On-Orbit Quartz Crystal Microbalance Measurements of Molecular Deposition on Russian and U.S. Space Stations

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Abstract. This paper presents Russian and U.S. on-orbit measurements of molecular flux deposition onto quartz crystal microbalances (QCMs). QCMs have been used to characterize the induced environment on Russian and U.S. Space Stations. These measurements were crucial in understanding actual induced molecular deposition levels and the effects of solar exposure on QCM measurements and spacecraft contaminant sources, as well as the importance of contamination control to ensure successful science operations. Further, collaboration between both sides has been an important science benefit of the International Space Station Program.

INTRODUCTION

A spacecraft generates its own induced environment while in space. This induced environment is unique to each spacecraft. Further, interactions of natural space environments with the spacecraft's induced environment produce a variety of effects on space systems. These effects directly impact spacecraft systems and scientific equipment, and affect mission performance.

Spacecraft induced environment disciplines have gained considerable importance over the past twenty years, both in Russia and in the United States. Since the mid-seventies, scientists from both countries, engaged in space environment effects research, came to the same conclusion: the successful study of spacecraft induced environments is impossible without research under actual spaceflight conditions.

Both Russia and the United States have successfully flown Quartz Crystal Microbalances (QCMs) on space stations. This paper summarizes QCM measurements on Skylab, Salyut-7, Mir and ISS.

SKYLAB QCM MEASUREMENTS

The Skylab space station was launched in May 1973 and it operated unmanned for 9 months, until February 1974 (SL-1). It was manned for a total of 171 days by three separate crews, SL-2 (28 days), SL-3 (59 days) and SL-4 (84 days). Eight QCMs were installed on Skylab to measure molecular deposition from induced environments. [1, 2] Two of the eight QCMs were not activated during flight so all Skylab QCM measurements were derived from the six remaining units.

Of the six active Skylab QCMs, four were mounted on the Apollo Telescope Mount (ATM) truss on the –Z side of the Multiple Docking Adapter, MDA. These QCMs were designated as EREP QCMs (EREP stands for Earth Resources Experiment Package). One facing +X (toward the Command and Service Module, designated CSM +X), one facing –X (toward the Orbital Workshop, designated OWS -X) and two facing –Z (nadir orientation when the vehicle was in the Z local vertical orientation, one designated AMB –Z and Z50 -Z).

Two QCMs were mounted on the ATM sun shield and designated HCO and NRL-B. These QCMs were intended to measure return flux and had no spacecraft surfaces within their field-of-view. Both were oriented in the +Z direction (zenith orientation when the vehicle was in the Z local vertical orientation). The location of this complement of 6 active QCMs and the Skylab configuration is shown on Figure 1.

During the SL-1 unmanned phase, the EREP QCMs recorded the following deposition levels (Figure 2 shows a plot of the Skylab EREP QCMs for SL-1/2): 0.34 $\mu g/cm^2/day$ on OWS –X, 0.21 $\mu g/cm^2/day$ on CSM +X, 0.03 $\mu g/cm^2/day$ on AMB +Z and no accumulation on Z50. The two QCMs mounted on the ATM sun shield, HCO and NRL-B did not record mass accumulation during this period.

