25th International Electric Propulsion Conference, August 24-28, 1997, Cleveland, Ohio

1 kW Hydrazine Arcjet System Development

Martin Riehle, Helmut L. Kurtz and Monika Auweter-Kurtz
Institut für Raumfahrtsysteme, Universität Stuttgart
Pfaffenwaldring 31, D-70550 Stuttgart, Germany
phone: ++49-711-685-2394. fax: ++49-711-685-3596
email: ep@.irs.uni-stuttgart.de http://www.irs.uni-stuttgart.de

York E. Viertel
Daimler-Benz Aerospace AG, Space Infrastructure Division
Hünefeldstraße 1-5, D-28361 Bremen, Germany

ABSTRACT

*In the frame of the contracts of the German space agency **DARA**, a co-operative project between the Daimler-Benz Aerospace **(DASA)** and the Institute for Space Systems **(IRS)** was initiated in 1990 to develop a hydrazine arcjet thruster system in the power range of 1-2 kWe. Firstly aimed for application for NSSK, the goals has then been modified to a 1 kW system in the second phase of this contract, in order to fit the requirements for orbit adjustment of small telecommunication satellites. The hydrazine arcjet system is now in the state of an improved engineering model and currently readied to undergo system level tests and qualification procedures. The paper gives an overview of the project and presents the current status with special emphasis to the work packages that are related to the IRS.*

INTRODUCTION

The demand for high specific impulse thrusters for station keeping of GEO telecommunication satellites has generally raised the interest in electric propulsion (EP) as an alternative superior to the conventional chemical thrusters. Especially the relatively simple thermal arcjet thrusters offer significant advantages in operational flexibility and increasing the payload. These types of thrusters are also much easier to integrate into existing satellite bus systems compared to any other kind of EP device. Thus development programs were started in the USA[1] which resulted in the first deployments on geosynchronous satellites of 1.6 - 2 kW hydrazine arcjets since 1993.

Some of the applications which were classically reserved for chemical propulsion were investigated with respect to the possible use of arcjets. One could be the GTO to GEO transfer of spacecrafts replacing impulsive maneuvers and increasing the payload up to 18 %[Ref]. Besides this special application, the class of thermal arcjets is also discovering new fields with the follow-on generation of small satellites in highly inclined orbits. The prospect of launching a great number of small satellites in LEO and MEO for telecommunication systems led to an extension of arcjet thruster systems towards lower power levels of about 500 to 1000 W, which are better suited to the smaller power installations on these satellites. They are also promising advantages for orbit adjustment compared to pure chemical thruster systems.

Such low power arcjet thruster systems are now under development in the U.S.A.[2] , Japan[3] and also in Germany. Here the German Space Agency **DARA** supports the basic development of such devices up to complete propulsion subsystems. In this context, a mainly technology driven project is supported as a co-operative work between Daimler-Benz Aerospace (**DASA**) and the Institut für Raumfahrtsysteme (**IRS**). This project concerns about the development of an engineering model of a 1 to 2 kW hydrazine arcjet system[1]. From this major development path, the **ATOS** 700 W ammonia arcjet system was derived and flight qualified[8] for orbit adjustment of the AMSAT amateur radio satellite P3-D. In the case of a successful operation, another future flight opportunity of the IRS low power arcjets could be the

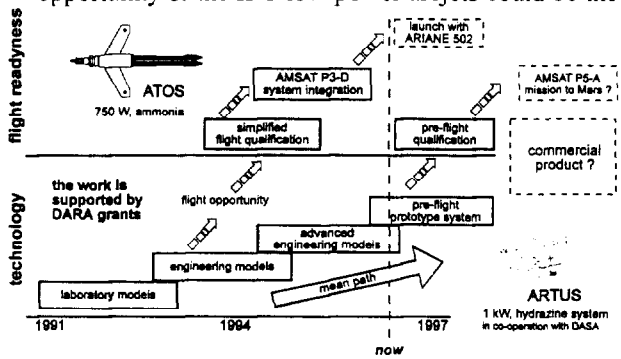

Fig. 1: Low power arcjet development at the IRS.

Copyright © 1997 by the Electric Rocket Propulsion Society.
All rights reserved.

of a successful operation, another future flight opportunity for the IRS low power arcjets could be the next AMSAT project P5-A[8]. This extremely challenging mission intends to place a relay satellite with additional scientific payload into a martian orbit. Fig. 1 gives an overview of the long term development activities and the relation of the flight projects mentioned above.

