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MEMS Technology Demonstration on Traveler-I

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Abstract

Traveler-I is a flight test platform for advanced micro-electro-mechanical systems (MEMS) devices that is being built at the University of Southern California (USC) and is to be flown aboard the next Scorpius® sub-orbital launch vehicle. Microcosm, Inc. and Scorpius Space Launch Company have initiated a program that currently provides sub-orbital launch opportunities, with the possibility of orbital flights in the future. Flight opportunities such as these allow for short duration missions where new technologies can be rapidly developed and tested in a launch and space environment. Traveler-I allows for low cost flight demonstration and testing of new and innovative MEMS devices such as a Free-Molecule Micro-Resistojet (FMMR) and a Knudsen Compressor. The FMMR is a MEMS-based propulsion system for low impulse bit delivery, which is designed to perform attitude control and primary maneuvers for nanosatellites. The Knudsen Compressor is a MEMS-based vacuum pump that employs the physical principle of thermal transpiration to drive a flow across an aerogel substance. Advances in MEMS capabilities have allowed the construction of micro-scale versions of space sensors such as mass spectrometers, optical spectrometers, and gas chromatographs. These devices require vacuum pumps to provide the necessary environment for their operation. Inexpensive and rapid access to space may eventually lead to low-cost testing, which supports rapid development and redesign so that more mature and reliable technologies can be used in future satellite systems, without the expense of designing, building and operating an entire satellite. In addition, the size of MEMS devices allows for the testing of multiple systems simultaneously. Traveler-I is a good example of how advanced technologies may be tested for low cost while reducing risk and development time for future programs.

I. Introduction

The need for developing and testing advanced Micro-Electro-Mechanical Systems (MEMS) for small satellites is increasing. As more nanosatellites and picosatellites are developed, there is an obvious need to scale down components in all systems to continue providing advanced capabilities in increasingly smaller packages. With stricter mass, volume and power constraints, it becomes more of a challenge to find technologies which scale-down efficiently; therefore it is critical to continue developing unique devices. MEM S fabrication technologies offer the opportunity to reconsider many systems aspects of nano- and pico-satellites. The current trends in MEMS with respect to full system integration, analysis and design will undoubtedly aid in the development of smaller spacecraft which will require the highest levels of system integration to be useful.

Even the smallest of spacecraft require some basic level of functionality that are provided by a number of subsystems such as power, communication, navigation, command and data handling, and payloads. Unfortunately, there are often limitations to how small traditional technologies can be scaled down. MEMS technologies provide an alternative that can offer comparable functionality of larger conventional devices in a smaller package. MEMS technologies also offer the potential for low-cost, high reliability, mass-produced systems.

MEMS technologies are already appearing in propulsion[1], attitude control and determination[1], and power generation[2] technologies. Current MEMS devices and applications include microgyros[3], microaccelerometers[4], miniaturized guidance navigation & control systems[3], smart fuses, health monitoring systems, chemical microsensors[5], and many other micro-and nanodevices. Currently, MEMS technologies are being driven by the development of technologies for other industries including the electronic, automotive and biomedical communities. Many of the developments in devices and fabrication techniques may also be applied to space applications.

One of the remaining issues governing the acceptance of MEMS in space applications is the qualification of the devices in launch and space environments. Being new technologies, MEMS devices are often immature and, therefore, are not considered for critical and costly space missions. Rapid testing, prototyping, and development is necessary to be able to bring these technologies into common use for space applications. As in any development program, MEMS concepts must go through an iterative cycle of design, fabrication, and testing. Establishing flight testing as an integral part of a development process from the beginning will allow technologies to mature much more rapidly. Of course, this is only applicable provided that frequent, low cost space flight opportunities are made available.

Benefits of Rapid Access to Launch Opportunities

A major concern in the small satellite community is the availability of launch opportunities at reasonable cost. Currently, access to space is expensive, and the process to get to space is painstakingly long. After taking into account the cost of a typical launch for a small payload, such as the development manufacturing, and operation, it is difficult to justify the expense of performing flight demonstrations for unproven technologies. Due to the high costs, there is tremendous pressure to have everything work the first time. However, experiments dictate that some level of risk or failure is acceptable.

In order to increase demand for access to space, costs must be reduced and frequency of launch opportunities must be increased. If the cost to launch a payload into space can be significantly lowered, it could attract development programs for space technologies to consider space-based testing as a complement to traditional ground testing methods. Ground testing provides an excellent method of reproducing elements of the space environment and allows testing to focus on their specific effects. Facilities exist to simulate conditions of microgravity, vacuum, thermal, radiation environments, vibrational, and acceleration loads. These types of testing facilities are essential for the development of space technologies; however, it is difficult to faithfully reproduce the ambient space environment. In order to test a device under all the synergistic effects of the space-environment, the only real alternative is to flight test. Space-based testing would also help to validate the feasibility of certain technologies for space application and justify further development.

Some of the launch costs can be alleviated when multiple spacecraft share launch opportunities. It is still a relatively expensive process and scheduling constraints can become overwhelming. Coordinating multiple missions to be ready for launch at the same time and accommodating scheduling delays typically requires long-term planning, on the order of years. This timeline is not conducive to missions for experimental testing of new technologies.

Space-based testing requires that launch opportunities be available on relatively short time scales, and that integration can be done with minimal impact to the launch vehicle or other payloads. Frequency of launch is essential to allow multiple iterations to be tested in reasonable time spans. For space-based testing to be useful, it will be necessary to consider alternative low-cost analyses and tests. For safety and reliability issues, it should be sufficient to provide analyses that indicate the payload poses no threat to the launch. The use of standard/mature interfaces and design methods for supporting structures and systems will help the reliability and general integration. Also, reusing test platform designs from one iteration to the next can help minimize integration time and complexity.

