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Status and Future of Research on Plume Induced Contamination

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Abstract

Spacecraft typically rely on chemical propulsion systems for active attitude and orbit control during cruise stage, and for entry, descent and landing on planetary surfaces. In addition to thruster performance parameters, spacecraft and mission designers must account for thruster plume impingement on adjacent surfaces (on the flight system, science instruments and on planetary surfaces). Plumes of chemical thrusters invariably interact with spacecraft surfaces, as the vacuum environment allows them to expand to well upstream the nozzle exit plane. Thruster plumes are thus a source of parasitic forces, moments, heat loads, and particularly of contamination and surface erosion. Plume contaminants may be gaseous, liquid or solid and have been demonstrated to severely degrade functional surfaces on spacecraft, affecting power and thermal budgets, as well as scientific payloads and mission design. Plume induced contamination can also impact mission science objectives since contaminants contains both organic and inorganic compounds, and current missions have highly sensitive instruments targeting detection of organics and life markers. It is thus mandatory to conduct plume contamination analyses when designing a space mission. As mission science objectives and evolving scientific instrumentation put ever more challenging constraints on contamination control, this paper reviews the existing plume induced contamination and erosion measurements on which current models rely. The data available from both, ground-based chamber tests and on-orbit flight experiments, is very limited. Most of the measurements obtained in ground-based vacuum facilities were conducted in the decades of the 1970s and 1980s, in vacuum environments that did not allow for prolonged free thruster plume expansion, and most of the data was taken near plume centerline. Shuttle-borne on-orbit experiments SPIFEX and PIC provided measurements of plume induced contamination as well as droplet impact damage, but give only integral account of liquid phase contamination at coarse spatial resolution. From the reviewed data, we identify several unexplored aspects pertaining to plume induced contamination, such as the impact of thruster start-up and shutdown on the production and distribution of droplets and particulates, the spatial, temporal and size distribution of droplets and particulates in the plume during start-up, steady-state and shutdown phases, the chemical composition of plume effluents, such as partial combustion/decomposition reaction products and the previously observed non-volatile residue, and the optical properties of plume deposits. We identify the need for further development in thruster plume modeling as well as ground-based and on-orbit testing, and propose a road map to improve plume induced contamination predictive capabilities by lowering model uncertainties.

Keywords: thruster plume, contamination, droplets, monopropellant, bipropellant, experiments

Acronyms/Abbreviations

AEDC	Arnold Engineering Development Center
EVA	Extra-Vehicular Activity ("spacewalk")
FORP	Fuel-Oxidizer Reaction Product
GHe/LHe	Gaseous/Liquid helium
MMH	Monomethyl hydrazine
NTO	Nitrogen Tetroxide
PIC	Plume Impingement Contamination
QCM	Quartz Crystal Microbalance
QTGA	QCM Thermogravimetric Analysis
SEM	Scanning Electron Microscope
SPIFEX	Shuttle Plume Impingement Flight Experiment
STG-CT	DLR High-Vacuum Plume Test Facility Göttingen – Chemical Thrusters
UDMH	Unsymmetrical dimethylhydrazine
XPS	X-Ray Photoelectron Spectroscopy

1. Introduction

Spacecraft chemical thrusters, i.e. propulsive devices that generate thrust from converting the energy released in a chemical reaction of their propellants to kinetic energy through gas expansion, are commonly used since the early days of space flight to control the attitude and orbit of a spacecraft or to decelerate planetary probes in their approach to their landing site. Hydrazine and its derivatives are an established propellant choice, as they remain chemically stable over the mission life time (many years or even decades) and possess high energy content. The energy conversion is achieved through catalytic decomposition in monopropellant thrusters, or through hypergolic reaction with an oxidizing agent such as (di-)nitrogen tetroxide (NTO), which is often paired with mono-methyl hydrazine (MMH) or unsymmetrical dimethylhydrazine (UDMH).

In the absence of a surrounding atmosphere, i.e. in the vacuum of space, the plume gas exhausted at hypersonic speeds from the thruster tends to spread widely upon leaving the thruster nozzle, with a fraction of the plume gas expanding to upstream the nozzle exit plane (backflow). The plume species, including partially complete reaction products thus inevitably impinge on surfaces in the vicinity of the thruster, notably on the spacecraft itself, thus being a source of convective heat flux, parasitic forces and moments, as well as contamination. Depending on the thruster's mechanical construction, its operation and history as well as on the propellants used, the plume exhaust may carry particulates (catalyst bed fines, solid nitrate particles) and droplets of incompletely reacted propellant, all of which may impair functional surfaces of a spacecraft or the cleanliness of a landing site. We collectively refer to the (typically adverse) effects of plume exhaust as plume induced contamination.

In designing a spacecraft equipped with chemical control thrusters and its mission, an analysis of potential plume induced contamination is imperative, and predictive capabilities (i.e. plume contamination models) of a fidelity suiting the design phase and mission objectives are required. As mission science objectives and evolving scientific instrumentation put ever more challenging constraints on contamination control, this paper reviews the literature on existing plume induced contamination and erosion measurements on which current models rely, and suggests improvements required to establish models with lower uncertainties.

The paper is organized as follows: Existing plume induced contamination and erosion measurements are reviewed in Sec. 2. , giving an overview of the openly accessible literature on dedicated ground-based and on-orbit tests. A roadmap to an improved characterization of plume induced contamination is proposed in Sec. 3. , and general conclusions are drawn in Sec. 4.

2. Review of existing plume induced contamination and erosion measurements

2.1 Ground-based chamber tests

A number of ground-based experiments have been performed since the 1960's to study the effect of thruster plume contamination on functional spacecraft surfaces such as mirrors, thermal control coatings, solar arrays and glass. The best documented experiments were carried out in the United States by NASA, Air Force and their industry contractors, and more recently in Germany. The particular challenge associated with ground-based plume contamination analysis lies with maintaining an appropriate vacuum level even during thruster operation, as otherwise the plume expansion in the test chamber and thus the transport of contaminants is not representative of that in space [1]. We aim here to give a brief and chronological overview of pertinent experiments, their

main results and the conditions under which they were obtained.

2.1.1 United States Air Force (AEDC, AFRPL)

Among the earliest reports on plume contamination investigations is that of Burch [2], investigated the contaminating effects of a Prototype Bell MMH/NTO engine with nominal thrust just over 100N. Tests were conducted in the AEDC Mark I Aerospace Environmental Chamber, whose vertically installed test section of 19.8m height and $\varnothing 10.7\text{m}$ was equipped with gaseous helium (GHe) cooled cryo-panels. The thruster was operated both in long (3 to 8s) and short-duration pulses (22.5ms on, 3s off), causing the initial vacuum of about 7×10^{-6} mbar to break down to about 1.5×10^{-3} mbar during engine operation. Silica and Pyrex samples were exposed to the plume, along with Platinum-mirrors and three thermal coatings. The authors note a clear hazy film of clear viscous liquid being deposited on the samples and brown viscous liquid collecting on the nozzle lip during pulse mode operation. Maximum solar absorptance increased by 25% to 147%, depending on the sample material. Transmittance of the silica sample was observed to change by up to 30% during post-test measurement.