Hydrazine Arcjet System

Beginning in 1991, the work at the IRS has been focused around the topics related to low power arcjet thrusters and propulsion subsystems. As depicted in figure 1 the major path can be identified with the ongoing development of the so called **ARTUS** (**A**rcjet **T**hruster **U**niversity of **S**tuttgart) thruster family.

This project is a cooperation together with Daimler Benz Aerospace based on their experience with monopropellant hydrazine thrusters and power augmented catalytic thrusters. The responsibility for the overall arcjet system including power control electronics and hydrazine decomposer lies with DASA-RI in Bremen. The IRS in Stuttgart is mainly concerned with the arcjet thruster itself, the performance tests and diagnostics. The partitions of the major work packages between DASA and the IRS during this project are divided according to the scheme depicted in figure 2. After a detailed application study which is discussed in the following in more detail, the goal of the project is now confined to develop a 1.0 kW hydrazine arcjet system, e.g. for orbit raising and acquisition of small LEO satellites. At the end of the current phase, the system will finally be qualified as a pre-flight prototype model by the end of 1997[5].

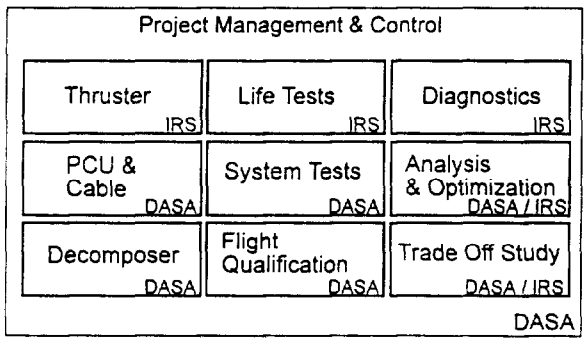

Fig. 2: Work packages for arcjet system development.

Application Trade-Off Study

A trade-off study was performed by the DASA satellite system engineering department in 1993 and 1994[9]. This study identified and assessed promising applications for hydrazine arcjet systems in comparison to both ion thrusters as well as the baseline standard propulsion systems without electric propulsion.

The method which was chosen within this study to compare the benefits of using thrusters with a higher specific impulse was to increase the payload mass with the decreasing mass of the wet propulsion subsystem accordingly. Thus, the financial benefit was evaluated.

From this trade-off, one can derive that the most promising commercial application for arcjets at present and in the near future is for orbit raising and acquisition of small LEO satellites from 300 to 800 kg launch mass. These satellites are of special interest if they have payloads with high power demands which can be non-operational while the arcjet is firing. Thus, no or only low mass penalties for the power supply system are caused by the arcjet electric demands. Therefore, especially LEO communication satellites such as the GLOBALSTAR satellite system are typical fields for commercial arcjet application, particularly because of the numbers to be built.

A summary showing masses, important performance data and cost benefits calculated for a reference satellite is depicted in Table 1.

The implementation of the "Model Arcjet 2" reference configuration results in relative costs for payload capacity of only 82 %, whereas Model 2 represents a configuration with two arcjets of 125 mN thrust and 1214 W total electrical power each. Prompted by the results of this study, the DASA / IRS team decided to reduce the specified overall power to 1.1 kW using 1.0 kW for the arcjet itself.

For the second 'typical' arcjet application, north-south stationkeeping of GEO satellites, the study identified fewer advantages of using an arcjet system compared to other options such as ion thrusters. This is mainly due to the fact that GEO satellites usually have no monopropellant subsystem because they use bi-propellant systems for insertion into GEO orbit and for attitude and orbit control as unified propulsion systems. A detailed mission analysis and optimization study revealed major advantages for the use of hybrid propulsion systems on direct broadcasting GEO satellites[10]. Using the arcjets also for the GTO to GEO transfer, such a Hybrid platform revealed an increase of revenue of 18% compared to the Hotbird-Plus system layout. This cost advantages results from a 30% reduction in propellant mass but a 55% increase in the number of transponders.

System Specification

As a result of the above mentioned, electrical power for the arcjet system has been reduced to the lower

end of the initial power range of 1-2 kW. Hence, the performance and interface data are now specified as:

Thrust:	100 - 150 mN
Specific Impulse:	500 - 550 s
Total Impulse:	400 000 Ns
Accumulated On-Time:	1000 h
System Mass: (incl. PCU and cable)	5.5 kg
Bus Power:	Up to 1.1 kW
Bus Voltage:	28 VDC
Arc Power:	up to 1.0 kW
Arc Current:	7.5 - 11 A
Arc Voltage:	80 - 120 VDC
Propellant:	High Purity Hydrazine (N_2H_4)
Mass Flow:	25 - 15 mg

Table 2: Specifications for 1 kW hydrazine system.

