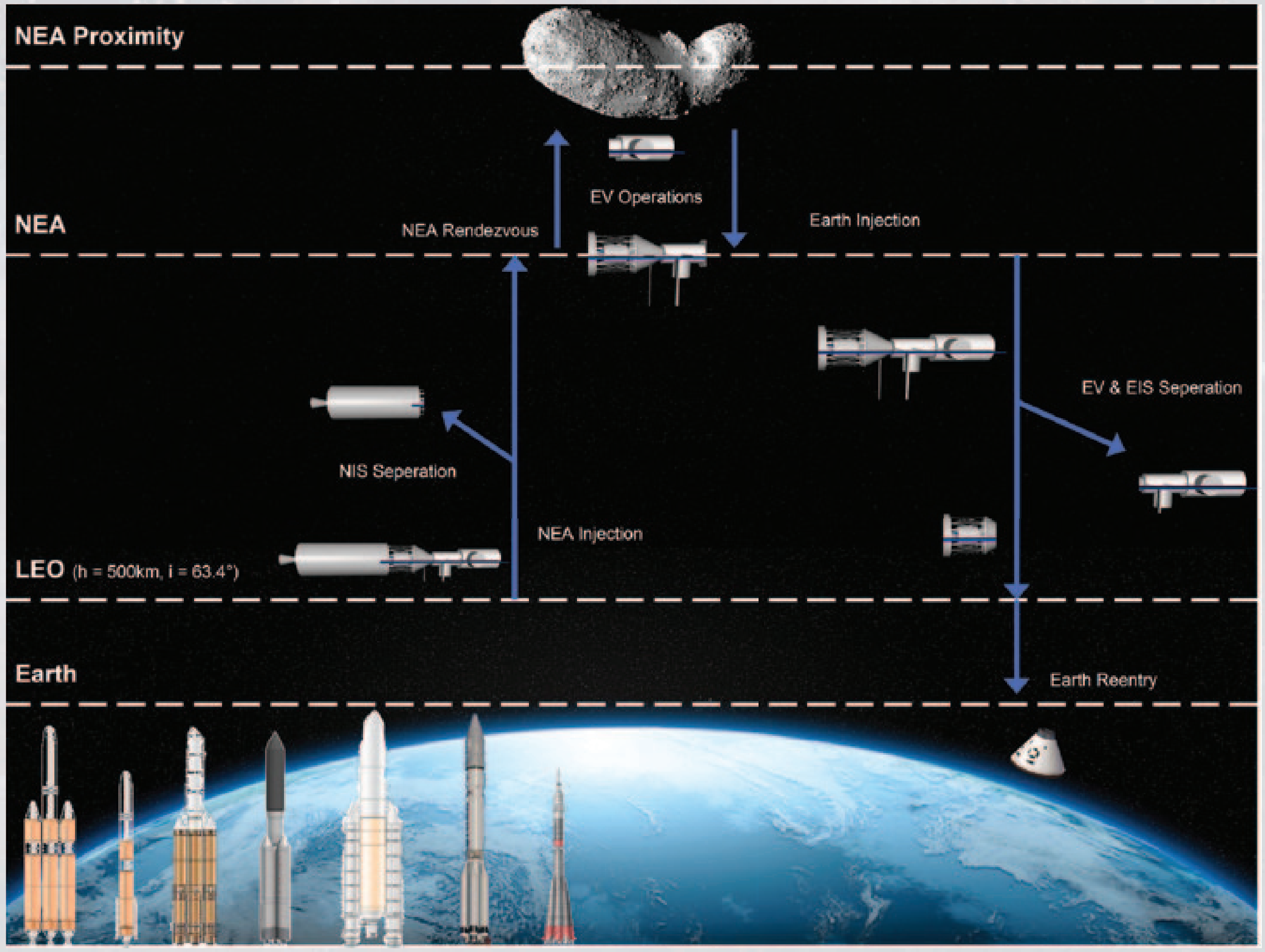
Derivation of payloads from stakeholder objectives

The scientific payload is chosen to satisfy the two main mission objectives, which are to gain knowledge about asteroids and to investigate human long-duration deep-space missions. The needs of various stakeholders are addressed with an instrument suite derived by looking at top-level science objectives and requirements. In addition, storage boxes are included in the payload to accommodate up to 100 kg of samples.

Proximity operations start after rendezvous with the asteroid at a larger distance of more than 20 km. After approaching the asteroid, the home position of the spacecraft is reached at a distance of about 1 km. Now global mapping and tomography are undertaken including the selection of interesting sites to visit later in the mission. After this initial reconnaissance phase, the Exploration Vehicle separates from the Mother Vehicle and advances into closer proximity, taking two crew while one remains in the Mother Vehicle. The Exploration Vehicle matches the rotation of the asteroid while the Mother Vehicle remains at the home position situated inertially with respect to the asteroid such that solar eclipses are avoided and the

Exploration Vehicle is available for communication most of the time. In this mission concept, attaching the spacecraft to the asteroid is at first discouraged. The composition, surface material, and structural integrity of the asteroid are too poorly known at this time to design a reliable docking system. Proximity operations such as experiment deployment or conduction as well as technology testing near and on the asteroid surface are conducted during astronaut EVAs supported by the robotic arm similar to current ISS repair operations or with manned maneuvering units. One technology to be tested is a combined system of harpoons and drills with which the astronauts try to attach themselves to the surface. A similar system is installed on the Exploration Vehicle and can be used to dock the spacecraft to the asteroid provided the previous testing was successful on the particular surface.

- **Transportation & Logistics**
  At the time of this study, it is assumed that there will be no heavy-lift launcher available time of for the first planned mission. Therefore in-orbit assembly of the spacecraft and the transfer stages is necessary using only available commercial heavy-lift launchers or planned launchers with a high probability of realization. As a disadvantage, the spacecraft has to be built from elements weighing between 20 t to 35 t which is the maximum payload to LEO of a single launcher. Concept BLUE's mission to Apophis can be split into the steps as seen in the bat chart below. The use of many different launch systems from different international providers enables the optimization of the launch manifest and the participation of many international partners. The launchers are chosen depending on payload volume and mass, which reduces cost. The first propulsion stages of the Exploration Vehicle are launched shortly before the actual departure of the spacecraft from LEO in order to reduce the cryogenic propellant's boil-off. For the Apophis mission, the duration of the assembly is 91 days. Time between two launches is set to 14 days in order to provide enough time for the assembly process in space. The assembling orbit has a declination of i=63.4°.



Manned Launches
In order to transport the three astronauts into space, the Soyuz spacecraft is used. The Soyuz has proven to be very reliable for crew transport into LEO for many decades. The Orion capsule is not used in the launch and assembly process as a crew transportation vehicle because it is a central part of the Exploration Vehicle and a connection between the transfer stages and the node. Therefore it has to be integrated early in the assembly process while the astronauts arrive shortly before the departure from LEO.

Assembly of the exploration vehicle
The first and central module to be launched is the Node with the attached solar arrays, the robotic arm and the Orion capsule. Afterwards the robotic arm performs an automatic berthing maneuver with the other components. This technique was already tested in the Orbital-Express mission and is also part of the berthing procedure of the Japanese HTV at the ISS. Sensor systems based on radar, lidar, GPS or Galileo are used for the autonomous rendezvous maneuvers and the approach to the Node.