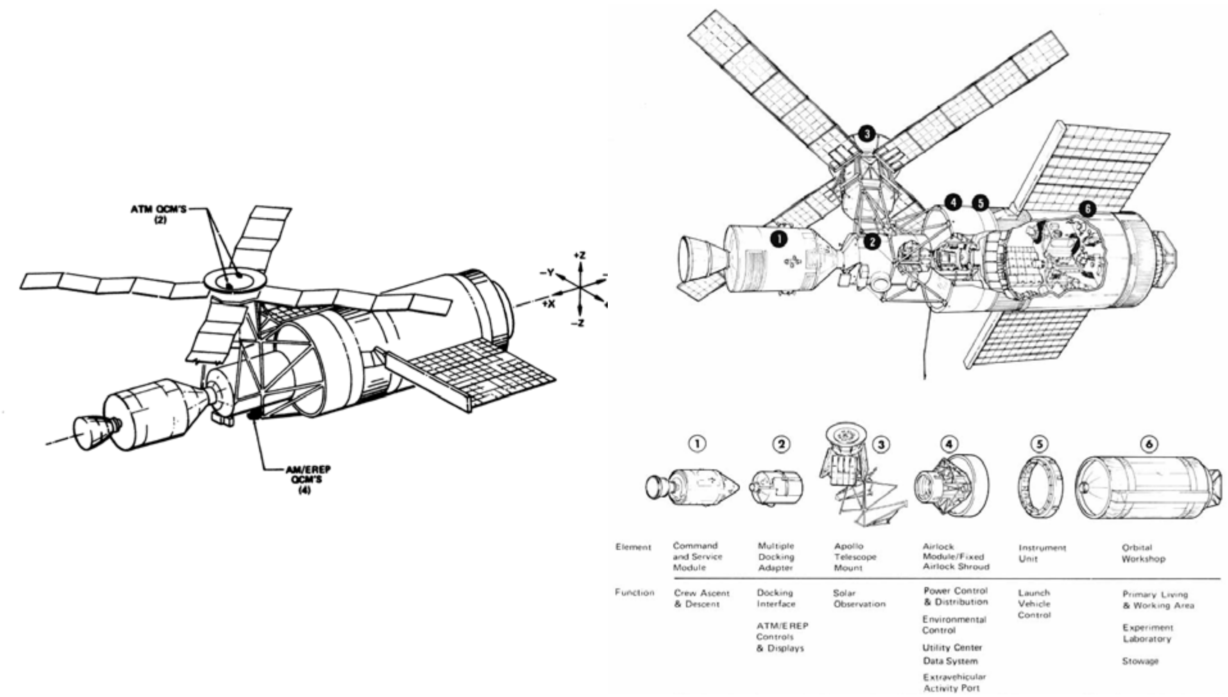


FIGURE 1: Skylab QCM Locations and Configuration.

During SL-1/2 rendezvous and fly-around, the OWS QCM recorded 0.14 μg/cm^2 of deposition while the CSM QCM recorded 0.556 μg/cm^2 of deposition (which is consistent with the exposure to the CSM).

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

During the hard docking the CSM QCM recorded a deposition of 16.7 μg/cm^2 during the Stand-up Extravehicular Activity (SEVA) and docking. This accumulation was followed by decay at a rate of 6.15 μg/cm^2/hr. The OWS QCM recorded 0.323 μg/cm^2 during this period. Rapid mass accumulation and decay was observed in conjunction with thruster firings.

During the SL-1/2 manned phase, the CSM QCM continued to record decay until around day 152. The OWS QCM continued to record collection at a rate similar to the accumulation rate during SL-1. The AMB QCM recorded an increase in accumulation rate, from 0.097 μg/cm^2/day to 0.216 μg/cm^2/day, and the Z50 QCM started to show an accumulation rate of 0.097 μg/cm^2/day. The increase in the AMB and Z50 QCM measurements during this period were peculiar as the CSM was not in the field-of-view of these QCMs.

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 comparable depositions to those of the SL1/2 approach were recorded during SL-3 rendezvous and docking (day 209). This is 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 μg/cm^2 of accumulation from the fly-around.

EREP QCM measurements were also made during the SL-3 manned phase. Measurements made during the initial period (days 209-219) show the effect of materials outgassing from the new Command and Service Module. The CSM +X QCM deposition rate increased by a factor of 3 while the deposition on the –X and –Z QCMs increased by a factor of 2.

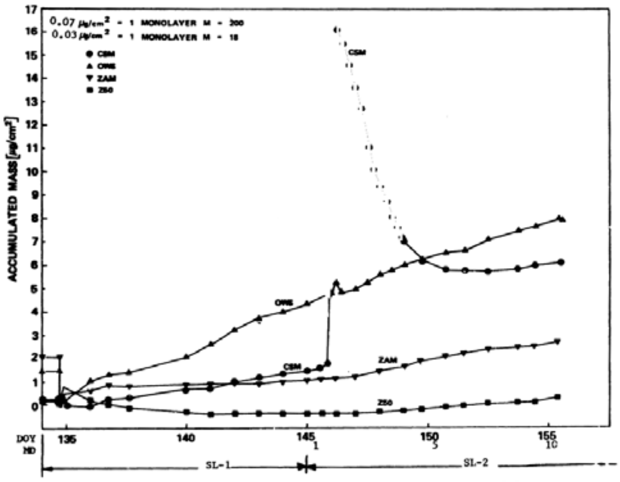


FIGURE 2: SL-1/2 EREP Long-Term Deposition.