These data are minimum goals for the current phase The requirements will be increased for some of the performance data during further development.

Results and Current Status

A first engineering model #1 was built and integrated into the complete system in 1996. The configuration

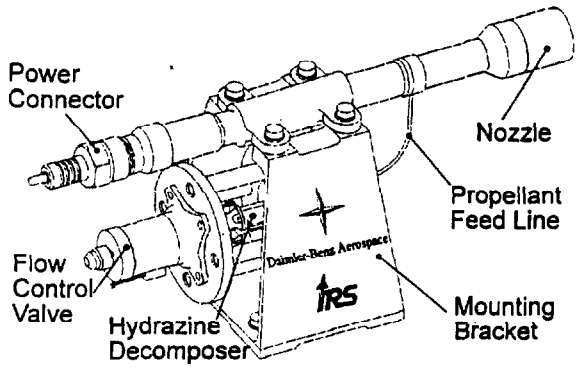

Fig. 3 : Engineering model #1 of the 1 kW hydrazine arcjet system for initial system level tests.

with a preliminary mounting bracket that has been used for sub-component and initial system level tests is depicted in figure 3. This configuration still excludes the PCU and power cable that will be introduced in the upcoming tests of the improved engineering system model #2 which is currently under construction.

The main objectives of the development efforts during this year's frame is to demonstrate a pre-flight prototype arcjet system meeting all the system specifications that could be space qualified with only minor modifications.

Main Data	Model MP	Model Arcjet1	Model Arcjet2	Remarks
Satellite Launch Mass	**400 kg**	**366 kg**	400 kg	Multiple Launch (i.e. Delta II)
Fuel for Orbit Acquisition	47 kg	21 kg	23 kg	include orbit raising
Orbit Mass	353 kg	345 kg	377 kg	
Mission Fuel	6 kg	3kg	3kg	including rephasing
Margin	22kg	10kg	11kg	include post life boost
Dry Mass	325kg	332kg	362kg	
Rel. Payload Ratio	38%	37%	38%	related to dry mass
Rel. Payload Capacity	**100%**	100%	**133%**	channels and pointing
Mission Duration	7.5 years	7.5 years	7.5 years	
Power Demand	**1031W**	1031W	**1214W**	
Specified Power Margin	5%	5%	5%	
Solar Generator, EOL	**1118W**	1118W	**1318W**	
Solar Gen., BOL	**1392W**	1392W	**1641W**	
Operation. Margin, BOL		1161W	1384W	for arcjets
Rel. Costs, Payload Capacity	**100%**	101%	**82%**	
Arcjet Thrust		**100 mN**	**125mN**	
Arcjet. Accumulated On-Time		333 h	292 h	
MP = Monopropellant System				Data for Leo 1390 km orbit height

Table 1: Arcjet application study for mobile communication satellites in low earth orbit.

In the following paragraphs, the sub-components will be described in more detail.

Hydrazine decomposer and FCV

According to the low mass flow constraints, a decomposer / valve unit was built as a derivative from a small and well-proven DASA monopropellant thruster. This unit was then tested separately for more than 600 hours. Since the arcjet system is designed to cover not only the 1000 W range but also power inputs down to 600 W, the tests were conducted with mass flow rates down to 14 mg/s. The mass flow rates have to be reduced to 20 to 15 mg/s for these power levels; therefore, the decomposer was also tested successfully in this operation range. The reduction was achieved by the application of a suitable orifice (Viscojet).
The test sequence consists of run-in firing, performance mapping and life firing tests (typically 1h On/0.5h Off) with intermittent health checks. The purpose of these tests was to verify the feasibility of the low mass flow rates corresponding with heat removal, injection patterns and life effects. Up to now the decomposer as a single unit has accumulated up to 600 hours simulating blow-down pressures from 22 bar down to 8 bar. Within the complete range down to mass flow rates of only 14 mg/s, the performance was excellent. As of yet no pressure degradations have occurred. Post test inspections showed only slight degradation. Being derived from flight design and using only well-proven procedures, the decomposer and the flow control valve design can be seen as near flight.

