Micro Pump Technology and Applications

Frank T. Hartley

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive, Pasadena CA 91109

Introduction
The Jet Propulsion Laboratory (JPL) is a NASA Federally Funded Research and Development Center (FFRDC). It is endowed with NASA equipment that is managed and staffed by California Institute of Technology with a highly educated and world-class community of six thousand engineers and scientists. JPL's principal NASA responsibility is to design, build, test and operate robotic spacecraft for the exploration of the solar system and to observe our universe across the whole EMR spectrum. Essentially, to go where no one has gone before and, in doing so, determine the origins of our solar system and the universe.

The days of large, multi-instrumented, billion-dollar robotic spacecraft are over. The emphasis is now on miniaturizing instruments and spacecraft and reducing the costs of fabrication, test, launch and operation. The ramifications of miniaturization are global, encompassing every element of a spacecraft, instrument, lander or penitrator. Micro pumps, valves and flow meters were conceived to address the variety of fluid flow control elements. This paper discusses the evolution of this technology from other MEMS programs and presents a variety of' space' applications.

Derivative MEMS
The derivative MEMS technologies came from a NASA advanced technology development contract with JPL and Northeastern University for the fabrication of nano-g accelerometers (range 10“2 - 10“* g over 0.0001 - 25 Hertz bandwidth) to measure b-i-axial orbital drag on the Shuttle and Space Station. [1,2,3]

The specific innovations that led to realization of a robust micro pump were zero thickness wafer bonding and encapsulation technique that enabled the intimate joining of two wafer surfaces: intra- and wafer-to-wafer inter-electrical contacting or electrical isolation[4,5,6]; and the high force electrostatic 'caging' mechanism'.

In the nano-g accelerometer zero thickness referenced bonds were essential to attain tight spatial tolerancing. A eutectic bonding procedure was developed where etched channels were created in the bond regions (Figure 1) on which a spreading layer of metal was deposited and patterned in the channels. Finally, the bond metal was deposited and patterned on top of the spreading layers in such a way that it protruded above the wafer surface and was narrower than the spreading layer so its volume was less than the volume of the channel. When two dice prepared in this way are brought in contact and heated, the bond metal melts and spreads by wicking and capillary forces, reducing the spacing between the wafer surfaces to zero.

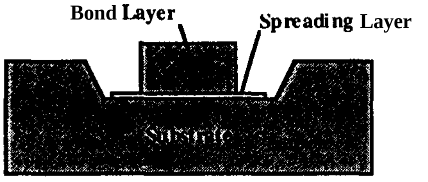

Figure 1 Zero **Thickness Eutectic Bonding**

Where contact metals are, or are beneath, the spreading layers, this bonding procedure provides electrical inter-connection between wafers in addition to hermetic sealing.

The nano-g accelerometer contained a flimsy proof-mass suspension system and a fragile tunneling tip, both of which required protective, re-deployable electrostatic 'caging' during quiescent handling and high acceleration or shock loading. Figure 2 presents such an inovative 'caging' mechanism. This is the top view of the force plate die where the metal platen is covered with an oxide layer (0.5 µm) to prevent an electrical contact between the proof mass and the force plate when the proof mass is being electrostatically clamped.

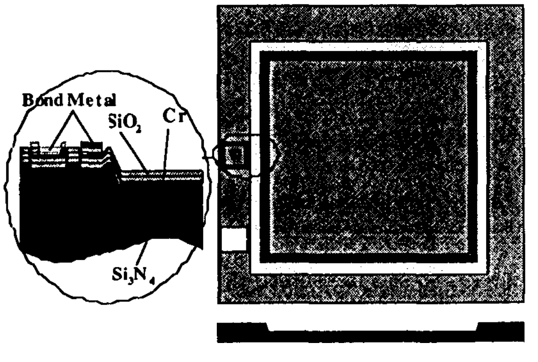

Figure 2 Top View of Force Plate

The electrostatic force relationship is

$$F_c = \frac{\varepsilon_{ox} . A . V^2}{2d_{ox}^2},$$

where ε_{ox} is the dielectric constant of oxide (4x8.85 x10⁻¹²Newton/Volt')
A is area of conductive strip
V is applied voltage
and d_{ox} is the thickness of the LTO (0.5 µm).

