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ADVANCED PROPULSION CONCEPTS

Presentation to the
Space Transportation Propulsion Technology Symposium
Pennsylvania State University
June 27, 1990

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OUTLINE

This presentation will discuss a variety of Advanced Propulsion Concepts (APC). The focus will be on those concepts that are sufficiently near-term that they could be developed for the Space Exploration Initiative (SEI) on a time scale consistent with the President's call for a return to the Moon and a landing on Mars by July 20, 2019.

Several other advanced concepts, such as nuclear thermal propulsion and megawatt-class electric propulsion, have been presented earlier; this presentation will discuss high-power (multi-megawatt) electric propulsion, solar sails, tethers, and extraterrestrial resource utilization concepts. This will be followed by a summary of these concepts and some general conclusions on their technology development needs.

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OUTLINE

- Introduction
- Focus on Near-Term Advanced Propulsion Concepts That Can Be Developed for the Space Exploration Initiative :
  - Multi-Megawatt Electric Propulsion
  - Solar Sails
  - Tethers
  - Extraterrestrial Resource Utilization
- Summary and Conclusions

INTRODUCTION

As a general definition, Advanced Propulsion Concepts (APC) are those propulsion concepts beyond advanced chemical (e.g., O_2/H_2) propulsion. These advanced concepts hold the promise of significantly benefiting the Space Exploration Initiative (SEI) missions of the 21st Century. However, other than the very near-term nuclear thermal propulsion and megawatt-class electric propulsion concepts discussed previously, these APCs discussed here will require significant further research in order to resolve issues relating to feasibility, performance, or mission benefit. Depending on the maturity of a given concept, the required research can range from proof-of-principle experiments for far-term concepts to experiments designed to quantify performance parameters (e.g., specific impulse, efficiency, thruster lifetime, etc.) for the more near-term concepts. Finally, note that although most of the mission applications discussed in this presentation will be for the piloted lunar and Mars missions, these APCs can also be used for a number of the unmanned precursor missions of the SEI. More generally, APCs can be applied to a variety of ambitious unmanned missions such as outer-planet orbiters, sample returns, or interstellar precursor missions.

When assessing the missions benefits of APCs, the two primary figures of merit that are typically used are the total transportation system initial mass in low Earth orbit (IMLEO) and the mission trip time. The total IMLEO can include the "dry" mass of the vehicle (engines, propellant tanks, etc.), its propellant, a propellant "tanker" if the propellant is launched separately from the vehicle, on-orbit constructed or support facilities (e.g., space station), and, finally, the payload. Often IMLEO is used as the primary figure of merit since it directly relates to the launch costs for transporting materials from the Earth to low Earth orbit (LEO). In general, savings in IMLEO, and thus launch costs, for an advanced concept (as compared to a state-of-the-art system) are used to offset the development costs of the advanced system.

One interesting result of mission trade studies of APCs is that their benefit is a function of the mission size; in general, the "bigger" the mission, the more the benefit of the APC. This is one reason why APCs are often considered for the large piloted missions of the SEI. This behavior is seen because, in general, state-of-the-art (SOA) systems have a small fixed mass (e.g., dry mass) as compared to the APC system; however, the propellant mass required for the SOA system increases with increasing mission "size" (payload mass, Delta-V) more rapidly than for the APC system due to the higher specific impulse (I_{sp}) of the APC system.

Trip time can also be an important factor in assessing the mission benefits of APCs, since the longer the trip time, the higher the operations costs, and the higher the required system reliability and lifetime. Also, for missions like a lunar base buildup, trip time can impact the vehicle fleet size if the trip time is too long to allow re-use of the vehicle on the required delivery schedule. Finally, trip time is especially important for piloted missions because of the effects of long exposure of humans to weightlessness or radiation, or to the psychological effects of long-duration missions. This is especially important in piloted Mars missions, since most high-thrust (ballistic) missions have trip times of several years. As will be discussed below, some low-thrust APCs can reduce this trip time to one year or less.