Thruster Development at the IRS

The ARTUS development started in 1991 with a relatively simple laboratory model to investigate the basic relations of constrictor, nozzle and electrode configuration for radiation-cooled low power arcjets[11]. Derived from these data, a first baseline engineering model #1 was built for the nominal power level of up to 2.0 kW that was valid throughout the first project phase. The main purpose of this early model was to collect first experiences in design, construction and handling of such devices. As depicted in figure 1 these efforts led to a first flight opportunity on the AMSAT P3-D satellite. Based on the proven technology, a 700 W ammonia thruster was derived from a slightly down scaled design. This ATOS arcjet was then successfully tested in a 1000 h life test and flight qualified as a complete propulsion subsystem.
As mentioned in the paragraph concerning the mission analysis, the work was then focused on a lower power level of 1.0 kW in the second project phase. Due to the fact that the overall heat losses increase with decreasing thruster size, the design philosophy is important to return as much of the energy as possible back into the propellant. Therefore, we decided to introduce regenerative cooling of the nozzle itself. With a massive thruster head that is needed to provide sufficient radiation surface, it is easily possible to create internal gas channels for better preheating of the propellant.
With the following engineering model #2 both steps, the reduced power as well as the improved regenerative design, were considered. First initial performance tests and temperature mapping were carried out solely with the thruster. This model was then integrated into a first engineering system depicted in figure 3. The results of the tests on this system level led then to the advanced engineering model #3. The construction and initial acceptance tests of this model were just recently finished. Now it is about to be integrated into the final engineering system. Finally, this configuration has to undergo the life test and qualification procedure under full QA conditions of flight projects such as GLOBALSTAR.

The major design features and key issues are pointed out in more detail below.

- Nozzle and constrictor design
  The initial constrictor diameter of 0.65 mm for the 2 kW power level was reduced to be in the range of 0.4 mm according to the decreased power level and according to the results of a calculation approach with the semi-analytical 3-channel model[12]. The nozzle's divergent half angle was kept at 20° and the overall expansion ratio is now 1 : 250. Further experiments served to fix the convergent angle as well as the direction, angle and the number of the propellant injection holes for stable operation conditions.

- Cathode and gap adjustment
  The cathodes were all made of 2% thoriated tungsten standard rods for welding application. The

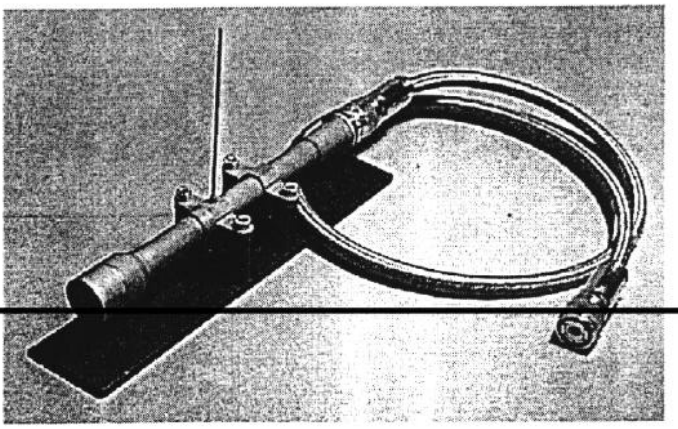

Fig. 4: Arcjet thruster EM #3 incl. power cable ready for system integration.

tip half angle was gradually increased to 35°. A pre-shaping of the tip in order to simulate the run-in wear was introduced but not found to be very effective. The cathode gap defined as the axial displacement from the contact condition could be varied for the first two generations of engineering models. It is now fixed for the recent configuration and set to 0.6 mm. Higher values increase not only the operation voltage but also the time of the undesirable instable start-up sequence.

- Power interface

Due to the lack of off-the-shelf solutions for high temperature, pressure and vibration-proof electrical feed-throughs, a modified automobile spark plug was selected as the power connector. This simple and cheap device has proved safe for low power arcjet operation up to 20 A and ignition voltages up to 3000 V. Even at temperatures above 300°C no leakage was detected. Therefore, this item was selected for application in the previous engineering models as well as for the ATOS ammonia thruster development and qualification. A co-axial high power feed-through was designed similar and compatible to a MIL standardized high current DC-connector for the recent model #3. This new component has to meet the thermal requirements of 180-200°C in the worst case.

