Comparing NASA and ESA Cost Estimating Methods for Human Missions to Mars

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ABSTRACT

To compare working methodologies between the cost engineering functions in NASA Marshall Space Flight Center (MSFC) and ESA European Space Research and Technology Centre (ESTEC), as well as to set-up cost engineering capabilities for future manned Mars projects and other studies which involve similar subsystem technologies in MSFC and ESTEC, a demonstration cost estimate exercise was organized.
This exercise was a direct way of enhancing not only cooperation between agencies but also both agencies commitment to credible cost analyses. Cost engineers in MSFC and ESTEC independently prepared life-cycle cost estimates for a reference human Mars project and subsequently compared the results and estimate methods in detail. As a non-sensitive, public domain reference case for human Mars projects, the "Mars Direct" concept was chosen.

In this paper the results of the exercise are shown; the differences and similarities in estimate methodologies, philosophies, and databases between MSFC and ESTEC, as well as the estimate results for the Mars Direct concept. The most significant differences are explained and possible estimate improvements identified. In addition, the Mars Direct plan and the extensive cost breakdown structure jointly set-up by MSFC and ESTEC for this concept are presented.
It was found that NASA applied estimate models mainly based on historic Apollo and Space Shuttle cost data, taking into account the changes in technology since then. ESA used models mostly based on European satellite and launcher cost data, taking into account the higher equipment and testing standards for human space flight.
Most of NASA's and ESA's estimates for the Mars Direct case are comparable, but there are some important, consistent differences in the estimates for:

- Large Structures and Thermal Control subsystems;
- System Level Management, Engineering, Product Assurance and Assembly, Integration and Test/Verification activities;
- Mission Control;
- Space Agency Program Level activities.

If human missions to Mars could be accomplished according to the Mars Direct plan, with its relatively short development schedule and accepting the higher risks associated with the very limited testing philosophy, the estimates show that a human Mars program could cost less than the Apollo moon program. However, the development cost estimates were found to be very sensitive to potential mass growth of the launcher and spacecraft elements.

While it was not explicitly addressed in this study, one way to enable a short development cycle and limited test scenario as assumed in the Mars Direct plan is by performing predecessor missions to mature the required technologies and processes prior to the human Mars mission. These

activities would require additional time and funding in advance of the human mission development.

INTRODUCTION

Scientific, public and political interest in organizing human missions to Mars is increasing, due to the recent findings of satellites and landers sent to the Red Planet by NASA and the European Space Agency. Mars appears to harbor vast amounts of water, which is currently trapped as sub-surface ice but may once have covered the planet with oceans and rivers. In the past, Mars may have nurtured life and there is a slim chance that simple organisms even manage to survive on the dusty, dry planet today.

As both NASA and ESA are now seriously studying human Mars missions, the need for accurate cost estimating tools and methodologies for large international projects, and in particular human Mars projects, is increasing in both agencies.

To compare working methodologies between the cost engineering functions in NASA Marshall Space Flight Center (MSFC) and ESA European Space Research and Technology Centre (ESTEC), as well as to set-up cost engineering capabilities for future manned Mars projects and other studies which involve similar subsystem technologies in MSFC and ESTEC, a demonstration cost estimate exercise was organized.
This exercise was a direct way of enhancing not only cooperation between agencies but also enhances both agencies commitment to credible cost analyses. Cost engineers in MSFC and ESTEC independently prepared life-cycle cost estimates for a reference human Mars project and subsequently compared the results and estimate methods in detail. As a non-sensitive, public domain reference case for human Mars projects, the "Mars Direct" concept was chosen.

It is important to emphasize that the focus of this exercise was not to endorse any type of architecture in any way. Mars Direct was chosen due to its non-sensitive, public domain nature and the fact that it incorporates basically all elements of a typical manned interplanetary mission. The quantified results presented in this paper are only used for the purpose of exposing findings in cost estimating practices.
There are studies currently being conducted both within ESA and NASA that analyze various architectures with a higher fidelity level and broader scope (i.e. including safety, operability, and performance). The results from these exercises might or might not concur with the estimate results quantified in this exercise. The study described in this paper is more concerned with the *hows* and *whys* of the estimate than with the resulting *what*.

The exercise described in this paper was conceived and completed prior to President Bush's announced vision for space exploration, and the presented architecture and costs are not related to that proposal. However, because the exploration initiative is likely to involve international participation, the knowledge gained concerning NASA and ESA cost estimating methods for such programs is relevant and timely.

MARS DIRECT

The Mars Direct plan is a low-cost approach for human missions to Mars, mainly invented and publicized by R.M. Zubrin, in which the mass to be launched is dramatically lowered by In-situ Resource Utilization.
A Mars Direct mission starts with two launches of an "Ares" heavy lift booster. The Ares launcher is a Space Shuttle-derived design, taking maximum advantage of existing hardware. It uses Shuttle Advanced Solid Rocket Boosters, composed of Advanced Solid Rocket Motors (development cancelled 1993), a Shuttle External Tank modified for handling

vertically-mounted payloads, a new engine boat tail structure, and a new Lox/LH2 third stage for trans-Mars injection of the payload.

The first booster delivers an unfueled and unmanned Earth Return Vehicle (ERV) to the Martian surface. Via basic chemical reactions and powered by a small nuclear reactor, the ERV fills itself with methane/oxygen bipropellant manufactured from the CO_2 in the atmosphere and a limited onboard supply of Hydrogen.

Once the propellant production is complete, a second launch delivers a Habitation vehicle with four crewmembers to the prepared site. During their transit to Mars, artificial gravity is achieved by rotating the Habitat and the upper stage of the Ares booster, which are connected to each other via a long cable. A gravity force 1/3 of that on Earth, similar to the conditions on Mars, is assumed to be sufficient to ensure optimal crew functionality right after landing.

On Mars the astronauts conduct extensive regional exploration for 1.5 years. After that, they launch themselves onboard the ERV capsule back to Earth using two rocket stages filled with the manufactured propellant. No artificial gravity is deemed necessary during the journey back. The ERV capsule directly re-enters the Earth's atmosphere to land on the surface.