A series of experiments was conducted in Space Chamber No. 4 at AFRPL, to study contamination from a 110N Hamilton Standard Hydrazine monopropellant thruster [3] and 98N Marquardt R1E MMH/NTO bipropellant motor [4]. Space Chamber No. 4 measures 4m in length and 2.4m in diameter, its mechanical and diffusion pumps are augmented by a 2.25m² LN₂ cryo-panel. The thrusters were operated in single pulses of 100ms (biprop.) and 200ms (monoprop.) at a vacuum level of 0.4mbar during firings, with several minutes in between pulses to allow the chamber pressure to return to its initial 2.5×10^{-5} mbar. Witness coupons (thermal control paint, solar cells, glass) were mounted in a 1m² plate downstream of the thruster, parallel to the plume axis and about 90mm away from it. While the monopropellant thruster plume appeared to have little effect on the thermo-optical properties of the witness coupons, brownish material was reported to collect at the nozzle lip of the bipropellant thruster. The exhaust contaminant found on the witness coupons has been identified as MMH-nitrate in a related study [5] and was observed to change from a crystalline structure to a viscous substance when moved from vacuum to atmospheric conditions. The study notes a permanent transmittance decrease on the glass samples, as well as a thermal paint reflectance decrease of up to 25% at a wavelength of 420 μm .

2.1.2 NASA Lewis Research Center

In the early 1970's, NASA Lewis Research Center (LRC) carried out a detailed and well-documented investigation into the contaminating properties of a

scaled 22.5N Marquardt R-1D MMH/NTO thruster [6]–[9] in the context of the Skylab mission (cf. Sec. 2.2.1). Tests were conducted in the LRC Solar Simulator Facility, that features a cylindrical test section 4m high and 2m in diameter. The test section walls may be cooled with liquid/gaseous helium, to permit cryo-pumping of hydrogen, a major exhaust plume constituent. With the additional introduction of an argon leak to facilitate cryo-trapping of hydrogen gas, the authors report an initial vacuum $<10^{-6}$ mbar and approximately 7×10^{-5} mbar during thruster operation. The thruster is placed such that the nozzle axis is perpendicular to the chamber axis and operated in pulses of 50ms to 200ms duration. Witness coupons of $\varnothing 25$ mm (quartz samples, coated Al-mirror, fused silica, thermal control paint) were installed in a plate downstream of the plume, parallel to the nozzle axis and 100mm away from it. Transparent droplets ($<\varnothing 500\mu\text{m}$) of irregular shape and non-uniform distribution were found on the quartz samples (circular droplets on mirror), along with particulate matter of $5\mu\text{m}$ to $20\mu\text{m}$ typical dimension, the source of which is unclear. The study authors notice the liquid contaminant to be hygroscopic, and caution that exposition of the samples to atmosphere changes the properties of the contaminant. Fast measurements of liquid flow rate showed, that the oxidizer-to-fuel ratio experiences variations for pulse duration <120 ms, and it is argued that these oscillations, together with the valve's dribble volume, may largely contribute to the production of liquid contaminants [8], with shorter pulses leading to increased contamination.

In a series of experiments dedicated to plume contaminant distribution [9], transmittance measurements indicated an unexpectedly high amount of contamination at 85° angle from the plume centerline: transmittance generally decreased with increasing angle between sample and nozzle centerline (and with decreasing wavelength), approximately proportional to the calculated mass density distribution. Despite careful control of thruster parameters, the authors find large variations in mass deposits measured with QCMs.

2.1.3 Jet Propulsion Laboratory

After having served as a high-vacuum, low re-emittance test environment for cold-gas plume sources, the Molsink test facility at the Jet Propulsion Laboratory (JPL) was used to study the effect of thruster aging on plume-induced contamination [10]. Molsink features a near-spherical test section of $\varnothing 3$ m, equipped with tightly spaced fins to hinder molecular transport back into the chamber. The wall and fins are cooled with GHe to 15K–20K and are titanium coated to be able to getter hydrogen and helium. The initial obtainable vacuum level is reported to be on the order of 10^{-9} mbar. A 0.44N Hamilton-Standard (REA 10-18) Hydrazine monopropellant thruster with Shell 405 catalyst was fired

at five QCMs, all situated in a plane perpendicular to the nozzle axis and about 1.13m downstream from its exit. The QCMs are spaced such as to be at angles 0° , $\pm 15^\circ$, $\pm 30^\circ$ to the nozzle axis. After 130,000 pulses, the thruster seemed to produce less ammonia and a 46% decrease in mass deposition at 144K crystal temperature was observed. It is further noted, that the thruster flow rate diminishes non-linearly with the number of pulses (starting from about 20,000), which is attributed to fractured catalyst bed particles leading to a tighter packing of the catalyst material, thus increasing the pressure drop (30% decrease in peak thruster chamber pressure). It is stated as a known fact, that these fractured fines eventually get expelled through the nozzle.

2.1.4 Arnold Engineering Development Center

The very same aged thruster has been handed to Arnold Engineering Development Center (AEDC) by JPL with an estimated history of 200,000 pulses, and an experimental study was conducted there with the goal of characterizing both the gas dynamic and contamination properties of the vacuum plume expansion in AEDC's Research Vacuum Chamber (RVC) [11]. The RVC is 3m long and 1.2m in diameter, equipped with a closed-loop GHe-pump and a 371 LHe-pump supplied from a 500l Dewar tank. The initial vacuum is stated to be about $<10^{-7}$ mbar, which during thruster operation (140ms on, 9.96s off) breaks down to just under 10^{-3} mbar. The chamber is equipped with a mass spectrometer, QCMs, a laser Raman/Rayleigh scattering system, electron beam fluorescence and a particle collection network. The authors observe a significant quantity of liquid particulates in the forward-flow region for all test conditions of the aged thruster, which is larger yet during the initial pulses of a pulse train. Significant amounts of hydrazine were found near the plume centerline, though the engine performance remains seemingly unchanged.

The 0.44N Hamilton-Standard engine was subsequently refurbished and a new catalyst bed installed, before a similar test program was conducted for comparison to the aged state [12]. While condensate was still present in the plume, an order of magnitude less Rayleigh scattering signal was observed as compared to the aged thruster, but scattering signal was still an order of magnitude higher for the initial pulses of a pulse train. For both the aged and refurbished thruster, the recorded mass deposit increased with decreasing catalyst temperature. The study repeats the previously drawn conclusion that engine performance parameters are not suitable for contamination monitoring or characterization.

In a parallel activity, the plume contamination from various modifications of a 22.2N MMH/NTO bipropellant engine (Aerojet AJ10-181) is studied in AEDC's Aerospace Chamber 10V. The outer vacuum vessel of Aerospace Chamber 10V is 6.1m long and 3m

in diameter. The chamber is equipped with an LN₂-liner, a \varnothing 1.8m GHe-pump and a liquid helium driven cryo-pump. The thruster axis is aligned with the chamber axis and remains fixed. In a first phase of the experiments [13], the experimental setup comprises eleven temperature controlled QCMs, cameras for the infrared (IR) and visible (VIS) light spectrum, a fast-scanning mass spectrometer, laser thickness monitoring, IR spectroscopy, witness plates and an electron beam system. Objectives were ambitious: to development and demonstrate cryogenic pumping capability in Aerospace Chamber 10V, to measure the mass flux in the plume back-flow (up to 147° from axis), to characterize gaseous, liquid and particulate plume constituents and assess their impingement effects, and to verify the models used in the CONTAM code [14] to assess potential contamination from the bipropellant thrusters to be used on the Space Shuttle, which was then under development. Though many parameters were varied throughout the study, a few general findings are stated: QCM results of back-flow mass flux measurements become erratic when vacuum level is raised above 10⁻³ mbar, and it is noted that a reduced mean free path resulting from an increase in vacuum chamber pressure during the firing sequence was likely to invalidate the measurements (the background pressure in this study was reported to not exceed 10⁻⁵ mbar during firing). Comparison with a then state-of-the-art plume model [15] showed, that it underpredicts the plume gas back-flow, and an empirical model was proposed instead. The study reports findings of clear liquid droplets (\varnothing 10 μ m to 300 μ m) on aluminum substrate. The droplets are stable under atmospheric conditions, but turn brown after heating. Viscous brown droplets, resembling the heated clear droplets, but in the size range from 300 μ m to 5mm were also found, as are crystals with characteristic sizes spanning the entire range of observed droplet dimensions (5 μ m to 5mm). The authors remark on seeing run patterns near the crystals and speculate, that these crystals have been liquid when deposited on the witness samples. This suspicion is promoted by the observation, that the phase of the contaminants depended on the chamber's warm-up cycle.