- Materials, coatings and joining

Tungsten and molybdenum based rhenium alloys are used because of the advantages in the material properties and stability reasons in the major and most forward joint between the nozzle and the housing. The very attractive particle strengthened materials[13] that extends the limits of constrictor design are not available within the financial boundaries of the project. Nickel and cobalt based superalloys were applied for the remaining parts of the housing or functional components. All the metal parts forming the outer walls were joined together by space qualified EB welding methods or by a single EB brazing for the transition from the molybdenum to the nickel alloys.

Insulation is provided by boron nitride or silicon nitride parts for the elements with complex geometriesor higher structural loads. The main insulation is realized by a simple tube made from oxide ceramic.

One major step in design improvements was the introduction of high emissivity coatings in order to reduce the thermal loads to the thruster and to the mechanical interfaces. A thin PVD deposited tungsten-carbide layer was determined to be the most promising coating for the complete outer housing surface. This measure increased the emission coefficient ε from less than 0.4 to values about 0.8. The effectiveness of this measure depicted in figure 5 is quite impressive. Over an accumulated operation time of about 100 hours with an earlier engineer model, the coating showed excellent long-term stability.

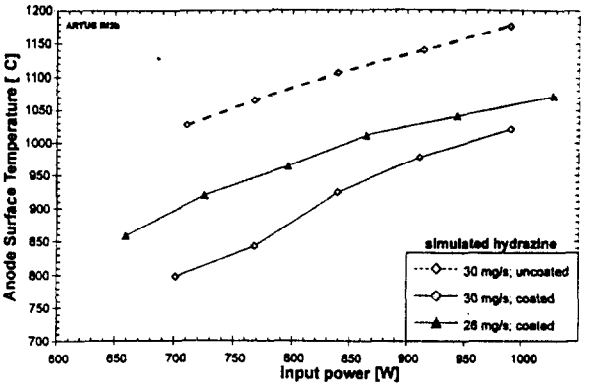

Fig. 5: Influence of high emissivity coating on anode surface temperature.

In total the thruster mass (including power-connector) amounts to 360 g at an overall length of 230 mm. The arcjet thruster ready for system integration is depicted in figure 4. The remaining margins for further mass reduction and structural optimization will be examined by the on-going experiments.

Test facilities

For the performance mapping, thermal measurements and endurance tests, two similar IRS test facilities, tank 5 and tank 11, are prepared for low power arcjet operation.

Tank 11, which is schematically depicted in figure 6, is made of stainless steel with a diameter of 1.2 m and length of about 1.3 m. A three-stage pumping system

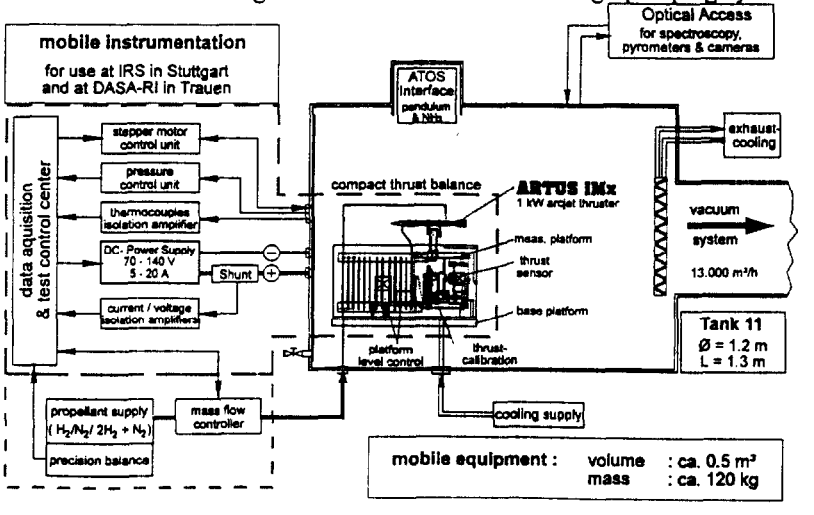

Fig. 6: Low power test facility with mobile instrumentation.

is capable of providing a sufficient background pressure of < 5 Pa at all tested mass flow rates. The propellant feed system was adapted to the constraints of extremely low mass flow rates and was also extended for the use of ammonia. For safety reasons the hydrazine has to be simulated by a N_2:H_2 mixture of ideally decomposed N_2H_4. The mass flow rates are adjusted by conventional thermal mass flow controllers (TMFC) and are additionally checked on-line by a high precision weight balance. The accuracy of these combined measurements is better than 1%. The tank is equipped with an inverse pendulum type thrust balance where the pendulum deflection of < 1 mm is detected by a linear displacement transducer. If thrust has to be measured, the thrust balance can be calibrated before and after each test to guarantee maximum accuracy. Furthermore, the tank is equipped with a wide variety of feed-throughs and observation ports for all kinds of diagnostical access. The main thruster operation parameters are collected and computed by a PC-based data acquisition. A high-speed transient recorder can be used to monitor short-time events and during arc ignition. The overall accuracy for the most sensitive arcjet performance indicators was determined to be ±1.5 % for the I_{sp} and ±2.5 % for the thrust efficiency.