The FAST Small Experiment Program[6]

In response to the need for rapid, low-cost access to space, Microcosm and its commercial partner, the Scorpius Space Launch Company have initiated a program that offers no-cost flight opportunities for small experiments. Under the Free Access to Space Testing (FAST) program, small experiments are offered at no cost the excess capacity onboard the launch vehicle and limited amounts of power and telemetry.

Initially, the FAST experiments will be limited to captive payloads aboard the suborbital rockets. As the program evolves rides will be extended to orbital launch vehicles, as well. In many ways the captive payload scenario is ideal for many applications of space-based testing. The need to design a fully functioning spacecraft is eliminated. The experimenter does not have to be concerned with setting up long-term ground operations and infrastructure to maintain and eventually de-orbit a spacecraft. The FAST program offers numerous other advantages for space-based testing including:

- More flight opportunities
- Rapid data recovery
- Rapid reflight possibilities
- Testing in a launch and space environment
- Support for multiple payloads

With numerous flight opportunities, a case can truly be made for setting up programs to perform space-based testing.

MEMS Technology Demonstration – Benefit of University Flight Demonstrations

University programs generally possess complementary views to the FAST program. The ability to conduct experiments at low cost allows for valuable learning opportunities for students and the demonstration of new technologies within a typical research budget. A primary focus of performing space-based experiments becomes inexpensive technology demonstration, education, and workforce development. The space community, as a whole, can benefit from these types of University programs.

Simple experiments can be performed relatively quickly and often, which utilizes the special limitations that university students can bring to the project. A key factor for university research is the turnaround time on a given project. Students tend to be more interested in projects that are realizable within their academic careers. In many cases, a full satellite mission cannot be completed before a student graduates. However, a single experimental payload could easily be developed and integrated into a standardized bus within a matter of months so that a student could very easily see an entire experiment through from start to finish.

Typical university projects can concentrate on specific elements of a particular device, fabrication process, material study, or similar concepts that can help advance the understanding of fundamental processes required to improve existing technologies. Other useful projects may take existing technologies and examine ways of adapting them to space applications. It is also feasible to consider flying complex integrated systems that have already matured but have not yet flown. The advantage of MEMS technologies, in this respect, is their small size, mass and power requirements, which allows many devices to be flown simultaneously. The university environment can often support this need to perform multiple experiments. There is often an abundance of interest from highly skilled and motivated students and faculty at the prospect of being involved with projects that will be launched into space.

University programs also bring an element of low-cost approaches to the experimental process. Often students are not set in their ways of thinking, and are often motivated to try new and innovative approaches. Tempered with the right mentorship, this can lead to excellent results. In keeping with an experimental philosophy, the ability to keep costs low allows numerous approaches to be investigated and allows for the occasional failure.

Traveler-I

The Traveler-1 MEMS Technology Demonstrator is an experimental project that allows students within the USC Student Microsatellite program to get hands-on experience by working in laboratory settings on systems design, integration, testing, and analysis. The main goal of the experiments is to conduct meaningful research supporting the development of MEMS technologies for space applications. Traveler-I consists of four MEMS-related experiments that will be integrated into a single deliverable unit. The experiments include the testing of a MEMS fabricated vacuum pump called the Knudsen Compressor, a MEMS fabricated magnetometer which uses magnetoresistive sensors, and the micro-propulsion experiments, which include the MEMS fabricated Free Molecule Micro-Resistojet (FMMR) and the FMMR propellant tank. The experiments have been chosen based on research currently done at the University of Southern California that could be readily adapted for a flight experimentation in a relatively short time.

II. Scorpius® Launch Vehicle & Interfaces

Traveler-I is intended to fly aboard the SR-XM-2 Developmental Vehicle (prototype of SR-M suborbital vehicles), which is currently in preliminary design. The current launch date is set for late 2003 at White Sands Missile Range (WSMR). The SR-XM-2 will be testing a 20,000lb thrust engine design, and is expected to reach altitudes in excess of 200km. The flight provides several minutes of launch loads in excess of 6g, near vacuum conditions, and microgravity. Details about each of the Scorpius® launch vehicles and the status of the Scorpius® program are given elsewhere.[7,8].

For the purposes of Traveler-I, the launch profile and interfaces are sufficient to design the flight test bed. Traveler-I will be situated in the equipment bay of the SR-XM-2. A payload envelope of 24” x 16” x 8.5” max has been allotted as shown in Fig. 1. The payload will be attached to the primary bulkhead and the equipment panels for support. The design of the outer structure of Traveler-I is still under review. A number of structural configurations are being considered, such as a completely self-contained box and a simple equipment panel that can support experimental modules individually.

