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Basic Research and Technologies for Two-Stage-to-Orbit Vehicles

Final Report of the Collaborative Research Centres 253, 255 and 259

Edited by
Dieter Jacob, Gottfried Sachs
and Siegfried Wagner

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1 Introduction

In 1989 the Deutsche Forschungsgemeinschaft established three Collaborative Research Centres concerned with hypersonic vehicles at the Rheinisch-Westfälische Technische Hochschule Aachen, the Technische Universität München and the Universität Stuttgart. The final report presents a selection of recent research results and an overview of the activities and the organization of the network which evolved during the past fifteen years.

The research was focused on basic aspects of future reusable space transportation systems and covered the areas of overall design, aerodynamics, thermodynamics, flight dynamics, propulsion, materials, and structures. The underlying configuration which served as a guideline for detailed research consisted of a two-stage-to-orbit vehicle with the ability to start horizontally. The first stage had an airbreathing propulsion, the second stage a rocket propulsion. Both stages were designed to return to earth and land horizontally on adequate airports.

A major part of the research dealt with experimental and numerical aerodynamic topics ranging from low-speed to hypersonic flow past the external configuration and through inlet and nozzle. The low-speed flow past the lower stage was investigated for a large range of Reynolds numbers in different wind tunnels including a test period at high Reynolds numbers with a large model in the German-Dutch Wind Tunnel (DNW). The studies at high Mach numbers included the very complex interference between the lower stage and the upper stage during the initial flight and during stage separation and the aero-thermodynamic heating. In all cases experimental and numerical approaches were employed.

Another major part of the research was concerned with flight mechanics. One aspect was trajectory optimization which was dealt with in cooperation of mathematicians and engineers. A further aspect relates to stability, control and flying qualities, the treatment of which includes a collaboration with the NASA Dryden Flight Research Center using their unique simulation and flight test facilities. Moreover, the flight dynamics of the separation manoeuvre was subject of the research activities, employing also wind-tunnel tests at the Institute of Theoretical and Applied Mechanics of the Russian Academy of Sciences in Novosibirsk.

The re-entry phase was investigated both experimentally and numerically. Plasma wind tunnels were built to generate high-enthalpy plasma flows and to investigate the interactions with heat shield materials. The experimental investigation was accompanied by numerical simulation of the flow field inside the ground test facility and around a space vehicle re-entering the Earth's atmosphere. New aero-thermodynamic models enabled a successful post-flight analysis of the MIRKA re-entry. Re-entry experiments for in-flight investigation of plasma flow and material response were successfully flown on capsules such as EXPRESS and MIRKA; others are about to be flown on missions such as EXPERT.

For the overall design investigations a propulsion simulation model including the jet and ramjet modes was developed. The efficiency of supersonic and hypersonic airbreathing propulsion depends strongly on the efficiency of inlets and nozzles. Therefore, several numerical and experimental projects dealt with these components of future space planes. In other projects methods to reach stable supersonic combustion were investigated.

Structural research and development was predominantly coupled to the needs for high-temperature resistant structures for space vehicles. During the re-entry phase from orbit to earth temperatures of more than $1600\,^{\circ}$C are reached. For the application in a thermal protection system (TPS) and also as a material for the use in hot structures, like control surfaces, a new type of ceramic matrix composite was developed on the basis of carbon fibres that is called C/C-SiC. The technology of thermal protection systems reached a maturity that allowed a flight experiment with a representative TPS structure on the surface of a Russian FOTON research capsule that was scheduled for a micro-gravity mission in orbit with subsequent re-entry to earth.

This final report presents some of the most recent results obtained in the disciplines required for the design of future space planes. In additional chapters the unique model established for the cooperation of three cooperative research centres at different universities is described and analyzed.