The test facility was originally built for the ATOS life-time qualification[7] with autonomous 24-hour operation using adapted long-time safety and recording options. It is now refurbished and updated in order to mobilize the complete measurement equipment for dual use at the IRS and at the DASA location for hot firing tests with real hydrazine.

Performance and system tests

At this stage of investigation, only preliminary performance data could be given for the integrated systems. Therefore, only initial test data from the run-in tests of the arcjet thruster itself are depicted in figure 7 and figure 8. The intended thrust level of 100-125 mN could be demonstrated easily with a nominal mass flow rate of 26 mg/s covering the power range from 650 W up to 1 kW. As expected, the specific impulse also reaches the specified 500 s. Detailed performance data will be published as the system tests are finished.

The complete system of engineering level 2 was integrated in 1996 and went through a set of functional tests to define test sequences for further qualification tests and to reveal major design imperfection. For example, the structural tests were carried out with the full vibrational loads as for the GLOBALSTAR propulsion system. The system's frequency response as well as the post test inspections confirmed the approach for the recent design.

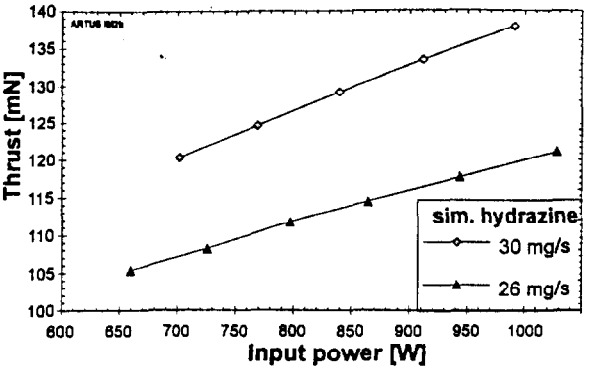

Fig. 7 : Thrust level versus el. input power for top mass flow rates (only arcjet thruster).

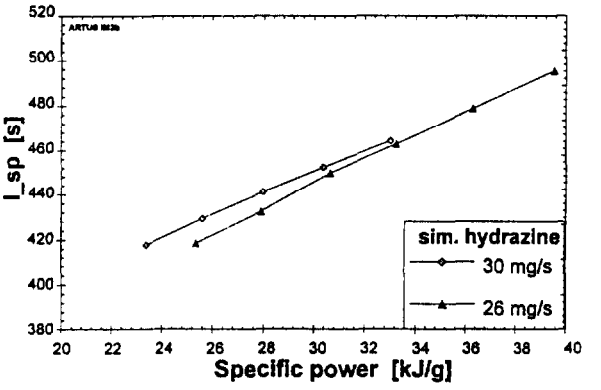

Fig. 8 : Specific impulse over specific input power (only arcjet thruster).

The tests that were conducted on component level as well as on subsystem level are briefly listed below.

- Acceptance tests on component and system level.
- Random and sinus vibration with qualification loads.
- Thermal vaccum and EMC tests.
- Hot firing cycle for life test demonstration.

Detailed results of system level test and qualification will also be published at the end of the project.

Analysis and simulation

In order to optimize the structural and thermal response, massive thermal and structural analysis is carried out both at DASA-RI and at the IRS. While the IRS concentrates on the more detailed modeling of the thruster itself, DASA is more concerned with overall system aspects and the dynamic modeling. Using different numerical approaches (Finite Differences vs. Finite Elements) with the same materials and experimental database, attempts were made to validate and to continuously improve the modeling so that the number of further hardware tests can be reduced.