During the SL-1 unmanned phase, the EREP QCMs recorded the following deposition levels (Figure 2 shows a plot of the Skylab EREP QCMs for SL-1/2): 0.34 μg/cm^2/day on OWS –X, 0.21 μg/cm^2/day on CSM +X, 0.03 μg/cm^2/day on AMB +Z and no accumulation on Z50. The two QCMs mounted on the ATM sun shield, HCO and NRL-B did not record mass accumulation during this period.

ASTRA-1 FLIGHT EXPERIMENT ON SALYUT-7

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 (Soviet) flight experiment to study spacecraft induced environments: Astra-1.

The Astra-1 (or "UMR-Astra") apparatus was mounted on the Salut-7 Space Station. Two QCMs (designated QCM21 and QCM24) were mounted on the Salyut-7 Crew Compartment and oriented along the Salyut-7 X-axis (±X) and two additional QCMs (designated QCM31 and QCM34) mounted on the Docking and Transfer Compartment. The QCM's were built by IPG and MAI, with a working range of $4 \cdot 10^{-8}$.to.$1.6 \cdot 10^{-4}$ g/cm^2. Initial QCM readings were: $1.0 \cdot 10^{-7}$, $1.7 \cdot 10^{-6}$ and $2.8 \cdot 10^{-6}$ g/cm^2.

Initial measurements were made after launch on June 4, 1982, when sensors were isolated from the ambient environment and on June 14, 1982, just after removal of the protective cover. QCM21, QCM24, QCM34 recorded the following deposition levels: $2.6 \cdot 10^{-6}$, $2.9 \cdot 10^{-6}$ and $4.7 \cdot 10^{-6}$ g/cm^2. QCM31, and later on QCM34, became saturated and stopped recording mass accumulation.

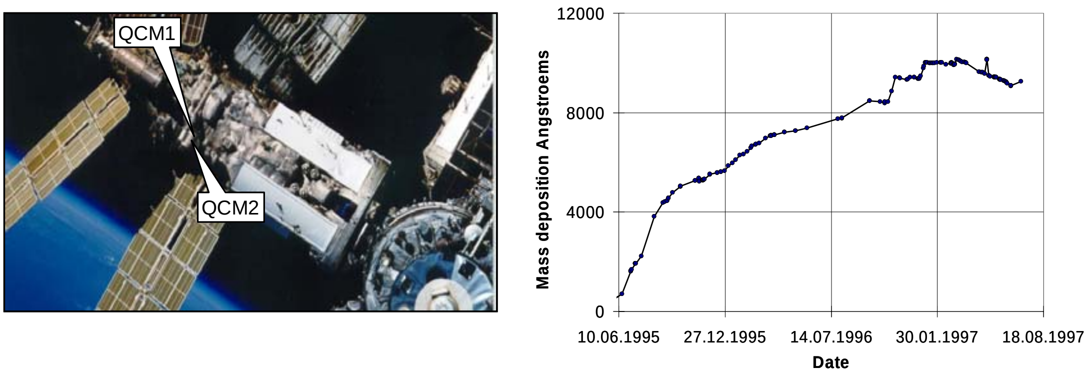
Unfortunately three days after the start of systematic switching of the apparatus (June 27, 1982) QCM21 and QCM24 (12 hours later) also became saturated and stopped making measurements. These QCMs saturated with a molecular deposit on the order of $1 \cdot 10^{-5}$ g/cm^2.

This data can be 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 to $9.2 \cdot 10^{-12}$ g/(cm$^2 \cdot$sec). During the non-quiescent period, deposition level of 5.8 to $7.8 \cdot 10^{-11}$ g/(cm$^2 \cdot$sec) during the Soyuz-T6 docking and ~$1.4 \cdot 10^{-11}$ g/(cm$^2 \cdot$sec) after docking.

