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MINI-MAGORION: A PULSED NUCLEAR ROCKET FOR CREWED SOLAR SYSTEM EXPLORATION

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ABSTRACT

Andrews Space has been awarded a NASA SBIR for the investigation and experimental verification of the Mini-MagOrion (MMO) concept. The MMO concept is a GigaJoule scale pulsed nuclear fission device, where low mass criticality is accomplished by the electromagnetic compression of individual fission pellets. The resulting fission reaction produces a highly energetic plasma, which is then expanded through a magnetic nozzle. Experiments on the Sandia National Laboratory Saturn and Z pulsed power machines were utilized to determine concept feasibility, and the results are presented. The design of the propulsion system based on the Mini-MagOrion concept, together with a look at the accompanying vehicle design and anticipated system performance are also discussed. An analysis of engine / nozzle interaction is presented, together with associated requirements on the vehicles power and thermal management subsystems. Vehicle performance assessments are given for crewed and robotic missions to the inner and outer solar system, indicating favorable capabilities based on near-term achievable technology.

INTRODUCTION

From January 2001 through 2003 Andrews Space has conducted research on improving the original Orion concept, receiving funding under NASA's SBIR program and from the Department of Energy. The concept – termed Mini-MagOrion (MMO) – reduces the size of the original Orion concept through the use of magnetic implosion technology.

Historical Background

Human exploration and exploitation of the solar system requires spacecraft with advanced propulsion systems capable of generating tens of kilometers per second of delta velocity while carrying large (> 100 metric ton) payloads. This requires very high energy densities and very high exhaust velocities. The original Project Orion was initiated by the Advanced Research Projects Agency in 1958 and cancelled in 1965. It was an effort to develop a rocket propulsion system using successive explosions of small nuclear bombs, with the hope that this nuclear pulse concept could provide capable propulsion for human exploration of the solar system.

In June 2000 Andrews Space concluded a Phase I SBIR on a further iteration of the Orion concept, termed MagOrion[1], which introduced a large (2 km diameter) superconducting ring to interact with the plasma debris of the nuclear explosive pulses, instead of the pusher plate of the original Orion concept. This enabled specific impulses above 10,000 seconds with initial system Thrust to Weight ratios from 0.2 to 10, depending on pulse frequency, pulse yield, and degree of tamping.

However, the study also identified potential showstoppers for MagOrion, such as superconductor limitations, and the political difficulty of launching a device capable of ejecting nuclear explosives at high repetition rates. These concerns led to the next iteration in the Orion family of designs, discussed in the presented paper.

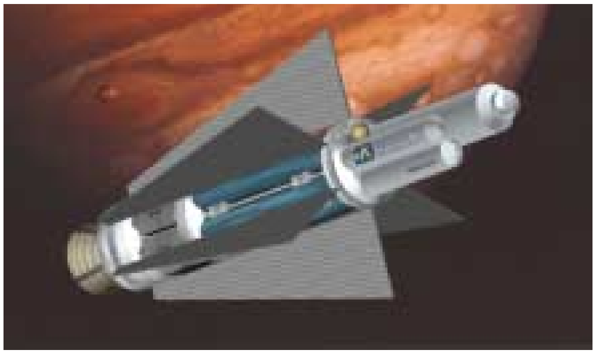

Figure 1: Mini-MagOrion artist drawing.

Mini-MagOrion Overview

At the heart of the Mini-MagOrion concept (Figure 1 above) is the idea of compressing initially subcritical fission assemblies by use of an imploding Z-pinch. This enables the lower yield values, external

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triggering of the fission reaction, and reduces the severity of the environment in which the engine has to operate. The MMO program included the analysis of solid, high Z material compression, paired with the experimental verification / calibration of the analysis.[2]

The specific composition of the fissile material in the compression target has a large impact on the requirement for maximum compression needed to achieve criticality. The program investigated a variety of fissile materials for suitability to the MMO concept, and performed neutron transport analyses to determine total yield, burnup fractions, required amounts of neutron reflectors and initiation neutron sources. The design settled on a baseline calling for the use of a hollow sphere of ^{245}Cm with an additional layer of Beryllium as a neutron reflector. An external neutron source is likely required to achieve well-timed criticality.

The ratio of the energetic yield released by the fission reaction, and amount of material expelled in each pulse is of critical importance in trying to achieve the very high exhaust velocities (10-30 km/sec) needed for efficient interplanetary travel. The program has investigated the possibility of Low Mass Transmission Lines (LMTL) fabricated from Mylar. Experiments were performed on the Sandia National Laboratory Saturn machine. Results indicate that transmission lines weighing as little as 2 kg may be sufficient to deliver the required currents into the Z-pinch used to drive the MMO compression.

The efficient conversion of the energy transferred into the plasma by the fission reaction into forward momentum of the spacecraft is another critical aspect of the MMO system. The team developed tools to analyze multi-coil magnetic nozzle configurations, and assessed a variety of designs for propulsive efficiency at minimum mass and power requirements. Both particle trajectory based models and MHD based fluid models were utilized.

Driving the magnetic compression implosion at high repetition rates (1 Hz) and the level of reliability needed for a crewed system requires the use of large, redundant pulsed power supplies. During nominal operation a small fraction of the energy (< 1%) produced by the fission reaction is recycled to recharge the pulse power banks. In addition, a steady state power supply is also needed to initially charge the system, or restart the engine in the case of a misfire. The mechanical design of an engine capable of repetitively discharging the pulse units at rates of up to 1 Hz is also a formidable engineering task.

