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THE MET (MICROWAVE ELECTRO-THERMAL) THRUSTER USING WATER VAPOR PROPELLANT

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ABSTRACT

The research program to develop the MET (Microwave Electro-Thermal) thruster at Research Support Instruments, Inc. (RSI) using a variety of propellants is described. The MET has undergone dramatic evolution since its first inception, and it is now moving towards flight development. The MET uses an electrodeless, vortex-stabilized microwave discharge to superheat gas for propulsion. In its simplest design, the MET uses a directly driven resonant cavity empty of anything except gaseous propellant and the microwave fields that heat it. It is a robust, simple, inexpensive thruster with high efficiency, and has been scaled successfully to operate at 100 W, 1 kW, and 50 kW using 7.5, 2.45 and 0.915 GHz microwaves respectively. The 50 kW, 0.915 GHz test was perhaps the highest power demonstration of any steady state Electric thruster. The MET can use a variety of gases for fuel but the use of water vapor has been shown to give superior performance, with a measured specific impulse (I_{sp}) of greater than 800 s. When this added to the safety, ease of storage and transfer, and wide availability of water in space, the potential exists for using a water-fueled MET as the core propulsion system for refuelable space platforms.

INTRODUCTION: MET THRUSTER RESEARCH

The MET thruster was first conceived in the 1960's when it became apparent that microwaves could be used to create electrodeless discharges in cylindrical resonant cavities to heat gas for space propulsion. The electrodeless discharge, it was thought, would allow high efficiency heating of gases with a large reduction in erosion of thruster surfaces (Jahn 1968). However, early versions suffered from inefficiencies and problems of plasma stabilization - the tendency for the plasma to move to the antenna - that made simpler electric thrusters appear far more promising. Increases in microwave source efficiency led to a resurgent of interest in the 1980's, first at University of Michigan (Whitehair 1987), and then by Dr. Michael Micci at the Pennsylvania State University, supported by NASA and the Air Force Office of Scientific Research (e.g., Sullivan 1991). NASA efforts culminated in an 11 kW thruster being run using 0.915 GHz (915MHz) at NASA Glenn Research Center (Power 1993).

Evolution of the MET

Early models of the MET were hindered by the requirement of a quartz tube to stabilize the plasma in the resonant cavity (Whitehair 1987). The heat loss to the tube walls limited efficiency and high power operation. To overcome this problem, Dr. Micci found that the use of bluff bodies to create a turbulent eddy in the fuel flow and axi-symmetric drive of the cavity could stabilize the discharge (Balaam 1995). This was successful due to the importance of the Paschen parameter E/P for gaseous discharges, so that the plasma would tend to be stabilized by the low pressure region of the turbulent eddy, and the coaxial antenna would tend to create a field maximum at the preferred location of the plasma. It was found the that the TM_{011} was the superior cavity mode to heat the gaseous fuel near the nozzle. Inspired by the work at NASA Glenn involving use of a vortex to achieve similar effects in a large quartz tube, and with the encouragement of workers at RSI, Dr. Micci and graduate student Daniel Sullivan were able to create plasma discharges stabilized by vortex gas injection and coaxial drive alone, so that no quartz tube or bluff body was necessary (Sullivan 1994). The MET had thus evolved into a much simpler and efficient device, with a thrust chamber containing nothing but gas dynamic flow and microwave fields. However, the device still remained a bulky and complicated device due to problems of microwave delivery to the thrust chamber, which utilized a waveguide, three stub tuner, and ferrite isolator between the cavity and the magnetron microwave source.