In general, for missions in cis-lunar space, high-thrust propulsion system, such as chemical or nuclear thermal, generally have shorter trip times than low-thrust systems, such as electric propulsion. However, for missions beyond the Moon, low-thrust APCs, which can thrust continuously for days to years, can have a shorter trip time than high-thrust systems which must coast ballistically to their target. Thus, APCs often show a trip time benefit only for missions beyond the Moon.

Finally, other factors that can be of interest include the schedule requirements (i.e., can the APC be developed in time to meet the mission schedule), nuclear safety (and its impact on operations and nearby vehicles), and development costs. In the case of development costs, synergisms may exist between different agencies; for example, the technology of the nuclear power system required for a high-power nuclear electric propulsion vehicle is of interest to the National Aeronautics and Space Administration (NASA), Department of Energy (DoE), and Department of Defense (DoD).

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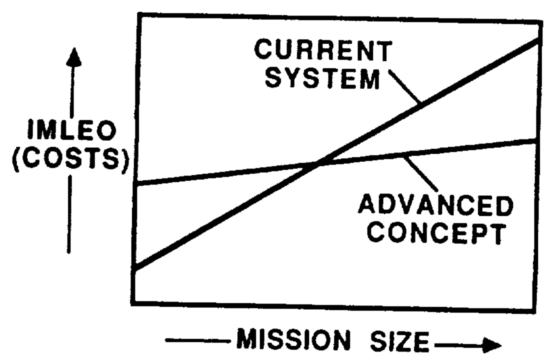
INTRODUCTION

- Advanced Propulsion Concepts (APC) Are Those Concepts Beyond Advanced Chemical
  - Promise Significant Mission Benefits for the Space Exploration Initiative (SEI) Missions of the 21st Century
  - Require Further Research to Demonstrate/Quantify Performance

- Primary Figures of Merit Used in Assessing APCs Are the Total Transportation System Initial Mass in LEO (IMLEO) and Trip Time
  - IMLEO -> Launch Costs
  - Trip Time -> Ops. Costs, Reliability, Fleet Size, Life Sciences
  - Other Factors Include Risk (Schedule), Nuclear Safety, and Development Costs



ADVANCED PROPULSION CONCEPTS

As discussed previously, the focus of this presentation will be on those Advanced Propulsion Concepts (APC) that can be developed in time to support the piloted lunar and Mars SEI. The most near-term APCs, discussed in previous presentations, are nuclear thermal propulsion and electric propulsion, including both solar electric propulsion (SEP) and nuclear electric propulsion (NEP), at power levels up to a few megawatts. High-power (>10 MW_e) SEP and NEP, solar sails, tethers, and extraterrestrial resource utilization for propellant production will be discussed in detail in this presentation.

There are a wide variety of other Advanced Propulsion Concepts that are not being discussed because they are more far-term, require a large on-orbit infrastructure, or do not provide major benefits to the SEI in terms of IMLEO or trip time. For example, exotic chemical propellants, such as atomic or free-radical hydrogen, may greatly enhance launch vehicle performance, but they should be considered far-term since significant research is required at this point to even demonstrate feasibility. Similarly, fusion and antimatter propulsion, which may enable very fast trips in the solar system (e.g., a two-month round trip to Mars with fusion propulsion), are also far-term. Laser or microwave beamed-energy concepts are applicable to only cis-lunar space (because of optics transmission range limitations) and may require a large on-orbit infrastructure (e.g., laser power stations, relay mirrors, etc.). Solar thermal propulsion, rail guns, and mass drivers may provide significant reductions in IMLEO for cis-lunar operations but only modest reductions in IMLEO for Mars missions. Also, since they are low-thrust systems, they will have a longer trip time for cis-lunar missions than high-thrust concepts.