No on-orbit assembly or orbital rendezvous is required in any phase of the mission. Moreover, the different mission elements are designed for a maximum of commonality. For instance, the same Lander Module system is used to land both the ERV and the Habitat on Mars.

THE COST BREAKDOWN STRUCTURE

The exercise was to cover a full life-cycle cost estimate, including:

- Flight equipment development and production;
- Ground infrastructure development and production;
- Flight and Ground Software development;
- Operations costs;
- All System Level costs, including those at Space Agency level.

For sufficiently accurate estimates and in order to provide enough detail for the estimate comparisons, it was deemed necessary to set up a cost breakdown to subsystem level for the main flight vehicles. For supporting ground elements on Earth and Mars, as well as for parts of the Ares launcher, it was decided to limit the breakdown to less detail.

Since public Mars Direct documentation did not provide the required level of detail, the authors of this paper set up a more exhaustive equipment and activities cost breakdown themselves, including necessary, assumptions on technical details such as mass, type of technology, redundancy etc. The final breakdown structure used for the cost estimates is shown in table 1.

COST ESTIMATES GROUND RULES AND PHILOSOPHY

To enable direct comparisons, the following ground rules have been accepted:

- All estimates in fixed 2002 economic conditions;
- One U.S. Dollar is assumed to equal one Euro;
- The total development phase from project initialization till the launch of the equipment for the first Mars mission is 8 years;
- Funding for the complete development phase is assured from the start of the project;
- Multiple NASA/ESA centers are assumed to be involved for major subsystems and spacecraft elements;
- All developments will adhere to normal NASA and ESA requirements for manned space systems;
- For the NASA estimate, all development is assumed to be done in the US;
- For the ESA estimate the project is considered to be mainly a European effort except for the Ares launcher,

which is based on US Space Shuttle technology.

- The cost estimates include all costs for government support and supervision; i.e. they are "full cost" estimates.
- In all total costs for major elements a 30% cost margin is included, due to the currently rather low technical, operational and organizational definition of the Mars Direct plan.

All estimates were conducted with the philosophy that ESA or NASA is going to lead the development and operation of the Mars Direct architecture. Hence, all methodologies, philosophies, and tools used in the estimates are the same as those that would be applied for a real case.

For all elements in the cost breakdown structure, both the initial non-recurrent costs for the development as well as the operational recurring costs have been estimated. For the spacecraft, the production and tests of the first (Proto) Flight Models are included in the development costs.

As for the Apollo project, critical equipment and spacecraft will likely be qualified in limited, non-operational missions before the first actual operational manned Mars landing. For the assessment of the total non-recurring development costs, a spacecraft flight test plan thus had to be defined. Upon request, R.M. Zubrin suggested the following low-cost approach:
First, an Ares would launch an unmanned Habitation module into low Earth orbit. Next, a Space Shuttle would bring a crew to the orbiting Habitat, in which they would live for some six months. The astronauts would briefly test the Habitat in microgravity conditions (in which it will operate for a few hours during the operational Mars missions) and then for an extended period as a tethered, spinning space station with artificial gravity. Apart from the Habitat, this first mission would flight-demonstrate the Ares launcher, except for Trans-Mars injection.
Next, an Ares would send an ERV and Lander module to Mars, demonstrating the complete Ares operation, Mars entry and landing systems, and the ERV fuel manufacturing system. If the ERV functions as specified, it will be used to return the first Mars crew to Earth. This crew would be launched onboard a Habitat/Lander at the next launch window. At the same time, another ERV/Lander would be send to Mars for the second crewed mission. It would also serve as a back-up for the first crew, in case problems arise with the first ERV.
In this flight qualification approach, the Habitat is only tested once in Earth orbit before operational use, and the ascend and return to Earth of the ERV is not tested at all. It is doubtful that NASA or ESA would follow such a rather risky approach under the current safety rules. However, to remain true to the Mars Direct approach it was nevertheless used as the baseline for the cost estimates.

COST ESTIMATE TOOLS

The NASA estimates are primarily based on the NASA-Air Force Cost Model (NAFCOM Ver. 2002) for hardware estimates and COMET/OCM (Nov. 2003 version) for support and operations estimates. Secondary estimating tools and methodologies consisted of:

- Cost Estimate Relationships (CERs) based on NAFCOM data;
- PRICE-H;
- SEER-H;
- Historical Analogies;
- Vendor Quotes.

Over 60% of the NASA estimates were performed using NAFCOM, which has two distinct estimating methodologies:

- Complexity Generators (a multi-variable model taking in account such factors as heritage, manufacturing methods, engineering management, year of technology and new design percentage)
- Conventional CERs (primarily weight based)

NAFCOM is the primary tool used for launch vehicle and satellite estimates within

NASA. The main benefit of NAFCOM for the Mars Direct exercise is the database populated with Gemini, Apollo, Skylab and Shuttle data. This data is directly related to manned spaceflight, dealing with similar requirements and systems as those to be used in the Mars Direct program. However, the data is relatively old and sometimes represents obsolete technology and methodologies. To solve this problem, the historic data was normalized to take into account the improvements in technology, development methods and production processes over time by use of "year of technology" factors.

COMET/OCM is one of the tools used by NASA to estimate operations and support for launch vehicle systems. This model was chosen on the basis of its availability.

ESA applied a mixture of in-house build CER tools based on Excel, as well as the commercially available tools PRICE-H and TRANSCOST.

ESA has much less data on large manned space systems than NASA and therefore mainly used tools based on unmanned spacecraft data, adding cost multiplication factors to take into account the higher equipment and testing standards for human space flight.

The benefit of the data used by ESA is that it is very recent, incorporating the actual, current state of the technology and the market. Recent stepwise "jumps" in technology and costs over time can be identified, which are sometimes not captured by the gradual "year of technology" normalization factors used in NAFCOM. However, the setting of proper "human-rating factors" to be applied to satellite CERs and the stretching of the tools beyond their normal application (for instance, because equipment masses in human spacecraft tend to be much higher than for unmanned satellites and probes) poses some challenges.