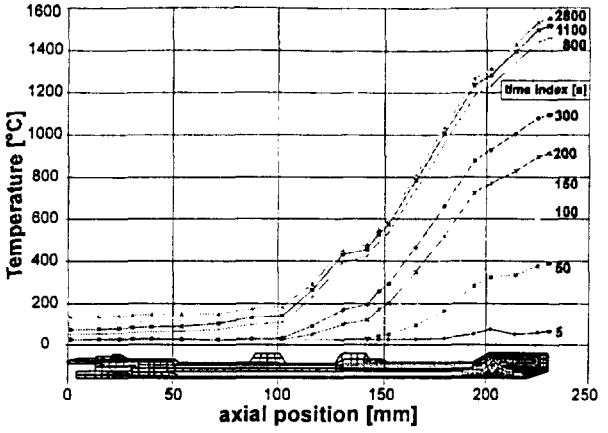

Fig. 9 : Time dependent temperature distribution along the thruster's surface.

The thermal analysis at the IRS is performed with a high functional finite element library providing all kinds of features for the detailed thruster optimization. This includes instationary, non-linear conduction with temperature dependent material properties, internal Navier Stokes convection and radiation interchange. In order to reduce the amount of large scale and time consuming real 3D calculations, several assumptions were made to manage the application of 2D-axial symmetric modeling.

Based on the extensive thermal measurements and on the validation runs carried out with the predecessor engineering models, the design presented in the previous sections was determined to meet the thermal requirements set for the pre-flight prototype. A maximum temperature of 150-180°C is allowed at the arcjet's rear power interface assuming in the worst case that the thruster mounting is thermally isolated. The predicted temperature distribution and thermal response for a simulated operation point of 1 kW@20 mg/s can be seen in figure 9. It shows that it is not problematical to stay below the major thermal design limits for the power connector interface. The further experiments will show whether the thruster can be shortened to improve the dynamic stability and to reduce the weight.

In addition, the structural analysis is accompanied by plasma flowfield simulation. The CFD codes and tools are also available or are being developed at the IRS.

For further insight into the energy loss mechanisms and to determine the plasma characteristics, the IRS plume diagnostic tools such as emission spectroscopy, Langmuir probes or Fabry-Perot interferometry will be applied parallel to the ongoing system pre-flight qualification.

PCU-Status

Currently, two different laboratory version PCUs are used for ground testing of hydrazine arcjet thrusters. Related to the electronics, data and experience were gained concerning reliable ignition voltage levels, arc current and voltage ranges including their proper regulation/control, as well as functional behaviour during abnormal conditions (i. e. overload or unforeseen arc breakdown).

As shown in figure 10, the current engineering bread-board PCU consists of a main converter operating in push-pull configuration, acting as a current source to maintain the arc. The converter's output filter is combined with an arc ignition unit generating high voltage pulses of up to four kilovolts. Due to the power level of about 1 kW and the ignition transients, EMC-aspects are very important, making effective filtering necessary in the main converter's primary circuit (among other precautions).

Sequence control of all PCU operations is done by means of an integrated control unit. Together with some periphery, e. g. for H/K, data generation / signal conditioning, this unit acts as an interface between the PCU power electronics and an external control unit (data management system, DMS).

At this stage of the project only space-qualified parts were used. After having demonstrated the full functionality and performance, major components could be integrated into customized hybrids. At least for the power converter this measure would be neccessary to fulfill the mass and volume requirements for any flight type PCU.

In addition, a power transmission interface to the arcjet thruster is now available. This interface that principally can be space-qualified also replaces the spark plug solution at the thruster's power I/F. According to MIL standards, the selected type of high power connector and also the power cable meets the thermal and EMC requirements.

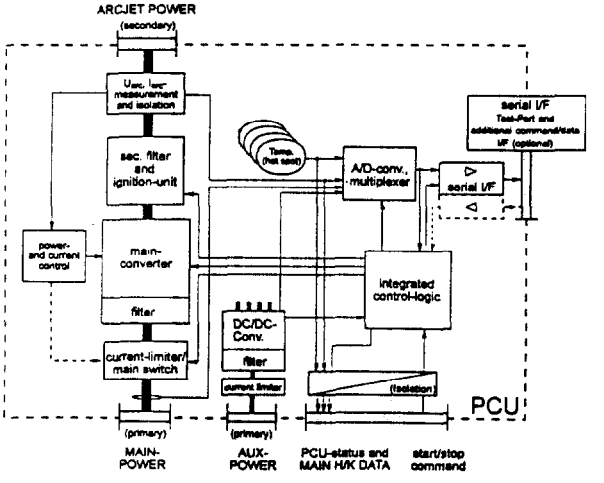

Fig. 10 : Scheme of engineering bread-board PCU.