Where the distance (d_{ox}) is small, at fictions of a µm, it is clear that small voltages generate large electric fields of Mvolts/m, which in turn produce significant attractive forces. For larger voltages, the attractive forces increase with the squared function of the applied voltage. The breakdown electric field strength of the insulation layer sets the limit for attainable 'caging' forces.

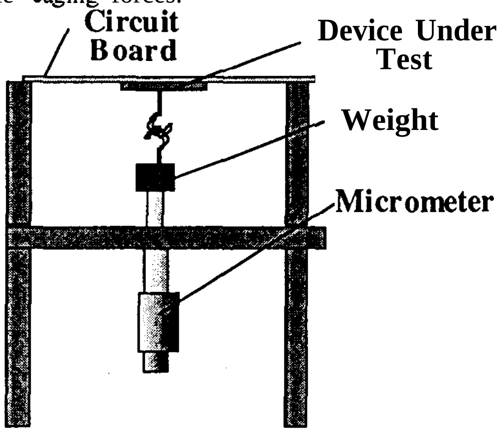

Figure 3 Text Fixture For Electrostatic Force Measurement

A test procedure was established to undertake the empirical measurement of these electrostatic clamping forces. The procedure involved the assembly of a test stand (Figure 3), which consisted of mounting a 'half' accelerometer in a test fixture along with a hook, a weight, and a micrometer with a non-rotating spindle. The 'half' accelerometer consisted of a force plate and a proof-mass assembly package that was clamped electrostatically. A hook was glued to the center of the proof mass using epoxy. A weight with an axial eye-screw is set on the spindle so that the eye was placed over the hook but was not supported by the hook. An HP 4277A capacitance bridge was used to monitor the capacitance between the proof mass and the force plate. It contained a built-in DC bias supply that was used to apply an electrostatic field between the proof mass and force plate during the test. The bias was initially adjusted to a high voltage. The spindle was lowered until the proof mass was supporting the entire weight. The bias voltage was then lowered until the electrostatic force could no longer support the weight, and the capacitance decreased when the weight falls.

By varying the weight, the ability of the system to withstand acceleration could be determined. Because the proof mass weighs 0.2 grams, an effective increase of 1 g in acceleration is simulated for each 0.2 grams of weight added. It is thus a simple matter to obtain a 200 g simulated acceleration by providing an aggregate weight of 40 grams. The circles in Figure 4 represent the measured voltages and the equivalent accelerations for three different weights. The left hand line in the Figure represents the zero air gap theoretical relationship for holding voltages, minimum value of about 0.1 volts for 1 g, for perfectly flat dice in contact with each other.
Measurements of the capacitance showed that instead of the expected 3 nanofarads, the actual capacitance was approximately 300 picofarads. These results suggested that the proof mass and force plate do not conform to one another. Surface profiles of the proof mass and force plates indicated that as much as 10 microns of variation were typical on the proof masses. Also, microscopic inspection revealed that small particles were present in the LTO deposition, which prevented the proof mass from coming into intimate contact with the force plate. The collective effect of the low spatial variation of surface flatness and the LTO particles increase the effective platen gap and thus both the voltage required to hold the proof mass against gravity and the electrically capacitance.