MET in Compact Form

In the new device, it was found by workers at both Penn State and RSI that the cavity electric properties changed dramatically upon plasma ignition and assumption of steady state operation. Before plasma ignition, the cavity behaved as a very high Q resonant cavity with narrow resonance and high reflected power; however, after ignition, the cavity Q collapsed to near unity due to the power absorption in the plasma, with almost no reflected power and a broad resonance. This can be easily seen from the equation for

$$\Delta f = \frac{f}{Q} \qquad (1)$$

frequency spread in the cavity

And with power absorption per wave cycle,

$$\Delta W = \frac{W}{Q} \qquad (2)$$

Obviously, for Q~1 the resonance conditions of the cavity are almost non-existent, and the energy per cycle absorbed is almost total; both conditions lead to almost no reflected power from the cavity.

Therefore, for a cavity loaded with a very strongly absorbing plasma, the three stub tuner was not needed, and neither was the ferrite isolator. Thus, the physics of a low Q cavity allowed the design of the MET to be greatly simplified by inserting the output antenna of a magnetron directly into the base of the resonant cavity. The resonant cavity then functioned like a holrahm or optical furnace with two focal points: the microwave source sat at one focal point, and the target plasma sat at the other. Once the plasma ignited in the cavity, the absorption of power from the magnetron was so complete that the magnetron needed no reflection protection. This resulted finally in 1994 in a very light, simple design for a MET thruster that could be mounted on a vacuum thrust stand or a spacecraft with only a fuel line and high voltage connections being necessary. The design of the MET has evolved quickly and is now a compact unit suitable for space-flight development (see Figure 1).

The MET thruster was found to scale successfully to both small power and higher power by designing the devices so that the parameter □=Power/(wavelength)^3 was held constant. This meant that a higher power device needed to go up in wavelength, and smaller powers went to shorter wavelengths. Successful MET operation at 50 kW at 915 MHz and 150 W at 7.5 GHz was achieved easily. The operation of the 50 kW and 150 kW was very similar to that of the 1 kW version. Operation and approximate cavity dimensions of all three models are shown in Figure 2.

OPERATION OF THE 2.45 GHZ MET IN THE 1 KW RANGE.

The MET was developed using 2.45 GHz microwave sources because of their availability and low cost. It was possible to modify microwave oven magnetrons for use in MET thrusters for experiments that placed the magnetron at risk, such as the first direct drive experiments. Because commercial magnetrons use air as a high voltage insulator, in order to run the MET on a vacuum thrust stand, the magnetron at the MET base were enclosed in an airtight sealed container with ports for cooling water and high voltage cables. A picture of the MET in this configuration is shown in Figure 3. The magnetrons were modified to accept water cooling by removing air cooling fins and wrapping a cooling water pipe around the core.

MET research was historically limited in budget, so the cost of materials was a constant concern. For the RSI design, aluminum was used in the MET structure because of low cost and oxidation resistance, the diaphragm separating the discharge chamber from the aft magnetron output antenna was made of boron nitride because of its high temperature limit and low loss tangent, and the nozzle was made of graphite because of its high temperature limit and low cost.

Once the MET was constructed in this way, the thruster could be operated on a vacuum thrust stand using nitrogen and helium as propellants. In general, the MET performed with impressive I_{sp}, efficiency, and reliability, particularly considering that no optimization on nozzle design had been done. Operation in vacuum was particularly simple: A photodiode-triggered solenoid valve controlled propellant flow. With the valve closed, the magnetron was energized, and residual low pressure gas in the thrust chamber formed a diffuse glow discharge; when this occurred, the photodiode triggered the solenoid, and as the flow initiated, the plasma collapsed rapidly from the wall into an ellipsoidal discharge, with the plasma forming a virtual plug in the nozzle (explanation in Sullivan 1994) and causing a chamber pressure rise from ~ 1 Torr to greater than 500 Torr.