A main difference between NASA's and ESA's cost estimation tools is that those of NASA are based on actual, "as spent" cost data, while ESA mostly uses cost data that is contractually agreed before the actual start of the development.

Contract data does not show cost growth during the project's life-time as actual cost can. However, in ESA's case the cost and technical data is very coherent and organized during the proposal phase, but is hard to track after the signing of contracts. ESA feels that without careful analysis of which cost overruns are due to initial underestimation, and which are caused by stochastic events such as test accidents, technical changes, poor management etc., actual cost data should not be used. At present, ESA's cost information does not allow such analyses.

Another difference is that NASA's NAFCOM model generally uses more technical input parameters than ESA's models. This could imply more accurate estimates, reacting on multiple cost drivers. However, it was found that NAFCOM as well as models based on PRICE-H and SEER can allow for significant levels of subjectivity in the estimates and therefore need to be handled with care and by cost experts only.

ESTIMATES AND COMPARISONS

After initial estimates were performed separately at NASA and ESA, the results and methods were compared in detail.

Many significant differences were found to be caused by different interpretations of the equipment assumed to be included in certain subsystems, and differences in assumed Technology Readiness Levels. This shows that the cost estimates rely heavily on accurate information on the type and development status of spacecraft equipment, even though the estimates may only be performed at subsystem level. This was especially the case for items such as the surface Rovers and Field Science Equipment, for which only broad system level information was found and defined.

After refinement of the technical details and assumptions where necessary, many important estimate differences still remained. These were found to be caused by fundamental differences in the tools and reference data used by NASA and ESA.

Figure 1 shows the NASA and ESA main elements cost estimates for the total costs for all development (including test flights) plus the first operational Mars mission, for all main mission elements. Figure 2 shows the same for the second Mars mission, which includes only recurring costs. The main estimate differences and their primary causes are indicated in both figures, and described hereunder.

Large Structures and Thermal Control

On large structural elements (such as the spacecraft Main Structures, Heat Shields and Propellant Tanks) and on large Thermal Control subsystems, NASA's estimates for both development and recurring costs tend to be much higher than those of ESA (up to over 200% for development and up to over 300% for recurring). These differences have been accredited to the differences in the data used. NASA's approach was to base its cost off of historical Apollo and Shuttle data, then find ways to model effects of improved engineering, manufacturing, and general technology trends over time. ESA's approach was to rely on models based on recent data on ESA satellites, then find ways to model the differences in Platform, i.e. the quality and testing standard difference between unmanned and human space projects.

The two different strategies lead to surprisingly similar results for most hardware elements, but in the case of "big, dumb" structures and thermal control there seemed to be major discrepancies. NAFCOM (version 2004) will have some changes to its Structures CER to counteract some of these discrepancies. Though there can be a certain amount of convergence for these structures, the main underlying issue is that most data on large exploration missions and launch vehicles is 20 to 40 years old. The question is: are the trends that this data shows still valid?

Software

No software information could be found for Mars Direct. Without some form of independent variable (i.e. SLOC, functions points, objects) it is very difficult to estimate cost for software. ESA developed ROM estimates based on mission and spacecraft analogies, i.e. type of payload, complexity of the attitude control requirements etc., whereas NASA assumed that most software is embedded into the avionics CERs. This made a detailed comparison of avionics and software estimates impossible, but the total costs for these combined cost elements were relatively similar for the NASA and ESA estimates.

System level AIT/V and Project Office

NASA applies three levels of System Level Assembly, Integration and Test/Verification (AIT/V) and three levels of System Level Project Office (Management, System Engineering and Product Assurance). However, only those at Launcher Stage / Spacecraft level and Project (Prime Contractor) level are visible in the WBS. This is due to the way the data was normalized at the subsystem level in NAFCOM.

ESA accounts for System Level AIT/V and Project Office at each Launcher Stage / Spacecraft Module level, at Complete Spacecraft level and at Project level.

This difference made it often difficult to directly compare system level AIT/V and Project Office costs. Instead, rolled-up system level cost estimates had to be compared. In these comparisons, NASA's AIT/V and Project Office numbers were consistently and significantly higher than those of ESA. This could be due to the historical nature of each agency's database or it could account for different ways of doing business in NASA and ESA. This is difficult to conclude from this manned mission exercise alone; it would be interesting to see how these costs compare for a less complex, unmanned satellite or space probe.

Mission Control
A significant difference in estimate results was also found for Operations, specifically caused by the Mission Control cost estimate. NASA estimated these costs in analogy to current costs for NASA's Mission Control teams, assuming Mission Control personnel now working for the Space Shuttle and ISS programs will gradually start working for Mars Direct. This minimizes the training required, causing NASA's Mission Control estimates for the development phase and first mission to be the same as for subsequent missions.
ESA's estimate is a "bottom-up" approach, listing the envisioned ESA personnel required. ESA assumed that all Mission Control personnel will initially need to be newly trained, while for the second mission the training will be much more limited.
The result is that the estimates of NASA and ESA for the development phase and first operational mission are similar, but based on very different assumptions, while the ESA estimate for subsequent missions is much lower.
In effect, ESA's estimate represents a Mission Control approach that is much leaner and more automated than is currently the case at NASA. Whether such an optimistic approach will really materialize in the future remains to be seen.

Space Agency Program Level
The largest single discrepancy between the two estimates was found to be the difference in Space Agency Program Level costs. This cost is accounting for government Management and Engineering, Product Assurance and AIT/V control to the project.
NASA's estimate was derived by using historical NASA agency costs as a percentage of procurement for programs such as the Space Shuttle and Space Station. The estimate of ESA was based on a "bottom-up" approach, listing the required personnel typically required in ESA for the various tasks.
The main reason for the large difference lies in the history of the agencies; whereas NASA has always been heavily involved in high risk, high profile missions dealing with human lives, ESA primarily deals with smaller, unmanned systems.