December 2003

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2 Network Organization of Collaborative Research Centres for Scientific Efficiency Enhancement

Dieter Jacob, Gottfried Sachs, and Siegfried Wagner

2.1 Introduction

Three initiatives for Collaborative Research Centres of the Deutsche Forschungsgemeinschaft evolved in the late eighties, at the Rheinisch-Westfälische Technische Hochschule Aachen, the Technische Universität München and the Universität Stuttgart. After exploratory and advisory talks with the Deutsche Forschungsgemeinschaft, principles for research planning and cooperation were established, resulting in a concept for a framework of research and organization of the initiatives. This concept is based on the following elements:

- Each initiative for a Collaborative Research Centre proposes its own, independent research programme which can be realized even if another initiative fails. Each research programme has an own concentration on points of emphasis as part of the overall theme.
- The research programmes of the initiatives should be complementary.
- The complementing of the research programmes must not confine the decision such that approval of all Collaborative Research Centres becomes imperative.

After successful passing the review procedure, the following three Collaborative Research Centres have been established by the Deutsche Forschungsgemeinschaft in 1989:

- Collaborative Research Centre 253 "Fundamentals of Space Plane Design" at the Rheinisch-Westfälische Technische Hochschule Aachen,
- Collaborative Research Centre 255 "Transatmospheric Flight Systems" at the Technische Universität München,
- Collaborative Research Centre 259 "High-Temperature Problems of Reusable Space Transportation Systems" at the Universität Stuttgart.

2.2 Organization of Collaboration

For organizing the collaboration of the three Collaborative Research Centres, a Compound Network was established. It has the following structure:

1. Steering Committee
A Steering Committee consisting of the Speakers of the three Collaborative Research Centres was established. The Steering Committee meets several times a year and is responsible for the following topics:
   - strategic planning for future research programmes;
   - coordination of main research activities between the Collaborative Research Centres;
   - laying down of principles and goals of the collaboration among the Research Centres as well as with external partners from research institutions and industry;
   - planning of joint activities for the presentation of research results;
   - planning of joint education activities for students as well as engineers and scientists.
2. The Collaborative Research Centres exchange their research results and inform each other about ongoing and planned work.
3. Data banks concerning the air and combustion gases will be jointly generated.
4. The Collaborative Research Centres will inform each other about test configurations and models and use the same or similar models.
5. The Collaborative Research Centres present research results in a joint manner at national and international scientific meetings, conferences, etc.

2.3 Efficiency Enhancement in Research

The Compound Network of the Collaborative Research Centres enabled an enhancement of efficiency in research. Basically, resources and competences of the three Collaborative Research Centres could be brought together to yield synergy effects and improvement of research efforts.

At the working level, advantages resulted from mutual contacts and visits as well as from the exchange of scientists. Furthermore, working groups could be established to address specific subjects (numerical methods, measurement techniques, etc.). Other joint activities relate to the development of computer codes and software or verification of numerical results.

Contacts and cooperations with external scientist groups were also promoted by the Compound Network. This concerns university institutes and research establishments as well as industry companies.

A further enhancement of the research efficiency relates to large research facilities which may not be accessible for a single Collaborative Research Centre. As an example, the three Collaborative Research Centres jointly conducted a large experimental project at the German-Dutch Wind Tunnel.

The establishment of the Compound Network led to an increase in competence. Thus, the position of the three Collaborative Research Centres as cooperation partners of research and industry was strengthened. This resulted in a further advantage since industry expressed their willingness for a continuous support concerning computational techniques, data, and experimental facilities. Another result was the participation of the Collaborative Research Centres in national and international research programmes, like the German Programmes TETRA "Technologien für zukünftige Raumtransportsysteme" and ASTRA "Ausgewählte Systeme und Technologien für zukünftige Raumtransportsystem-Anwendungen" as well as the European Programmes FESTIP "Future European Space Transportation Investigations Programme" and FLPP "Future Launcher Preparatory Programme" (planned). Moreover, working groups with representatives from research and industry were established. In addition, scientists conducted flight experiments related to aero-thermodynamics and materials on the re-entry missions EXPRESS, MIRKA and IRDT. Surface protection layer development for thermal protection system materials of future reusable vehicles is funded within a programme by the State of Baden-Württemberg.