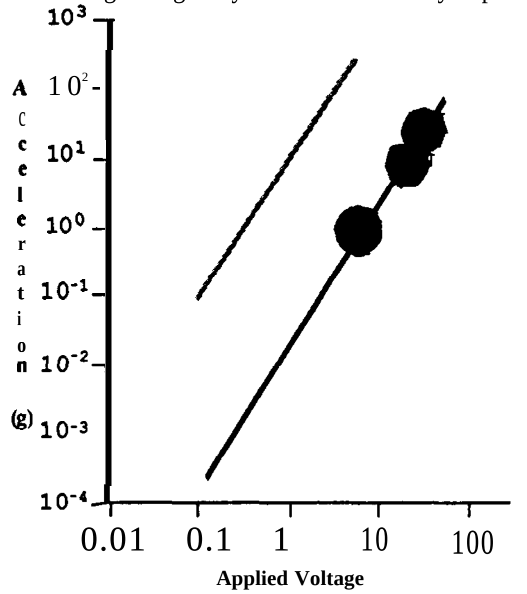

Figure 4 Experimental And Theoretical Holding Voltage/Acceleration Relationships

An equivalence model was constructed which consisted of an aggregate of parallel plate, uniform oxide and air-gap spacing capacitors. This equivalence relationship is represented by

$$F_e = \frac{\varepsilon_{air}.\varepsilon_{ox}.A.V^2}{\left[2(\varepsilon_{air}.d_{ox} + \varepsilon_{ox}.d_{air})^2\right]}$$

where ε_{air} is the dielectric constant of air, and
d_{air} is the weighted average thickness of the air gap,

In Figure 4 the holding voltages required to withstand various accelerations for weighted average thickness of air (or vacuum) gap provides a reasonable fit line through the discrete the experimental data points. The effects of the low spatial variation of surface flatness and the LTO particles on spacing and thus holding voltage are evident.

Peristaltic

Peristaltics is a form of fluid transport that occurs when a progressive wave of area contraction or expansion propagates along the length of a dispensable tube containing a liquid. Physiologically, peristaltic action is an inherent neuromuscular property of any tubular smooth muscular structure. This characteristic is put to use by the body to propel or to mix the contents of a tube, as in the ureters, gastrointestinal tract and the bile duct.

The following description outlines the mechanisms of a reverse engineered micro peristaltic - type pump[8]. Envision a substrate in which a smooth contoured concave channel has been etched, the whole surface coated with a thin metal layer and, over this metal, a thin coating of insulation material. When an electrically conductive membrane is clamped in intimate contact with the thin insulation layer of two shells (as illustrated in Figure 5) and a voltage is applied to the lower metal layer and the membrane, an electrostatic attractive force pulls the membrane down into the channel. The membrane rolls down the surface of the insulation because the greatest attractive forces are generated where the distance from the conductive strip are smallest (i.e. insulation thickness). Conversly, when a voltage is applied to the upper metal layer and the membrane, the membrane rolls up the surface of the insulation of the upper channel.

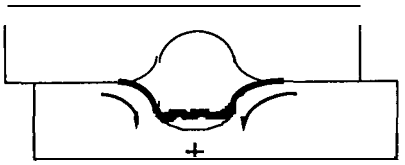

Figure 5. Electrostatic Actuator - Lower Shell

As demonstrated in the 'caging' application small insulation thicknesses, fractions of a μm, lead to significant electrostatic forces. Flexable membranes are largely unaffected by the surface flatness and the LTO particles' separation of rigid platens and thus peristaltic pumping forces are more representative of the theoretically ideal case. Essentially the break-down electric field strength of the insulation layer sets the limits on pump pressure and pumping rate for an electrostatic peristaltic pump.