OVERALL ESTIMATE RESULTS

Table 2 shows a summary of NASA's and ESA's estimate results for the Development phase (including test flights) and the first operational Mars mission. Table 3 shows the same for the second operational flight, involving only recurring spacecraft.

Comparison with R.M. Zubrin's numbers
In the early 1990's R.M. Zubrin published that the total development cost for Mars Direct were estimated to be around $20 billion, and each operational mission would cost about $2 billion. In today's economic conditions, that is equivalent to about $29 billion for development and close to $3 billion for each flight, i.e. the development and first mission would cost some $32 billion.
It is not clear whether R.M. Zubrin's numbers include a substantial project maturity cost margin (30% in the NASA and ESA estimates), but with or without margin, the development + first mission cost as published by R.M. Zubrin is somewhere between ESA's and NASA's estimate.
However, the recurring costs per flight are expected to be significantly higher than assumed by R.M. Zubrin, according to ESA's and especially NASA's estimates.

Comparison with Apollo
It is interesting to see how the Mars Direct estimates compare to Apollo historical program costs.
Table 4 shows a comparison at the total Program level, assuming 10 missions would be made over a period of 10 years for Mars Direct (for comparison purposes only, such a scheme is not proposed in the Mars Direct plan). The development of the Saturn 1 and Saturn 1B launchers is not included, as also the development of Space Shuttle equipment is not included in the Mars Direct estimates.
According to R.M. Zubrin's cost numbers, Mars Direct would cost about half that of Apollo, for a similar number of missions.

NASA's estimate indicates the costs would be about 80% of the Apollo costs, while according to ESA's estimate it would be close to 60%.
According to the estimates, under the hypotheses of Mars Direct, a human mission to Mars would thus probably cost less than the Apollo program, for the same number of operational missions.
However, this is only valid under the conditions that Mars Direct requires much less new technology development and ground and test flights than the Apollo program. Moreover, the Mars Direct scenario is very dependent on the process of producing propellant out of the Martian atmosphere, which may cost much more to develop than currently estimated. The basic chemistry of the process has been demonstrated on Earth, but making it work on Mars to automatically tank an Earth Return Vehicle may prove to be difficult.

COST GROWTH ANALYSIS

Due to the complexity and the magnitude of a program like the Mars Direct concept, a probabilistic estimate would be preferred to the deterministic results stated above. The deterministic estimates conducted by both ESA and NASA were conducted with the assumptions and spirit of R.M. Zubrin. A proper probabilistic cost analysis, encompassing all the cost impacts of uncertainties and risks associated with the system's technical and programmatic definition, is out of the scope of this paper. However, there is a need to show some quantitative sensitivity. A cost growth potential analysis was performed by NASA to illustrate how sensitive the Mars Direct concept cost is to:

- heritage assumptions;
- mass growth;
- testing methodology;
- and the cumulative effect of these three parameters.

In the original baseline estimate, a good deal of heritage was given to the Ares launcher due to the fact it is a Shuttle derivative. Credit was also given to the Habitat and ERV due to an assumed high level of commonality between various subsystems. A cost growth sensitivity analysis was performed for the case of less Shuttle heritage and less Habitat/ERV commonality.

Historically, mass estimates have increased dramatically for space systems. The Shuttle experienced a 25% mass growth through its development. Therefore, a potential mass growth was assumed for Mars Direct. Two runs were performed: the first assuming a 10% weight growth in the Ares launcher with a 20% growth in all other hardware items; the second assuming a 15% weight growth in the Ares launcher with a 30% growth in all other hardware items. These weight allowances are typical for a Phase A type of study.

The Mars Direct concept assumes a lean testing methodology. A sensitivity analysis was also performed to account for increased testing in hardware as well as extended LEO testing.

Table 6 shows a summary of NASA's cost growth results for the development phase (including test flights) and the first operational Mars mission, whereas Table 7 shows the results for the second operational mission.
The cumulative cost increasing effect of the parameters taken into account for the sensitivity analysis shows that the Development + First Operational Mission cost could go up by about 50%, indicating that this estimate is very sensitive to the considered parameters. However, the cost of the Second Operational Mission would increase only by less than 10% under the same assumptions. Mass growth accounts for most of these potential cost increases.

CONCLUSIONS

It was found that NASA applied estimate models mainly based on historic Apollo and Space Shuttle cost data, taking into account the changes in technology since then. ESA

used models mostly based on European satellite and launcher cost data, taking into account the higher equipment and testing standards for human space flight.
Most of NASA's and ESA's estimates for the Mars Direct case are comparable, but there are some important, consistent differences in the estimates for:

- Large Structures and Thermal Control subsystems;
- System Level Management, Engineering, Product Assurance and Assembly, Integration and Test/Verification activities;
- Mission Control;
- Space Agency Program Level activities.

If human missions to Mars could be accomplished according to the Mars Direct plan, with its relatively short development schedule and accepting the higher risks associated with the very limited testing philosophy, the estimates show that a human Mars program could cost less than the Apollo moon program. However, the development cost estimates were found to be very sensitive to potential mass growth of the launcher and spacecraft elements.

While it was not explicitly addressed in this study, one way to enable a short development cycle and limited test scenario as assumed in the Mars Direct plan is by performing predecessor missions to mature the required technologies and processes prior to the human Mars mission. These activities would require additional time and funding in advance of the human mission development.