- **Propulsion**
  The first stage is used to propel the Exploration Vehicle from the assembly site in LEO to the transfer trajectory towards the asteroid. In order to fulfill the requirement to develop new technology for activities on the way to interplanetary flight, Team BLUE decided to develop a new transfer stage for this purpose. To simply use existing upper stages in high numbers would be a possible approach, but this reduces the technical development and diminishes payload capacity by penalties due to additional structural mass. The requirements for that stage are comparable to the one on the Ares V Upper Stage, but with the constraint, that there is no super heavy lift launcher available:

Required	LH2	LOX
Mass (kg)	12,205	70,794
Density (kg/m³)	71	1,140
Volume (m³)	171.91	62.1

  - Payload of approx. 50 t into the NEA transfer orbit
  - 20 t – 35 t components for the stage
  - Volume restriction because of payload fairing size

Hydrogen tanks	
Radius (m)	2.85
Length (m)	6.8
Area (m²)	121.76
Max. Pressure (bar)	30
Material	Titanium
Density Tank (kg/m³)	4,460
Thickness (m)	$6.95 \cdot 10^{-3}$
Tank Dry Mass (kg)	3,775.1
Fuel Mass per Tank (kg)	12,319.89
Mass Engine (kg)	2,430
Additional Mass Factor	2
Tank Wet Mass with Engine (kg)	22,300

Oxygen tanks (4x required)	
Radius (m)	2.2
Length (m)	1.05
Area (m²)	44.92
Max. Pressure (bar)	30
Material	Titanium
Density Tank (kg/m³)	$5.37\ 10^{-3}$
Thickness (m)	1,075.1
Tank Dry Mass (kg)	12,319.8
Fuel Mass per Tank (kg)	18,201
Additional Mass Factor	2
Tank Wet Mass (kg)	20,351

As the primary engine for the first stage the J-2X engine from Pratt & Whitney Rocketdyne is chosen. This engine, using cryogenic LH2 / LOX as propellant, is currently not fully developed, but the first test burn is scheduled and it is assumed to reach the proper TRL including qualification flight by 2025. With the parameters of the J2X Engine, the payload mass and the required Δv of 3.97 km/s, the propellant mass and volume are calculated.

The mass of the liquid oxygen cannot be launched in a single shot. Hence, the LOX tank is split into four smaller, separate tank units of 20 t mass each. The hydrogen tank in combination with the engine beneath can be transported to LEO in one launch. The size of the tanks for the Apophis mission is given below:

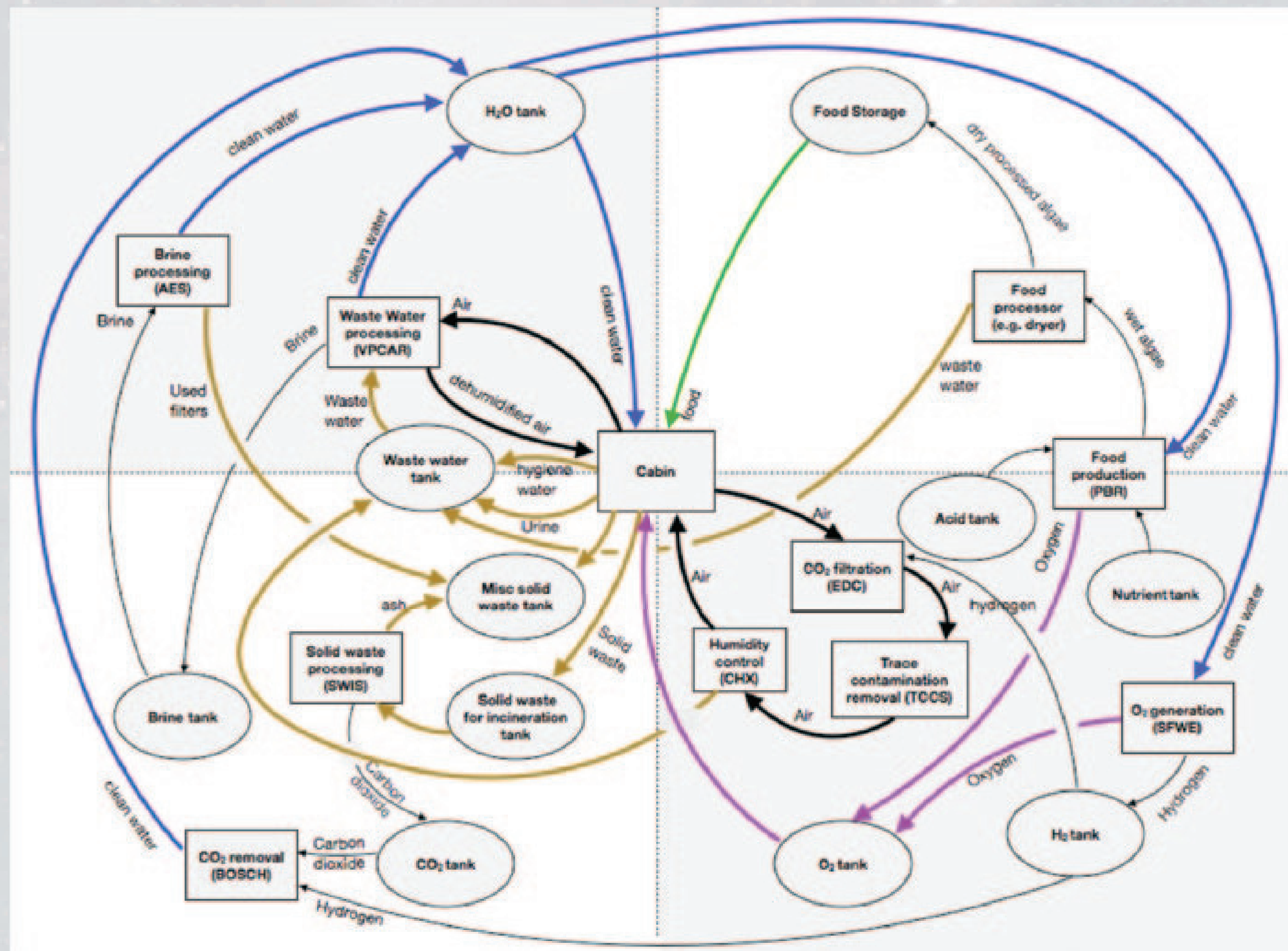
An additional mass factor is chosen because of further structural parts that will be added to fix the tanks and to connect them. The whole stage assembled in LEO is given below: The first transfer stage is entirely newly developed and therefore needs to be tested thoroughly. As a backup first transfer stage for the Apophis mission, there is also the possibility to use four Ariane ESC-ME stages. The first three have a reduced tank due to the maximal payload mass of the launcher, whereas the last one is fully filled. For journeys to other asteroids the number of necessary stages rises significantly (up to 9-10). For the rendezvous with the NEA and the injection into a transfer orbit back to Earth, a stage with sufficient Δv-capability and storable propellant is chosen. The estimation of the total cargo mass for the transfer back to Earth is approximately 20 t including the re-entry capsule Orion, the node with solar panels, and the EV. The Breeze-M upper stage is selected as a second transfer stage. It consists of the S5.98 M engine with a specific impulse of 325.5 s and a combination of core tank and external tank with a total propellant mass of 19,800 kg. The engine can be restarted several times and is already space-proven. The mixture of N2O4 and UDMH is a perfect propellant to be stored. In the mission to 1999 AO10 with the highest values of required Δv for the two maneuvers, two Breeze-M stages with additional tanks of 2,700 kg of each propellant are used.