High Pressure Operation

It was discovered that high pressure in the discharge ($P > 500$ Torr) chamber was essential to stable and efficient operation at low Q. This fact has been recently supported by work at Aerospace corporation with the assistance of RSI (Diamant 2001). The exact dynamics of the gas, plasma, and microwaves are quite complex and so could only be explored experimentally in MET research programs. However, it is apparent that a key parameter is the rate of electron-neutral collisions, which is controlled by gas density or pressure in the chamber. If pressure is high, microwave energy is converted to heat in a highly localized region, and a sharp plasma-gas interface is formed. If the pressure (and thus collision rate) is low, then the interface between plasma and gas becomes diffuse and enlarged, and heating is less effective. High pressure means high gas density and a highly resistive plasma, because of the high rate of electron-neutral and neutral-neutral collisions transfer energy rapidly from microwave fields to heat. The process of energy transfer is apparently a multi-step process, with electrons being accelerated by the microwave electric fields, the electrons transferring energy to molecular or atomic vibrational modes through collisions, and then vibrational modes equipartitioning energy into thermal kinetic energy (primarily via neutral-neutral collisions). During MET development at RSI, pressures below 500 Torr often resulted in unstable operation, with pressure slowly dropping, leading to a “glow mode” similar to that seen by DC arcjet experimenters. In this mode the electrons decouple from the ions and neutrals, becoming essentially collisionless. When this occurs, a highly conducting, very low pressure plasma forms, and electrons reflect large amounts of power back into the microwave source, leading to direct drive magnetron shut down or burn out. At the same time, the electrons couple very little energy into neutral or ion heating. Electrons are thus hot, but neutrals and ions remain cold. In such cases, the MET would give I_{sp} only like a cold gas thruster (indicated neutral gas temperatures of room temperature), while the electrons had reached 10,000K or above. Thus, high pressure operation was essential to good MET operation and high I_{sp}.

It became apparent that the MET discharge behaves in a very generic manner for a variety of gases when run at high pressure (low chamber Q) manner. In this mode, both helium and nitrogen formed similar discharges and ran at similar thrust efficiencies.

The performance of the MET was measured for nitrogen and helium gases at 1 kW by taking the MET thruster to NASA Glenn and running on NASA’s inverted pendulum vacuum thrust stand. In these tests, an I_{sp} in the range of 250 s was found for nitrogen at thrust efficiencies of 35% in terms of power to the magnetron. These results were duplicated at RSI using a different thrust stand design. One method for reducing the engineering difficulties of MET propellant delivery (particularly useful for water operation) was to use a “Chinese Fish Trap” thrust measurement device (Cheng 1984). This device absorbed the momentum of the plume rather than the force applied to the thruster. The momentum trap resembled a muffler (cylinder with perforations to relieve pressure buildup). The nitrogen propellant results agreed within 10% to those of the NASA Glenn data obtained on a conventional inverted pendulum thrust stand. On the RSI stand, helium gas achieved 400 seconds I_{sp} at 35% efficiency. The results obtained by RSI are shown in Figure 4. Recent results at The Aerospace Corporation have validated these values; Aerospace researchers have achieved 418 s I_{sp} with helium and 243 s I_{sp} with nitrogen. It should be noted that the efficiencies in Figure 4 include the factor of the magnetron efficiency, which for commercial magnetrons is approximately 70%; thus the thermodynamic efficiency of the thruster is close to 50% in terms of conversion of microwave energy into directed kinetic energy.

WATER VAPOR AS PROPELLANT

At the request of NASA Goddard personnel, RSI attempted to use water vapor as a fuel in the MET. This request was motivated by a desire to launch small satellites from the space shuttle that could be boosted to higher orbits. Operation on water vapor at RSI was surprisingly successful and resulted in stable compact discharges at high pressure. Operation of the MET on an inverted pendulum thrust stand in vacuum would have required either the piping of hot steam through flexible hose to the thruster, or a self contained vaporizer to place on the MET. The transmission of steam to the MET thrust chamber by flexible hose would have created the opportunity for condensation of the steam in the lines, leading to errors in mass flow measurement. The most straightforward solution to this problem would have been to create a self-contained vaporizer to mount on the MET having short steam connection to the thrust chamber. This vaporizer would either continuously vaporize liquid water supplied by a flexible hose or else have its own metered water reservoir. The construction of a self-contained water vaporizer for the MET posed serious problems, not the least of which was the possibility of venting boiling water into the vacuum system and shutting down the experiment. For these reasons, the momentum trap thrust stand was used. This method of thrust measurement enabled the MET with its water vaporizer to be mounted outside the vacuum thrust chamber, where its operation was much simpler.