Solar thermal propulsion is a very near-term propulsion concept (under development by the Air Force) that is especially suited to cis-lunar missions; it has many of the specific impulse (I_{sp}) advantages of nuclear thermal or laser thermal propulsion, but without the nuclear reactor or laser system infrastructure of the latter two. Similarly, rail guns and mass drivers have several benefits for operations in cis-lunar missions. Although they are essentially electric propulsion concepts, they can use any material as "propellant"; thus, lunar-produced materials (including raw lunar soil) could be used as propellant, thereby greatly reducing the required IMLEO. However, rail guns and mass drivers should be considered as far-term concepts, in part because of the need for a pre-established lunar materials production infrastructure. There is also the need for significant technology development of the thrusters, although some of this technology is being addressed by DoD programs.

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ADVANCED PROPULSION CONCEPTS

- **Focus on Near-Term Advanced Propulsion Concepts (APC) Likely to Have an Impact on the Lunar and Mars SEI**
  - **Nuclear Thermal***
  - **Solar and Nuclear Electric Propulsion (MW* & MMW)**
  - **Solar Sails**
  - **Tethers**
  - **Extraterrestrial Resource Utilization**
- **Other APCs Probably More Far-Term, Require S[illegible]ificant On-Orbit Infrastructure, or Don't Satisify Both [illegible]ar and Mars SEI**
  - **Exotic Chemical (Atomic Hydrogen)**
  - **Beamed Energy (Laser, Microwave)**
  - **Solar Thermal**
  - **Rail Gun / Mass Driver**
  - **Fusion**
  - **Antimatter**

*** Discussed in Previous Papers**

MULTIMEGAWATT ELECTRIC PROPULSION

Multimegawatt (>10 MW_e) SEP and NEP have the potential for both reducing IMLEO and trip time. For example, in a split Mars mission, where the cargo is sent on a slow, low-energy trajectory and the piloted vehicle is sent on a fast, high-energy trajectory, NEP and SEP cargo vehicles operating at tens of megawatts of power have an IMLEO one-third that of a chemical (O_2H_2) aerobraked vehicle. This large savings in IMLEO (about 1000 metric tons for a 400 metric ton payload) is offset somewhat by the long trip time of the low-thrust SEP and NEP cargo vehicles as compared to the high-thrust chemical vehicle (600 to 700 days at 10 MW_e versus ~290 days Earth-to-Mars trip time, respectively), although the electric propulsion vehicles are returned to Earth for later re-use.

However, the primary advantage of high-power electric propulsion is that it can provide the short round-trip times that may be mission enabling for the piloted portion of a Mars mission. For example, at power levels of 100 to 150 MW_e, an NEP vehicle can achieve a one-year round trip to Mars. The potential for high-power NEP to enable this short trip time is very important, since the round trip time of high-thrust ballistic trajectories (typically two to three years) far exceeds U.S. or Soviet continuous manned experience in space. The long trip times required for piloted Mars missions raise serious health and safety issues. Most notable among these is the problem of long periods of weightlessness (bone and muscle mass loss, etc.). Even if artificial gravity is employed, there still remain the risks associated with prolonged radiation exposure (cosmic rays or solar flares) and the psychological impacts of confinement in small isolated groups. These problems can be accommodated for trip times of one year or less based on the success of Soviet long-duration space station missions.

Finally, both SEP and NEP are candidates for the cargo mission. The specific mass of the NEP system is generally less than that of the SEP system in the multimegawatt range, so the NEP vehicle is lighter. However, the NEP vehicle requires an orbit transfer vehicle (OTV) to operate from LEO to a nuclear safe orbit (NSO), typically 1000 km in altitude, where the NEP vehicle operates. This infrastructure overhead, although small, results in the NEP system having roughly the same IMLEO as the SEP system for a given power level, although the NEP vehicle will be somewhat faster than the SEP vehicle due to its lower mass and constant power output.