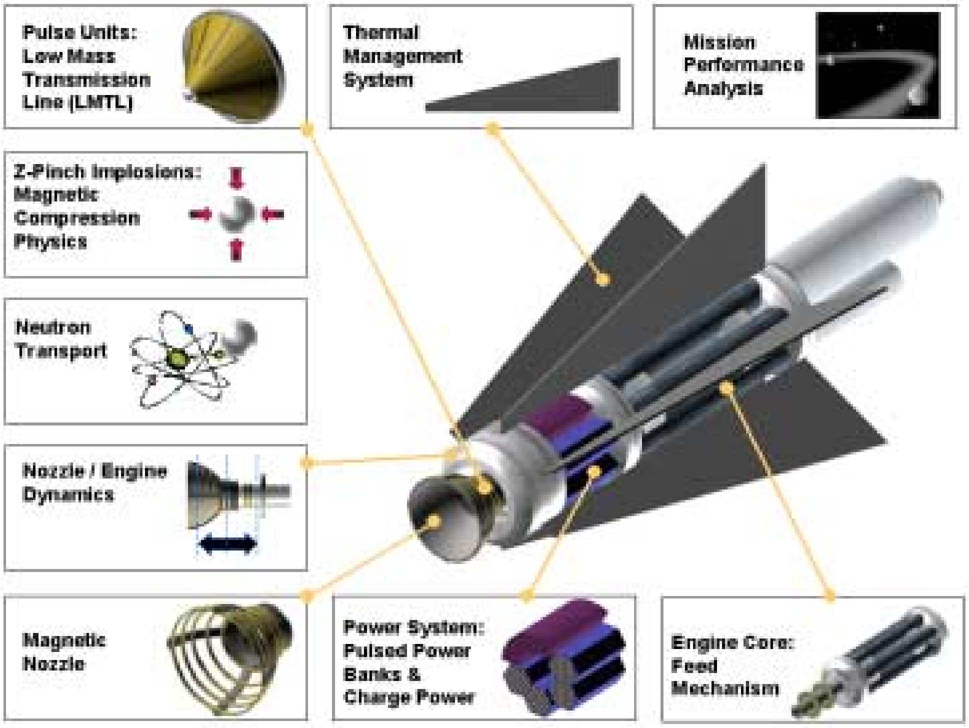

Figure 2: Mini-MagOrion system overview.

MMO Physics

The critical mass of fissile materials can be reduced substantially by compression. The mass scales with the square of the material density; therefore, even modest compression ratios are highly beneficial in reducing the mass and yield of the resulting explosion. The MMO program investigated the compression of material using the large magnetic pressure that can be generated using pulsed power technology.

Compression Modeling

Pulsed power technology is capable of delivering very high currents. The present Sandia National Laboratory (SNL) Z accelerator has a peak current of approximately 20 MA, which is delivered in 100 ns. This current can be used to generate very high pressures; as an example, 20 MA with a pinch radius of 3 mm results in a magnetic pressure of approximately 7 Mbar.

The maximum compression can be obtained in spherical geometry. A z-pinch can provide an almost spherical implosion[3] ("quasi-spherical") using the geometry shown in Figure 3.

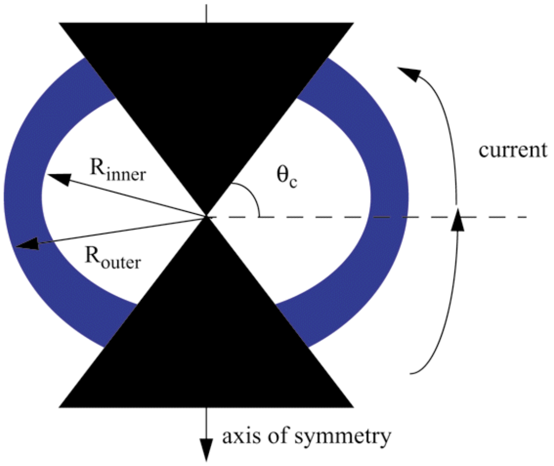

Figure 3: Quasi-spherical z-pinch geometry. The blue region is the fissile material to be compressed and the black conical region acts as a slide surface.

The investigative approach of the program included analysis of 2-D quasi-spherical implosions, computational modeling of 1-D geometries, and experimental implosion of cylindrical z-pinch liners in the SNL Z-machine. Since the peak current and rise time requirements of the z-pinch are the driving factors in the sizing of the power systems, a number of materials were investigated for suitability (Figure 4). ^{245}Cm emerged as the preferred baseline material.

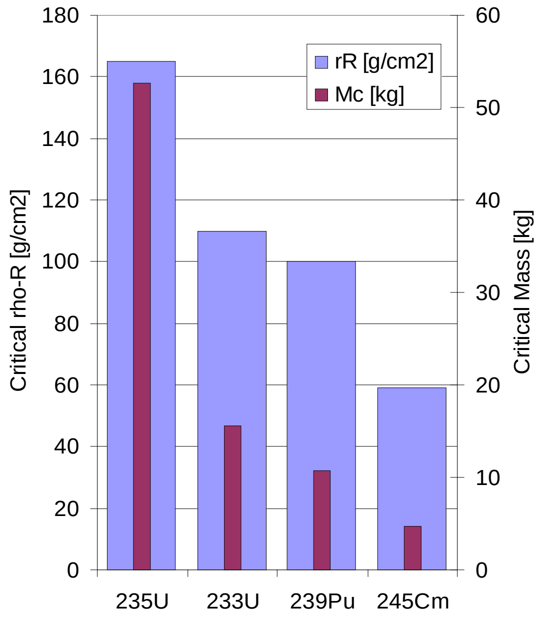

Figure 4: Fissile material properties.