Preliminary data, taken by the authors at RSI using these methods, showed that water gave excellent performance, with $I_{sp} > 800$ sec (see Figure 4), apparently due to the lightness of the water molecule and possible recombination of the hot atomic oxygen and hydrogen created by the thermally disassociated water molecules streaming through the exhaust nozzle. This preliminary data has been approached by the performance measured at The Aerospace Corporation, which found an I_{sp} of 428 seconds in high pressure discharges, with some indications that this could be improved (Diamant 2002). This high measured performance, and the lack of visible emission from the water fueled MET exhaust plume (suggestive of thorough recombination in the nozzle), indicates that water may be a nearly ideal fuel for many space propulsion applications. However, water, because of its two-phase nature and ability to quench electric discharges (possibly through electron-oxygen attachment) if vapor pressure is not well regulated, presents many engineering difficulties to the experimenter.

THE WATER VAPORIZER

Experience at RSI showed that operation of the MET on water vapor appeared to require that the ratio of electric field to chamber pressure stay within a tighter range for water vapor than for other gases, presumably because of water vapor's tendency to attach electrons and thus quench discharges. Because of this, water vapor pressure had to be well-regulated. Running water vapor in the MET is not for the easily discouraged experimenter. Operation of the MET at high chamber pressure, above 500 Torr, was essential to high I_{sp}. Indeed, it was not straightforward to achieve this high pressure; at very low pressures (below 500 Torr), the tendency of water to quench the discharge prevented increasing the pressure to the easier-operate high range. As a result, it was \ found at RSI that best way to run the MET thruster on water at high chamber pressure was also the simplest: a boiler with a constant pressure, toggled by a solenoid valve, quickly increased the chamber pressure of the MET into the desirable > 500 Torr range, avoiding a slow transition through the low pressure regime. In the boiler, liquid and gaseous water were kept in contact at an interface. When the boiler was then connected to the thrust chamber,the liquid gas interface allowed the thrust chamber pressure to be the vapor pressure of the hot liquid water in the boiler. If a fluctuation in the thrust chamber plasma caused the pressure to drop, the liquid water simply boiled more vigorously to raise the pressure back to its proper point of operation. If pressure went up, the liquid boiled less vigorously and the pressure relaxed back to steady state. A boiler vaporizer with a liquid-vapor interface thus allowed the liquid water to do pressure buffering on the system. However, it must be stressed that workers at The Aerospace Corporation recently succeeded in running the MET on water vapor at high I_{sp} using a continuous flow vaporizer (Diamant 2002) by simply increasing the microwave power to overcome water quenching during the slow transition through low pressure.

It can be said while the nitrogen and helium MET thruster is in the process of space hardware development, the water MET is still a physics experiment, and has not yet been reduced to engineering practice. The difficulties of propellant delivery must be overcome if the MET running on water is to gain acceptance as a space propulsion option. In particular, engineering problems of vaporizing and delivering water at regulated pressure into the MET discharge chamber, in a compact unit that can be made integral to the MET and thus function on a vacuum thrust stand, are considerable, and require further research and development.

SUMMARY AND DISCUSSION

The MET thruster has now been run in a compact 100 W form at 7.5 GHz , 1 kW at 2.45 GHz, and at 50 kW using 915 MHz microwaves. Microwaves can be generated efficiently (> 90% at 915 MHz) and beamed for long distances coherently. On a spacecraft, the microwaves can be received on an antenna and fed directly into the thrust chamber without any intermediate conditioning. This suggests the MET thruster is highly compatible with a space transportation infrastructure based on large scale nuclear or solar power stations and antennas beaming power for orbital transfer, or even for powered landings in reduced gravity environments such as the lunar surface.