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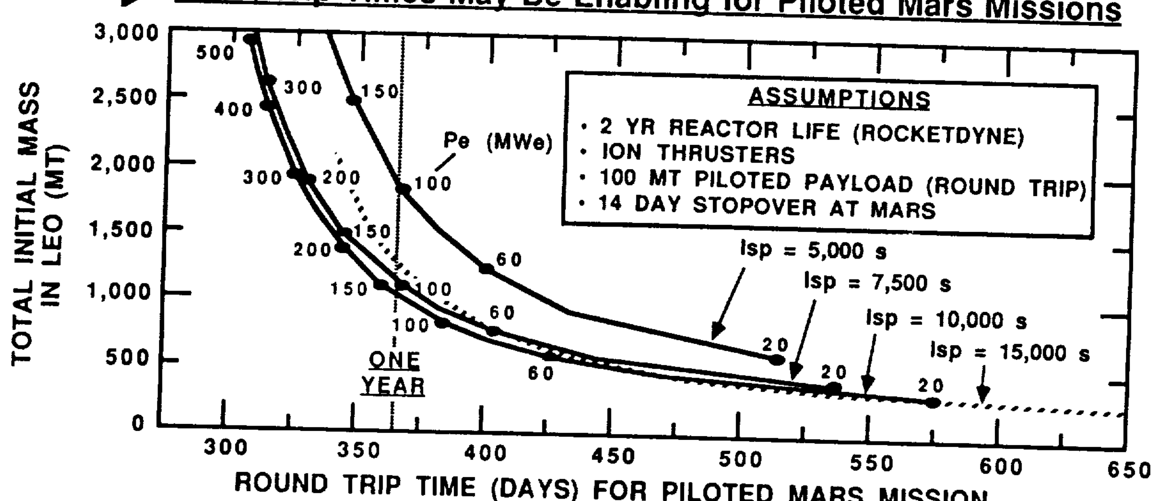
MULTIMEGAWATT ELECTRIC PROPULSION

- **Potential for Both Reduced IMLEO and Short Trip Times for High Power (> 10 MWe) Electric Propulsion**

⇨ **Short Trip Times May Be Enabling for Piloted Mars Missions**



- **MMW Solar Electric Propulsion (SEP) and Nuclear Electric Propulsion (NEP) Are Both Options**
  - **MMW NEP Has Lower Specific Mass Than SEP, but NEP Requires Nuclear Safe Orbit (NSO) Operation and LEO-to-NSO Transport Infrastructure**

MMW NEP NUCLEAR ELECTRIC POWER SYSTEMS

The performance of multimegawatt (MMW) NEP vehicles depends critically on the specific mass of the nuclear electric power system. For the MMW power regime (>10 MW_e), high-temperature dynamic power conversion systems provide significant mass savings over the static power conversion systems favored at low power level (<1 MW_e). There can also be significant economics of scale at the higher power levels since many of the fixed-weight components become a small fraction of the total system mass. For example, the figure illustrates the power system specific mass of a solid-core reaction system with a dynamic Rankine power conversion cycle. These values are taken from an on-going study by Rocketdyne addressing system concepts for MMW steady state Strategic Defense Initiative (SDI) applications. This is one of several concepts being investigated by the DoE for the Strategic Defense Initiative Office (SDIO); there is a strong synergism between these applications and the NEP systems discussed here.

This figure illustrates the effect of power level on specific mass; for example, the specific mass varies from 3.0 kg/kW_e at 10 MW_e to 1.9 kg/kW_e at 200 MW_e. As with many space power concepts, the system mass and the vehicle configuration are dominated by the waste-heat radiators. The vehicle is configured such that the radiators, payload, and propulsion system are behind the reactor's shadow shield. The payload is placed far away from the reactor to minimize radiation dosage, and the thrusters are oriented so as to not impinge the exhaust plume on the radiators and possibly heat them or deposit materials that could change the emissivity of the radiators.