Simulations were performed to determine the peak current needed to drive an implosion (Figure 5).

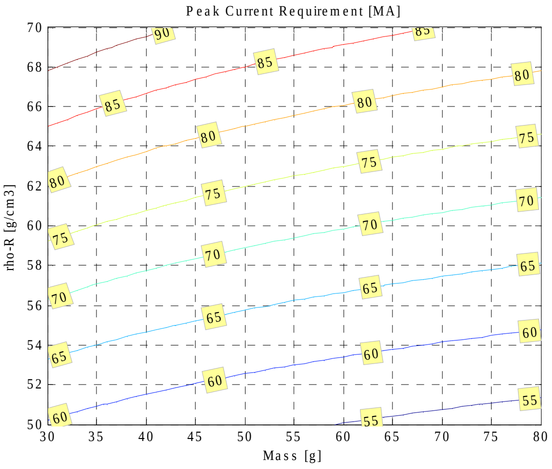

Figure 5: Peak implosion current requirement as function of target mass and critical ρR.

Compression Experiment

In order to calibrate the numerical modeling efforts, implosion experiments were performed on the SNL Z-machine. Since the implosion characteristics depend strongly on material conductivity and equation of state, the experiment used both aluminum and gold targets in a purely cylindrical geometry. Both materials are well understood, aluminum is frequently used on the SNL Z-machine, and gold was selected as a non-toxic representative of high-Z materials. The target thickness had to be selected so that the resulting implosion time matches the current profile produced by the Z-machine. The aluminum liner was constructed with a 2.42 mm outer radius, and a radius to thickness aspect ratio of 3. The gold target had a 2.00 mm radius and an aspect ratio of 10. Both geometries were anticipated to result in identical implosion times, thus simplifying diagnostic timing.

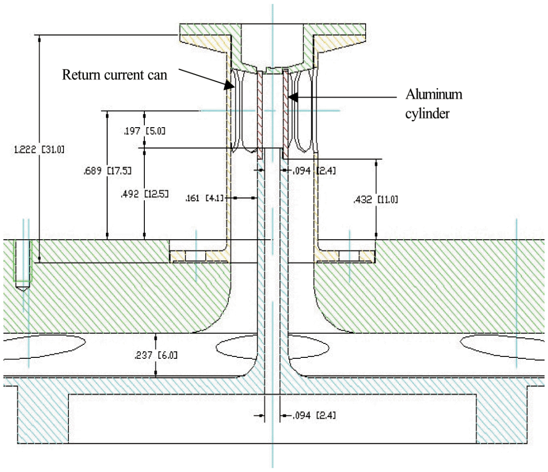

Figure 6: Hardware design for the aluminum cylindrical compression target and assembly.

A total of five diagnostic types were fielded:

- A terawatt source x-ray backlighter, using bent crystal shadowgraphy to determine the size of the target at peak compression.
- Active shock breakout using a laser reflecting of the electrode surface imaged on a streak camera to determine the time progression of the implosion shock front.
- Magnetic field (B-dot) probes.
- A number of CCD X-ray cameras to indicate the current path during the implosion discharge.
- Various current measurements.

Although three shots were planned, only two were completed in the time available to the experiment. The first shot used the aluminum target, successfully captured the backlighter image, but failed to obtain a shock breakout image. The second shot utilized the gold target, successfully captured a shock breakout picture, but did not obtain data from the backlighter.

Figure 7 shows the backlighter image captured on the anticipated time of peak compression of the first shot. The image is a negative, so the dark regions correspond to locations where the x-rays did penetrate (no material obscured the view). The dark irregular region on the right is the gap between the plasma blow-off from the outside post and the liner plasma.

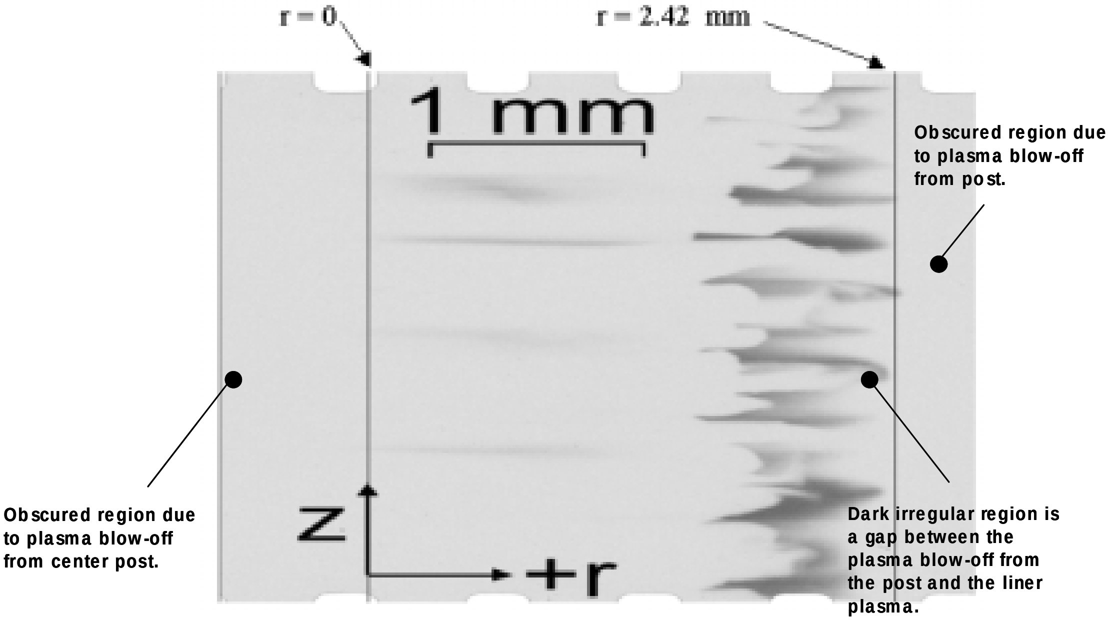

Figure 7: Backlighter image captured at anticipated peak compression time during the first (aluminum) shot.