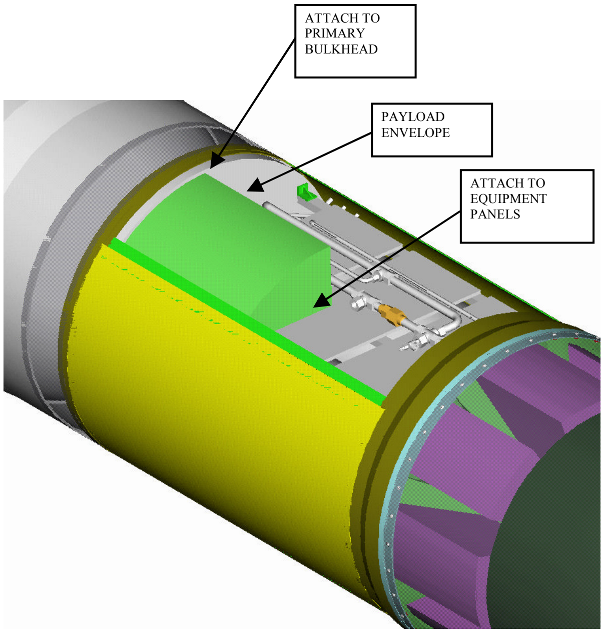

Figure 1. Diagram of experimental payload envelope

To simplify interfaces between Traveler-I and the SR-XM-2, a single power supply and telemetry link will be provided to Traveler-I. Keeping interfaces simple helps to ensure that integration issues between an experimental payload and the launch vehicle are minimized. As such, experiments can be added or removed from a flight depending on their state of readiness, without significant impact on the launch vehicle. This level of flexibility is critical to the concept of rapid flight and reflights.

On the SR-XM-2, the nominal power expected from the vehicle will be approximately 1 amp at 28 volts. DC power will be distributed to all systems and experiments using a 5V bus and a 12V bus. This configuration provides flexibility to handle the power requirements from all experiments.

The telemetry link will consist of a serial 19200 baud RS-232 link, providing a total of up to 5 KHz bandwidth analog data. The data from each experiment's output lines will be sampled at a rate of 2Hz and multiplexed to provide a single continuous stream of data. Higher sampling rates could be achieved; however, for the Traveler-I setup, the selected data rate is sufficient to exceed the current experimental requirements.

A number of Commercial-Off-The-Shelf (COTS) sensors will be used to characterize the payload environment and provide critical environmental data for each experiment. The parameters that are of interest for Traveler-I are temperature, pressure, and acceleration. For example, temperature measurements will be provided by J-type thermocouples, using a thermistor as the reference junction. The thermocouples will be distributed around the entire Traveler-I structure and will be used for specific application on the Knudsen Compressor, FMMR and propellant tank experiments. Pressure sensing will be handled using two types of absolute pressure sensors, one with a range of 0 to 15 PSIA, and the second with a range of 0 to 1 PSID for more accurate measurements at low pressures. Acceleration will be measured using a 3-axis digital accelerometer. The accelerometer data will be used to assess launch loads on the experimental units. Data from all the COTS sensors will be used to create trajectory profiles of the payload environmental characteristics that will support the post launch analyses of all the experiments and possibly the launch vehicle itself.

While maintaining minimal interfaces, it is still critical to be able to demonstrate that the experimental payload poses no risk to the launch vehicle. The fundamental safety requirements for the SR-XM-2 launch are to identify all hazardous materials and ensure that any pressure vessels are designed with large safety margins. Traveler-I is not anticipating carrying any hazardous materials and all pressure vessels for the MEMS experiments are intended to operate at relatively low pressures.

III. Traveler-I MEMS Technology Demonstration

Magnetometer Experiment

Magnetometers are commonly found on LEO spacecraft and used as a method of simple and reliable attitude determination. The magnetometer experiment on Traveler-I is to examine the feasibility of using magnetoresistive sensors for space. While the magnetoresistive sensors may not exactly fit the strict definition of MEMS devices, the approach of integrating and testing miniature technologies for space applications is in keeping with the concept of MEMS technology demonstration.

The magnetoresistive sensors are configured as a simple 4-element wheatstone-bridge that converts magnetic fields to a differential output voltage. The sensors are made from a thin nickel-iron film that is deposited on a silicon wafer and patterned into resistive strips. Under the influence of an applied magnetic field, an output voltage change is experienced due to a change in the bridge resistance.

The sensors being considered for the Traveler-I flight experiment are the Honeywell HMC1021Z and HMC1022 models, which are single-axis and dual-axis respectively. The sensors were provided by Honeywell Solid State Electronics and are being considered for the Traveler-I flight. Specifications for the sensors are available from Honeywell[www.magneticsensors.com].

The magnetoresistive sensors will be integrated into a single 3-axis magnetometer configuration. The magnetometers will be tested and calibrated using a magnetic field simulator constructed by using Helmholtz coils shown in Fig. 2. The Helmholtz coils are used to cancel out the Earth's magnetic field and provide a computer controllable uniform magnetic field in a small region of space. By placing the magnetometers inside the simulator and varying the field produced, characteristic response profiles will be empirically derived for each magnetometer configuration. This is a good example of how simple ground testing can complement space-based testing.

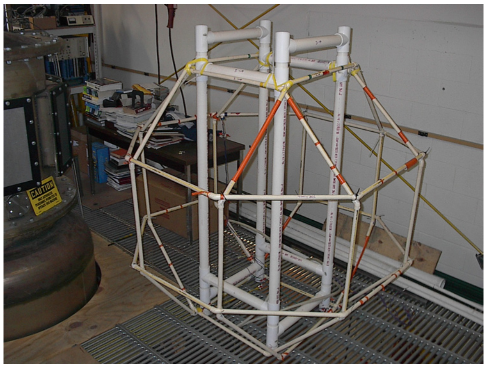
Figure 2. Magnetic field simulator to be used for lab testing the student's magnetometers.

Ideally the devices are being flown to measure the earth's magnetic field, but there is a high probability of significant magnetic interference from surrounding experiments and rocket equipment. Fluxgate magnetometers shown schematically in Fig. 3 will be flown alongside the magnetoresistive sensors as a means of comparison to known devices. The data provided may be useful in further characterizing the payload environment.