ASTRA-2 FLIGHT EXPERIMENT ON MIR

Two QCMs were used in the Astra-2 flight experiment on the Mir Space Station(Ref. [4]). They were installed in a pressurized unit mounted on a 2-meter arm on the Mir Spektr module. The dynamic range of the Astra-2 QCMs was identical to the one on Astra-1 QCMs.

The Astra-2 QCMs were not thermally controlled and sensor operating temperatures were not measured. However, the Astra-2 pressurized unit maintained temperatures above 0°C. The location of Astra-2 QCMs is shown on Fig. 3(a).



(a) (b)

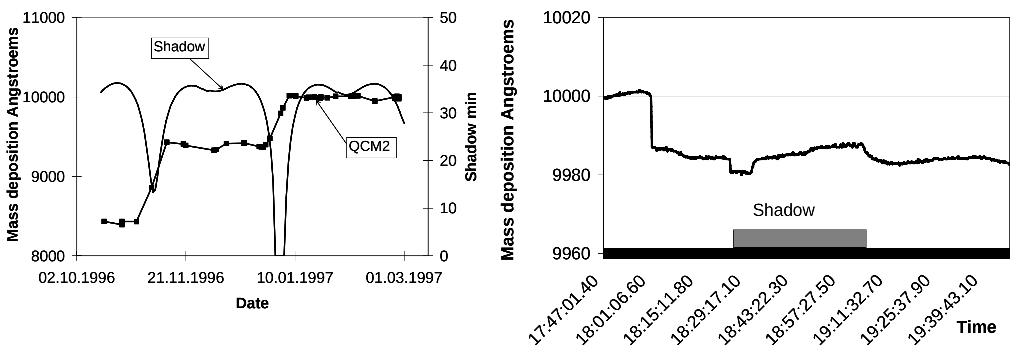
FIGURE 3. Astra-2 QCM locations on the Mir Space Station (a) and total Astra-2 QCM2 readings (b).

Astra-2 experiment started on May 22, 1995, 48 hours after the launch of Spektr. Contaminant deposition measurements were made during two years. The QCM 1 protective cover was open on June 15, 1995. A change in Astra-2 QCM frequency of 1Hz corresponds to mass change of 10^{-8} g/cm^2 (assuming a contaminant density of 1g/cm^3). Initial QCM readings before opening were $1.13 \cdot 10^{-5}$ for QCM1 and $3.1 \cdot 10^{-6}$ g/cm^2 for QCM2. Abnormal QCM1 behavior (out-of-range readings) appeared for the first time on August 15, 1995 during a solar orbit (solar orbit means that shadow duration on orbit is zero or near zero, as opposed to the usual half-hour). After this date, QCM1 continued to exhibit erratic readings.

QCM2 worked more reliable and showed slow mass increase. No significant changes in contaminant deposition rates were recorded during Shuttle, Soyuz and Progress docking and during the PIC flight experiment. The average recorded contaminant deposition rate was approximately $5 \cdot 10^{-11}$ g/(cm^2·sec) in the initial phase of the experiment until September 8, 1995. From that point, the average contaminant deposition rate was approximately $1 \cdot 10^{-12}$ g/(cm^2·sec) until December 26, 1996. At the end of the experiment, a small mass loss was recorded. Astra-2 QCM2 measurement are shown on Figure 3(b).

Astra-2 measurements show periods with significant increases in contaminant deposition rate. To better understand the reasons for this behavior, the presence of solar illumination was analyzed. These periods with significant increases in contaminant deposition rate were found to correlate with solar orbits. However, this was not the sole reason for these readings. The QCM sensor had to be in local shadow simultaneously with the surfaces in its field-of-view being heated by the Sun. Observations of increased contaminant deposition rates were only made under these conditions. This is illustrated on Fig. 4(a). One hypothesis is that heating of external surfaces intensifies during solar orbits, producing more intensive evaporation of contaminants (particularly for porous materials). Conversely, during a period from March through June of 1997, a loss of accumulated mass on QCM2 was recorded when surfaces within its field-of-view were in solar shadow most of the time.

Interesting features were recorded at the end of Astra-2 flight experiment. During the period in shadow, contaminant deposition levels increase, but during Sun exposure periods, while overall contaminant deposition levels decrease, significant jumps in readings were also recorded (Fig. 4(b)).