Inspection indicates that the outer boundary of the liner has a radius of roughly 1.65 mm. However, the radius originally predicted at the time of peak compression was 0.5 mm. One possible explanation is that the image was not captured at the time of peak compression. Figure 8 shows the currents recorded at locations within a few centimeters of the outer liner and at the post-hole convolute, where the currents from four separate transmission lines are added prior to being delivered into the load.

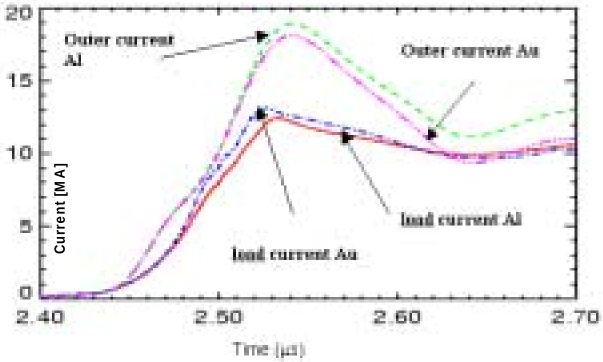

Figure 8: Current data from both shots (aluminum and gold targets) at the load and the convolute.

The difference between the outer currents and the load currents is indicative of losses due to a higher than predicted load inductance. Post experiment simulations based on the reduced current into the load showed good agreement with a liner radius of 1.6 mm at the time of image capture. It can therefore be concluded that the higher inductance resulted in a lower load current and slower implosion, which caused the diagnostic to be triggered before peak compression was reached.

Figure 9 shows the image from the streak camera of the shock breakout diagnostic captured on the second shot (gold target). At the time of the trigger the picture shows the full span of the pinch target. The t=0 point indicates the anticipated start of the target implosion; the actual implosion is again delayed by approximately 8-10 ns. The diagnostic indicates that a strong shockwave did develop, but at a later time than predicted.

As in the previous shot, post-experiment current data was used in the model to obtain an updated prediction of the implosion time, which resulted in a prediction of 20 ns. The discrepancy illustrates the need for further calibration of the model via additional experimental data points.

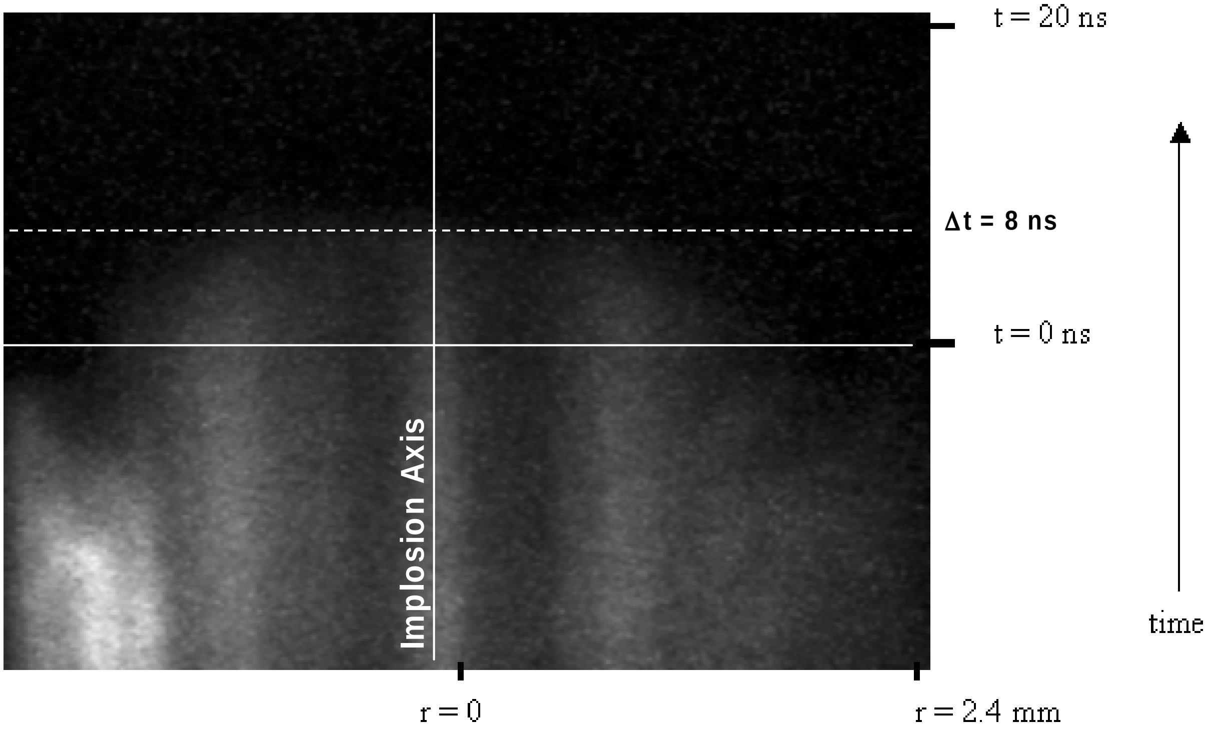

Figure 9: Shock breakout diagnostic camera image from shot number 2 (gold); implosion starts approximately 8 ns later than originally predicted, but 12 ns earlier than predicted with post experiment current data.