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Table 1: Cost Breakdown Structure

Ares Heavy Launcher

- Advanced Solid Rocket Boosters
  - *Nozzle*
  - *TVC system*
  - *Case*
  - *Rear Skirt*
  - *Igniter*
  - *Thermal protection*
  - *Propellant grain*
  - *Electrical systems*
  - *Pyro Safety systems*
  - *Separation Rockets*
  - *Assembly, Integration and Tests*
  - *Management, Engineering and Product Assurance*
  - *Ground Support Equipment*
- Stage 1
  - *Modified External Tank*
    - *Structure*
    - *Hydrogen Tank*
    - *Oxygen Tank*
    - *Thermal Protection*
    - *Electrical systems*
    - *Pyro Safety systems*
    - *Separation Rockets*
    - *Thermal Control*
  - *Engine Pod*
    - *Space Shuttle Main Engines*
    - *Piping, valves, filters etc.*
    - *Structure and Thermal Protection*
  - *Assembly, Integration and Tests*
  - *Management, Engineering and Product Assurance*
- Stage 2
  - *Rocket Stage*
  - *Vehicle Equipment Bay (VEB)*
  - *Engine*
    - *Structure*
    - *Attitude Control System*
    - *Guidance, Navigation & Control*
    - *Telemetry*
    - *Data management system*
    - *Electrical systems*
    - *Pyro Safety systems*
    - *Thermal Control*
  - *VEB Assembly, Integration and Tests*
  - *VEB Management, Engineering and Product Assurance*
  - *VEB Ground Support Equipment*
- Interstage
- Payload Adapter
- Payload Fairing
- Onboard Software
- Launcher System Level Development
  - *Launcher Development Management,*
- Direct Operations Cost
  - *Transportation of Launcher Elements*
  - *Pre-Mission*
  - *Mission*
  - *Public Damage Insurance*
  - *Propellants and Pressurants*
    - *Stage 1 Liquid Hydrogen propellant*
    - *Stage 1 Liquid Oxygen propellant*
    - *Stage 2 Liquid Hydrogen propellant*
    - *Stage 2 Liquid Oxygen propellant*
- Indirect Operations Cost
  - *Programme Administration & Quality Control*
  - *Ground Segment Maintenance and Improvement*
  - *Taxes*
- Flight Test + Analysis
- Design Maturity Cost Margin

Lander Module (for ERV and Hab)

- Lander Subsystems & S/W
  - *Landing Engines + Tanks + Piping*
  - *Structure (including Landing Leg Structure)*
  - *Electrical Systems*
  - *Thermal Control*
  - *Heat Shield Separation Pyrotechnics*
  - *Landing Leg Deployment Mechanisms*
  - *Onboard Software*
- Propellants and Pressurants
  - *Liquid Hydrogen propellant*
  - *Liquid Oxygen propellant*
- Mars Aerobrake Heat Shield
- Lander Module System Level
  - *Lander Integration & Tests*
  - *Lander Management, Engineering and PA*
  - *Lander Ground Support Equipment*
- Design Maturity Cost Margin

Earth Return Vehicle

- Earth Reentry & Habitation Capsule
  - *Environmental Control and Life Support System*
  - *Crew Facilities Furniture and Interior*
  - *Guidance, Navigation and Control*
  - *Reaction Control System*
  - *Onboard Data Handling System*
  - *TT&C with HGA*
  - *Solar Arrays*
  - *Electrical Power Distribution & Control*
  - *Harness*
  - *Batteries*
  - *Structure*
  - *Thermal Control*
    - *Radiator*
    - *MLI, Heaters, Pumps etc.*
  - *Mechanisms*
    - *HGA Rotation and Pointing Mechanism*
    - *Solar Array Drive Mechanism*
  - *Aeroshell for Earth reentry*
  - *Earth Parachute System (incl. canisters etc.)*
  - *Onboard Software*
  - *Assembly, Integration and Tests*
  - *Management, Engineering and Product Assurance*
  - *Ground Support Equipment*
- Mars Ascent Stage 2
  - *Fuel Tank*
  - *Oxidiser Tank*
  - *Rocket Engines*
  - *Nozzle*
  - *Piping, valves, filters etc.*
  - *TVC system*
  - *Structure*
  - *Electrical systems*
  - *Thermal Control*
  - *Separation Pyrotechnics*
  - *Assembly, Integration and Tests*
  - *Management, Engineering and Product Assurance*
  - *Ground Support Equipment*
- Mars Ascent Stage 1
  - *Fuel Tank*
  - *Oxidiser Tank*
  - *Rocket Engines*
  - *Nozzle*
  - *Piping, valves, filters etc.*
  - *TVC system*
  - *Structure*
  - *Electrical systems*
  - *Thermal Control*
  - *Separation Pyrotechnics*
  - *Assembly, Integration and Tests*
  - *Management, Engineering and Product Assurance*
  - *Ground Support Equipment*
- Automated Propellant Production Unit
- EVA Suits
- Provisions
- Hydrogen feedstock (for propellant production)
- ERV System Level
  - *ERV Integration & Tests*
  - *ERV Management, Engineering and PA*
  - *ERV Development Ground Support Equipment*
- Design Maturity Cost Margin

Mars Habitation Module

- *Environmental Control and Life Support System*
- *Crew Facilities Furniture and Interior*
- *Laboratory Equipment*
- *Guidance, Navigation and Control*
- *Reaction Control System*
- *Onboard Data Handling System*
- *TT&C with HGA*
- *Solar Arrays*
- *Electrical Power Distribution & Control*
- *Harness*
- *Batteries*
- *Structure*
- *Thermal Control*
  - *Radiator*
  - *MLI, Heaters, Pumps etc.*
- *Mechanisms*
  - *HGA Rotation and Pointing Mechanism*
  - *Solar Array Drive Mechanism*
  - *Tether System*
    - *Tether deployment mechanism*
    - *Tether*
- *Onboard Software*
- EVA Suits
- Provisions
- Hab System Level
  - *Hab Integration & Tests*
  - *Hab Management, Engineering and PA*
  - *Hab Ground Support Equipment*
- Design Maturity Cost Margin

Mars Surface Elements

- ERV SP-100-like Nuclear Power Generator
- ERV Light Truck, methane/oxygen driven
- ERV Radio Landing Beacon
- HLV Open Rover
- HLV Pressurised Rover
- HLV Field Science Equipment
- Design Maturity Cost Margin