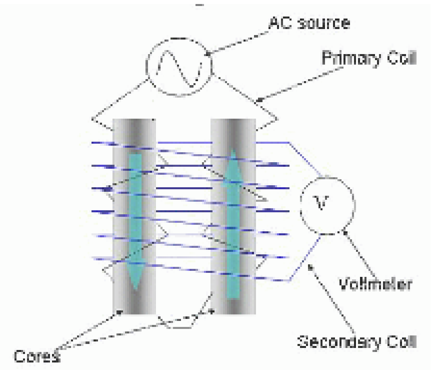

Figure 3. Diagram of fluxgate Magnetometer

Micropropulsion Experiments

The majority of proposed microsatellite missions require means by which satellites are deployed, constellations are formed, altitude is changed, attitude is changed, and orbits are maintained. Therefore, micropropulsion can be mission enabling for microspacecraft missions. MEMS technology offers several advantages for micropropulsion systems.[9] First, a large degree of miniaturization is possible with current MEMS fabrication techniques which can begin to accurately fabricate feature sizes on the order of a few microns. A high degree of miniaturization allows for the possibility of high thrust to mass ratios for propulsion systems.[10] Second, a large degree of integration is possible between the thruster and its components such as valves, regulators, and the propellant feed system. Finally, MEMS fabrication requires the use of silicon or silicon derivatives such as silicon carbide or silicon nitride. These materials typically possess very high yield strengths, which are important for pressurized systems such as propulsion components.

Of course, the use of MEMS technologies in micropropulsion systems also has several disadvantages. Among the disadvantages are the limitations of materials that can be used in the fabrication process, the development time and cost of new fabrication techniques, which push the state-of-the-art, and the availability of fabrication laboratories.

Traveler-I will incorporate two micropropulsion system experiments in developmental support of the Free Molecule Micro-Resistojet (FMMR). The first experiment will be to test the survivability and performance of the MEMS fabrication and packaging of the FMMR. The second experiment is a phase separation and filtering concept for the FMMR propellant tank design. The micropropulsion experiments are described in detail in the following sections.

Free-Molecule Micro-Resistojet

The FMMR is a MEMS fabricated electrothermal propulsion system designed for on-orbit maneuvers of nano- and pico-spacecraft. Electrothermal propulsion defines a class of thrusters that heat propellant molecules electrically. In the case of resistojets, the propellant flow is heated by passing it over an electrically heated solid surface.[11] In high pressure operation, a fraction of the propellant molecules are heated by direct impact with the high temperature surface while the remaining flow is heated by intermolecular collisions. However in the FMMR, which operates at very low stagnation pressures, the molecules are heated only by direct interaction with a surface held at elevated temperature since intermolecular collisions are negligible.

As shown conceptually in Fig. 4, the propellant gas enters the FMMR stagnation chamber through propellant inlets that are connected to the propellant tank through a MEMS valve and filter assembly. The device operates at unusually low pressures (50-500 Pa) giving the propellant gas molecules a mean free path on the order of the expansion slot width. Energy is imparted to the propellant gas through collisions with the expansion slot walls maintained at an elevated temperature prior to exiting the device. The FMMR operation and performance relies on the transfer of energy into the propellant gas through molecular collisions with the heated expansion slot surfaces. For electrothermal devices, the thrust varies linearly with the operating temperature while the specific impulse goes with $T^{1/2}$. Therefore there is a limited benefit to increasing the operational temperature of a resistojet with a practical limitation caused by material properties.

The fabricated FMMR shown in Fig. 5, is uses a heated slot configuration, which was chosen for its design simplicity and minimal fabrication cost. These design benefits come at the cost of increased power consumption to heat a rather large surface area compared to optimized designs.[12] The FMMR thrust chip is fabricated from a 400 µm thick silicon wafer with a 5000 Å thick silicon nitride layer. The silicon nitride layer acts as an electrical insulator between the silicon substrate and a vapor deposited thin film heater. For flight operation of the FMMR, parametric studies have indicated that an operating temperature of 600 K for the heater chip is optimum. This tends to maximize the use of power for a given specific impulse.

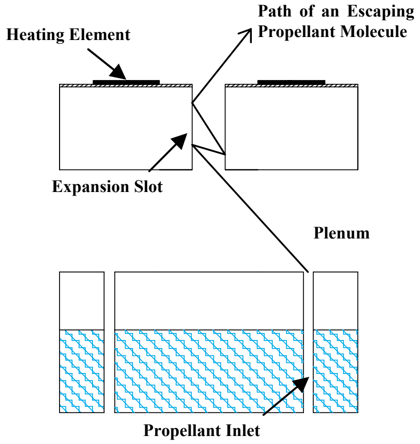

Figure 4. Diagram of FMMR process

At free molecule conditions, the geometry of the expansion orifice is not critical for thruster performance; therefore, a long, narrow slot is chosen due to ease of fabrication (over a micronozzle geometry) and the minimization of single-point failures due to contaminants plugging small orifices. With MEMS Deep Reactive Ion Etching (DRIE) fabrication techniques, the expansion slot size can be machined with a width as small as ~ 1 µm; however, the nominal FMMR geometry used in this study has 40 slots with a slot width w = 100 µm, a length of 1 cm, and a depth of 400 µm. The DRIE technique is also capable of producing slot angles of very close to 90° with the width to depth ratio used here.