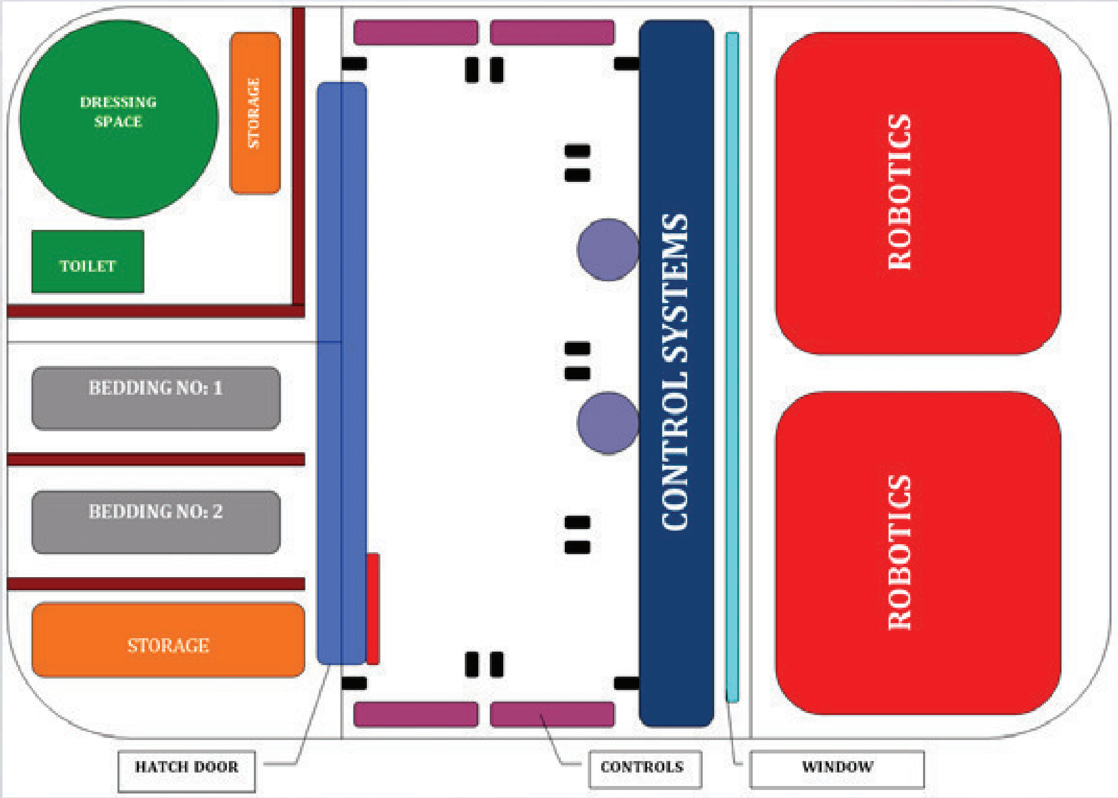
- **Energy Management**
  The Electrical Power System (EPS) of Concept BLUE is designed as a separated system for the Mother Vehicle and the Exploration Vehicle. During transfer from LEO to the asteroid, Team BLUE identified peak power requirements of 11.25 kW_{el} for the complete spacecraft. During NEO operations when the MV and EV are disconnected, peak power requirements are 4.7 kW_{el} for the MV and 7.2 kW_{el} for the EV. Electrical power is generated by a photovoltaic system using conventional Gallium Arsenide (GaAs) solar cells. At the MV two solar arrays are installed with a total panel area of 101 m² and a mass of 407 kg. The solar cells of the EV are body-mounted. The main electrical power source of the EV during NEO operations are NiH2 batteries. NiH2 batteries on the MV are a backup system in case of solar array failure. The total EPS mass is 1,409 kg. The Thermal Control System (TCS) of Concept BLUE is a separate design for the MV and EV as well. A maximum heat load of 30.9k W_{th} is identified in LEO. The TCS heat rejection capability is 12.8 kWth for the MV and 18.6 kW_{th} for the EV. The spacecraft is insulated by silvered Mylar foil. A combination of active and passive thermal control elements ensures an efficient and reliable operation of Concept BLUE. Deployable heat pipe radiators allow heat rejection. The total TCS mass is 998 kg.

	Mother Vehicle	Exploration Vehicle
EPS, generation	GaAs solar cells 18.8 kW_{el} (BOL) arrays: 2 x 101 m², 407 kg	GaAs solar cells 1.4 kW_{el} (BOL) body-mounted: 10 m², 30 kg
EPS, storage	NiH2 batteries 10 kWh_{el}, 124 kg	NiH2 batteries 66 kWh_{el}, 825 kg
TCS	12.8 kW_{th} using • 2 depl. heat pipe radiators, 10 m x 2 m and 160 kg each • 102 kg CHX and fluid loop (water & ammonia)	18.6 kW_{th} using • 2 depl. heat pipe radiators, 4.2 m x 6.9 m and 233 kg each • 110 kg CHX and fluid loop (water & ammonia)

Thermal protection is necessary for re-entry into Earth's atmosphere. Team BLUE chooses the Orion capsule which is designed for a crew of six and re-entry from deep space. Calculated re-entry velocity is 12.5 km/s. Heat loads are not analyzed as Orion is assumed as a developed technology.

- **Life Support & Human Factors**
  The life support system is split into two parts, one for the Mother Vehicle and one for the Exploration Vehicle. The Exploration Vehicle is stocked with sufficient water, oxygen, and food for the duration of the stay on the asteroid. Water and oxygen are provided by the life support system of the Mother Vehicle. The Exploration Vehicle is equipped with basic air treatment units: LiOH for carbon dioxide removal, a trace contaminant removal unit, and a dehumidifier. All solid waste, wastewater, and urine are stored in tanks. The life support system





of the Exploration Vehicle can also be used as a backup for the life support system of the Mother Vehicle when both vehicles are docked. A hybrid-regenerative system was designed for the Mother Vehicle. Dry mass of the entire system is 2.6 t and the peak power requirement is 6 kW. Total pressure of the cabin air is set to 70 kPa in order to decrease structural mass requirements and reduce leakage. Therefore, the oxygen portion of the cabin air is maintained at 30 vol% to compensate for the decreased pressure. Carbon dioxide is removed using an Electrochemical Depolarized Concentration (EDC) unit and oxygen is produced using water electrolysis (SWFE). The carbon dioxide is reduced by two systems: the major part is processed by a Bosch reactor producing solid carbon and water while the smaller portion is consumed by microalgae cultivated in a photobioreactor (PBR), which also produces oxygen. The algae also serve as food but about 75 % of food is supplied from storage. A centralized system is chosen for water treatment because of its low mass. All wastewater and urine are sent to a VPCAR unit to produce potable water. The VPCAR unit has high energy requirements but sufficient solar energy is available. Brine produced by the VPCAR is processed by an air evaporation system (AES). In case of VPCAR failure, it can also be used to treat a small amount of waste water. About half of the solid waste is incinerated by SWIS, the rest is stored for disposal. Critical systems identified are carbon dioxide removal, humidity control, and oxygen supply. Because of the small pressurized volume, a failure of the EDC leaves only seven hours before a toxic level of 1 vol% is reached. Upon failure of the CHX unit, relative humidity increases rapidly within a day to saturation level (100 %), endangering electronics. In case of failure of oxygen supply, the crew has only 7 hours before asphyxiating conditions (16 vol%) are reached. The space allocated for each person is 20 m³ combining the area in Orion capsule, Node, and Exploration Vehicle. The interior design of the Mother Vehicle is shown above. This provides a very low degree of isolation, but since there are only 3 crew members, isolation is not a major issue. The compartments are arranged keeping human factors engineering at its core and allocating open compartments for minimal confinement. The daily crew schedule allots 8.5 hours for work, including planning and coordination as well as daily systems operation tasks. Also 8.5 hours are allowed for sleep. The remaining time is used for exercise, meals, and personal hygiene.