The MET is simple, efficient, can be scaled efficiently to high powers and high I_{sp},and it can be run on water vapor, perhaps the most common chemical compound in the Cosmos. Water is found on the poles of the Moon, Mercury, and Mars, and is abundant in the outer solar system. Water is easy to transfer between spacecraft and to store and accumulate in space. Water is also an element of all human spaceflight, where it is byproduct of fuel cell operation, a source of oxygen, and essential for human life and health functions. This means that a water handling infrastructure exists on all human flight missions in space and can thus be expanded to accommodate propellant water. All of this means that the MET, using water as a propellant, has enormous potential for human spaceflight missions, most principally those to the Moon and Mars.

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FIGURES

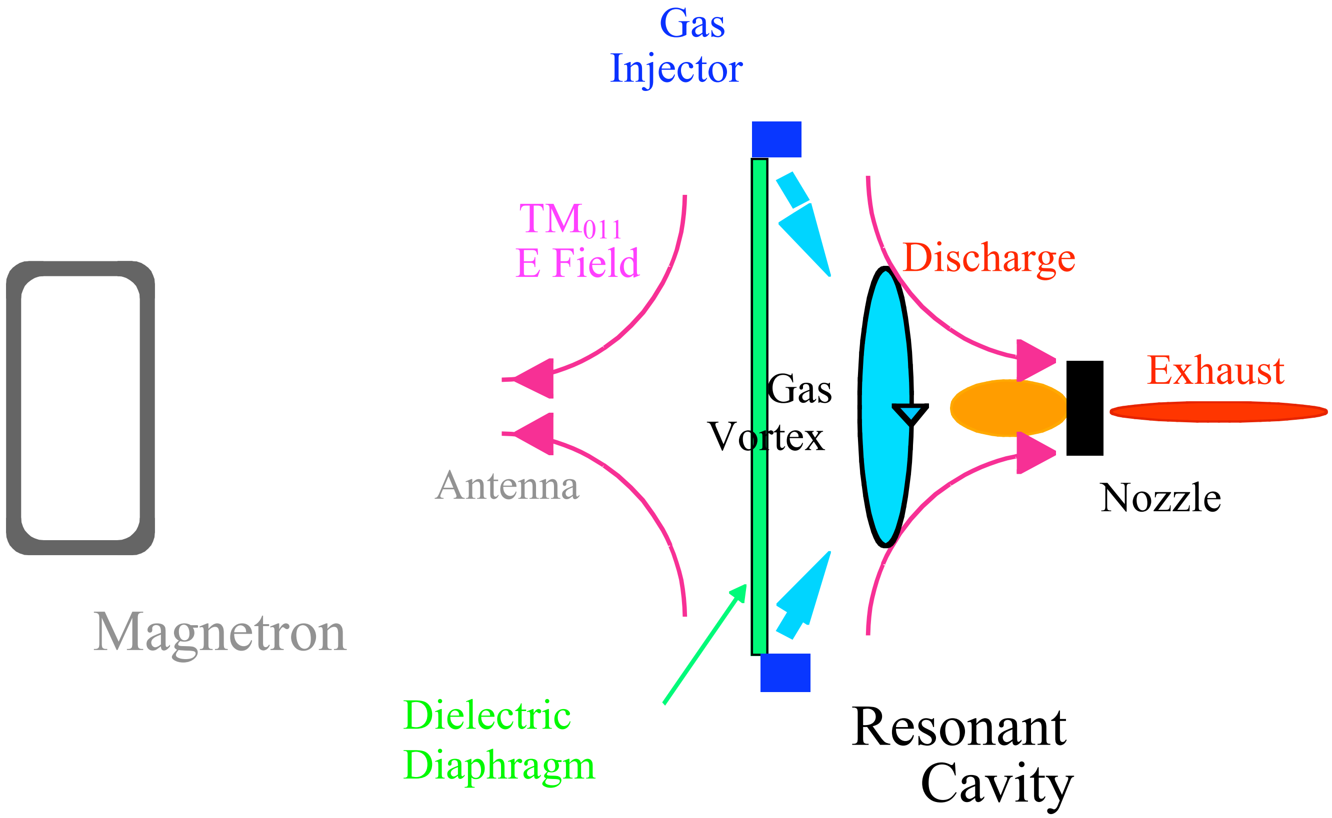


Figure 1: A diagram of the MET thruster in its present form. The magnetron generates microwaves from high voltage DC power.