2.4 Efficiency Enhancement in Teaching and Education

The establishment of the Compound Network also enabled an enhancement of the efficiency in teaching and education. This is of particular importance for hypersonics because of the backlog demand in this field.

A very effective means were the Space Courses which were jointly held by the three Collaborative Research Centres at the Rheinisch-Westfälische Technische Hochschule Aachen, the Technische Universität München, and the Universität Stuttgart. The Space Courses which had a duration of two or three weeks were offered to graduate students as well as to participants from research establishments, industry companies, and administration agencies. There was great interest in the Space Courses not only from Germany but also from other countries.

There are manifold other activities of the Compound Network supporting and enhancing the efficiency in teaching and education. Joint seminars and workshops were conducted, yielding an exchange of experiences and results between members of the Collaborative Research Centres. Moreover, working groups supported the education of students and young scientists. A further possibility concerns the participation of members of a Collaborative Research Centre in doctoral theses of another one.

Further activities enhancing the efficiency in education relate to joint research programmes, yielding unique experience for the involved young scientists. This concerns the already mentioned experimental programme at the German-Dutch Wind Tunnel. Another activity was a joint wind tunnel test programme at the Institute of Theoretical and Applied Mechanics of the Russian Academy of Sciences, Siberian Branch in Novosibirsk, Russia, offering experience on cooperation with scientists from abroad.

2.5 Internationalization

The competence which the Collaborative Research Centres have attained led to a greater visibility, both nationally and internationally. The Compound Network has gained recognition in various countries. Multiple invitations came from Europe, the USA, and Japan to give an overview of the German university research on hypersonics. Furthermore, the joint arrangement of workshops with participants from various countries contributed to the international recognition of the Compound Network. This is also true for the joint organization of sessions in international scientific congresses in Germany as well as in other countries.

Many research activities developed on an international basis. There was a very successful collaboration with the NASA Dryden Flight Research Center in Edwards, California, over many years, leading to the utilization of flight test and simulation facilities which are unique in the world. Another international cooperation effort was the already mentioned wind tunnel test programme of the Institute of Theoretical and Applied Mechanics in Novosibirsk. The participation in the European programmes FESTIP and FLPP is another example. There are many other research activities with scientists from other countries, contributing to the international visibility of the Compound Network.

The international visibility of the Research Network also holds for the teaching and education activities. There were students from other countries, purposefully approaching the Collaborative Research Centres for diploma theses. Other successful activities concern research stays of young scientists at the Collaborative Research Centres abroad and vice versa. The great interest of people from other countries in the Space Courses is also evidence of the international visibility.

A most remarkable activity which gained both national and international recognition is the exhibition “The New Way into Space – Space Transporters of the Next Generation" of the Deutsche Forschungsgemeinschaft. This exhibition which is concerned with the research of the Compound Network was displayed with great success in various cities in Germany, like Bonn, Stuttgart, München, Aachen, Berlin, and others. An international version of the exhibition was shown in several countries within the scope of the Concerted Action "Joint Initiative for the Promotion of Study, Research, and Training in Germany" of the German Federal Ministry of Education and Research, the States of the Federal Republic of Germany, and other institutions. The fact that the Deutsche Forschungsgemeinschaft selected the subject of the Compound Network for these exhibitions is evidence of its successful research work.

2.6 Final Remarks

The experience which the involved scientists gained with the Compound Network is very positive. It strengthened their activities in research and teaching. This also holds for their relation and cooperation with external partners from research institutions and industry, both nationally and internationally. To sum up, it can be said that the Compound Network of the three Collaborative Research Centres 253, 255, and 259 turned out as an appropriate means to efficiently organize the research work for a subject which is sufficiently broad.