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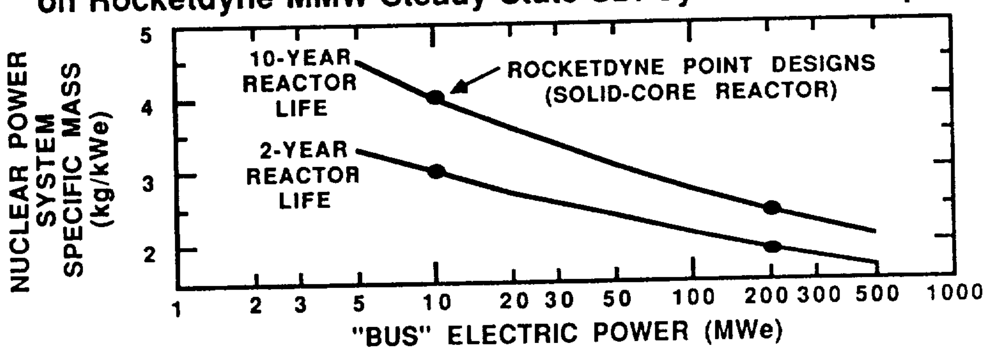
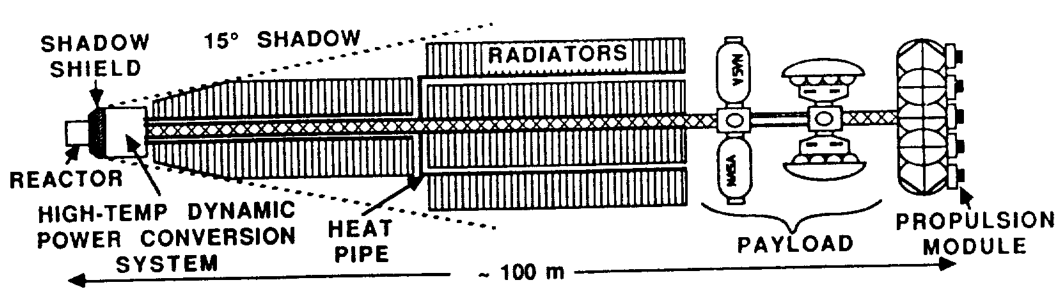
MMW NEP
NUCLEAR ELECTRIC POWER SYSTEMS

- High-Power (> 10 MWe) Space Nuclear Power System
  - High-Temperature Dynamic Power Conversion System
  - Significant Economies of Scale
- Example : Solid-Core Reactor & Dynamic Rankine Cycle Based on Rocketdyne MMW Steady-State SDI Systems Concepts





As mentioned earlier, MMW SEP systems can compete with MMW NEP for the Mars Cargo mission, as shown in this figure. Since it is non-nuclear, an SEP vehicle can operate directly from LEO, thereby avoiding the infrastructure overhead associated with an NEP vehicle. Also, advanced solar photovoltaic power systems may be directly competitive with nuclear power systems. For example, for the SEP system shown here, the specific mass of the power system is 3.6 kg/kW_e; based on the Rocketdyne study discussed above, a nuclear power system with a 10-year operating life would have the same specific mass at a power of 20 MW_e. However, the nuclear system does provide constant power whereas the solar power system's output drops off as it moves away from the sun. Interestingly, because efficiency of the GaAs photovoltaic cells assumed in this example increases with decreasing temperature, the power output is slightly better than a simple $1/R^2$ distance relationship. Finally, note that it is both the lower specific mass and the constant power output that gives high-powered NEP the advantage in trip time over SEP.

One potential drawback of MMW SEP is the lack of significant economies of scale at higher powers due to the modular nature of the solar photovoltaic arrays. In fact, there may even be negative economies of scale due to added structural complexity (e.g., active structure control) or increased mass and losses in the transmission lines. The latter effect is due to the relatively low voltage output of the solar arrays (several hundreds of Volts), resulting in the need for large bus bars at high powers. By contrast, the power output from a nuclear power system with dynamic power conversion can be at high voltages (several thousands of Volts), thereby minimizing transmission line losses and mass. This issue needs to be addressed in future studies.

Another issue relating to solar photovoltaic power systems is the impact of radiation degradation on the cells due to passage through the Van Allen radiation belts. Other studies have shown that a single round trip can result in as much as a 50% degradation in power output; however, in the example shown here, no radiation degradation was assumed based on the assumptions of a fast trip time through the radiation belts coupled with techniques for minimizing cell damage (e.g., high-temperature annealing, radiation-resistant materials, etc.). The issue of radiation degradation, and its impact on vehicle performance, will continue to be an area requiring further technology development and mission analysis.