The use of a previously un-fielded load type clearly resulted in unanticipated inductance and current characteristics. The resulting challenges in diagnostic timing yielded only one backlit image, which was not coincident with the time of peak compression. The additional x-ray diagnostics (CCD cameras) measured the total radiated power emitted by the pinch at a level indicating an estimated temperature of 40 eV. At this temperature aluminum has an opacity of nearly 1000 cm^2/g, and as little as 1% of the liner mass spread out evenly would have been opaque to the backlighter. Therefore, the image may have been dominated by a small fraction of the liner mass, ablated early on and left behind in the implosion. At least one shot with both a backlighter image and the shock breakout diagnostic were necessary to make a more definitive assessment of the level of compression actually achieved.

Low Mass Transmission Lines

The MMO program also studied Low Mass Transmission Lines as a means of repetitively driving Z-pinches. Low mass transmission lines (LMTL) help reduce the cost of z-pinch driven space propulsion while increasing the theoretical limit of obtainable specific impulse for a given pulse yield. Experiments were performed on SNL's Saturn machine to determine if such thin electrodes can efficiently carry the required current. The tests were performed with various thicknesses of materials, and the results indicate that LMTLs should efficiently carry the large z-pinch currents needed for pulsed power driven nuclear rockets.

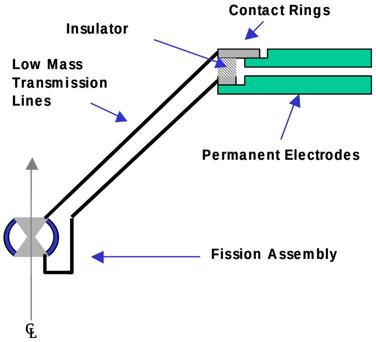

Figure 10: Low Mass Transmission Line (LMTL).

Current generated from a pulsed power network is delivered through a section of permanent transmission line and then through a section of LMTL (which will be destroyed each shot.) to the micro explosive unit. The plasma generated from the LMTL material and the explosive unit will be expanded at high velocity. The portion of this mass that expands toward the impulse chamber will stagnate against the field generated by the magnetic nozzle and be redirected downward to participate as expelled rocket propellant.

The experimental results indicate a minimum electrode thickness is required to avoid excessive resistive losses. It appears that 20 μ of Mylar is sufficient to carry the current with acceptable resistive losses. This result indicates that a transmission line with a mass as little as 2 kg could be used for space propulsion applications. Transmission line mass as a function of the current rise time was also investigated to estimate the specific impulse that could be obtained with a pulsed power driven fusion or fission rocket. The results indicate that very high values (thousands of seconds) are possible at moderate yields (order of tens to hundreds of GJ).

Fission Materials & Neutron Transport

Several materials were investigated for use as the primary fissile agent. Candidate materials were required to meet a number of criteria: low ρR (enabling low yield criticality at minimum compression ratios), low spontaneous fission fraction (storability of the propellant for long duration space flights), and show peak compression intervals needed to generate 60+ generations of neutrons (implying short generation times of $\sim 10^{-9}$ seconds or less), while maintaining a minimum burn-up fraction of ~10% of the available material.

The ρR for most common fissionable materials was found to be quite large, posing considerable technical challenges when trying to enable low yield fission via magnetic compression. Thus ^{245}Cm was selected as the baseline fission material. ^{245}Cm is available in the product of commercial reactor waste, and while expensive in terms of procurement cost, it was the most promising candidate addressing all the criteria listed above. The baseline design calls for a compression target made of 42.8 g of ^{245}Cm and 15.2 g of Be as a reflector. Analysis indicates that this assembly will exhibit a 10% burn up fraction, and require a compression ratio of 10 at 135 g/cm^3 final density. The criticality was determined to be $7.6 \cdot 10^{-8}$ sec at peak compression and a compressed target radius of 0.468 cm.

Due to their low spontaneous fission fraction, the MMO targets will require a separate neutron source, and initiation time is an important factor if the source production interval is shorter than the compression time. Most neutron sources in common use today have relatively long production times on the order of $\sim 10^{-5}$

seconds. Analysis indicates that it may be possible to directly integrate a Deuterium/Tritium diode into the compression assembly, which will fuse under compression and release 14.1 MeV neutrons starting of the fission reaction of the ^{245}Cm.

Mini-MagOrion Vehicle Concept

Several MMO engine designs were examined with the selected baseline concept scale and layout shown in Figure 11.

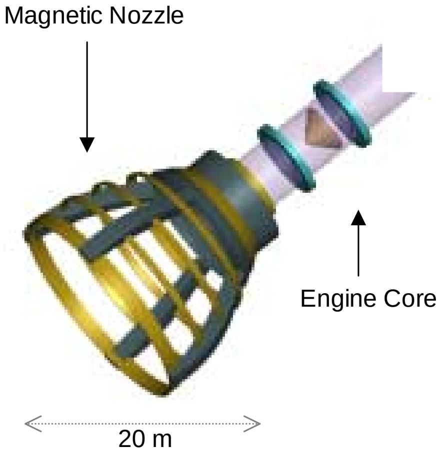

Figure 11: Baseline MMO engine design.