Earth Ground Infrastructure

- Launcher Ground Infrastructure
  - *LaunchPad*
  - *Launcher Processing Facility*
  - *Launch Control Facility*
  - *Ground Support Equipment*
  - *Ground Facilities Software*
- Mars Vehicles Ground Infrastructure
  - *Vehicles Processing Facility*
  - *ERV Processing Ground Support Equipment*
  - *HLV Processing Ground Support Equipment*
  - *Lander Processing Ground Support Equipment*
- Mission Control Facility
- Ground Stations
- Crew Training Facility
  - *ERV Flight Simulator*
  - *HLV Flight Simulator*
  - *Mars EVA Simulator*
- Ground Facilities Management & Engineering
- Design Maturity Cost Margin

Prime Contractor Programme Level

- Prime Contractor Program Level Management
- Prime Contractor Program Level Engineering
- Prime Contractor Program Level Product Assurance
- Prime Contractor Program Level AIT
- Design Maturity Cost Margin

Space Agency Programme Level

- Space Agency Program Level Management
- Space Agency Program Level Engineering
- Space Agency Program Level Product Assurance
- Space Agency Program Level AIT
- Design Maturity Cost Margin

Operations

- Mission Control Unmanned Mission
- Mission Control Manned Mission
- Mission Control Training
- Ground Stations
- Crews
- Recovery, Search and Rescue
- Design Maturity Cost Margin

Figure 1: Development + first operational mission costs

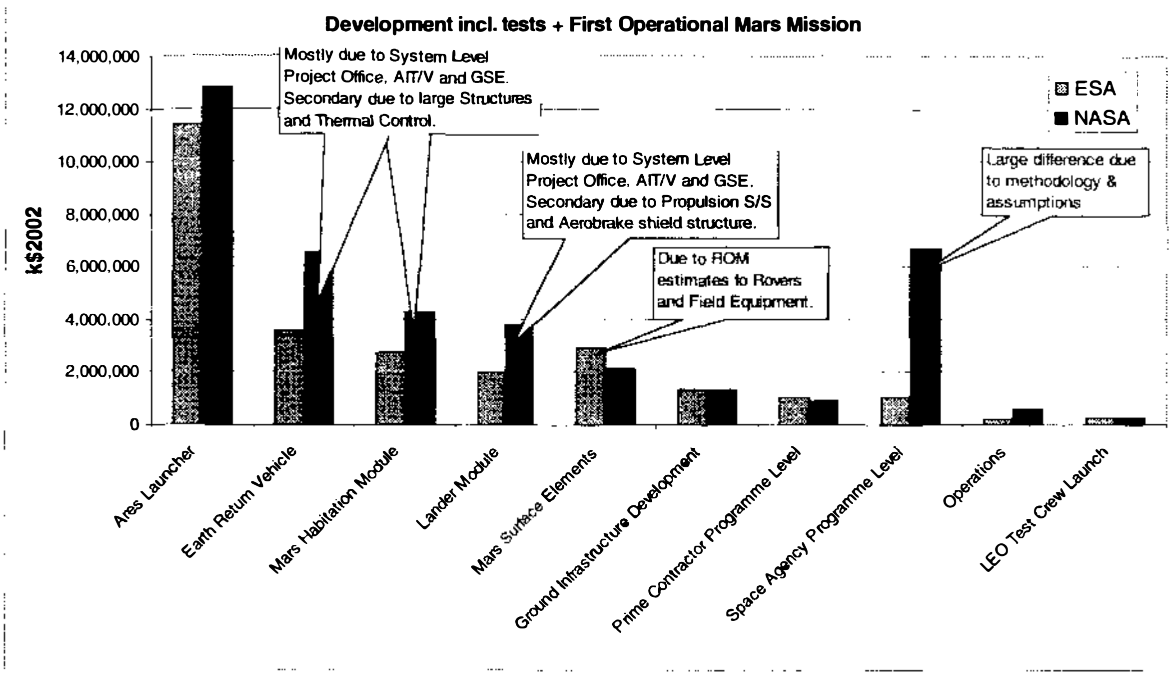
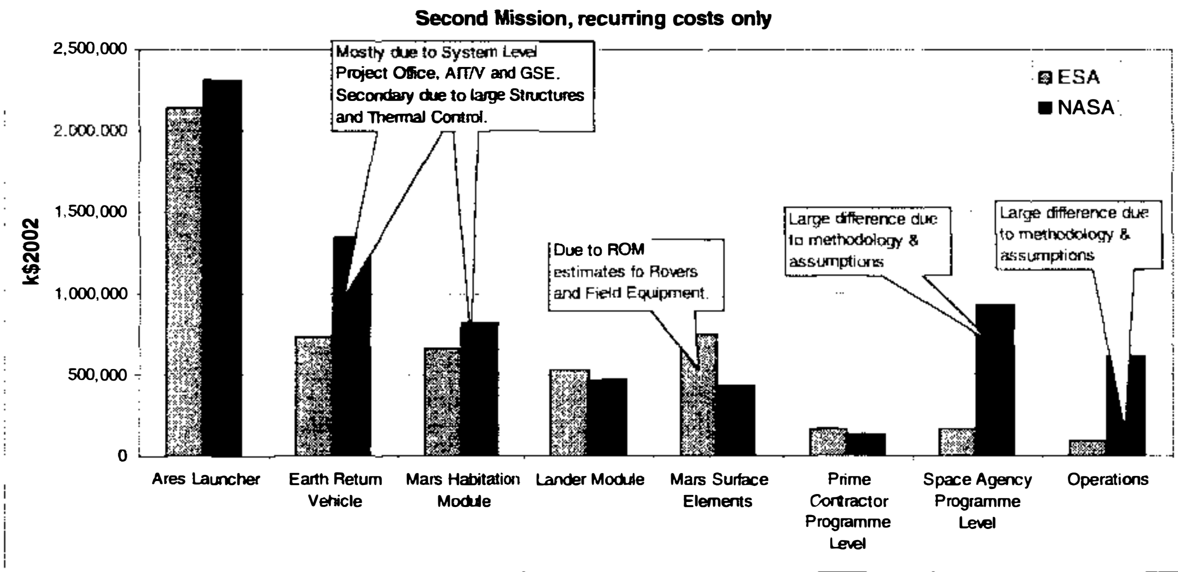


Figure 2: Second operational mission costs



These numbers are presented only for the purpose of exposing findings in cost estimating practices. Whether the cost estimates are realistic is directly linked with the credibility of the Mars Direct assumptions from a technical, programmatics and safety point of view. A study on this was not part of the exercise described in this paper.