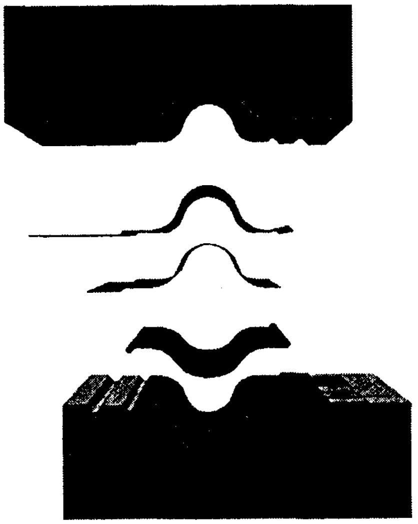

Figure 6. Exploded View Of Micro Peristaltic Pump

Figure 6 presents an exploded diagram of two complementary smooth concave channel pump shells, patterned series of electrically conductive strips, insulation layer, and the flexible electrically conductive membrane. Figure 7 illustrates the assembled micro peristaltic pump where the two substrates sandwich a single membrane between them. A hermetic seal is created by the compression of the membrane and the outer eutectic bond wall.

Earlier the effect of applying voltages to the lower and upper conductive surfaces were discussed. When a suitable voltage between the membrane and each of the conductive strips is applied in succession, the membrane is pulled into the channel and successively along the length of the channel. And, when the actuator elements are connected to the outputs of dual interlaced and interlocked shift registers, the membrane initially flows along the upper channel surface before the membrane is released for several periods (zero), drawn down into the lower channel and along the lower channel surface.

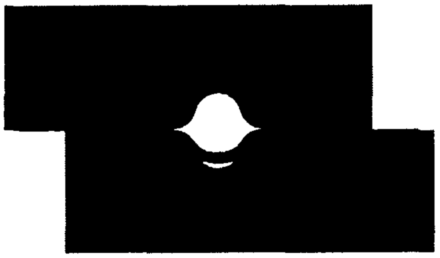

Figure 7. Assembled Micro Peristaltic Pump

This actuation progression of a membrane "wall" across the composite channel provides a miniature peristaltic pump. Alternate inversions of the bit streams sequences creates multiple membrane "bubbles" that move down the channel (Figure 8), pushing the entrapped fluid in front of and pulling the fluid behind each membrane "wall." The electrostatic actuator has no resistive loss so pump power is only consumed by the membrane, in the compression work function and in circulating the fluids through micro channels.

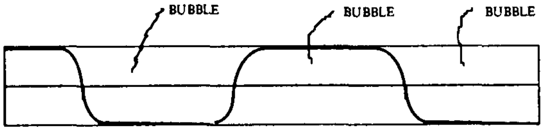

Figure 8. Multiple "Bubble" Peristaltic

This miniature digital peristaltic pump architecture represents a true two-dimensional analog of the three-dimensional peristaltic mechanisms that arc endemic in living organisms. It is valueless and impervious to gas bubble entrapment that has plagued other attempts at miniature pumps. Also it does not require priming and can tolerate the adherence of small foreign particles (gracefully degraded) on channel or membrane surfaces. The pump is self-purging, tending to push everything before the membrane in its intimate rolling motion across the channel surface. This basically digital pump can transport fluids or vapors over an extended range of flow rates, is impervious to high mechanical shock or vibration, is a positive displacement flow meter, and can function in a static mode as a valve.

Spaceflight Applications

Spaceflight hardware is made up of two broad categories: the spacecraft, penetrator or lander, and the payload of instruments. The spacecraft engineering functions that are pump or valve related are propulsion, orientation, thermal management and propellant management. Elevation control is relevant for aerobots and thermal management is required for aerobots, penetrators and landers.

Propulsion management requires pressure regulation and isolation of both propellant and oxidant. Valve modulation can be used for pressure regulation and fluid isolation can be achieved with low leakage valves. A variant of the peristaltic pump can, if the electrostatic force exceeds supply pressure, provide a fast valving regulator function. And impervious membraned valves can provide fluid isolation. The electrostatic flexible membrane valve (see Figure 9) is a

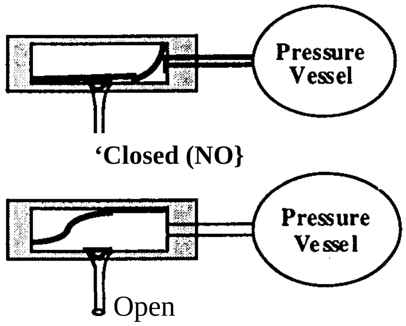

Figure 9 Electrostatic Valve

normally open device and can only regulate and seal when powered. As the electrical insulation in these valves is very high, current flow and thus power requirements are minute. Hence provided power is perpetual, as is the case on spacecraft, electrostatic valving is viable.