(a) (b)

FIGURE 4. QCM2 readings on solar orbits (a) and during the total period (b).

Astra-2 results show the complex and sometimes ambiguous character of on-orbit contamination. Deep understanding of these processes requires detailed knowledge of spacecraft orientation, solar illumination, and the dynamics of the thermal environment of the spacecraft and sensors.

SHUTTLE-MIR QCM MEASUREMENTS
THE PLUME IMPINGEMENT CONTAMINATION (PIC) FLIGHT EXPERIMENT

The purpose of the PIC[3] flight experiment, conducted during Space Shuttle mission STS-74, was to measure plume induced contamination produced by U.S. and Russian thrusters (Orbiter PRCS and Russian 130N model 11D428A-16 used on the Mir Space Station). Data gained from this experiment was critical in the development of the bipropellant plume contamination model for the Russian 130N engine, which is used extensively on the Russian Segment of the ISS, as well as in the Progress and Soyuz vehicles.

Russian 130N thruster measurements were made for ten sets of ten 100ms pulses (total of 100 pulses with a total on-time of 10s), on plume centerline, at a distance of 40 feet. Orbiter PRCS thruster measurements were taken for two groups of ten 80ms pulses (total of 20 pulses with a total on-time of 1.6s), on plume centerline, at a distance of 34.7 feet. The QCM (Quartz Crystal Microbalance) was canted at an angle of 35° with respect to the centerline flux stream during PRCS firings.

PIC QCM frequency measurements for the Russian 130N thruster are shown in Fig. 5. The ten spikes correspond to ten cycles of thruster firings. Each spike corresponds to ten 100ms pulses with 700ms off time between pulses. This cycle was repeated ten times, with a one-minute rest period between firing cycles.

Analysis of the raw data showed rapid evaporation of exhausted contaminants during the one-minute rest period between each group of ten pulses (or one "spike"). During a rest period, an average of 79.3% of the mass deposited evaporated. This effect was due to the composition of the contaminant flux and to the temperature of the QCM, which is seen in Figure 6. The average temperature seen during the test of the Russian 130N thruster was 293K.

To quantify the initial contaminant deposit, excluding the rapid evaporation effect, the initial deposit is calculated by summing the increase in frequency (Δf) values for all 10 spikes. The decrease in frequency during the evaporation period is not included in this sum since it is related only to the evaporation of the deposited contaminant. The result is a total increase in frequency (Δf) of 580Hz, or an initial mass flux of 0.256 $\mu g/cm^2/s$.

The sudden increase in frequency, noted past the 20.75hrs mission elapsed time (MET), occurred as a result of activation of the QCM heater. The heater was employed to bake-off residual contamination in preparation for the next measurement point.

Further, the QCM frequency readings are also affected by temperature shifts. Upon return to Earth, the PIC QCMs were tested for temperature effects and calibration curves were generated. The difference between the frequency prior to the firings and the final frequency is 28Hz. This value has to be corrected to account for the increase of temperature of the QCM surface, which results in a frequency shift of 15Hz. This corresponds to a final mass deposition of 0.0193 $\mu g/(cm^2 \cdot s)$.

The evaporation of the initial contaminant deposit during the measurement period (approximately 0.5hrs) was pronounced. The ratio of final (permanent) deposit to the initial deposit was 0.075 (or 7.5%).

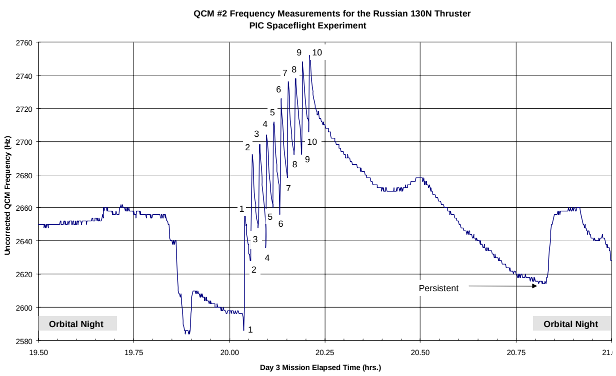


FIGURE 5. PIC QCM frequency measurements for the Russian 130N thruster.