Evidence of a Compound Network as an efficient possibility of organizing research in a greater framework is also due to the statement of the German Wissenschaftsrat on the development of the programme for the Collaborative Research Centres from 23 January 1998. Here, the Compound Network of the three Collaborative Research Centres 253, 255, and 259 is recognized and a stronger networking of thematically related Collaborative Research Centres is also recommended for the future.

3 Overall Design Aspects

3.1 Conceptual Design of Winged Reusable Two-Stage-to-Orbit Space Transport Systems

Stefan Lentz, Mirko Hornung [*], and Werner Staudacher

3.1.1 Background and Introduction

During the Space Race – from the fifties to the eighties – money was almost irrelevant to bring anything alive, which went to orbit and beyond. Those days could be characterized as paradise for rocket scientists, engineers, conceptualists and lots of men with brilliant or weird ideas on both sides of the iron curtain. Some concepts and ideas came to the drawing board and entered life (Apollo and Space Shuttle, Saljut, Buran, Mir etc.) and some – or most of them – went into the drawer or just became paper planes. Eventually, the curtain dropped and space flight slithered into a crisis; money became a factor which could not be disregarded, economical aspects gained in importance and as a consequence lots of concepts died. The cold war and national prestige driven high tech aerospace machinery began to stutter.

The American partly reusable Space Transportation System STS or "Space Shuttle" was still suffering from the Challenger catastrophe and was just too expensive to place satellites into orbit with human assistance. The two major expendable rocket systems Delta and Titan – which were derivatives from intercontinental ballistic missiles concepts – were unreliable and ineffective for a rising demand in commercial payloads. Russian launchers still were not or only hardly accessible. It was the age of the European Ariane rocket which was especially designed to place (commercial) payloads into orbit and, in addition, due to the lack of other competitors. Although Ariane IV was very versatile and

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successful, it was still an expendable system and thus expensive. In the fading of 20th century it was realized, that exorbitant costs for access to space need to be reduced drastically to give further rise of attractiveness for space transportation and exploitation. Auspicious and ambitious fully reusable concepts like the American National Aerospace Plane, the German Sänger or the British HOTOL emerged from this proposition. National prestige and still a kind of cold-war-thinking led to excessive requirements resulting in insuperable technical and financial obstacles. However these concepts showed the right trend for long-term future launchers. Cost reduction strategies for present expendable rockets led to increasing and multiple payload capabilities and heavier and bulkier systems such as Ariane V, Delta IV and Atlas V, which share a hard-fought market, especially since Russian low cost carriers are available [1].

Today the expense factor is a major and global approved criterion for the development of future space transportation systems. A cost-efficient and reliable launcher is vital to win the leading market position. After initial success in the commercial space market, Europeans need to find alternatives for the cost-intensive expendable systems to maintain or regain their position in the global market. The logical and in the long term only reasonable consequence is the design of reusable space transportation systems, which keep down non recurring costs (design and development) as well as recurring costs (production and operations) and finally allow "aircraft-like" operations. To achieve these requirements several strategies and philosophies exist [2–4].

At the present time, design and development of reusable space transportation systems is still in a conceptual phase. The state-of-the-art is rather seen as prospect and can be classified as highly evolutionary. The continuous quest for solutions and the exigency of an evolutionary process are reflected in a multitude of more ore less favourable design alternatives and concepts, preferences depending on strategies and experiences from the past. An example for a widespread investigation is the FESTIP (Future European Space Transportation Investigations Programme) system study of ESA, in which 7 system concept families with 19 variants of space launchers were analyzed. This system study can be seen as a paradigmatic characterization from an European view, since American concepts were also incorporated. On the other side of the Atlantic several American studies exist such as the SLI (Space Launch Initiative) of NASA [3–6].

A major problem is the justification of Reusable Launch Systems (RLV). Current number of world wide launches is below 100 per year but only few of them are performed by at least partially reusable Space Shuttle. This market is shared among the major competitors as the USA, Europe, Russia, Japan and (soon) China. Even the United States' share of the market (including commercial and governmental launches) is too small to overcome the break even point for the development of a fully reusable launch vehicle [7].