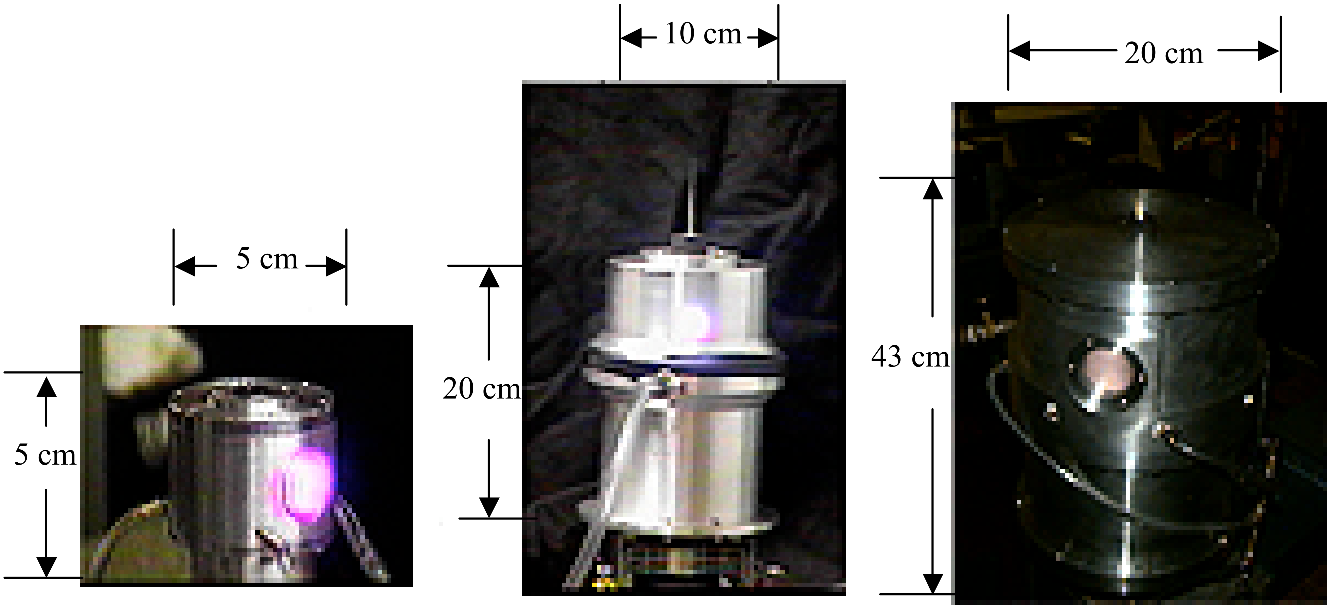