Figure 12 shows the sequence of events during a single pulse cycle. (1) The cycle begins with a pulse unit in place and ready for ignition, while both blast doors are closed. The magnetic nozzle assembly is at the top of its amplitude (fully extended) (2) As the discharge is initiated by the power system, the rearward door is opened to admit the next pulse unit into the feed system, after it has been injected by the rotating carousel assembly (not shown). The force of the escaping plasma interacts with the magnetic nozzle, which in turn travels in the direction of the vehicle front, beginning its compression cycle and transferring a quasi-steady force into the vehicle. (3) With the discharge completed and the plasma dissipated, the remaining momentum continues the compression motion of the magnetic nozzle assembly. The rearward blast door is completely closed in anticipation of releasing the next pulse unit into the combustion chamber. (4) The forward blast door is now opened and as the magnetic nozzle assembly swings through its point of maximum compression (most forward position), the new pulse unit is inserted into the combustion chamber at a velocity matching that of the assembly at the point of contact. The assembly containing the new pulse unit continues its swing to the point of maximum extension, where the cycle repeats.

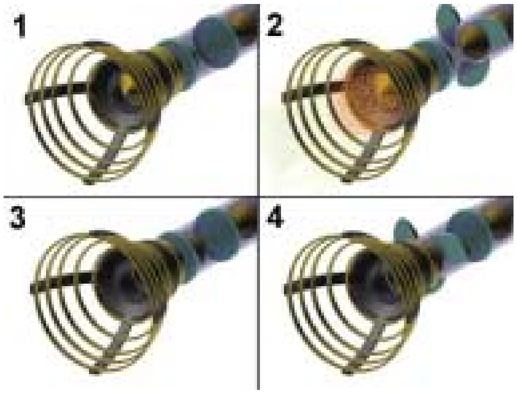

Figure 12: MMO engine pulse sequence

Each individual pulse unit consists of the implosion target, the conically shaped Low Mass Transmission Line (LMTL), and a contact assembly at the edge of the LMTL fashioned from aluminum. Figure 13 shows the basic layout and scale of a single unit.

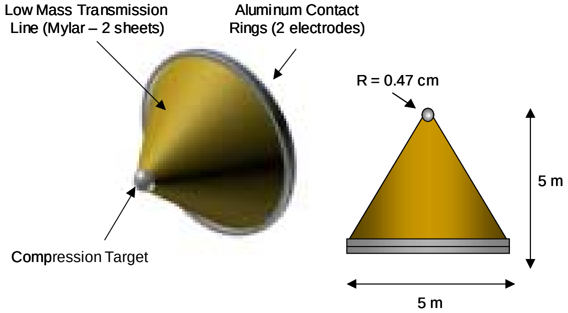

Figure 13: Pulse unit geometry and dimensions (drawing not to scale for illustration purpose).

Multiple feed tubes are arranged in a rotating assembly that feeds individual pulse units into the center tube and from there into the main engine for detonation (see Figure 2). This design allows for redundancy and the possibility of using more than one kind of pulse unit, resulting in a step-wise variable specific impulse engine.

In order to direct the plasma resulting from the explosion towards the rear of the vehicle a magnetic nozzle is utilized. The MMO team utilized particle trajectory (developed at the University of Washington) and MHD (MACH2) based analysis to investigate nozzle characteristics and establish a baseline suitable to the MMO vehicle concept. The final baseline nozzle, produces 1,870kN of thrust, 16,000 seconds of specific impulse and a nozzle efficiency of 87.1% at a yield of 340GJ per implosion.

It consists of 5 coils distributed over 11 meters with coils preferentially clumped near the axis, each carrying 10 MA of current. The total array mass is approximately 200 metric tons.

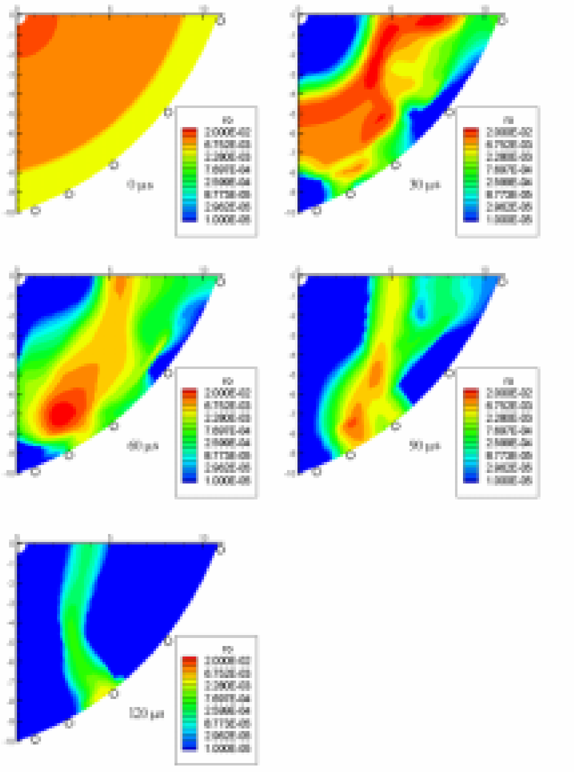

Figure 14: Time progression of plasma density contours during single pulse in the baseline nozzle.

The power supply for the Z-pinch implosion should provide a current evolution with approximately a 70 MA peak current, which rises in 1 µsec and is sustained for 1 µsec. The current decrease is unimportant since the implosion interrupts the current. The electrical power requirements for the magnetic nozzle are determined by the final nozzle design (magnetic field and coil locations). The power requirements of the two systems are sufficiently different that individual power supplies should be tailored to each system.