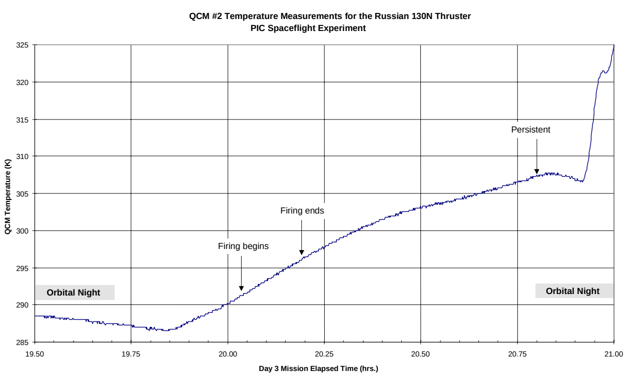


FIGURE 6.PIC QCM Temperature Measurements for the Russian 130N Thruster.

ISS BKDO QCM MEASUREMENTS (RUSSIAN SEGMENT)

On-orbit contamination measurements on ISS were conducted in July 2004, using the BKDO device. BKDO was equipped with two QCMs similar to the Astra-2 sensors, but with built-in quartz temperature control. BKDO is located on the Docking Compartment 1 (DC-1) of the ISS Russian Segment. QCM sensors oriented in ± Y direction.

On July, 1st, 2004, the ISS crew installed the BKDO unit on the DC-1 external surface. Initial QCM readings after installation were $2.8 \cdot 10^{-5}$ g/cm^2 for QCM1 and $2.7 \cdot 10^{-5}$ g/cm^2 for QCM2.

In a manner similar to the Astra-2 experiment, the BKDO QCM1 displayed unstable operation, sometimes recording out-of-range measurements and eventually not yielding reasonable data by the end of July. BKDO QCM2 readings were more stable and recorded up to $3.25 \cdot 10^{-5}$ g/cm^2 until July 11, 2006. However, QCM2 readings dropped to $1 \cdot 10^{-5g}$/cm^2 on July 20, 2006 and shortly after to zero. The average contaminant deposition rate recorded during the stable period was $9 \cdot 10^{-12}$g/(cm^2·sec) for QCM1 and $5 \cdot 10^{-12}$ g/(cm^2·sec) for QCM2.

CONCLUSIONS

QCMs have been used to characterize the induced environment on Russian and U.S. Space Stations. These measurements were crucial in understanding actual induced molecular deposition levels and the effects of solar exposure on QCM measurements and spacecraft contaminant sources, as well as the importance of contamination control to ensure successful science operations.

QCMs installed on the Skylab Space Station, launched in 1973, recorded the first measurements of the Skylab induced contamination environment. Deposition induced by materials outgassing as well as thruster firings were recorded and provided insight into the relative contributions from each contamination source. While the Skylab QCM measurements answered many questions, they also identified a need for better characterization of plume induced contamination.

Four QCMs were installed on the Salyut-7 Space Station. This flight experiment, named Astra-1, made the first measurements of induced molecular deposition on a Russian space station in 1982. The results of the Astra-1 flight experiment were essential to the successful realization of the Salyut-7 scientific studies and the overall research program. Astra-1 measurements were also used in the development of induced environments modeling capabilities in Russia.

The Astra-2 flight experiment followed from 1995 to 1997, with two QCMs installed on the Spektr module of the Mir Space Station. This flight experiment made molecular deposition measurements over a period of two years.

As in Skylab, Astra-1 and 2 QCM measurements were crucial to develop a better understanding of induced environments and also in identifying a need for better characterization of spacecraft induced contamination.

The PIC (Plume Impingement Contamination) flight experiment was conducted during the Shuttle-Mir Program (STS-74) in 1996. This Flight Experiment was part of the International Space Station Phase 1 Risk Mitigation and Technology Demonstration Experiments and also a collaborative effort between both countries. PIC QCMs measured contaminant deposition from U.S. and Russian thruster firings. PIC measurements have been the basis for ISS plume contamination model development. The experiment was successful in characterizing the initial contaminant deposition as well as the evaporation of the contaminant layer.

In 2004 the BKDO flight experiment made the first measurements of Russian Segment contaminant deposition on ISS. Collaboration between both sides has been an important science benefit of the International Space Station Program.

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