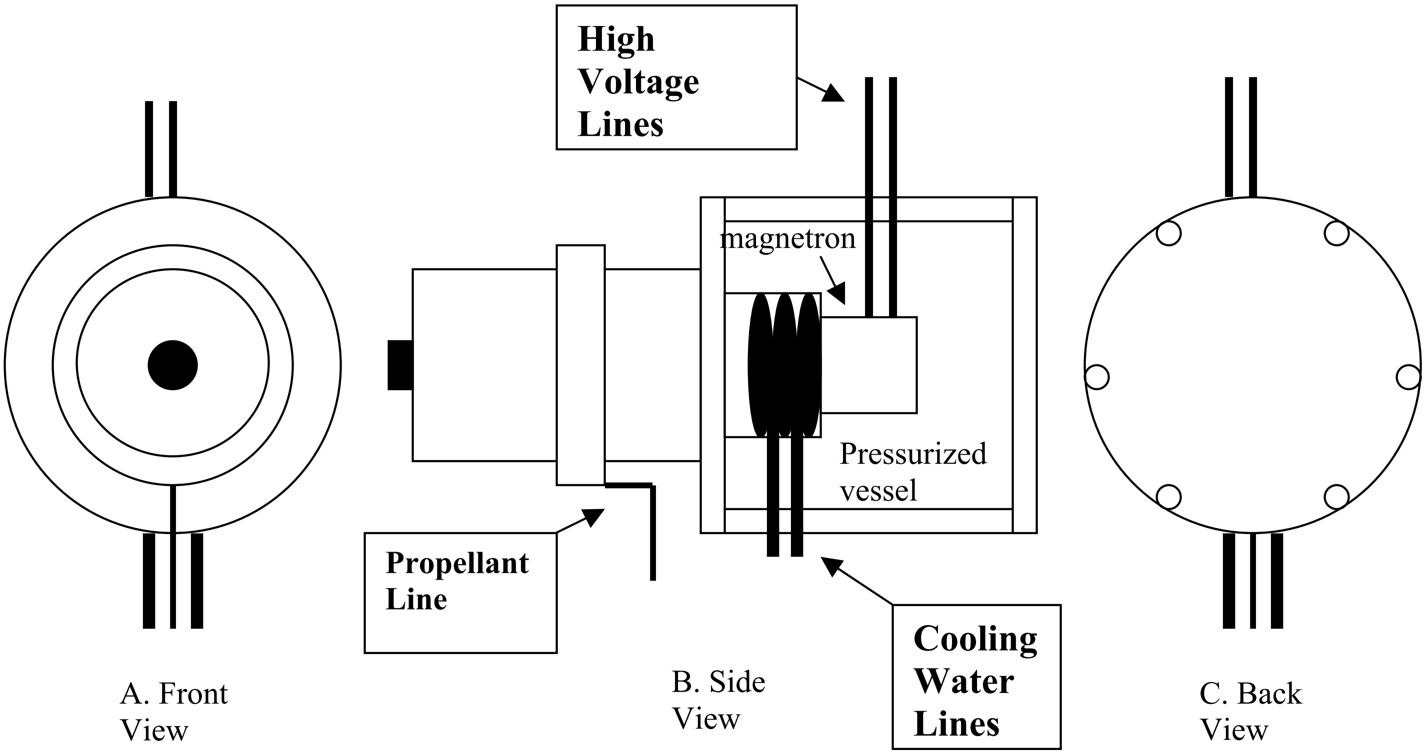