In a second phase of the AEDC bipropellant thruster investigation, Powell *et al.* [16] focus on *in-situ* droplet characterization, using laser light scattering diagnostics in the forward region of the plume exhaust. For a 20ms thruster pulse at nominal chamber pressure and propellant ratio, the authors determine the droplet size during firing to 0.35 μ m (with 30% uncertainty). At shutdown, the particle size was determined to be less than 0.1 μ m but the 25-fold light intensity is found to be indicative of a droplet density after shutdown that is three to four orders of magnitude higher than immediately before shutdown. Two reproducible signal spikes are reported after shutdown that appears to be related to the

thruster operation. A separate report [17] lists the results of mass flux measurements obtained with the QCMs in the plume back-flow region, from 60° to 135° off axis.

In what appears to be the last report on the bipropellant thruster investigation at AEDC, Curry *et al.* [18] summarize their findings on time- and space dependence of particle efflux from a pulsed bipropellant engine and note, that "[...] formation of particulates by the incomplete combustion of fuel droplets is [...] difficult to predict theoretically, and recourse must be made to experimental studies".

2.1.5 Hamburg University of Technology, Germany

From 1983 to 1990, an extensive effort to characterize and model thruster plumes was sponsored by the European Space Research and Technology Center (ESTEC) of the European Space Agency (ESA), and carried out at the Hamburg University of Technology (TUHH) by H. Trinks. A number of bipropellant thrusters was tested in the course of the program, with a focus on Messerschmidt-Bölkow-Blohm (MBB) 10N thruster SKA795 [19], but also other bipropellant engines: an MBB 5N thruster SKA1016, Marquardt 22N R-6C, Bell 22N, Aerojet 22N AJ 10-219, and Aerojet 66N AJ 10-220 [20], [21]. One hydrazine monopropellant thruster, the MBB-ERNO 5N thruster was also investigated [21]. The tests were conducted in the HAMBURG test facility of \varnothing 1.2m, that has been extended from 2m to about 3m in length and received larger GHe-cooled cryo-surfaces in the course of the study. The author claims that the facility was able to maintain a background pressure on the order of 10⁻⁵ mbar during thruster operation, though judging by the published sketches of the facility, this claim must be questioned. Most data, especially concerning droplet outflow and impingement is collected near the nozzle axis, however. Though an impressive array of diagnostic techniques was employed (including mass spectrometry, heat flux sensors, laser light scattering, electron beam fluorescence, QCMs and high-speed photography), no further description of the measurement techniques is provided and some results are presented in a rather qualitative way, which makes evaluation of the results and comparison to previous findings difficult. Plume induced damage (craters) to poly-imide film (Kapton®) is observed [22]. Nevertheless, the experimental results were used to support the development of the CONTAM software.

While a number of the presented findings lack a critical discussion (e.g. the inconsistencies in droplet sizes identified for the MBB 10N near the thruster axis, as inferred from witness plates situated well in the continuum core of the thruster plume), the proposed systematic and standardized experimental exhaust plume analysis procedure [23] may serve as a guide to build future plume impingement effects databases. The functional form of the analytical model proposed by

Trinks [21] to analytically describe the angular distribution of plume fluxes forms the basis of currently employed plume contamination models [24].

2.1.6 German Aerospace Center (DLR), Göttingen

The equipment used by Trinks at TUHH was moved to the German Aerospace Center (DLR), Göttingen, in the mid 1990's in order to revise and expand on the experiments conducted in the HAMBURG test facility, under sponsorship of ESTEC. DLR Göttingen currently operates two test facilities dedicated to research into plume impingement effects from chemical attitude control thrusters: the mechanically pumped Contamination Chamber Göttingen (CCG), and the sophisticated DLR High-Vacuum Plume Test Facility for Chemical Thrusters (STG-CT) [25]. In an initial technology transfer program, the focus was on replicating some of Trinks' results in the vacuum facilities at DLR. The 10N MBB bipropellant thruster used by Trinks however was not in production anymore, and tests were conducted instead with the significantly redesigned 2nd generation 10N thruster manufactured by EADS Astrium (now ArianeGroup).

In a series of experiments dedicated to demonstrate bipropellant droplet contamination in the back-flow of the thruster, nozzle "collars" (discs concentric to the nozzle axis) made of aluminum and acrylic were placed 10mm upstream of the nozzle exit, and subsequently inspected. Fig. 1 shows a section of the contaminated aluminum collar, with the cut out for the nozzle visible near the upper edge. The droplets of brownish liquid that were previously seen in other experiments, apparently also reach the upstream vicinity of the nozzle. The deposit appears permanent, with droplets as large as 1mm.

In a report to ESTEC, Dettleff [26] summarizes experiments on the effect of inadequate pumping speed on plume expansion: If the mass flow rate of the thruster exceeds the pumped rate, a barrel-shock forms around the downstream plume core, beyond which the flow is no



Fig. 1. Droplets collected upstream of 10N bipropellant thruster nozzle



Fig. 2. Test section of DLR High-Vacuum Plume Test Facility STG-CT

longer representative of free plume expansion. Furthermore, strong convective flow was observed in CCG that persisted long after the thruster (EADS Astrium 10N bipropellant thruster S10-18) was turned off. Such flow will transport contaminants to surfaces that are not directly impinged by the thruster, as has been observed for example in [4].

With STG-CT, DLR built and operates a unique vacuum facility, whose test section is entirely surrounded by a 30m² cryo-wall, which is kept at a temperature of about 4.2K by using liquid helium as a cooling agent. This low temperature is necessary to cryo-pump hydrogen, which is a major plume constituent. In order to keep the background pressure below 10⁻⁵mbar during thruster tests, one must maintain all cryo-surfaces below 4.7K, see also the discussion in [27] and [28]. Fig. 2 offers a view inside the copper-lined test section, with a thermally insulated thruster pack in the foreground.

2.2 Flight (on-orbit) tests

2.2.1 Skylab QCM measurements

The Skylab space station was launched in May 1973 and it operated unmanned for 9 months, until February 1974. Eight QCMs were installed on Skylab [29] to measure molecular deposition from induced

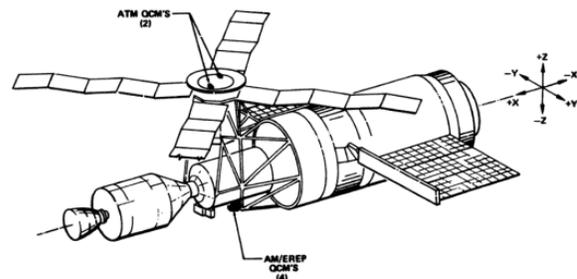


Fig. 3. Skylab space station configuration with QCM placement

environments, including thruster firings from the Skylab reaction control system and during proximity operations with Apollo (fly-around, rendezvous, dockings and separations).