- **Communication System**
  The ground segment uses the Deep Space Network (DSN) and the ESTRAK ground stations. The maximum distance encountered during all five missions is $7 \cdot 10^7$ km and no solar conjunctions occur during any of the missions. A deployable parabolic reflector with a diameter of 5 m, two redundant S-band feeds, and one Ka-band feed was designed for the communication between the Mother Vehicle and Earth. A parabolic reflector with a diameter of 0.1 m, one S-band feed, and one Ka-band feed was designed for the communication between EV and MV. The associated data rates are 19.2 kbps for the command S-band, 30 Mbps and 18 Mbps for the telemetry and data uplink and downlink, respectively. All signals have BPSK modulation and are in general not processed using forward error correction with the exception of the Ka-band communication from the Mother Vehicle to Earth.

- **Radiation Shielding**
  The different types of radiation (solar proton event, solar particle events, and galactic cosmic rays) are analyzed. A first calculation of the radiation shielding for the protection from galactic cosmic rays is conducted using the software CREME96. Part of the shielding is provided by air, water, and liquid hydrogen tanks around the Mother Vehicle. These elements are required by the life support system. The tanks are made up of aluminum, with a thickness 4 cm. For the parts not covered by tanks, a 6 cm aluminum shielding is provided. In order to calculate if this aluminum shielding provides enough protection, a quality factor of 3 has been used (as the content of the tank already provides protection shielding). However, a thickness of 5 cm is required, obtaining the following values. Using the software Spenvis, the amount of aluminum needed to shield the spacecraft under SPE including Solar Flares is then obtained. A radiation shielding of 40-60 mm is required, obtaining a total radiation of 0.1584-0.306 Sv/year (0.236 Sv for the length of the mission).

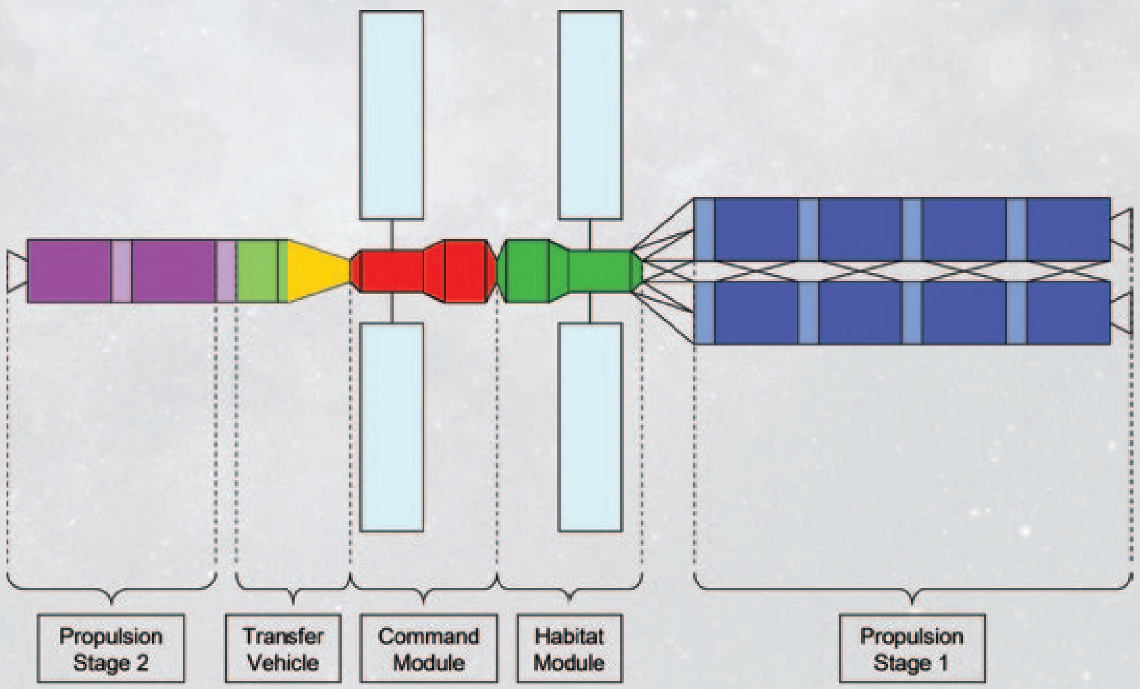
4. Team RED Design Results

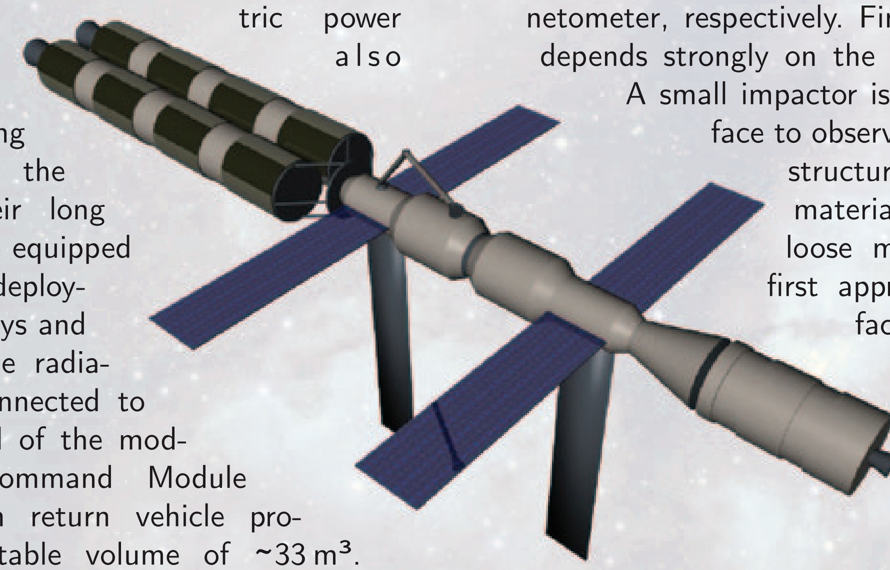
- **Mission Targets & Launch Windows**

Asteroid Designation	Departure Date	Total Δv [km/s]	Mission Duration [days]	Stay Duration [days]
2006 WB	30.05.2024	7.386	181	10
1999 AO10	18.08.2025	6.982	187	15
2004 MN4	01.06.2028	5.735	317	10
2009 UY19	27.10.2038	6.119	180	14

Team RED chooses four asteroids as mission targets. Missions to both obligatory targets 1999 AO10 and 2004 MN4, also called Apophis, are achieved. While the first two mission launches are quite close to each other, the remaining missions are spaced by more than ten years. Total Δvs vary greatly. The targets chosen can be reached on very short missions of around six months round-trip duration. The only exception is the mandatory target asteroid Apophis whose mission requires a much longer mission duration.