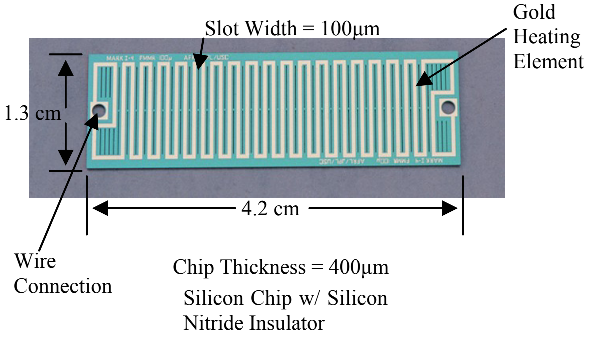

Figure 5. FMMR Chip

Figure 6 shows the MEMS fabrication techniques used to fabricate the FMMR heater chip shown in Fig. 5. The heater chips are fabricated from silicon wafers using standard MEMS processing techniques.[13] The devices are created by the selective removal or addition of materials. The layout of patterns is transferred to the silicon wafer using photolithographic patterning.

Masks, which have printed designs made at high resolution, have areas of transparent and opaque regions on a transparent sheet for image transferal to the wafer. Wafers are first coated with a thin, light sensitive material called photoresist that is exposed through the mask with a high-intensity ultraviolet light source. Once exposed, the transferred images are developed in a developer bath that removes exposed regions and leaves behind unexposed regions of photoresist. This patterned photoresist protects the underlying material during subsequent processing.

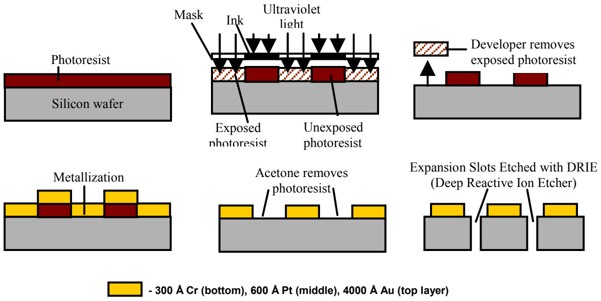

Figure 6. FMMR Fabrication Process

Metallization of the heaters begins by placing the exposed wafer in an electron-beam evaporator under high vacuum. The 200 µm wide heater element consists of a 300 Å thick chromium layer which acts as a bonding layer, a 600 Å thick platinum layer which acts as a diffusion barrier, and a 4000 Å thick gold layer which is the main current carrier. After the heater has been deposited, the wafer is placed in an acetone bath to remove the undeveloped photoresist. This liftoff procedure leaves the desired metal, thin film heater element.

The etching of the slots begins with coating another layer of photoresist on the same side of the wafer as the deposited heaters. The wafer is aligned using alignment marks created during the metallization process so that the expansion slots can be fabricated in the desired location between the legs of the heater element. After exposure of the wafer to the ultraviolet light source through the slot mask, the slot pattern is developed removing the photoresist where the slots are to be etched. The wafer is loaded in a deep reactive ion etching (DRIE) system to anisotropically etch the desired slots. The DRIE is a plasma etching system that provides a way to achieve high aspect ratio features in silicon. The basic principle of DRIE plasma etching is the generation of energetic ions (e.g. SF6+) that are accelerated towards the target substrate within an electric field.[13] The etching is accomplished through chemical reaction of the ions with the exposed silicon. The directionality of the accelerated ions gives the DRIE its anisotropy. The wafer is etched for approximately 155 minutes to completely fabricate the slots and release the FMMR heater chips. With the design shown in Fig. 5, eight devices can be fabricated on each 6-inch wafer.

Packaging for the FMMR consists of anodically bonding the heater chip to a Pyrex wafer. Before anodic bonding of silicon to Pyrex, the Pyrex wafers were metallized with the same type of metallization process as the heater chips which provides contact pads for wire bonding (electrical connection) to the device. Anodic bonding is a technique used to chemically bond a conductive substrate (silicon) to a sodium-rich glass substrate (Pyrex). The silicon and Pyrex are aligned and placed in contact with each other. The assembly is forced together with a force of 20-50 N while being heated to a temperature range of 350-450 C, which is sufficient to make the sodium ions in the Pyrex mobile. As shown in Fig. 7, a potential difference in the range of 700-800 V is applied between the two substrates causing the depletion of sodium ions from the glass-silicon interface. The ion depletion region results in a chemical bond between the silicon and Pyrex substrates.[13,14]

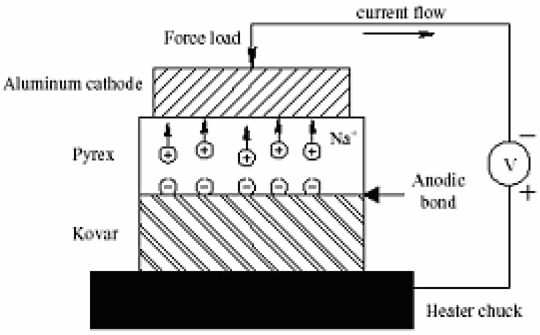

Figure 7. Schematic of the anodic bonding apparatus (Maluf,N.)

After anodic bonding, the final steps in the packaging process are to wire bond between the Pyrex metallized pad and the heater element on the FMMR heater chip and connect the heater chip/Pyrex part to a gas plenum. The electrical connection is made by ultrasonically wire bonding 25µm diameter gold wire between the Pyrex wafer and the heater chip. The entire assembly is then bonded to a Teflon plenum, which acts as the stagnation chamber for the thruster. In future designs, the resulting plenum would then be integrated with a MEMS valve assembly, a filtering and phase separation assembly and a propellant tank.