Six of the eight QCMs were activated during flight and all Skylab QCM measurements were derived from these six active units. Of the six active Skylab QCMs, four were mounted on the Apollo Telescope Mount (ATM) truss. These QCMs were designated as EREP (Earth Resources Experiment Package) QCMs and faced four directions. Two further QCMs were mounted on the ATM sun shield, intended to measure return flux. The location of this complement of 6 active QCMs and the Skylab configuration is shown on Fig. 3.

The two QCMs on the ATM sun shield did not record mass accumulation. These QCMs had no spacecraft surfaces within their field-of-view.

Fig. 4 shows a plot of the Skylab EREP QCMs for Skylab mission phases SL-1 and SL-2. During SL-1/2 rendezvous and fly-around, the QCM facing the Skylab Orbital Workshop (OWS) recorded $0.14\mu\text{g}/\text{cm}^2$ of deposition while the QCM directed to the Command and Service Module (CSM) recorded $0.556\mu\text{g}/\text{cm}^2$ of deposition, consistent with the exposure to CSM thruster plumes.

Measurements during the soft-dock maneuver showed an accumulation of $2.3\mu\text{g}/\text{cm}^2$ on the CSM QCM, followed by a decay of $0.162\mu\text{g}/\text{cm}^2$. The OWS QCM recorded an increase of $0.108\mu\text{g}/\text{cm}^2$ from the docking. These measurements were attributed to plume induced contamination from Skylab reaction control system (RCS) thruster firings. The remaining QCMs recorded $0.09\mu\text{g}/\text{cm}^2$ of deposition.

During the hard docking the CSM QCM recorded of deposition of $16.7\mu\text{g}/\text{cm}^2$ during the Stand-up Extravehicular Activity (SEVA) and docking. This significant accumulation was followed by decay at a rate of $6.15\mu\text{g}/\text{cm}^2/\text{h}$. The OWS QCM recorded $0.323\mu\text{g}/\text{cm}^2$ during this period. Rapid mass accumulation and decay

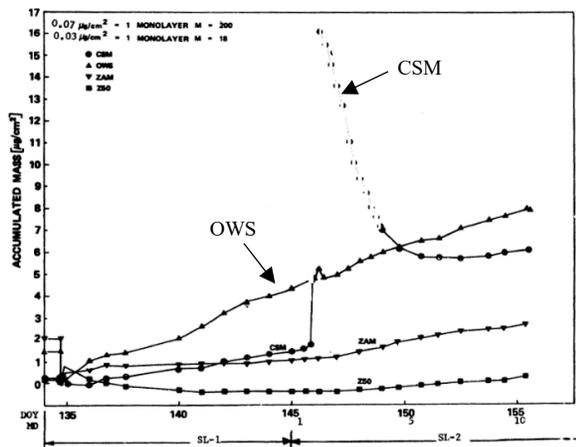


Fig. 4. Skylab SL-1/2 EREP QCM measurements

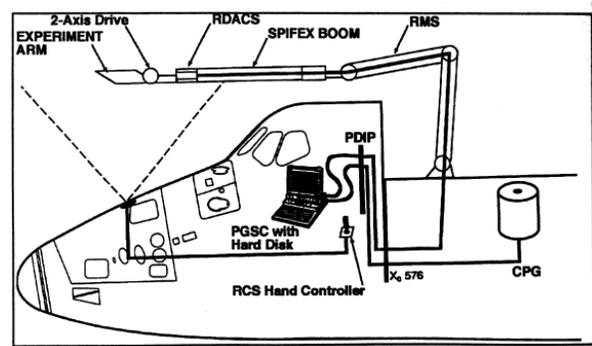


Fig. 5. SPIFEX Flight Experiment Configuration

was observed in conjunction with thruster firings. Surprisingly, during undock and fly-around (day 173), no accumulation was recorded on the EREP and ATM QCMs. However, there were RCS firings toward the ATM. No deposition comparable to those of the SL-1/2 approach was recorded during SL-3 rendezvous and docking, consistent with the reduced usage of the RCS engines for initial braking during approach. The CSM, AMB and Z50 QCM units recorded respectively 0.6 , 0.9 and $0.9\mu\text{g}/\text{cm}^2$ of accumulation from the fly-around.

While Skylab QCMs recorded a number of mass deposition events attributed to thruster firings, no correlations with thruster firing operational data were documented, and no plume induced contamination models derived from the Skylab data were published. However, Skylab demonstrated that QCMs could be used to characterize plume induced contaminant deposition and evaporation.

2.2.2 SPIFEX

The purpose of the Shuttle Plume Impingement Flight Experiment (SPIFEX) [30], [31], flown on the STS-64 Space Shuttle mission in September 1994, was to produce measurements of plume impingement forces, heating effects, static/dynamic pressures and plume induced contamination.

SPIFEX samples were mounted on the SPIFEX boom that was attached at the end of the Shuttle robotic arm (Remote Manipulator System, or RMS). Fig. 5 shows the configuration of the Orbiter, the Remote Manipulator System (RMS) and the SPIFEX boom used on this experiment.

Both Shuttle Primary Reaction Control System (PRCS) and Vernier Reaction Control Systems (VRCS) engines were fired 101 time in total, with varying pulse widths, distances and angles off-plume centerline.

Materials witness coupons (aluminum and Kapton®) were used in the characterization of plume induced contamination and droplet impact features. Data on plume induced contamination of SPIFEX witness coupons was obtained by Scanning Electron Microscopy

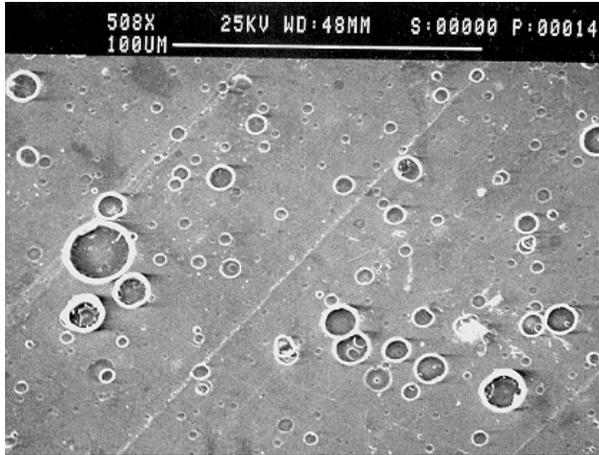


Fig. 7. Droplet impact features on a Kapton® witness sample

(SEM) and X-ray Photoelectron Spectroscopy (XPS) analyses of witness coupons.

From the XPS analysis, the permanent plume induced contaminant deposit was estimated at 1.5mg/cm². Elemental composition of the contaminant layer showed presence of nitrogen compounds (binding energy from the XPS analysis corresponds to a high-oxidation nitrogen slat, likely MMH-nitrates), iron and chromium.

Surface damage was confirmed with SEM imaging of aluminum and Kapton® witness coupons. The damage was a product of high-speed droplet impacts, and in the case of the Kapton® samples, also a product of the chemical reaction between the substrate and the propellant. Fig. 7 shows selected features recorded on a Kapton® sample.