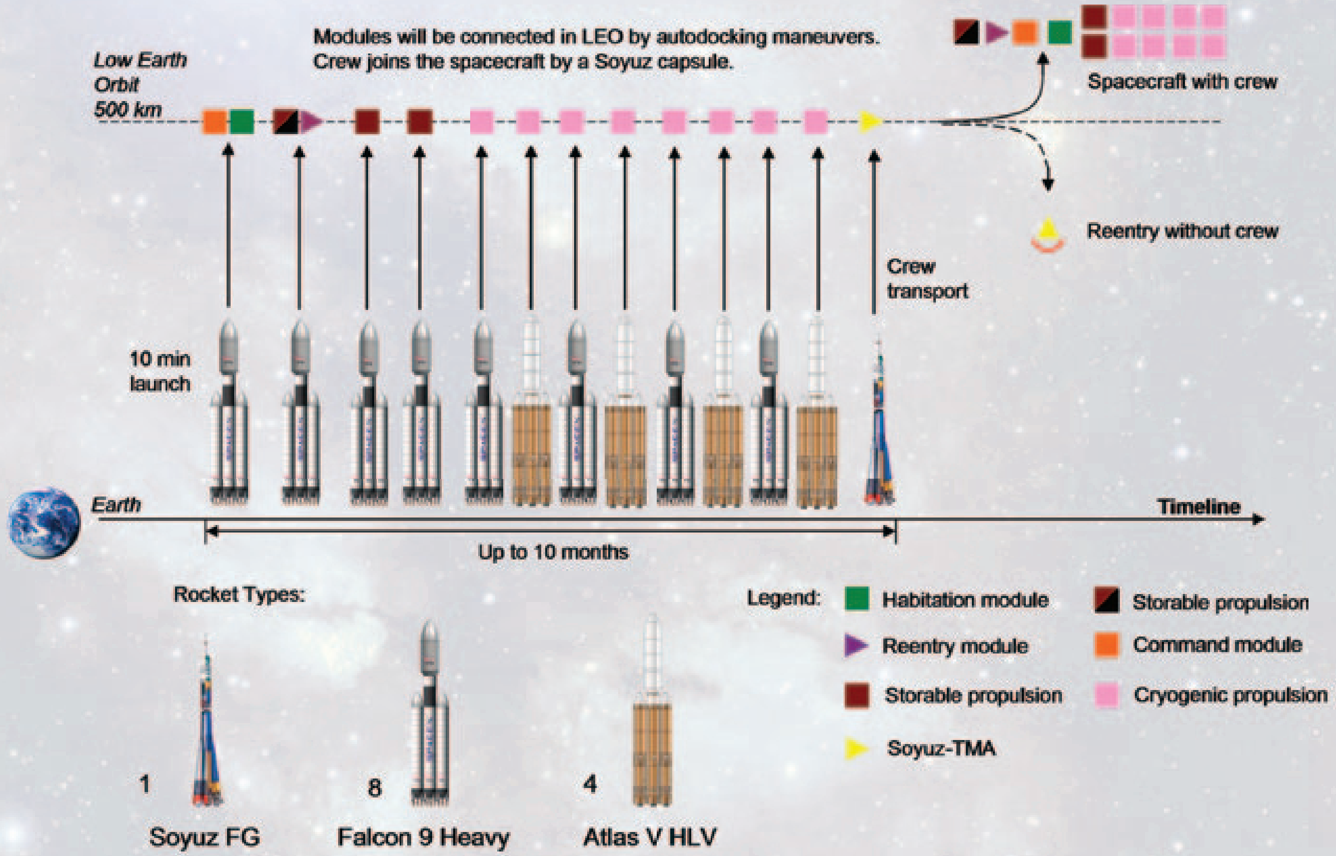
- **Configuration & Assembly**
The spacecraft has a total length of 72 m and a total mass of 317.8 t. The entire exploration vehicle consists of six elements: Command Module (CM), Habitat Module (HM) with airlock and docking system for Soyuz, Transfer Vehicle (TV) with re-entry capsule, Soyuz TMA, first propulsion stage and second propulsion stage. The exploration vehicle is fairly large, in terms of both mass and dimensions. Therefore, the spacecraft cannot be launched into space as a complete structure and modules or elements must be launched separately and assembled in space. The parking orbit where the spacecraft is assembled is at an altitude of 500 km. The propulsion stage 1 is used for the trans-NEA injection. It is composed of eight similar tank units with one rocket engine each. These eight sub-modules are linked in pairs building two strings such that two sub-modules can be fired simultaneously. The burned out pair is jettisoned and the next two stages are ignited until the entire stack is discarded. All sub-modules of the propulsion stage 1 use cryogenic liquid propellants (LOX/LH2) which are stored under zero boil-off conditions. The propulsion stage 2 is used to perform the NEO rendezvous maneuver. Similar to the first propulsion stage, it is composed of two similar tank units with one rocket engine each. These sub-modules are fired consecutively. This stage also uses the same type of cryogenic liquid propellants and the same zero boil off technology as the first stage. The Transfer Vehicle is composed of the Earth return injection stage (green) and re-entry capsule (orange). The capsule can carry up to three astronauts, similar to Soyuz-TMA, but has the ability to carry asteroid samples in an uncontaminated compartment, reachable from the outside with the robotic arm. The Command Module is designed to act as an independent habitable space station module. It accommodates a life support system, attitude and orbit control system, and electric power system. It also has a radiation shielding to protect the crew on their long journey. It is equipped with two deployable solar arrays and two deployable radiator panels connected to the outer hull of the module. The Command Module together with return vehicle provides a habitable volume of ~33 m³. The Habitat Module contains an equal interior structure as the Command Module and has its own life support system, attitude control system and electric power supply. Furthermore, it is equipped with the docking port for crew transport to the spacecraft, two exo-suits, and the robotic arm needed for the assembly of the entire vehicle on orbit and the deployment of space probes and experiments. For most of the modules an aluminum structure is used. Despite this being quite heavy (2.8 g/cm³) and having a coefficien of thermal expansion of around $23 \cdot 10^{-6}$ /K, it provides the strength needed and contributes to the radiation shielding required. The aluminum hull also protects the crew from harsh space environmental conditions such as vacuum and micrometeoroids or dust contamination at the NEA. Inflatable structures are not considered due to a low technology readiness level.





- **Payload & Operations**
After separation from the outbound burning stage at a distance of 50 km the spacecraft slowly approaches the asteroid down to a distance of 2 km. After the initial reconnaissance and system check out, the asteroid is globally mapped investigating dimensions and rotation and a possible docking site is chosen. The approach is then continued to 200 m altitude. During the subsequent phase, the surface and internal composition are mapped using cameras and spectrometers. Also, shape, surface temperature, and magnetic field are investigated with a laser altimeter, a thermal sensor, and a magnetometer, respectively. Final NEA descent depends strongly on the surface integrity. A small impactor is sent to the surface to observe the nature and structural integrity of its material. In the case of loose material, a robot first approaches the surface while guided by laser and connected to the spacecraft with tethers. It tests the surface material for the feasibility of anchoring. Along these tethers the crew can access the asteroid surface in order to conduct experiments including core drilling, to deploy seismometers and beacons, and to collect samples. The astronauts are supported by humanoid robots and the robotic arm mounted on the spacecraft. In case of solid material, the spacecraft is directly attached to the surface with dowels and tethers. When departing from the asteroid, the Habitat Module is separated and navigated toward the asteroid. The Habitat Module impacts the asteroid surface which is observed from the Command Module and measured by the previously installed seismometers. This experiment can yield significant insight and provide important information for future deflection missions.

- **Transportation & Logistics**
The intention is to use two or more similar types of heavy lift launchers in order to perform the assembly sequence in less time compared to the use of a single launch system. These launch systems should have similar characteristics in terms of payload capacity to LEO, production rate, and payload fairing dimensions. A large number of different launchers operated in parallel would decrease the to-



tal time until assembly complete, but would lead to many constraints for the development and qualification of different modules. This problem is solved with a trade-off, and the preferred option is to use only the Atlas V HLV and the Falcon 9 Heavy. Apart from these two launch systems, which are used for launching cargo only, a man rated launch system for the crew transport is needed as well. Since the only man-rated launch vehicle operational today and in the next years is Soyuz FG, this is be the selected one. In total 13 launches take place over 10 months. The order of launches and respective modules can be seen above.