The high currents and short rise times required by the implosion can be generated by charging a capacitor bank in parallel to a lower voltage and then using switches to connect the capacitor in series. This configuration is called a Marx bank. The Marx bank design requires ten 500 µF capacitors, each charged to 170 kV. The choice was driven by easily available capacitors at the rated voltage and capacitance. It is envisioned that the switches will be high voltage gap switches with low inductance. The charge supply is isolated from the capacitors through two 250 Ω resistors for each capacitor. The energy required for each implosion is $CV^2/2$ or 72 MJ. At a pulse rate of 1 Hz, the power requirement is 72 MW.

The complete power system consists of three subsystems: the implosion pulsed power supply, the magnetic nozzle power supply, and the space nuclear reactor to initially charge the pulsed system and power all other spacecraft functions. In regards to the pulsed power systems, two capacitor banks will be required to provide redundancy in the case of a non-successful pulse.

Performance Analysis Model

Given a desired exhaust velocity, the required yield is determined from

$$Yield = \frac{1}{2} \cdot M_{PU} \cdot \frac{c_e^2}{\eta_{nozzle} \cdot \eta_{coupling}} \qquad (1)$$

Where M_{PU} is the total mass of the Pulse Unit vaporized in the explosion, η_{nozzle} is the propulsive efficiency of the magnetic nozzle, and $\eta_{coupling}$ is the fraction of the yield energy released in the form of a hot plasma. Analysis indicates that nozzle efficiencies of up to 45% are achievable, while the coupling efficiency is estimated at 55%. The optimum specific impulse selection depends on these efficiencies, and total mission Δv. The resulting performance range is shown in Figure 15.

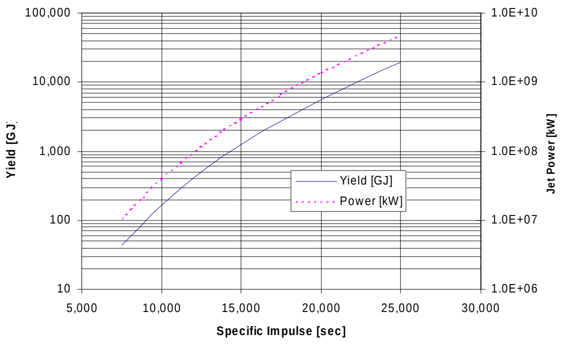

Figure 15: MMO performance envelope.

Figure 16 shows the MMO concept performance envelope in comparison to other current and proposed systems. Pulsed nuclear fission propulsion achieves the combination of high thrust values and specific impulse necessary for crewed exploration mission to both the inner and outer planets of the solar system.

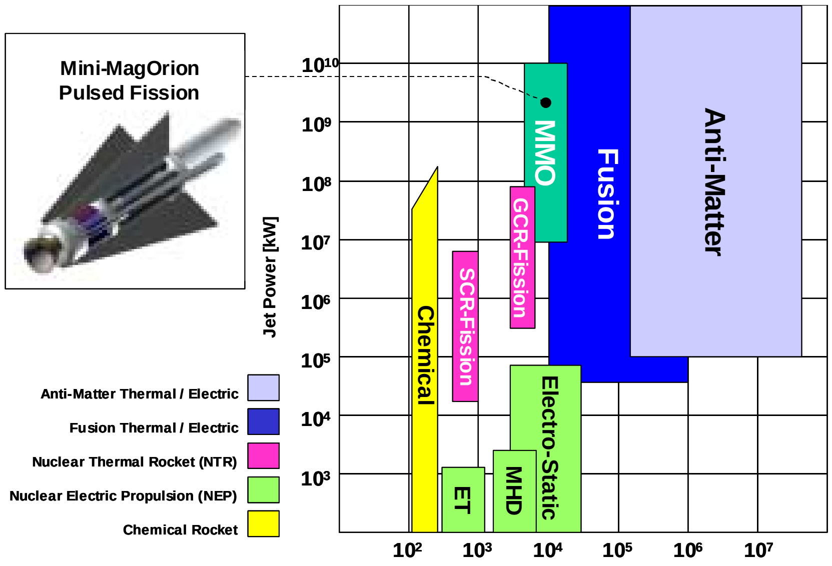

Figure 16: Comparison of thrust (jet power) and specific impulse values for various concepts.

The compression requirements over the range of the MMO performance envelope are shown in Figure 17. As the selected specific impulse increases, the yield increases, and the required compression ratio and peak current decrease. The current rise time increases as the implosion becomes slower due to the inertia of the larger implosion target. However, as the yield increases, the mass of the magnetic nozzle and associated power supplies also increases, driving up the total vehicle inert mass.

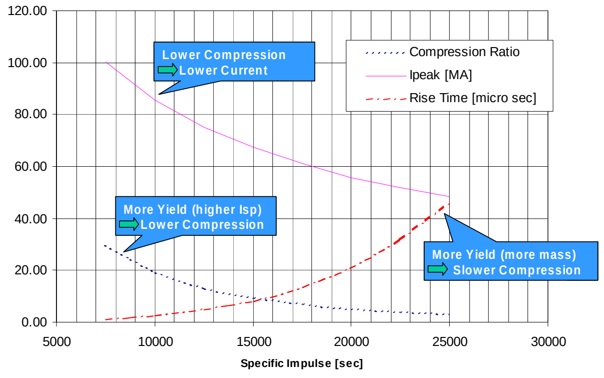

Figure 17: Compression requirements trend for the ^{245}Cm baseline vehicle vs. specific impulse.