The craters observed on the Kapton® sample are the result of impingement of chemically reactive liquid droplets (MMH dissolves Kapton®). Hence, the observed features are a product of both high-speed droplet impact as well as the chemical reaction between MMH and the Kapton® substrate. This chemical reactivity is likely to produce features of increased diameter when compared to non-reactive substrates with similar mechanical properties. The impact features ranged from 1-40µm in diameter and are not visible to unaided eye. From analysis of SEM images, 2,200 impacts/mm² were observed on Kapton® samples. The affected area represents approximately 10% of the total surface area of substrate.

Table 1: Size and number density of droplet impact features observed on aluminum sample

Feature	Diameter, in µm	Number per mm ²
Small craters	≤ 4	449
Medium craters	5 ... 10	231
Large craters	11 ... 20	60

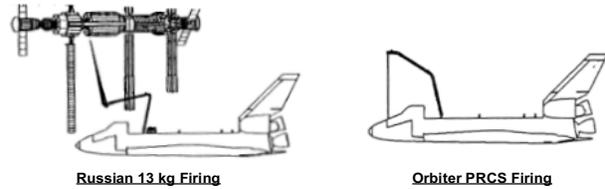


Fig. 6. PIC flight experiment configuration during Russian 130N and Shuttle PRCS thruster firings

The SPIFEX aluminum witness coupons show impact craters produced only by high-speed droplet impacts (aluminum is not dissolved by the unburned propellant, as in the case of Kapton®). The observed craters range from 1-20µm in diameter and are also not visible to unaided eye. From analysis of SEM photos, 740 impacts/mm² were observed on the aluminum sample. The pitted area represents approximately 4% of the total surface area of the sample. Table 1 details the features observed on the aluminum surface.

2.2.3 Plume Impingement Contamination (PIC) flight experiment

The purpose of the Plume Impingement Contamination (PIC) flight experiment [31], conducted during the STS-74 Space Shuttle mission in 1995, was to measure plume induced contamination produced by U.S. and Russian thrusters (3.87kN Orbiter F3U PRCS and Russian 130N model 11D428A-16), and to provide on-orbit data for the development of plume induced contamination and erosion models for the Space Station Program. QCMs were used to measure plume induced mass deposition, on the plume centerline, for each thruster tested. Data gained from this experiment was critical in the development of the Space Station bipropellant plume contamination model [24] for the Russian 130N engine, which is used extensively on the Russian Segment of the ISS, as well as the Progress and Soyuz vehicles. Fig. 6 shows the configuration of the Orbiter and the Remote Manipulator System (RMS) for the Russian 130N and the Orbiter PRCS thruster firings.

Measurements in the plume of the Russian 130N thruster were made for ten sets of ten 100ms pulses at a distance of 12.2m, and measured QCM frequency is

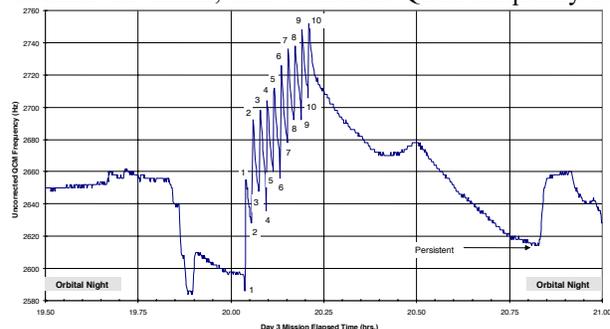


Fig. 8. PIC QCM frequency measurements for the Russian 130 N model 11D428A-16 thruster

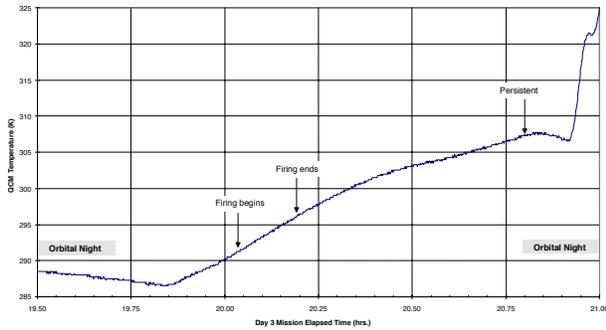


Fig. 9. PIC QCM temperature measurements for the Russian 130 N model 11D428A-16 thruster

shown in Fig. 8. The ten spikes correspond to the ten sets of thruster firings and each spike corresponds to ten 100ms pulses, with 700ms off-time between pulses. There was a one-minute rest period between individual sets. Analysis of the raw data shows rapid evaporation of exhausted contaminants during the rest period, during which an average of 79.3% of the deposited mass evaporated. This observed evaporation is due to the composition of the contaminant deposit and the temperature of the QCM, which is shown in Fig. 9. The average temperature seen during the test of the Russian 130N thruster was 293K.

The total increase in frequency, Δf , summed over the ten rising slopes associated with firings is of 580Hz, which translates into an initial net mass deposition rate of $0.256\mu\text{g}/(\text{cm}^2\text{s})$. The permanent mass deposition rate recorded was $0.0193\mu\text{g}/(\text{cm}^2\text{s})$. The evaporation of the initial contaminant deposit during the measurement period of approximately 0.5h was pronounced. The ratio of final (permanent) deposit to the initial deposit was 0.075.

Orbiter PRCS thruster measurements were taken for two sets of ten 80ms pulses at a distance of 10.6m on plume centerline, with a 45s rest between sets. A QCM was canted at an angle of 35° with respect to the centerline flux. Fig. 10 shows the QCM frequencies obtained for the PRCS thruster firings.

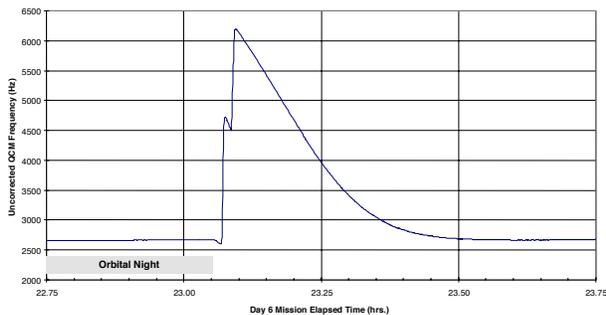


Fig. 10. PIC QCM Frequency Measurements for the Orbiter PRCS

The total frequency increase, Δf , excluding the observed evaporation during the rest period between firing groups, was 3802Hz. This corresponds to a total mass deposition of $20.515\mu\text{g}/\text{cm}^2$ when corrected to account for the effect of the 35° incidence angle between the plume mass flux vector and the QCM active surface. The initial deposition rate from the Orbiter PRCS thruster was $12.82\mu\text{g}/(\text{cm}^2\text{s})$ at 10.6m. The difference between the frequency prior to the firings and the final frequency is 72 Hz. This corresponds to a permanent mass deposition of $0.384\mu\text{g}/\text{cm}^2$ for the 1.6 seconds of total on time, or a net mass deposition rate of $0.24\mu\text{g}/(\text{cm}^2\text{s})$. The evaporation of the initial contaminant deposit during the measurement period was more pronounced than for the Russian 130N thruster. The ratio of final (permanent) deposit to the initial deposit was 0.019 for the Orbiter PRCS.

Impact features from droplet impacts during the PIC flight experiment were observed on the camera lens of the Orbiter Remote Manipulator System (RMS). The observed features were consistent with observations from the SPIFEX flight experiment. The impact features on the camera lens (fused silica) are not visible to unaided eye and did not degrade the quality of the video during the mission. From analysis of SEM images, 61 impacts/ mm^2 were observed during the survey of the lens surface. The pitted area represents approximately 1.8% of the surface area of camera lens (and a result of 120 pulses). Table 2 details the results from the SEM survey of the camera lens.