For the Traveler-I experiment, the FMMR heater chip will be anodically bonded to a 1mm thick Pyrex wafer, which in turn is epoxied to a Teflon plenum as shown in Fig. 8. Wire bonding will be performed between the

Pyrex wafer pads and the heater element on the FMMR heater chip. During the flight, the FMMR heater chip will receive power and the voltage, current, and temperature will be monitored. Two J-type thermocouples will be attached to the heater chip in different locations one being in the center of the chip while the other will be at the end near the interface with the Pyrex. The flight will demonstrate the survivability of the MEMS fabricated heater chip and the MEMS consistent packaging of the heater chip during launch and coast phases of the sub-orbital flight.

The FMMR heater chip is also scheduled to be flown on the Three Corner Satellites (3CS)[15], a joint University nanosatellite mission between the Arizona State University, New Mexico State University, and the University of Colorado. In this mission to be launched on the Space Shuttle in 2003, the FMMR heater chip is integrated into a macro-scale package. The main differences between the 3CS mission and the Traveler-I flight is the launch vehicle (higher g-loading for Traveler-I) and the packaging of the MEMS heater chip.

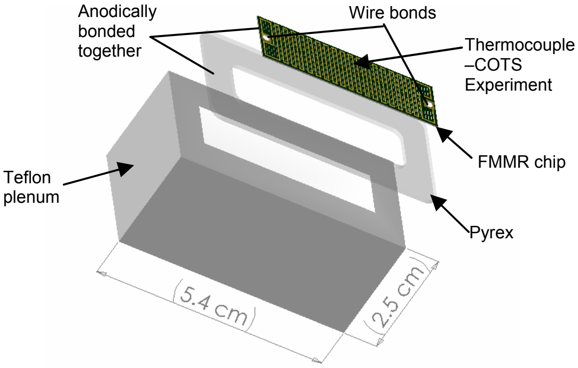

Figure 8. FMMR experimental setup.

Propellant Tank Design Project

The FMMR was designed to operate using water or ice as a propellant. Because of volumetric constraints on nano- and pico-satellites, liquid or solid storage of propellant is desired due to the relatively large storage density compared to high pressure gaseous propellant storage. Liquid or solid storage can also alleviate valve leakage concerns since propellants are typically not stored at high pressures. The goal of the FMMR propellant tank experiment on Traveler-I is to validate a method that can be used to phase separate the liquid water in the propellant tank from the desired vapor in the valve and thruster stagnation chamber vicinity. This will be done using a nano-porous membrane. The membrane will be porous with holes small enough (on average) that the forces due to surface tension will outweigh the forces experienced by launch. Figure 9 shows the possible launch configurations of the FMMR propellant tank. Either configuration (best-case and worst-case) must ensure that no liquid water can cross the membrane, while allowing water vapor to pass for use as propellant. The appropriate pore diameter and membrane thickness will be a function of water temperature, height of the column of water being carried, and the acceleration due to launch.

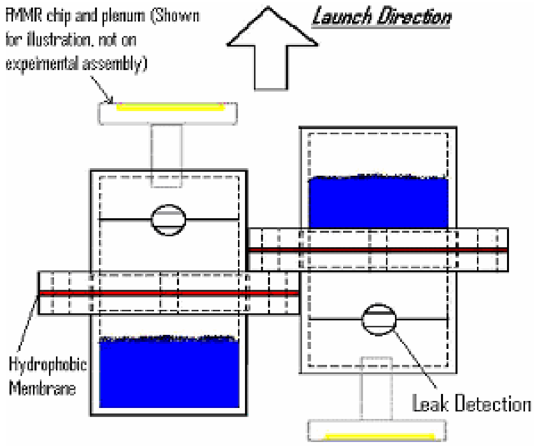

Figure 9. Possible launch configuration of flight experiment propellant tanks

The force due to surface tension of water in a pore is given by

$$F_{st} = \gamma(T) \cdot 2\pi r \cdot \cos(\theta) \qquad (1)$$

where γ is the temperature dependent surface tension, r is the pore radius, and θ is the contact angle between the pore wall and the liquid. For this application the nano-porous membrane must be hydrophobic to prevent surface tension driven capillary action. During launch, the surface tension is attempting to balance the launch forces on the column of water above the pore given by

$$F_l = \rho N g H \cdot \pi r^2 \qquad (2)$$

where ρ is the density of water, N is the number of g's experienced during launch, g is the gravitational acceleration, and H is the height of the water column in the propellant tank.

If it is assumed that the Traveler-I experimental payload will experience a worst case launch environment of 10 g, a nano-porous membrane with r = 700 nm would be required for the surface tension force to balance the launch force. This implies that a hydrophobic membrane with pore radius less than 700 nm is necessary for adequate phase separation (liquid / vapor) in the FMMR propellant tank.

Initial ground testing of a PTFE membrane has been performed using a hydraulic pressure assembly to simulate the forces due to launch. The membrane used has an average pore diameter of 200 nm and did not leak liquid water through the pores for forces far in access of those expected during launch; however, vapor water molecules are able to pass through the membrane which is critical for the operation of the FMMR. More testing will be performed as a function of propellant temperature to insure that the proper membrane has been identified.

During the Traveler-I experiment, a method is required to determine whether liquid water has penetrated the membrane. A printed circuit sensor has been developed to diagnose the presence of liquid water as shown schematically in Fig. 10. Two legs of a printed circuit will run in close proximity to each other without physically touching. A small voltage will be applied to one leg of the circuit. If water droplets in excess of the separation distance between the two legs of the circuit passes through the membrane, the circuit will be complete and a small current will be measured. The side of the propellant tank which houses the water detection sensor will be heated to insure that a false-positive is not given for condensate formed from water vapor on the back side of the nano-porous membrane.