- **Propulsion**

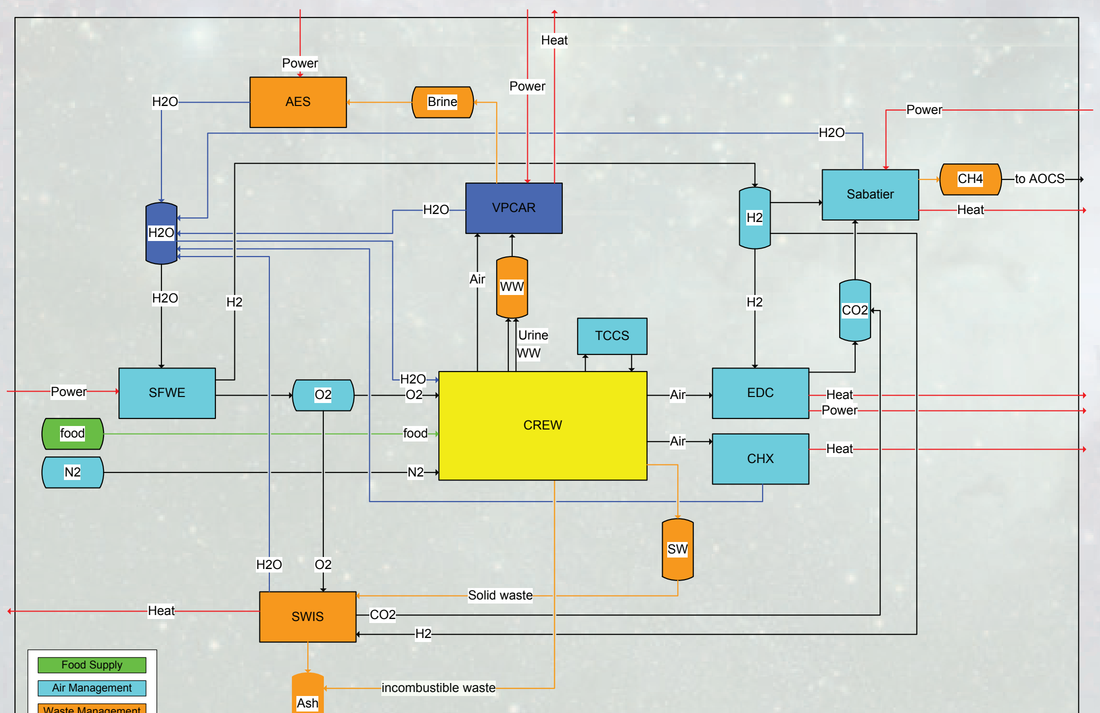
The first stage, which delivers the impulsive maneuver to get from low-Earth orbit to the transfer trajectory towards the asteroid, consists of eight identical cryogenic propulsion modules, stacked in two rows of four modules. Two modules are fired parallel. The entire exploration vehicle stack ends up with a total initial mass in LEO of 332,127 kg. The next table gives an overview of the total spacecraft mass evolution over the mission time: Cryogenic propulsion is used for the first burn (the outbound injection burn) and storable propellants for all the other impulsive maneuvers to prevent long term cryogenic fluid storage and reduce the additional mass this causes. The cryogenic stage tanks result in higher dry mass because of the insulation or active cooling methods. The VINCI (LOX/LH2) engine is selected for the cryogenic stages and SR-72 (MMH/N2O4) for the storable stages. The total module length is calculated with the nozzle folded, because this is how it is fitted inside the payload fairing of the launch vehicle. The Command Module, the re-entry capsule, and the Habitat Module with the science payload, together with the third stage are accelerated once the entire vehicle reaches the asteroid in order to match its velocity. The NEA arrival burn phase is made with two identical stages, each one with its own fuel and oxidizer tanks and engine. Only the Command Module and the re-entry capsule, which all together have a mass of 18,000 kg, return from the asteroid. That is the input for the in-bound Δv, giving the needed propellant and the mass for the stage that propels the Exploration Vehicle back to Earth. 2,655 kg of MMH and 5,444 kg of N2O4 are used for this burn. The third stage dry mass is only 387 kg. All the mentioned propulsion modules are launched up to LEO to be assembled with

Characteristics of EPS and TCS	
EPS, generation	multiple-junction solar cells 75 kW_{el} (BOL) arrays: 2 x 75m², 200kg PEM fuel cell testbed 8.3kW_{el}, 100kg
EPS, storage	LiPo batteries 4 kWh_{el}, 50 kg
TCS	19.2 kW_{th} using • deployable heat pipe radiators, 60 m², 900 kg • 572 kg CHX, heaters and fluid loop (water and ammonia); pumps, CHX, heater redundant • 219 kg MLI

the help of the robotic arm. As mentioned above, the outbound injection phase is made of four stages with two parallel modules each. To attach these structures, subjection devices are disposed axially. Between the two module bodies a juncture with hooks used to connect the two modules is placed. It is also considered to place small solid rocket motors on the last stage of the first and second maneuver to deflect them from the spacecraft's trajectory. If there is no maneuver, the burned out stage will follow the same trajectory as the spacecraft, and can impact to the asteroid at arrival. The same situation will happen for the second stage of the outbound braking maneuver and the final inbound maneuver. Consequently, the solid rocket motors alter the trajectory of the empty stage to avoid interference or collision.

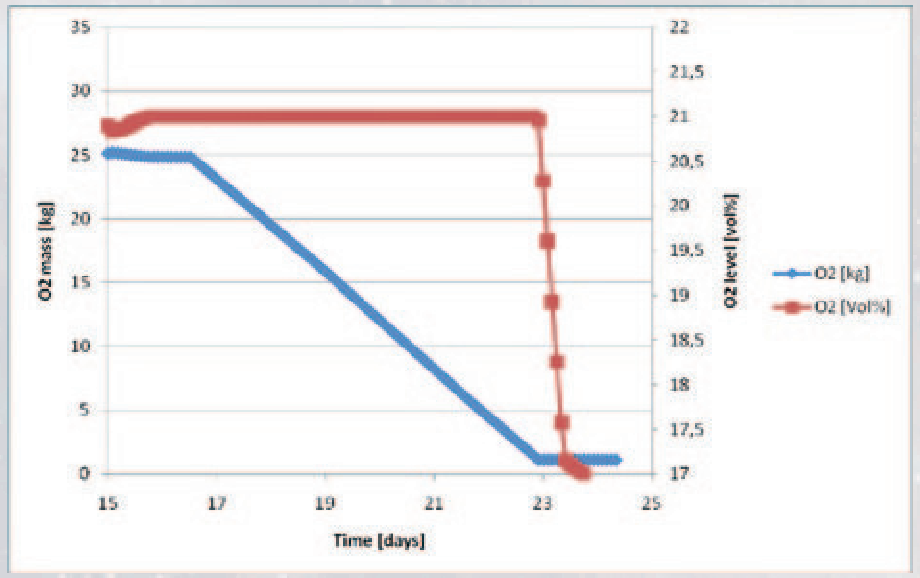
- **Energy Management**

The EPS of Concept RED consists of three-junction thin film solar arrays for electrical power generation and LiPo batteries for electrical energy storage. A solar array area of 150 m² provides a maximum power output of 75 kW_{el} (BOL). Energy storage capacity of the batteries is 4 kWh_{el}. A PEM fuel cell test bed allows additional power generation of 8.3 kW_{el}. The total EPS mass is 800 kg. The TCS of Concept RED provides active and passive thermal control elements. Heaters, heat exchangers, and fluid loops allow heat transport. The spacecraft is insulated by unpolished metals layer. Deployable radiators with an area of 60 m² perform a heat rejection capability of 19.2 kW_{th}. The total TCS mass is 1,691 kg. Thermal protection for re-entry into Earth's atmosphere was designed in detail by Team RED. The geometry of the capsule corresponds to the Apollo capsule and the Orion capsule. A re-entry velocity of 14 km/s is assumed which yields a thermal load of 6.7 MW/m² and a total integral heat load of 100 MJ/m². The ablative TPS material PICA is used. The



Environmental Control and Life Support System heat shield area is 36 m² and the thickness is 131 mm. The total TPS mass is 1,190 kg.