Table 2: Estimates for Development phase + First Operational Mission

Element	Number of Elements	ESA Cost Estimate [k$2002]	NASA Cost Estimate [k$2002]
Ares Launcher	3	11,394,000	12,808,000
Earth Return Vehicle	1	3,554,000	6,554,000
Mars Habitation Module	2	2,744,000	4,290,000
Lander Module	2	1,986,000	3,804,000
Mars Surface Elements	1	2,928,000	2,095,000
Ground Infrastructure Development	1	1,353,000	1,355,000
Prime Contractor Programme Level		1,061,000	933,000
Space Agency Programme Level		1,058,000	6,670,000
Operations		217,000	616,000
LEO Test Crew Launch	1	300,000	300,000
Total		**26,595,000**	**39,425,000**

Table 3: Estimates for the Second Operational Mission

Element	Number of Elements	ESA Cost Estimate [k$2002]	NASA Cost Estimate [k$2002]
Ares Launcher	2	2,140,000	2,314,000
Earth Return Vehicle	1	729,000	1,348,000
Mars Habitation Module	1	659,000	816,000
Lander Module	2	530,000	466,000
Mars Surface Elements	1	745,000	430,000
Prime Contractor Programme Level		166,000	130,000
Space Agency Programme Level		165,000	927,000
Operations		95,000	616,000
Total		**5,229,000**	**7,047,000**
% of Development + First Mission Cost		20%	18%

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Table 4: Program level cost comparison with Apollo

Total Program cost including 10 missions over 10 years, in Billion$2002		
Apollo Program excl. Saturn 1 and 1 B development	120	
Mars Direct Zubrin	55	without cost margins
Mars Direct (NASA)	98	
Mars Direct (ESA)	74	

Table 5: Elements cost comparison with Apollo

Apollo and Mars Direct Elements Cost comparisons	Development [M$2002]	Recurrent Cost [M$2002]
Saturn V launcher excl. Saturn 1 and 1 B development	42,000	2,400
of which for Pre-flight operations		163
Mars Direct ARES launcher (NASA)	10,500	1,200
of which for Pre-flight operations		95
Mars Direct ARES launcher (ESA)	9,300	1,100
of which for Pre-flight operations		213
Apollo Command + Service Module	15,000	400
Mars Direct ERV Capsule (NASA)	1,440	340
Mars Direct ERV Capsule (ESA)	1,240	300
Mars Direct Habitation Module (NASA)	3,470	820
Mars Direct Habitation Module (ESA)	2,100	660
Apollo Lunar Module	7,500	130
Mars Direct Lander Module (NASA)	3,570	230
Mars Direct Lander Module (ESA)	1,720	260
Lunar Rover	170	?
Mars Direct Open Rover (NASA)	180	28
Mars Direct Open Rover (ESA)	270	65
ALSEP experiments	180	130
Mars Direct Field Science Equipment (NASA)	12	5
Mars Direct Field Science Equipment (ESA)	320	110

These numbers are presented only for the purpose of exposing findings in cost estimating practices. Whether the cost estimates are realistic is directly linked with the credibility of the Mars Direct assumptions from a technical, programmatics and safety point of view. A study on this was not part of the exercise described in this paper.

Table 6: Potential cost growth for Development phase + First Operational Mission.