Figure 10 Honey Comb Thruster

In ion propulsion systems small high energy plasmas ionize small volumes of low pressure gas and high electric fields accelerate these ions to high exit velocities. Figure 10 is a cartoon of a honey comb ion thruster where each cell is separate ion engine. A miniature peristaltic pump is dedicated to each cell to seal off or provide metered gas flow.

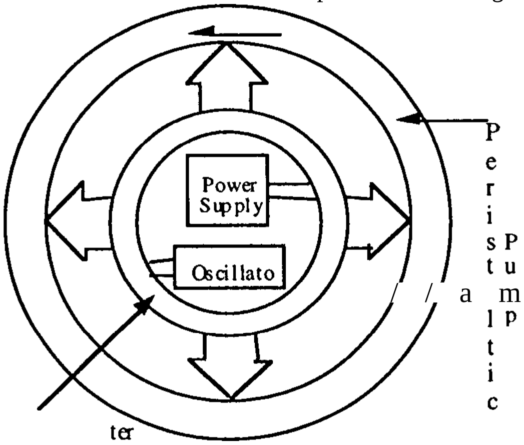

Figure 11 Fluidic Reaction Wheel

By controlling which engines in the army are operating the honey comb thruster can provide gimbal-less 'steering'. If some of the peripheral cells are offset from the perpendicular then spin control is possible. Finally the massive redundancy of the array increases the truster's reliability.

Inertial wheels are another technique utilized to maintain the orientation of spacecraft. Figure 11 presents a cartoon of a fluidic reaction wheel that consists of a closed toriodal pump[9]. The angular velocity of the fluid in the peristaltic toriod is increased or decreased to provide the requisite change in angular momentum. In miniature spacecraft multiple concentric 'wheels' could be located at the periphery of silicon disks running in the same or opposite directions depending on required reaction.

Effective thermal conductivity of fluid cooling loops are markedly superior to that of the best passive thermal conductive materials. A micro pump may be used to circulate a fluid between a thermal source and sink, effectively transferring heat both within the circulating medium by thermal mass transfer and between the medium and the source and sink by improved convective transfer. Micro channels have large surface area to cross section ratios which ensures intimate thermal coupling with forced flow gasses and micro channels.

Shuttle systems and many of the flight experiments utilize forced convective cooling. The mechanical nature of these cooling systems (fans) makes them the least reliably element in a thermal catastrophic failure scenario. This, and the crew fatigue through exposure to sustained high noise levels, was the impetus for the conception of a MEMS cooler.

Microstructure peristaltic pump-channel implementations, complete with substrate imbedded drive electronics, provide high thermal transfer coefficient 'breathing skin'*. In a nonvacuum environment such pumps draw from still air at the surface and expel away from the surface. The heat pump is not dependent on density gradients and gravity fields, as are convective heat sinks, and is thus space deployable. A small pump-channel cell may be bonded the surface of integrated circuit chips (*see 'hot body' Figure 12) to dissipate their heat directly: no forced ventilation, no orientation constraints, no noise, and no moving parts.

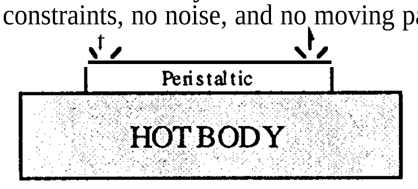

Figure 12 Forced Convective Transfer Heat Exchanger

With many pump-channel cells per square centimeter large area slabs may be bonded to the surface of power packs or system chassis to remove heat.