Table 1 shows a comparison of vehicle specifications for a total mission Δv of 100 km/sec. This mission capability would be sufficient for a 100 metric ton payload to reach Mars in 60-90 days, or Jupiter in about one year. The specific impulse is chosen at the point of maximum payload mass fraction.

Table 1: Comparison of vehicle parameters for concepts based on different fission materials.

Material	^{245}Cm	^{239}Pu/HC	^{239}Pu/NC	
Δv	100.00	100.00	100.00	km/sec
Isp	10,000	12,000	13,700	sec
Payload	100	100	100	tons
Ignition	712	1,012	1,310	tons
ρR-crit	65	110	110	g/cm2
Density Ratio	30	42	30	n/d
Yield	280	690	1360	GJ
I_{Peak}	80	146	135	MA
Thrust	1,100	2,262	3,908	kN
Thrust	247,000	508,000	879,000	lbf
Power	54,000	133,000	263,000	MW
Gain	560,000	385,000	361,000	ratio
α	380,000	427,000	529,000	W/kg
a-Max	0.44	0.53	0.64	g's
a-Min	0.16	0.23	0.30	g's

The first column shows the baseline concept utilizing ^{245}Cm as the fissionable material. Column 2 shows a vehicle based on ^{239}Pu with a high compression ratio of 42. Column 3 also shows values for a concept based on ^{239}Pu, but with the lower compression ratio of 30 (identical to the ^{245}Cm scenario). The scaling for both ^{239}Pu and ^{245}Cm based concepts (ignition mass and yield) as a function achievable compression ratio is shown in Figure 18 (next page).

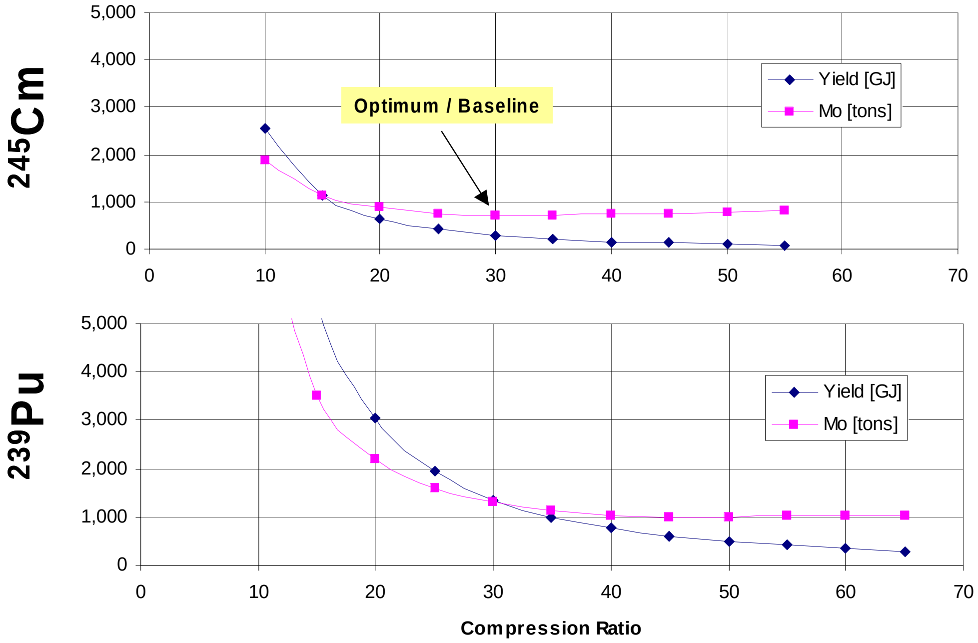

Figure 18: Vehicle scaling as a function of compression ratio, for both ^{245}Cm and ^{239}Pu powered concepts.

Summary

Based on the original Project Orion and the previously discussed MagOrion project, Andrews Space has developed the Mini-MagOrion concept and investigated it under a grant from the NASA SBIR Phase II funding program.

Mini-MagOrion utilizes pulsed power technology to compress initially sub-critical assemblies of fissionable materials by exposure to an imploding z-pinch magnetic field. The resulting hot plasma is directed with a magnetic nozzle to achieve a specific impulse range of 7,500 to 25,000 seconds, at a yield per pulse of 100 to 30,000 GJ.

Andrews Space and Sandia National Laboratories implemented a solid density, high-z material compression experiment, imploding both gold and aluminum liners in the SNL Z-machine. The main diagnostics fielded with the experiment were a terawatt x-ray source backlighter using bent crystal shadowgraphy and active shock breakout captured on a streak camera.

Two shots were performed in the allotted time frame; in shot 1 the backlighter captured an image, but the shock breakout diagnostic failed. In shot 2 the shock breakout diagnostic successfully captured an image, but the backlighter did not. The previously unfielded nature of the current loads led to unanticipated inductance characteristics and caused the diagnostics to trigger before the time of peak compression occurred. However, post-experiment analysis of the captured data was in rough agreement with the predictions of the analytical/computational model.

A baseline system design is presented utilizing ^{245}Cm as the fissionable material. The resulting vehicle is capable of providing a total mission Δv of 100 km/sec for a payload mass of 100 metric tons, at an ignition mass of 712 metric tons. Alternative concepts based on more available ^{239}Pu can achieve identical performance at ignition masses varying from 1,000 to 1,300 metric tons, depending on achievable compression ratio.

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