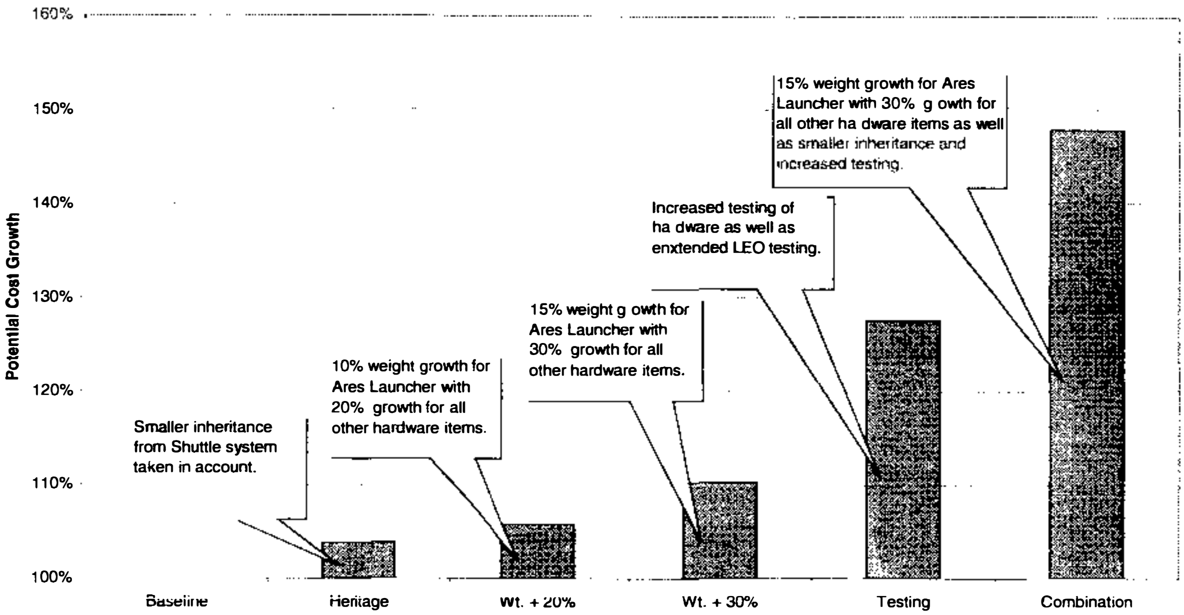
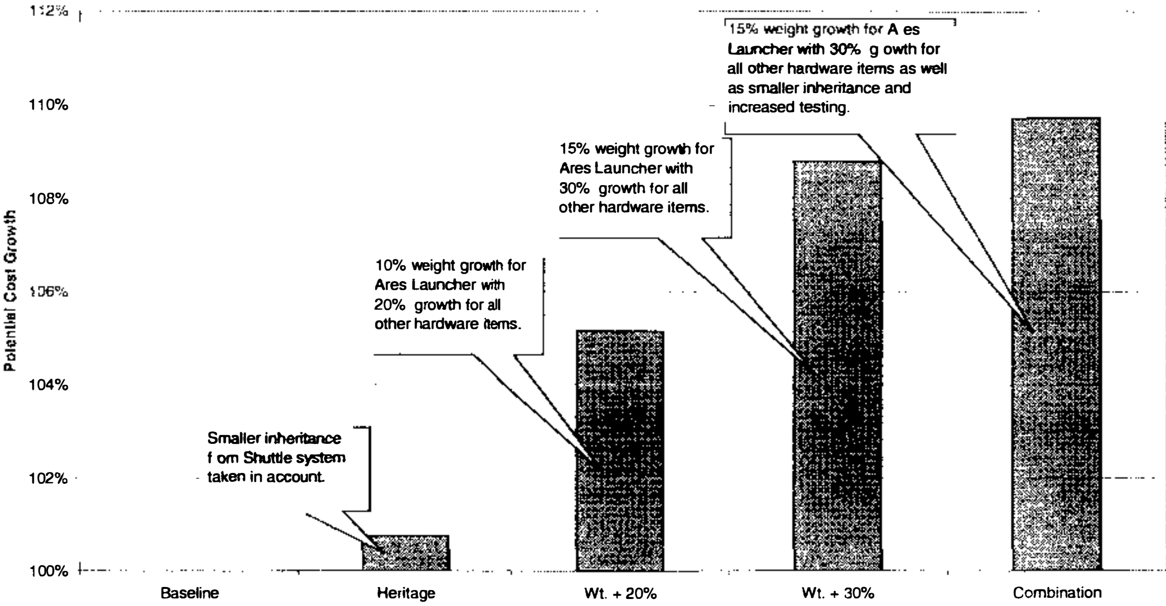


Table 7: Potential cost growth for Second, Operational Mission.



These values are presented only for the purpose of exposing findings in cost estimating practices. Whether the cost estimates are realistic is directly linked with the credibility of the baseline Mars Direct assumptions from a technical, programmatics and safety point of view. A study on this was not part of the exercise described in this paper.

Comparing NASA and ESA Cost Estimating Methods for Human Missions to Mars.

Scientific, public and political interest in organising human missions to Mars is increasing, due to the recent findings of satellites and landers sent to the red planet by NASA and the European Space Agency. Mars appears to harbour vast amounts of water, which is currently trapped as sub-surface ice but may once have covered the planet with oceans and rivers. In the past, Mars may have nurtured life and there is a slim chance that simple organisms even manage to survive on the dusty, dry planet today.
As both NASA and ESA are now seriously studying human Mars missions, the need for accurate cost estimating tools and methodologies for large international projects, and in particular human Mars projects, is increasing in both agencies.

To compare working methodologies between the cost engineering functions in NASA Marshall Space Flight Center (MSFC) and ESA European Space Research and Technology Centre (ESTEC), as well as to set-up cost engineering capabilities for future manned Mars projects and other studies which involve similar subsystem technologies in MSFC and ESTEC, a demonstration cost estimate exercise was organised. This exercise was a direct way of enhancing not only cooperation between agencies but also enhances both agencies commitment to credible cost analyses. Cost engineers in MSFC and ESTEC independently prepared life-cycle cost estimates for a reference human Mars project and subsequently compared the results and estimate methods in detail. As a non-sensitive, public domain reference case for realistic human Mars projects, the "Mars Direct" concept was chosen.

In this paper and presentation the results of the exercise are shown; the differences and similarities in estimate methodologies, philosophies, and databases between MSFC and ESTEC, as well as the estimate results for the Mars Direct concept. The most significant differences are explained and possible estimate improvements identified. In addition, the Mars Direct plan and the extensive cost breakdown structure jointly set-up by MSFC and ESTEC for this concept are presented.

Speaker biographies

Charles Hunt received his BS degree in Industrial Engineering from Tennessee Technological University prior to employment with NASA MSFC's Engineering Cost Office (ECO). Currently, he is supporting various NASA technology, engine, and space architecture projects and studies. Mr. Hunt is an active member in ECO's effort to hone, enhance, and develop cost credibility through parametric modelling. He is the designer of the Engineering Cost Office Liquid Engine Model (ECOLEM), a macro-level parametric regression-based engine model used for engine cost analysis at an early concept stage. He is also a member of the International Society of Parametric Analysts (ISPA) and the Society of Cost Estimating and Analysis (SCEA).

Michel van Pelt received his MS degree in Aerospace Engineering at Delft Technical University before joining ESA ESTEC's Cost Engineering Section in 1998. As a cost engineer, he is supporting various ESA Earth observation, satellite navigation, planetary probe and launcher projects during various phases. He regularly fills the cost engineering seat for the conceptual studies performed in ESTEC's Concurrent

Design Facility, and recently acted as System Engineer for such a study as well. In addition, he is the designer of the RACE model, and internal tool for fast cost estimates during the early phases of a conceptual design study. He is a member of the International Society of Parametric Analysts (ISPA) and Space Systems Cost Analysis Group (SSCAG). In his spare time he writes and edits articles for Dutch space magazines.

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