Thermal transfer capacity is further enhanced by the absorption or dissipation of latent heat generated from gas/liquid or liquid/gas phase transitions. These phase transitions can be orchestrated by pumping where compression liquefies and expansion vaporizes. The

Rankine vapor compression cycle defines such a heat engine. In a micro machined version of a closed loop vapor compression cycle as shown in Figure 9[10], the whole refrigerator, or a serial cascade of refrigerators, may be fabricated from two fused wafers.

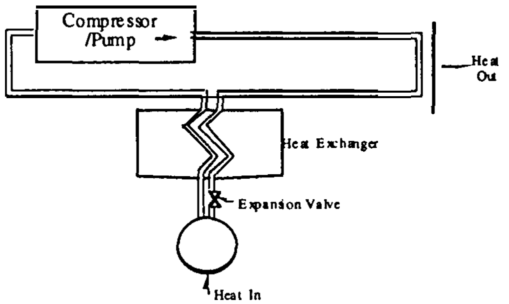

Figure 9. Compressor For Phase Interchange Heat Pump

A miniature peristaltic pump draws refrigerant vapor and compresses it. The gas is then cooled and condensed, the liquid is then cooled by convective transfer into the surrounding substrate micro channel and onto a highly thermally conductive heat exchanger created in the substrate. Another micro channel conducts the cooled liquid refrigerant to an expansion nozzle (valve) in a thermally isolated cold pad where the refrigerant expands into its vapor phase, drawing the latent heat of vaporization from the cold pad. This cold vapor is conveyed in yet another micro channel to the inlet port of the miniature peristaltic pump. The peristaltic pump exhibits very low vibration, as it has no reciprocating parts, but instead has a very low mass membrane that rolls across the surfaces of the channels.

The high thermal transfer capacity of fluid cooling (or heating) loops, and particularly phase change loops, are of significant interest in the thermal management of spacecraft and planetary rovers. In communication satellites, thermal management of individual high energy transmission amplifiers and fast computers are preferred to general electronic 'hot box' management, Another interesting thermal management application is the heating, rather than the more general cooling, of a Martian rover. During daylight, the heat absorbed in solar panels is collected in liquid forced through micro channels in rear of panels. This heat is transfered to, and stored in, thermal capacitors within the rover. In the evening, the heat bank warms the rover's quiescent electronics.

A sophisticated application of a phase interchange heat pump is the cooling of optical instrument's IR imaging objectives, specifically the space based focal plane cooling of a Quantum Well Infrared Photon (QWIP) detector. The QWIP focal plane temperature needs be maintained at 70 K for a heat load of 50-270 m W and a radiator temperature of 200 K. The most efficient cooling cycles are cascaded systems and the most expeditious means of implementing these cycles is the pseudo cascading of mixed gasses in a single expansion process. JPL[11,12] have extended the Russian[23] work on increasing the Joule-Thompson (J-T) cooling power with a variety of gas mixtures.

Figure 13 presents a plot of the temperature-entropy (T-H) diagram for the analysis of a five gas mixture with the high pressure (25 PSI) enthalpy data represented by 'squares' and the dotted best fit curve and the low pressure (5 PSI) enthalpy data represented by the 'circles' and dashed best fit curve.