Table 2: Size and number density of droplet impact features observed on the PIC camera lens

Feature	Diameter, in μm	Number per mm^2	Total number of craters
Small	2 ... 5	21	17790
Medium	6 ... 13	30	25830
Large	14 ... 24	10	8895

2.2.4 Astra-1 flight experiment

In the early 80's, a team of investigators from NPO-Energia (S.P. Korolev Rocket and Space Corporation), Institute of Applied Geophysics (IPG) and Moscow Aviation Institute (MAI) developed the first Russian flight experiment to study spacecraft induced environments, designated Astra-1 [32].

Astra-1 was mounted on the Salyut-7 Space Station. Two QCMs (QCM21 and QCM24) were mounted on the Salyut-7 Crew Compartment and oriented along the Salyut-7 X-axis ($\pm X$) and two additional QCMs (QCM31 and QCM34) mounted on the Docking and Transfer Compartment.

The measurements from the Astra-1 QCMs were used to calculate average deposition rates for two flight conditions: quiescent and non-quiescent. The non-quiescent conditions were a result of the docking of the

Soyuz-T6 vehicle on June 25, 1982. During the quiescent period, Salyut-7 contaminant deposition levels ranged from 4.2×10^{-6} to $9.2 \times 10^{-6} \mu\text{g}/(\text{cm}^2\text{s})$. During the non-quiescent period, deposition rates of 5.8×10^{-5} to $7.8 \times 10^{-5} \mu\text{g}/(\text{cm}^2\text{s})$ were recorded during the Soyuz-T6 docking and approximately $1.4 \times 10^{-5} \mu\text{g}/(\text{cm}^2\text{s})$ after docking. The data from Astra-1 demonstrated measurable levels of plume induced contamination during docking with the Soyuz spacecraft, and prompted the development of a follow-on flight experiment: Astra-2.

2.2.5 Astra-2 flight experiment

The Astra-2 flight experiment, flown on the Mir Space Station, utilized two QCMs (QCM1 and QCM2) installed in a pressurized unit attached to a 2m arm on the Mir Spektr module [32]. The Astra-2 QCMs were not thermally controlled and sensor operating temperatures were not measured. However, Astra-2 operating temperatures were expected to remain above 0°C . The location of the Astra-2 QCMs is shown on Fig. 11. The

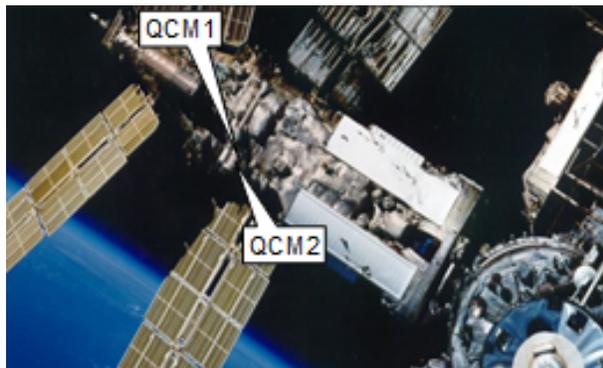


Fig. 11. Astra-2 QCM locations on the Mir space Station Spektr Module

Astra-2 experiment was deployed in May 1995, 48 hours after the launch of Spektr, and contaminant deposition measurements were made over a period of two years. However, QCM1 went out-of-range in August 1995 and did not yield usable measurements from this point. QCM2 worked more reliably, and measured a steady rate of mass accumulation.

Data obtained from Astra-2 QCM2 are shown in Fig. 12. No significant changes in contaminant deposition rates were recorded during Shuttle, Soyuz and Progress dockings, or during the PIC flight experiment, likely due to the lack of proximity and line-of-sight to the visiting vehicles and Mir thrusters, and low sensitivity of the QCMs. However, Astra-2 results demonstrate the complex character of on-orbit induced environments and contamination. Developing an understanding of these processes requires detailed knowledge of spacecraft orientation, solar illumination, and the dynamics of the thermal environment of the spacecraft and sensors.

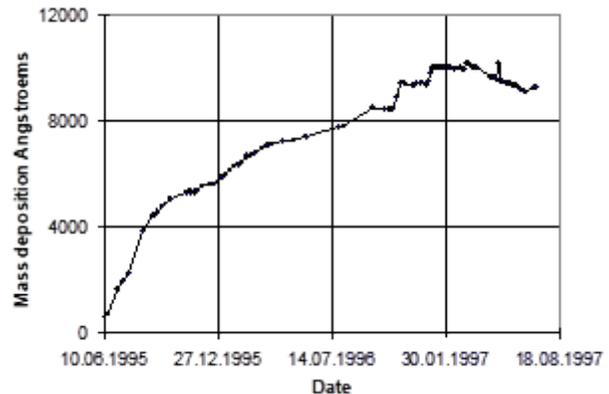


Fig. 12. Astra-2 QCM measurements from 1995-1997

2.2.6 Dvicon flight experiment

The Russian Dvicon flight experiment [33] was carried out on the Mir space station in November 1998 to characterize contamination of the external surfaces, induced by attitude control thruster firings. This flight experiment was developed when flight imaging indicated deposits of a dark, brownish appearance: liquid residue after attitude control thruster firings, with slow evaporation characteristics.

One of the objectives of the Dvicon flight experiment was to return a sample with plume contamination taken from the area surrounding attitude control thrusters on the Zvezda module (Mir Core Block) for analysis of chemical composition. The samples were taken from a region exposed to the back-flow region, behind the nozzle exit plane, Fig. 13. The samples were collected during a Russian EVA using a set of four-layer cotton wipes, stored in double hermetically sealed containers, returned to the Mir habitable volume, and later to Earth

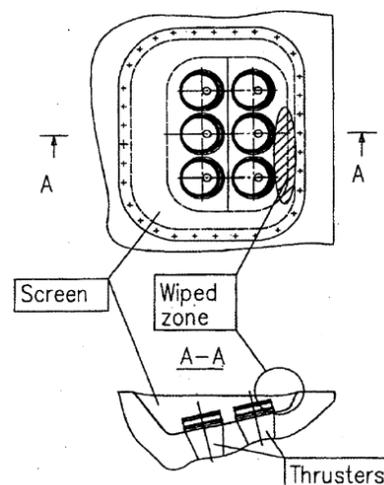


Fig. 13. Dvicon sampled area on Mir space station attitude control thrusters, behind thruster nozzle exit plane

for analysis. The collected residue was confirmed to be a liquid, having soaked through all four layers of the wipes.

The measured contaminant mass was estimated at 3.2g. A correlation between the measured mass of contaminants and thruster firings was not possible as the sampled surface was exposed to multiple attitude control thruster firings over a period of 12.5 years, estimated to be on the order of 150,000. The composition of the contaminants was determined through thermal-desorption and gas chromatography-mass spectroscopy (CGMS). The ratio of organic to inorganic compounds was approximately 45:50, and the inorganic portion contains NO and NO₂ in a ratio of approximately 1:1. The organic composition was consistent with UDMH/NTO fuel-oxidizer reaction products summarized in Table 3.