Figure 2: Photos of MET operation and approximate cavity dimensions at 100 W, 1 kW, and 50 kW



A. Front View

B. Side View

C. Back View

Figure 3: A diagram of the MET thruster as it was modified for operation on a vacuum thrust stand. The commercial magnetron was enclosed in a pressure vessel because it uses air as an insulator.

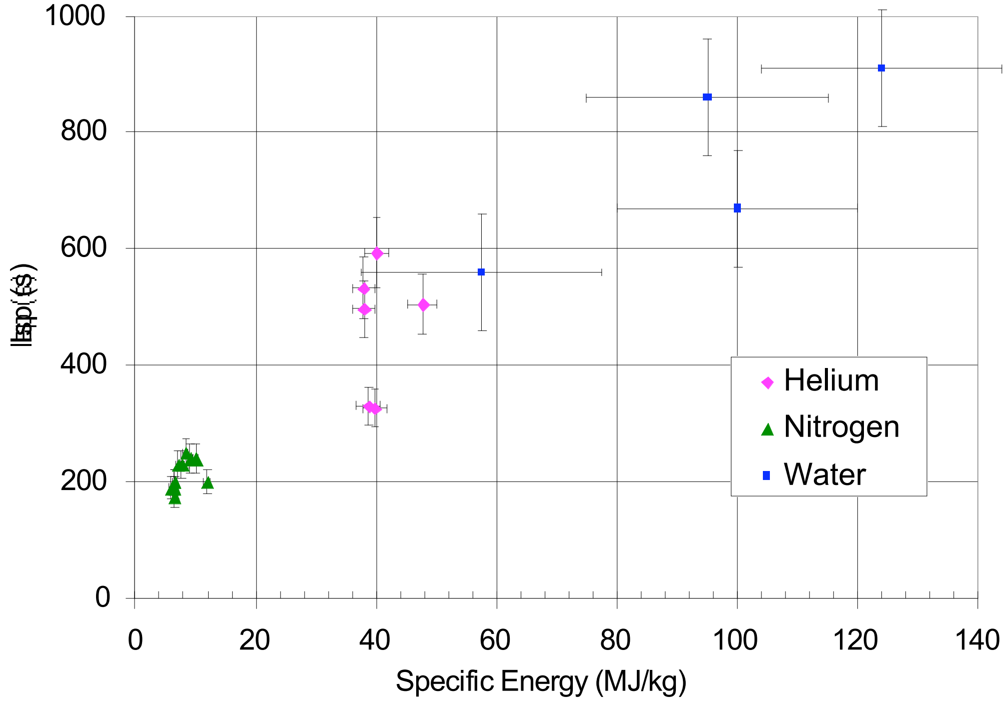


Figure 4. RSI data for specific impulse with various propellants as a function of specific power (input high voltage DC power divided by flow rate)

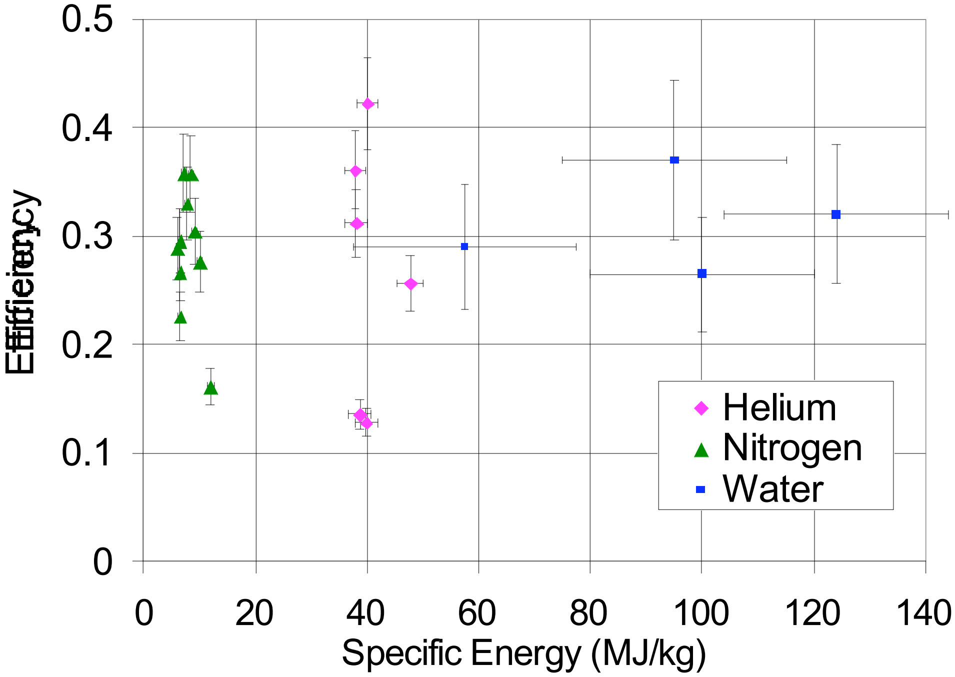


Figure 5. RSI data for efficiency with various propellants as a function of specific power