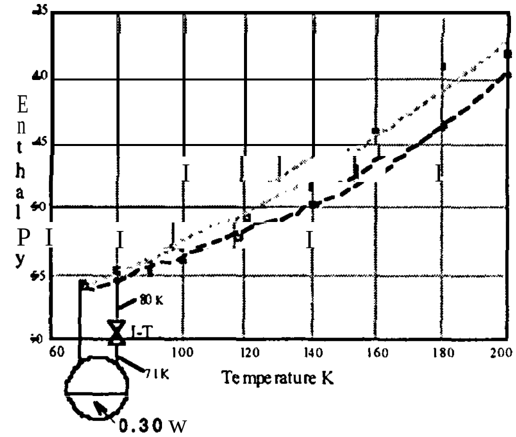

Figure 13 T-H Diagram For Selected Gas Mix

A preferred embodiment of a focal plane cooler would incorporate the whole system on two bonded (4" dia.) silicon wafers, The radiators would occupy the outer rim (0.75" both sides), the pump (pumps) and interchanger (interchangers) would be inboard and the 2 x 2 cm cold pad would be in the center. Using silicon as the substrate for the cooler has several advantages: the pump electronics can be incorporated directly into the substrate, silicon exhibits high thermal conductivity (particularly at low temperatures) and its micro machining chemistries and characteristics are mature. For space applications it may be prudent to have redundant pumps as a reliability measure, should a micro channel become blocked or a particular pump fail. Miniature pressure and temperature sensors could also be incorporated around the various micro channels to provide health monitoring and efficiency optimization capabilities,

Convective coupling between forced flow gasses and micro channel surfaces are high and channel surface area, relative to cross section, increases as dimensions decrease. The thermal conductive loss across thin silicon partitions between neighboring channels are also small particularly when these channels are contained within insulated silicon bridges. Such thermally isolated micro channel structures are very efficient heat exchangers.

The peristaltic pump is also a micro channel that can exchange compression heat with a neighboring channel to approach the efficiency of an isothermal compression cycle. The compression profile of a peristaltic pump is determined by the diminishing thickness profile of the actuator strips. For an ideal pump the step volume profile would be matched to the effective ratio of specific heats (γ) of the gas mixture and thermal gradient down the pump. Once this profile was determined, the photo lithographic masters can be computer generated with the required actuator spacings.

Were the complete cryo cooler fabricated out of two 4" diameter silicon wafers(see Figure 14), the total mass would be 35 grams, and with etched out bridges and non-utilized areas this mass would be less than 25 grams. A single peristaltic pump would weigh less than a gram. The J-T expansion valves would be just inboard of the focal-plane thermal insulation bridges where the parasitic heat loads would be balanced and the low pressure return conduit would pass back along the same bridge to cool the high pressure gas feed.

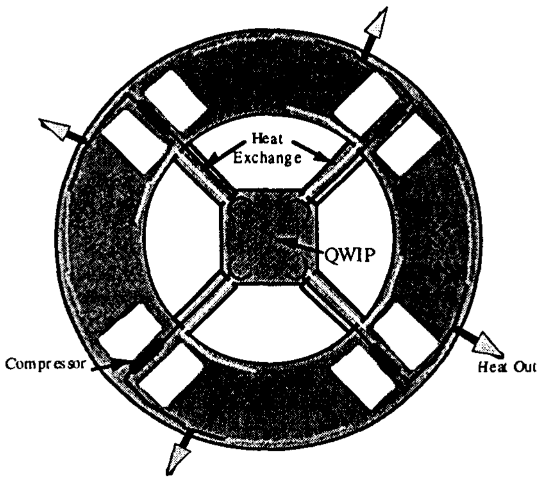

Figure 14 Wafer Cryo Cooler and Detector Mount

The reason for sending rovers, aerobots and penetrators to planets is to gain ground truth for the remote measurements of orbiters and telescopes. Atmospheric gas species and abundance are one such measurement class requiring a miniature gas analyser or mass spectrometer. Figure 15