As part of the Dvicon flight experiment, a materials sample tray was mounted adjacent to the attitude control thrusters and exposed to thruster firing over a period of 9 months prior to retrieval and returned to Earth for analysis. Also exposed was a piece of cotton braid that was returned for analysis. Fig. 14 shows the arrangement

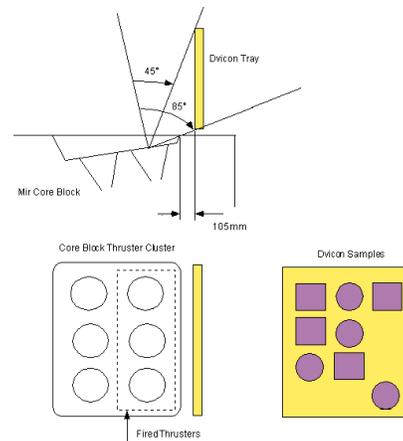


Fig. 14. Dvicon materials samples exposure tray

of the Dvicon tray with respect to the attitude control thrusters.

Analysis of the returned tray showed a FORP deposit of 0.2µm thickness, on average, which was attributed to plume induced contamination. Several of the compounds detected in the swipe, tray and braid, were derivatives of hydrazine, containing amine and nitroso groups and FORP. These compounds were of toxic nature and relevant in the development of EVA Flight Rules to mitigate contamination risks associated with the ingress into the habitable volume.

Table 3: Composition of plume induced contamination residue from the Russian Dvicon flight experiment

Compounds	m/z	%
NO	30	8.97%
CO2	44	9.52%
Ammonia	17	16.45%
Water	18	30.58% *
Dimethylamine	44	1.75%
Trimethylamine	58	0.50%
Formaldehyde dimethyl hydrazone	42	0.68%
Isocyanate derivative	56	8.30
Acetone dimethyl hydrazone (UDMH)	100	0.33%
Nitrosodimethylamine	74	3.87%
Dimethyl aminoacetonitrile	83	3.10%
N,N-dimethylformamide	73	1.06%
4-methyl pyrimidine	94	0.18%
Dihydrazone of hydrazine and acetone (hydrazine)	56	3.79%
1-methyl-1H-1,2,4-triazole	83	5.65%
4,5-dihydro-3,4,5-trimethyl-1H-pyrazole	97	0.67%
N,N-diethyl acetamide	115	0.42%
1H,1,2,4-triazole 3,5-diamino	99	1.14%
Heterocyclic nitrogen-containing compound	107	0.07%
Imidazole	108	0.19%
1H-1,2,4-dimethyl triazole	97	0.38%
6-methyl,4,5-diamino pyrimidine	124	0.37%
N,N-dimethyl urea	97	0.01%
N,N-dimethyl urea derivative	102	1.48%
1H-pyrazole 4-nitro	113	0.39%
UDMH derivative	121	0.09%
UDMH derivative	134	0.04%

*Water may have been caused by sorption from air.

2.2.7 Russian Kromka flight experiment

The Kromka flight experiment [34] was designed to evaluate the efficacy of a plume contamination shield design developed by RSC-Energia. These devices are

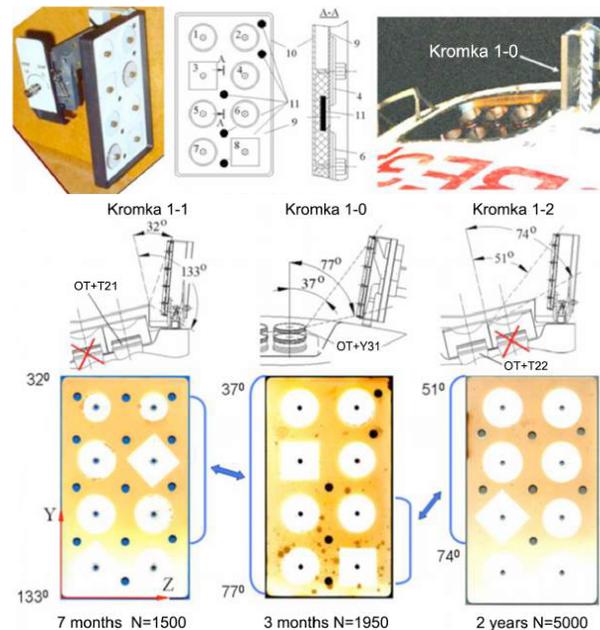


Fig. 15: Kromka configurations on the Service Module of the International Space Station

known as “GZU” (gas-dynamic protective devices), and they were deployed and installed on the Russian Service Module of the International Space Station in 2002. Kromka flight experiment trays were deployed in stages, one stage prior to GZU installation to establish a baseline (Kromka 1-0), and in three stages post-GZU installation (Kromka 1-1, 1-2 and 1-3; cf. Fig. 15).

The Kromka trays demonstrated that the GZU design was effective in significantly reducing the liquid-phase of the thruster plumes to an angle of approximately 60° from plume centerline.

3. Roadmap for future measurements

Though the threat of plume induced contamination from mono- and bipropellant chemical thrusters has long been realized and various programs were set up to build reliable tools and procedures for plume contamination prediction and control, no satisfactory understanding of the processes that promote the various observed contamination phenomena has been reached. This arguably is due to the complexity of the problem, requiring (perhaps not only) an understanding of fluid mechanics, molecular transport, surface physics, space physics, chemistry and space engineering.

In this section we identify the persistent main knowledge gaps in plume contamination research and propose test programs to appropriately address them.

3.1 Ground-based chamber testing

3.1.1 Improvements from past testing programs:

With the inauguration of the DLR High-Vacuum Plume Test Facility for Chemical Thrusters (STG-CT) [36] a test environment specifically designed for thruster plume analysis became available. The liquid helium driven cryo-pump, which encloses the entire 10m³ test section, can adsorb hydrogen (a main plume constituent) and thus maintain a vacuum better than 10⁻⁵mbar even during thruster operation. The design of the chamber permits studying the free expansion of plumes from pulsed mono- and bipropellant thrusters with up to about 20N thrust (on-times are limited by the power to which the cryo-pump is subjected). A rotatable thruster mount enables dedicated measurements in the plume back-flow. Standard diagnostic equipment, such as (cryo-proof) temperature-controlled QCMs, high-speed *in-situ* mass spectrometer and means to support material samples are available.

3.1.2 Knowledge gaps

A major concern with previous studies on plume induced contamination is the adequacy of the chamber background pressure *during* thruster operation, which depending on the thruster and the chamber’s pumping system may be many orders of magnitude higher than immediately before firing. Previous studies indicate [13], that a background pressure significantly larger than

10⁻⁵mbar will influence the plume expansion and thus potentially the contaminant flux (see also [35] for a brief discussion on the subject). STG-CT at DLR Göttingen is presently the only operational facility capable to maintain high-vacuum while firing thrusters (up to about 20N thrust, pulse mode), and comparison with a twin experiment in a conventionally pumped vacuum chamber would give insight into which thruster plume induced contamination phenomena are perhaps less sensitive to the background pressure and can safely be investigated in the cheaper and easier to operate conventional chamber.

Perhaps related to the above is the fact that very little data exists on potential spacecraft self-contamination due to gas or droplets in the plume back-flow. Some bipropellant engines produce a fuel film on the nozzle wall when the latter is still cool. That film was observed to reach the nozzle lip, from which it splatters into a domain with high angle from the plume axis. While previous experiments observed a droplet density distribution proportional to the gas density near the plume centerline, the Kromka (Sec. 2.2.7) and Dvicon (Sec. 2.2.6) flight-experiments have shown that such a relationship must not be assumed for higher angles off centerline, and certainly not in the backflow.

Dedicated and reliable experiments on the temporal and size distribution of droplets and particulates in the plume during start-up, steady-state and shutdown phases are sorely needed to inform models for engineering contamination analysis.