CONCLUSIONS

A series of low power arcjets is continuously being developed at the IRS and has now reached an advanced state[14]. The ongoing work on all aspects of subcomponents have led to a 1 kW hydrazine system that is about to be tested and qualified as a pre-flight engineering propulsion sub-system.
Derived from this technology driven major part of the project with hydrazine arcjets, a first ammonia arcjet propulsion system has been designed and put through a preliminary flight qualification procedure. Thus, the use of an arcjet system and its inflight testing should be suited to demonstrate the mature status that the IRS devices have reached in the meantime.

ACKNOWLEDGEMENTS

The work in developing arcjet systems presented in this paper was and is mainly supported by DARA grants #50-TT-9401, contract monitor Mr. H. Meusemann. This support is gratefully acknowledged by the authors.

REFERENCES

[1] Smith, R.D.; Yano, S.E.; Armbruster,K.; Roberts,C.R.; Lichtin, D.,"Flight Qualification of a 1.8 kW Hydrazine Arcjet System", IEPC Paper 93-007, 22nd IEPC, Seattle, WA, USA 1993.

[2] Lichon,P.G., McLean,C.H., Vaughan,C.E., Sankovic,J.; "Development of a 500 Watt Class Arcjet Thruster System"; IEPC-95-237; 24th IEPC; Moscow Russia 1995.

[3] Ogiwara, K., et al., "Study of 300W-Class Direct Current Arcjet Thruster", Paper 96-a-3-01, 20th ISTS, Gifu, Japan, 1996

[4] Riehle,M.; Hammer,F.; Kurtz,H.L.; Auweter-Kurtz, M.: "Low Power Arcjets for Small Telecommunication and Scientific Satellites", ESPC 97-B1/4, Second European Spacecraft Propulsion Conference, ESTEC, Noordwijk, NL, May 27-29, 1997.

[5] Viertel,Y.E.; Schmitz,H.-D.; Riehle,M.; Kurtz,H.L.; Auweter-Kurtz, M.: "Development and Test of a 1 kW Hydrazine Arcjet System ", AIAA-96-2960, 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference July 1 - 3, 1996 /Lake Buena Vista, FL.

[6] Messerschmid,E.W.; Zube,D.M.; Meinzer,K.; Kurtz,H.L.: "Arcjet Development for Amateur Radio Satellite", Journal of Spacecraft and Rockets Vol. 33, No. 1 pp. 86-92, Jan-Feb 1996.

[7] Messerschmid,E.W.; Zube,D.M.; Dittmann,A.: "System Verification and Integration of the ATOS Ammonia Arcjet", AIAA-96-2716, 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference July 1 - 3, 1996 /Lake Buena Vista, FL.

[8] Messerschmid,E.W.; Meinzer,K.; et.al.: "AMSAT P5-A to Mars", Proceedings of the Kick-Off Meeting 18./19. July 1996.

[9] Gruber, O.-H., "Arcjet-Antrieb für Mobilfunk-satelliten", DASA-Document E2AJ-TN-230W-00-02.DA, DASA, Munich, Germany, Dec. 1994.

[10] Schwer,A.G.; Messerschmid.E.W.; "System and Mission Optimization of Geostaionary Telecommunication Satellites using Arcjet Propulsion Systems", AIAA-97-2713, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference July 6 - 9, 1997, Seattle, WA.

[11] Kurtz, H.L., Zube, D.M., Glocker, B., Auweter-Kurtz, M., Kinnersley, M., Steenborg, M., Matthäus, G., Willenbockel, H., "Low Power Hydrazine Arcjet Thruster Study", AIAA paper92-3116, 28th JPC, Nashville, TN, 1992

[12] Glocker, B., Schrade, H.O., Auweter-Kurtz, M., "Performance Calculations of Arcjet Thrusters - The Three Channel Model", IEPC-93-187, Proceedings of the 23rd IEPC, Seattle, WA, 1993

[13] Chen,B.L.; Luo,A.; Shin,K.S.; "High - Temperature Mechanical Properties of W-Re-HfC Alloys", Refractory Metals: State of the Art 1988, pp 65-75.

[14] Auweter-Kurtz,M.; Glocker,B.; Gölz,T.; Kurtz,H.L.; Messerschmid,E.W.; Riehle,M.; Zube,D.; "Arcjet Thruster Development", Journal of Propulsion and Power Vol. 12, No. 6 pp. 1077-1083. Nov-Dec 1996.

[