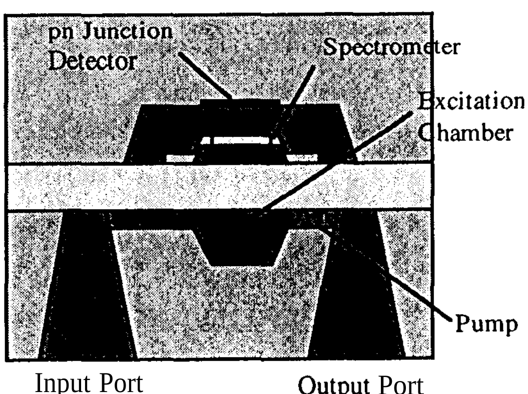

Figure 15 Schematic Representation of micro gas analyzer

presents a cartoon of a miniaturized gas analyser that incorporates all the components and operates under the same principles as conventional equipment. The instrument incorporates a miniature peristaltic pump, a wavelength resolving spectrometer [13,14] and a gas excitation chamber[16]. The pump continually draws and regulates the pressure of gas into the excitation chamber where it is ionized by a unique miniature plasma generator. Light emitted by the ionized gas is directed toward the miniature Fabry-Perot interference spectrometer and detector.

Acknowledgments
The author acknowledges both NASA and JPL for their support of the MEMS programs and would like to thank Prof. Paul Zavracky of Northeastern University for his collaboration on the nano-G accelerometer, and for his and Prof. Jeffrey Hopwood's contributions in the development of a miniature gas spectrometer. Jack Jones' contributions in determining the gas mixtures for micro cryo cooler are also appreciated.

References

[1]P.M. Zavracky, F. Hartley, N. Sherman, T. Hansen, and K. Warner, "A New Force Balanced Accelerometer using Tunneling Tip Position Sensing," 7th Int. Conf. on Sensors and Actuators, Yokahama, Japan, June 7-10, 1993.

[2]Frank T. Hartley and Paul Zavracky "NASA Ultra-Sensitive Miniature Accelerometer", Joint "1+]" Science Review USML- 1 and USMP- 1 with the Microgravity Measurement Group, September 22-24.1993, Huntsville, Alabama, USA.

[3]Frank T. Hartley, "Development Of A Small, Stable, Rugged Microgravity Accelerometer", August 1996, JPL D-13908.

[4]Frank T. Hartley, "Bonding, Interconnections and Thermal Conduction Between Electronic Circuit Chips", June 9, 1994, NPO- 19473, CIT No. 9062.

'Frank T. Hartley and Paul Zavracky "Method For Surface Referenced Low Temperature Bonding", July 19, 1994, NPO 19477, CIT No. 9078.

[6]Frank T. Hartley and Paul Zavracky, "Soldering Parts Together At Precise Faying Surfaces", 1994, NPO- 19473.

'Frank T. Hartley and James H. Wise, "Caging, Calibration, Characterization and Compensation of Microstructural Transducers", Patent Serial No. 08/106,448, August 16, 1993.

*Hartley, F. T., 'Micromachined Peristaltic Pump' U.S. Patent # 08/572,186, December 1995.

[9]Frank T. Hartley, "Micro Reaction Wheel", September 18, 1995

[10]Frank T. Hartley and Jack A. Jones, "Micro Joule-Thompson Cryo Cooler", November 1996, JPL D-14048.

[1] 'Jones, J. A., Petrick, S. W., and Bard, S., 'Mixed Gas Sorption Joule Thompson Refrigeration', U.S. Patent Pending, NPO-17569, 1991.

[12]Report JPL D-7977, 'Cryogenic Mixed Fluid Application Study and Computer Code Development', Jack A. Jones, December 1991.

[13] Vladimirr Nikolaevich Alfeev et al, 'Refrigeration For A Cryogenic Throttling Unit', British Patent #1,336,892, November 14, 1973.

[14]Ben P. Dolgin, Frank T. Hartley and Paul Zavracky, "Micromachined Tunable Filters for Optical Applications", May 21, 1994, NPO 19456, CIT No. 9060

[15]Ben P. Dolgin, Frank T. Hartley, Paul K. Henry and Paul Zavracky, "Micromachined Opto/Electro/Mechanical Systems", June 13, 1994, NPO 19467, CIT No. 9071.

[16]J. Hopwood, C.R. Guarneirii, S.J. Whitehair, J.J. Cuomo, J. Vat. Sci. Technol. 11(1),147, (1993).