- **Life Support & Human Factors**
The life support system is designed as physicochemical system. It has a total dry mass of 2.5 t and a total volume including storage tanks and compartments of 7.5 m³. While water and oxygen are mostly recycled, other



consumables such as food, nitrogen, and hydrogen must be supplied from storage. Total storage mass amounts to 1 t for the longest mission. Technologies used possess technology readiness levels of 6 and higher, ensuring the availability of the components by 2022. The atmosphere management comprises components for carbon dioxide removal (EDC), oxygen generation (SFWE), as well as humidity and temperature control (CHX). The carbon dioxide is reduced by a Sabatier Reactor to methane and water. Water is split by electrolysis into oxygen and hydrogen. The water treatment employs a stand-alone VPCAR capable of treating all types of waste water to potable water quality with only little need for post-treatment. The brine produced by the VPCAR is treated by an air evaporation system (AES) to further close the water cycle. A major part of the solid waste is incinerated to reduce required storage volume and to regain water and oxygen contained. The figure above depicts the mass flows and interactions in the life support system. Considering the rather small crew compartment, the most critical component of the system is the carbon dioxide removal unit EDC. In case of EDC failure during the inbound flight, simulations indicated a period of five to six hours until a critical carbon dioxide level of 1 vol% in the cabin atmosphere is reached. During the outbound flight, the period is prolonged to seven to ten hours. Another important component is the temperature and humidity control unit (CHX). If it fails, cabin air moisture rises to 100 % within two hours, extremely increasing the risk of electrical short-circuits. Oxygen contingency storage provides for one week in case of electrolysis (SFWE) failure. If oxygen is depleted, it takes about one day until the oxygen partial pressure in the cabin drops to a critical level, as indicated by the chart. Human factors issues include suitable zoning of spacecraft interior and proper color and illumination schemes as well as ergonomic work stations. The zoning allocates areas for social, private, and work activities. A crew social structure is proposed as one serves as commander, whereas the other two crewmembers have an equal standing in the hierarchy. From the professional point of view the crew is made of a pilot, a scientist, and a robotic controller. Coming from a military background, the pilot also acts as commander of the spacecraft. The crew schedule is arranged in a "round robin" format, a rotating schedule that allows alternating rest and work phases of the individual crewmembers. During the week the crew works ten-hour days and five-hour days on weekends. Eight hours are allocated for sleep and the remaining time is available for exercise, leisure, and social activities. Exercise equipment on board includes the Advanced Resistive Exercise Device (ARED) and a COLBERT treadmill & vibration reducing rack. Both enable µg-countermeasures. In total, the human factor equipment accounts for a mass of 1.8 t, comprising hygiene items such as towels and clothing, medical devices, and exercise equipment.

- **Communication System**
During all four missions, the maximum distance between the spacecraft and Earth is $7 \cdot 10^7$ km and can be covered with a direct link. No solar conjunctions occur. For the ground station segment parabolic reflectors of 70 m diameter are used, such as those of the Cebreros Satellite Tracking Station in Spain. A parabolic reflector of 6 m diameter is installed on the spacecraft and deploys after launch guaranteeing a sufficiently large gain and decreased power consumption. The data and telemetry link between the spacecraft and the ground segment is achieved using the Ka-band with a data rate of 5 Mbps. The command link uses the S-band with a data rate of 19.2 kbps. The antenna polarization is chosen to be circular. BPSK modulation guarantees simplicity of design at the cost of a slightly low signal to noise ratio. Forward error correction improves performance. The communication among spacecraft modules is accomplished with optical fibers.

- **Radiation Shielding**
Because interplanetary space missions are uncommon, no guidelines for maximum allowable dose of radiation exists. Therefore, LEO limits are used as an approximation. A shielding thickness of 25 mm is required, taking into account galatic cosmic radiation and solar particle events. It is assumed that solar particle flares do not occur during the time of the mission or occur very infrequently. The shielding is composed of a 5 mm aluminum layer and a 20 mm polyethylene layer, which contains hydrogen. Hydrogen is extremely beneficial in radiation shielding and reduces the overall mass considerably. No liquid or gas radiation shielding is considered due to the extra mass and volume caused by the storage tanks. The solar minimum, solar maximum, solar worst day, and solar peak values are determined and used to determine the absolute dose, the equivalent dose and the effective dose. The total radiation is calculated using the GCR and the SPE radiation expericend by astronauts (obtained with CREME96 and Spenvis, respectively). The total radiation for one year mission is 0.46 Sv (0.00126 Sv per day).

5. Design Evaluation

- **Evaluation Process**
  Throughout the design phase the team members gain considerable insight and experience in their respective fields of expertise and the available technologies, constraints and complexities. Thus, they are directly involved in the evaluation of the competing design concepts. The original teams are disbanded and the participants are assigned to one of seven evaluation committees depending on their role in the design phase, where they discuss and reflect their solutions and approaches taken.

  The aspects assigned to the evaluation committees are:

  - Programmatics
  - Configuration
  - Mission Design
  - Propulsion
  - Energy Management
  - Human Aspects
  - Operations

  Each committee consists on at least 2 members of each team and one staff member, who guides the discussions between the evaluators. They compare the two approaches and solutions and score both projects. In this section some of the evaluated aspects can be found. For each evaluated aspect, a weight was previously assigned by the staff, but this weight is not provided to the participants during the evaluation. Finally, using the scores given by the participants and the weight assigned, a final score is obtained for each concept.

- **Programmatics**
  Due to the involvement of more launch sites, Concept BLUE has an increased degree of international participation to its campaign. In terms of manufacturing and supply, both teams have equally involved the participating nations. Furthermore, both teams promoted the involvement of commercial partners. With respect to future missions to farther targets such as Mars and its moons, both concepts exhibit comparable capabilities regarding expandability.

- **Configuration**
  The first criterion to address is the overall size of the entire exploration vehicle of both teams. With a gross mass of 332 t in LEO before the departure to the asteroid, the Concept RED has more than double the mass of Concept BLUE. This results in more launches for the assembly phase and higher cost for the transportation to LEO. On the other hand, Concept RED can accommodate up to 4,000 kg of scientific payload. The vehicle of Concept BLUE uses deployable solar panels without rotary joints to track the sun. The entire spacecraft has to change its attitude for aligning the solar arrays to the sun. This makes the use of a simpler solar wing design possible, but poses limitations to the operations and causes a greater effort for the vehicle's attitude control system. Concept RED chooses to use only one airlock for EVA operations without a contingency airlock for the use in case of an emergency. Concept BLUE uses the Orion capsule, which has an additional hatch opening to space and can be sealed off and depressurized, to be used as an emergency airlock. Both designs have only one docking port available for rendezvous and docking with the crew carrying vehicle, namely the Soyuz spacecraft. Both designs lack an alternative docking port for rescue operations. Furthermore, modules and solar arrays are very close to the docking port which does not give much clearance for approaching or leaving vessels for crew transfer. Both teams come up with a good solution for the robotic assembly of the entire vehicle in space and both teams use the heritage of existing modules for the design of their exploration vessel. Concept RED even uses one design for two modules which should reduce the cost for development and manufacturing of the vehicle.

- **Mission Design**
  The major aspect of mission design is the aspect of target selection and the resulting hardware concept.
  Apart from the two mandatory mission targets, 1999 AO10 and 2004 MN4 Apophis, both teams choose to design a mission to the asteroid 2009 UY19. Team RED chooses one and Team BLUE two additional asteroids. The associated launch windows are chosen reasonably, although Team BLUE has an advantage through more evenly spaced launch windows with approximately one mission every three years. For both concepts mission durations and the time spent in close proximity of the asteroid are similar. Both system concepts accommodate three astronauts. Neither system concept incorporates reusable infrastructure and the degree of necessary hardware modification is similar. Concept RED requires more technology development and allocates more financial resources to this matter.