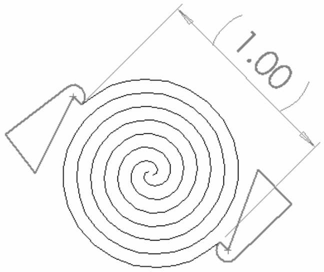

Figure 10. Etched circuit spiral pattern concept for leak detector.

Knudsen Compressor Experiment

Advances in MEMS capabilities have allowed the construction of micro-scale versions of space sensors such as mass spectrometers[16], optical spectrometers[17], and gas chromatographs[18]. These devices, although micro-scale in their construction, currently require macro-scale vacuum pumps to provide the necessary pumping environment for their operation. For these devices to be made entirely micro-scale they require micro-scale vacuum pumps to complete the system.[19] The recent availability of small pore, low thermal conductivity materials coupled with advances in MEMS fabrication techniques has made it possible to construct an entirely new kind of vacuum pump, the Knudsen Compressor, at the micro-scale.[20,21] Several attractive features for the Knudsen Compressor is that it has no moving parts and requires no oil or other supplemental fluids. Knudsen compressors have been shown to be theoretically capable of operating over the entire required pressure range, from about 10 mTorr to 760 Torr. Using the same membrane materials, in their small capillary radius limit (a few nanometers), the Knudsen Compressors could also operate as a micro-scale gas compressor operating from atmospheric pressure to pressures approaching 10 atm.

The Knudsen Compressor is a perfect example of a common theme emerging in the design of MEMS devices: resolving an old problem with devices based on physical phenomena that have long been neglected. The Knudsen Compressor is a MEMS based vacuum pump that employs the physical effect of thermal transpiration to drive the pump. Thermal transpiration (also called thermal creep) was described by Reynolds[22] in 1879. Knudsen built the first macro-scale multistage thermal transpiration pump (with 10 stages) in 1910.[23,24] Since then thermal transpiration pumps have mainly been laboratory prototypes. Their application has been limited by thermal inefficiency and low pumping speeds.

Thermal transpiration is a physical effect by which a temperature gradient along the length of a rarefied tube (a physical condition where the molecules interact more with the tube wall than each other) drives a flow through the tube. The tube diameters must be on the order of μm to nm for common pressures for the effect to occur. Nanoporous membrane materials, like aerogel, are used as porous transpiration membranes. Thermal transpiration does not occur in continuum tubes (a physical condition where the molecules interact more with each other than with the tube walls). A single stage is then constructed by combining a rarefied capillary section (where the temperature is increased) to a continuum connector section (where the temperature is lowered to its initial value). Stages are added in series until the desired pressure ratio is obtained. A single stage, along with the stage temperature and pressure distributions, is represented diagrammatically in Fig. 11.

Another possible application of the Knudsen Compressor is a high-pressure on-demand gas source for other MEMS devices (such as valves, actuators, lab-on-chips, etc.).[25] In this application the Knudsen Compressor would pump from atmosphere to a higher pressure instead of a lower pressure as in the vacuum pump application. The Knudsen Compressor requires transpiration membrane materials with smaller pore diameters (< 5nm) to operate at pressures above atmospheric pressure.

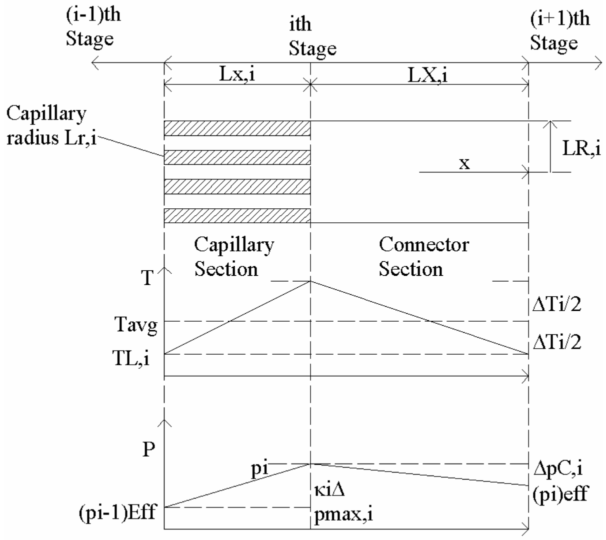

Figure 11. Knudsen Compressor Stage

For Traveler-I, a single-stage MEMS Knudsen Compressor will be fabricated and flight tested for application as a vacuum pump. The experimental goals are to complete the initial design of an entire pumping system (pump, driving electronics, diagnostics, and connections) and demonstrate operability and survivability in space and launch environments. The device will undergo extensive laboratory testing in preparation for flight.

Figure 12 shows the current design for the single stage Knudsen Compressor. The device is fabricated in layers and packaged together as shown in Fig. 13. The physical dimensions of the entire package are 42.5mmx45mmx23.6mm. The top plate and top cavity are conventionally machined out of kovar. The top bonding union, bottom cavity and bottom plate are all waterjet machined out of pyrex. The center chip is MEMS manufactured using the DRIE process. The aerogel transpiration membrane is bonded directly to the thermal guard wafer. The membrane is made from 2% carbon doped silicon aerogel, measuring 0.6 mm x 8 mm x 10 mm. The transpiration membrane will be optically heated by shining an infrared (IR) light source through the bottom plate to provide the temperature difference and stimulate the pumping effect. The infrared light source, an IR diode at 880nm wavelength, was chosen for its optical transmissivity through the Pyrex bottom plate and its absorbtivity in the carbon doped aerogel. An IR photodiode with peak efficiency at 880nm will also be used to verify the proper functioning of the emitter. Gas will be drawn in and exhausted on opposite sides of the top cavity.