During the plume investigations at Arnold Engineering Development Center in the late 1970’s (cf. [13], [16], [17]) suspicion was raised that the interplay of construction details of the thruster, notably the valves dribble volume, the injection mechanism, and the operation (pulse cycles) of the thruster work together to impact the production of droplets in bipropellant engines. It is today not entirely clear if or how well a general comparison of different thruster types (e.g. by a scaling argument) is possible, and which parameters drive e.g. droplet production the most. While a mapping of observed contamination properties from different thrusters may give trends to inform engineering models, sensitive missions require dedicated experiments with actual mission thrusters. This however is not always possible in ground-based facilities, and one would need to resort to thruster specimen of a similar construction.

We point out here that the last systematic plume contamination study is now about 30 years old, most of the thrusters described in this review are now out of production, and that it is mandatory to update the data on (potential) contamination induced from present day orbital control thrusters. From the authors’ discussion with contamination analysis experts in industry and agencies, a systematic study must involve an analysis of the chemical and mechanical interaction of plume

contaminants with relevant materials, such as optical and structural components.

3.1.3 Proposed test objectives

Two main paths for future test can be identified: mission-specific investigations, in which a very particular setup and thruster mode of operation are studied, and systematic investigations, that support development of general models for thruster plume induced contamination (though the results of mission-specific tests may of course support and enhance the systematic investigations, if not enable them).

An experiment-based contamination model with clearly quantified uncertainties is helpful in reducing design margins and builds trust in an analysis and a systematic investigation would comprise of:

- Selection of baseline engine, identifying currently popular thrusters
- Defining representative modes of operation
- Characterizing temporal and spatial expansion of thruster plume fluxes, gaseous, liquid or particulate, using in-situ mass spectrometry and light scattering/attenuation techniques.
- Exposing representative material samples (metals, plastics, coatings, paints) to the thruster plume at standardized locations, analyzing any damage or functional changes of the surfaces. The material sample coupons would be placed at various distances and angles off plume centerline, but perpendicular to the plume stream lines. The observed damage (craters or particle penetration) will be used to identify contaminant distribution, density and size, as was done with the SPIFEX samples (cf. Sec. 2.2.2 and literature referenced therein). Permanent contaminant coatings are characterized with spectroscopic techniques to measure the contamination-induced change to thermo-optical properties.

All of the above-mentioned techniques are available and are readily implemented in STG-CT.

An extended analysis would involve characterizing secondary contamination effects that arise from interaction of the contaminants with a representative space environment or with previously deposited, non-plume contaminants. This would encompass stability/volatility of contaminants and interaction with UV-light or atomic oxygen, for example.

To gain further confidence in the empirical models resulting from these experimental activities (or to point out their weaknesses), we strongly advocate comparison to on-orbit data.

3.2 On-orbit tests

While many flight experiments have been flown to characterize plume induced contamination and erosion,

the resulting measurements were limited to older MMH/NTO and UDMH/NTO thruster designs and still quite limited in the characterization of several parameters:

- Effects of pulse width (pulse firing duration)
- Distribution as a function of angle off-plume centerline
- Liquid phase distribution (droplet number density, droplet sizes and velocities)
- Liquid phase composition
- Evaporation characteristics of plume induced deposits over a range of surface temperatures
- Composition of plume induced deposits

The existing dataset from flight experiments supported the development of plume contamination and erosion models; however, the knowledge gaps limit the applicability of these models.

Measurements for newer thruster designs (e.g., LOX/hydrocarbon, LOX/propane, LOX/methane, Peroxide/RP1, NTO/propane) should be targeted in future flight experiments.

The International Space Station could be leveraged for such measurements since it is visited by a wide range of visiting vehicles employing a variety of thruster designs.

3.2.1 Capabilities for use of ISS as a test platform

The ISS, as an orbital platform for science, can be utilized for a comprehensive characterization of plume effects, including plume induced contamination and erosion.

ISS robotic assets, such as the Space Station Remote Manipulator System (SSRMS), can used to deploy, locate and orient an instrumentation package. Ideally, this package would consist of at least four QCMs, a mass spectrometer, and witness coupon cartridges (for return to Earth).

3.2.2 Improvements from past testing programs

An important improvement from past flight experiments would be to add the capability to adjust sampling frequencies on QCMs. Higher sampling frequencies would greatly improve the sensitivity of measurements for short pulses, while lower sampling frequencies offer greater resolution for measurements of evaporation.

Further, the capability to perform QCM thermogravimetric analysis (QTGA) would augment mass spectrometer measurements and support identification of chemical compounds. CQCMs cooled by liquid helium, operating near 4K, can condense and collect both gas and liquid-phase effluents during firings for quantification of the initial deposit. This can be followed by QTGA to support characterization of the

Table 4: Knowledge gaps and how to address them

Knowledge Gaps	Proposed methods
Effect of pulse width (transient effects from start-up and shut-down)	<ul style="list-style-type: none"> • QCMs with high-sampling frequency • mass spectrometry
Spatial distribution (distribution as a function of angle off-plume centerline)	<ul style="list-style-type: none"> • QCM sensors and materials witness coupons locations from plume centerline to the back-flow region
Liquid-phase distribution (droplet number density, droplet sizes and velocities)	<ul style="list-style-type: none"> • Materials witness coupons locations from plume centerline to the back-flow region
Liquid-phase composition	<ul style="list-style-type: none"> • Mass spectrometry
Evaporation characteristics of plume induced deposits over a range of surface temperatures	<ul style="list-style-type: none"> • QCM measurements
Composition of plume induced deposits	<ul style="list-style-type: none"> • QTGA • Mass spectrometry

deposited material. A mass spectrometer can be used during QTGA to support characterization of species.

Measurements of deposit residence times, sublimation and evaporation rates can also be accomplished by raising and holding CQCMs at temperatures that match flight conditions.

Characterization of droplet number density, size and velocity are also highly desirable. This can be accomplished indirectly through the use of witness coupons; however, real-time measurement capability is preferred.

The key areas with knowledge gaps and proposed methods to address them are summarized in Table 4.

4. Conclusions

Space mission science objectives and evolving scientific instrumentation place ever more challenging constraints on the control and characterization of contamination. Plume induced contamination is a major contamination vector for all types of space exploration missions: orbiters, lander, rovers and sampling missions.

This paper reviews the existing plume induced contamination and erosion measurements on which current models rely. The data available from both, ground-based chamber tests and on-orbit flight experiments, is very limited. Most of the measurements obtained in ground-based vacuum facilities were conducted in the decades of the 1970s and 1980s, in vacuum environments that did not support the required thruster plume expansion.

Flight experiment data from Space Shuttle, Mir and ISS flight experiments provided measurements of plume induced contamination as well as droplet impact damage, but give only integral account of liquid-phase

contamination at coarse spatial resolution, and are limited to three thruster designs, two of which no longer fly.

From the reviewed data, we identify several unexplored aspects pertaining to plume induced contamination, such as the impact of transient effects (thruster start-up and shutdown) on the production and distribution of droplets and particulates, the spatial, temporal and size distribution of droplets and particulates in the plume during start-up, steady-state and shutdown phases, the chemical composition of plume effluents, such as partial combustion/decomposition reaction products and the previously observed non-volatile residue, and the optical properties of plume deposits. We identify the need for further development in thruster plume modelling as well as ground-based and on-orbit testing, and propose a road map to improve plume induced contamination predictive capabilities by lowering model uncertainties.

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