- **Propulsion**
  The propulsion subsystem is designed with the aim to obtain a flexible configuration that can be used in all asteroid missions and can be expanded without any additional design or infrastructure costs for missions to further asteroids in the future. Concept BLUE uses a one-engine design with a single LH2 tank and four modular LOX tanks for their main propulsion stage. Concept RED on the other hand uses eight whole stages, each with its dedicated engine. These stages are stacked in two columns and are burned and discarded in pairs. The overall mass for Concept RED's primary propulsion stage is much higher compared to the one of Concept BLUE because more structural elements are required to stack and bundle the stages together. Also, the individual stage mass of Concept RED is greater because of additional insulation mass enabling zero boil-off cryogenic fluid storage. Taking this into consideration, the higher overall system and fuel mass may seem a disadvantage, but in fact higher score were given to Concept RED because the high mass is the result of a more elaborate design. Concept RED also allows its design larger growth potential and sufficient margins. The modular design of both concepts offers adequate mission flexibility. The use of LH2 and LOX for the fist stage and storable propellants for the second and third stages equals the specific impulse of the propulsion modules.

- **Energy Management**
  Both teams choose very similar EPS and TCS concepts and therefore receive equal scores. Both concepts use photovoltaic solar cells combined with secondary batteries for their EPS. The approach of Team BLUE is to use efficient but space proven technologies, whereas Team RED relies on new technologies, currently not space qualified. From this point of view, the EPS of Concept BLUE is heavier but more reliable than the EPS of Concept RED. Both TCS concepts consist of heat exchangers, pumps, fluid loops and deployable heat pipe radiators. The radiator concept of Concept RED is more efficien than the one of Concept BLUE. The radiator deployment design of Concept BLUE is more flexible. Regarding the TPS, Concept BLUE chooses the Orion vehicle as the re-entry capsule. Although the capsule is suitable for interplanetary re-entry trajectories, its development is frozen and no calculations are made. The Concept RED presents detailed calculations for a semi-ballistic re-entry capsule with an ablative thermal protection. Heat shield thickness and mass are calculated. Therefore Concept RED receives a higher score.

- **Human Aspects**
  The Human Aspects committee evaluates the approaches to life support, radiation protection and human factors engineering in the team concepts. Both ECLSS are comparable in performance, although different system concepts are utilized. Concept BLUE integrates a photobioreactor as biological component into the system, saving food storage mass. Concept RES's spacecraft relies on a more robust conservative approach using physicochemical systems only. Both systems take advantage of synergisms; Concept BLUE by using a photobioreactor providing synergy between atmosphere and food management; Concept RED by employing a Sabatier reactor supplying methane for propulsion. While Concept RED accepts a high energy requirement, Concept BLUE has slightly higher system dry mass. Overall, both teams score equal due to balance in advantages and disadvantages.
  Regarding human factors both teams address the same factors to an equal standard. In general, the approach to interior design, crew schedule, and composition followed the same concept.
  Both teams work out radiation protection concepts meeting requirements for maximum allowable radiation dose. Concept BLUE however researches on how often solar flares occur (2/year) and considers using solar satellites to predict the occurrence of solar flares to inform the astronauts when a solar flare occurs so they can enter their "safe zone". In consequence, Concept BLUE scored higher regarding radiation issues.

Space Station Design Workshop

- **Operations**
  Both approaches are very similar, especially for Payload and EVA requirements and opportunities. Concept BLUE has a better approach for the communication system, as they consider a redundant system for the communication between the Mother Vehicle and the ground stations and among vehicles.
  Both concepts use different approaches to perform their EVA. Concept BLUE performs EVAs while attached to the robotic arm, and if safety conditions permit, using a harpoon-drill-rope system. Concept RED has a humanoid robot for EVA assistance and a more detailed design for the soil sample retrieval and storage.
  Extensive distance measurements, seismic experiments, and core drilling are planned by both teams. The difference is that Concept BLUE includes a deep drilling, whereas Concept RED after departing from the asteroid impacts the Habitation Module, which will help to plan future deflection missions.

6. Conclusion

The SSDW 2010 conducted at the Institute of Space Systems of the University of Stuttgart was a successful, intensive, and interdisciplinary workshop with 32 highly motivated participants from all over the world. Considering current and future human exploration strategies, the students were tasked with a spacecraft for missions to Near-Earth Asteroids. They were assigned to outline flexible, sustainable, and extendable mission architectures from a large quantity of reachable asteroids and to design an appropriate spacecraft. For the first time in SSDW history, an interplanetary long-term mission was investigated.

Both teams were supported by a concise, yet flexible methodology, by customized, intuitive, rapid turn-around software tools, and by experienced scientific staff. Both elaborated mission architectures and spacecraft designs show a sophisticated work in all major aspects of conceptual design and meet the mission-specific and scientific objectives and requirements issued in the mission statement.

The continuously evolving SSDW methodology and tools were once more verified in creating a design environment for future space missions as well as educating capable system engineers. For the first time, the software tool COMICS was used to support the concurrent engineering design process. Future workshops will benefit from the SSDW 2010 findings and extend tool capabilities to further speed up the iterations of the design process with various levels of detail. As challenges and possibilities in human spaceflight are unlimited, there will be new exciting problems and scenarios to develop in future Space Station Design Workshops. Exploration mission scenarios to Moon, Mars, and further interplanetary destinations provide a great range of mission statements for the upcoming years.

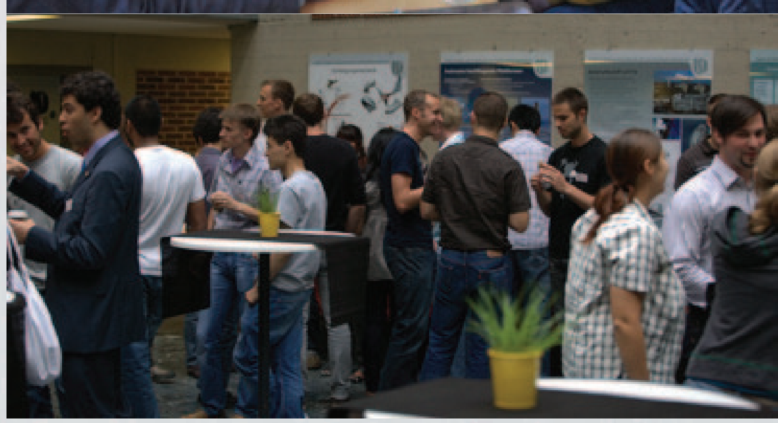
We want to thank all guests, participants, and supporters for their commitment and intense contributions that made this the SSDW 2010 such a success and valuable experience for all of us.

7. Impressions







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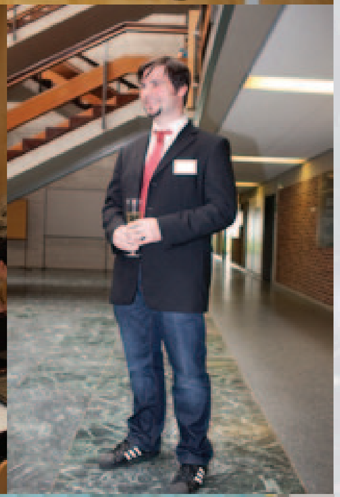


Space Station Design Workshop


SSDW
2010
EORED


TEAM RULES
John 95g
Sion 211 g
Water bottle: 1034 g

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