Initial laboratory testing is being performed on the pump with laboratory instruments to accurately measure the device's performance. Laboratory test data will be used to validate the flight performance. Eventually the pump will be integrated into a flight model, which will also undergo extensive laboratory testing.

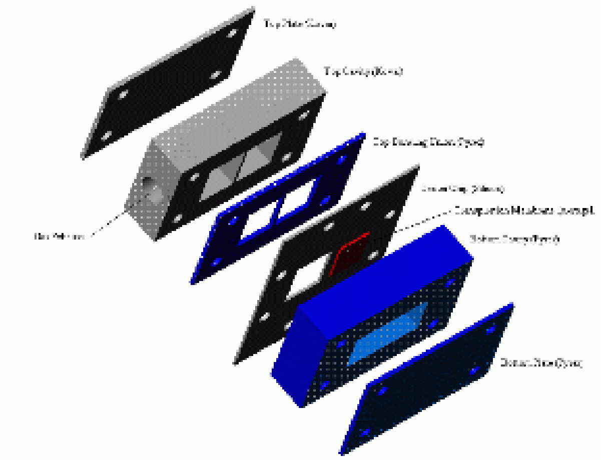

Figure 12. Expanded view of the current single-stage Knudsen Compressor design

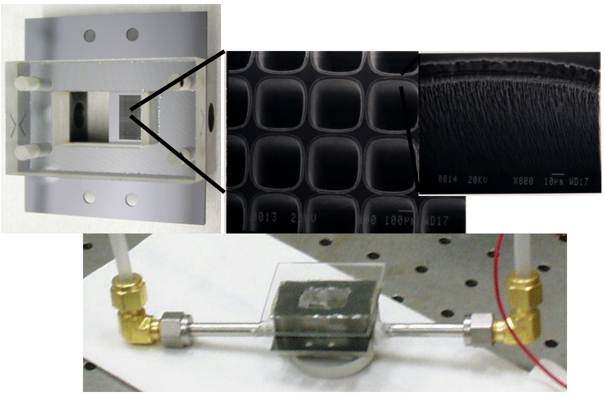

Figure 13. Pictures of single-stage Knudsen Compressor in an initial laboratory testing configuration.

The flight configuration, as shown in Fig. 14, will have the pump connected to short copper tubes that will contain the gas to be pumped. These tubes will be connected to a differential and an absolute pressure sensor. For the flight, the system will first be evacuated and then filled with slightly less than 1 atm of nitrogen gas. Results obtained from a single species of gas are easier to interpret. Using pressures slightly lower than atmospheric allows for leak detection. If the absolute pressure measured in the system increases then a leak exists and the gas in the system is no longer pure Nitrogen. The flight test process is very straightforward. To commence pumping, the IR emitter is used to heat the aerogel. The differential pressure across the device is measured by the differential pressure sensor. The IR photodiode will measure the intensity from the emitter to be able to compare pumping performance results with ground-based results. Data from these sensors will be sampled at a rate of 2Hz by the command and data handling processor onboard Traveler-I. The measurements will be taken throughout the entire flight trajectory.

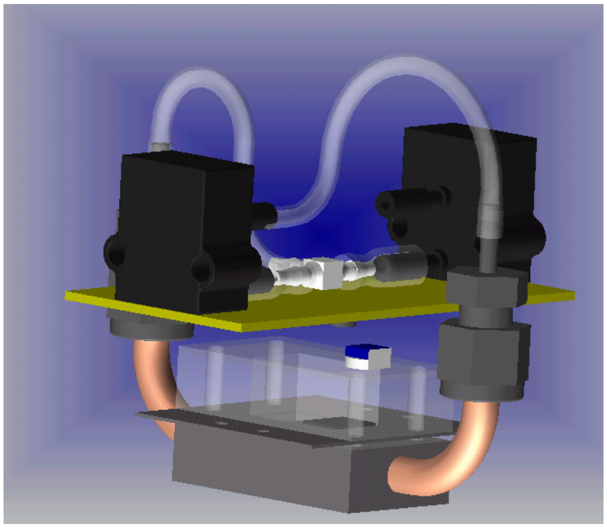

Figure14. Experimental flight setup of Knudsen Compressor

IV. Future Flight Opportunities

As stated numerous times, a key element of MEMS technology demonstration is the ability to rapidly advance the design and refly. There are already intentions of a next generation of the FMMR and Knudsen Compressor projects. Students will also be investigating other technologies that may be suitable for testing on a subsequent flight opportunity.

From its conception to launch, Traveler-I will take roughly 2 years to complete, including the post-launch analysis. However, development for subsequent launches should be significantly reduced, as many of the interfaces will already be developed. Leaving room for moderate changes and improvements between launches, the majority of work done on power systems, structural and thermal analysis, and data handling can be carried over.

To meet the possibility for rapid turnaround on subsequent launches, work for Traveler-II is expected to begin prior to the launch of Traveler-I. Preliminary designs for Traveler-II will be based on the assumption that everything was successful on Traveler-I. This puts much emphasis on rapid post-launch analysis. Any changes to designs are much more preferable early on in the design cycle. Traveler-II will aim to be ready for a launch within about 6 months of Traveler-I. In the future, the time between flights may be greatly reduced. As launches become more frequent and as more experiments take advantage of such flight opportunities, it would be ideal to see low-cost space-based experiments adopted as a routine approach to the development of technologies.

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