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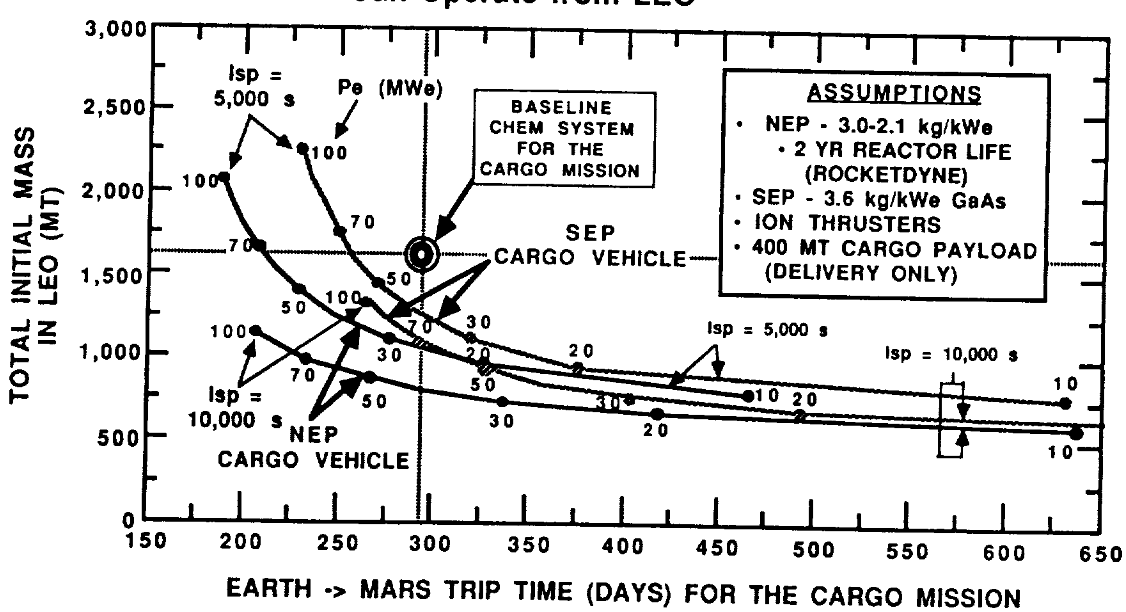
MMW SEP
SOLAR ELECTRIC POWER SYSTEMS

- High-Power (> 10 MWe) Solar Photovoltaic Power System
  - Example : Adv. GaAs Cells, No Radiation Degradation (?), 3.6 kg/kWe Specific Mass (Little Economy of Scale)
- May Be Competitive With NEP at Moderate Powers
- Non-Nuclear - Can Operate from LEO



MMW EP THRUSTERS

Various types of high-power electric propulsion thrusters are in development. For MMW SEP or NEP applications, it is very desirable to have thrusters that can operate at high power levels (1 MW_e or more) per thruster, so as to minimize the number of thrusters required and thereby reduce system complexity. High specific impulses (5,000 to 10,000 lb_f-s/lb_m) are needed. The optimum I_{sp} depends on the mission (Delta-V) and vehicle (specific mass, thruster efficiency, etc.), although values of I_{sp} in excess of 10,000 lb_f-s/lb_m tend to increase the mission trip time while only slightly reducing the IMLEO. It is also important that the thrusters have a high electric-to-jet power efficiency so as to maximize thrust per unit power as well as reduce thermal control requirements. Finally, a long thruster lifetime is desirable to minimize the number of spare thrusters needed to complete the mission. Unfortunately, there is no single type of thruster that meets all of these requirements; each of the thrusters discussed below has different advantages and disadvantages.

The two most near-term electric thrusters are the ion thruster and the self-field magnetoplasmadynamic (MPD) thruster. Ion thrusters currently operate at levels of one to ten kilowatts per thruster; advanced ion engines may be capable of a megawatt per thruster. By contrast, MPD thrusters begin to operate efficiently at powers of about a megawatt (or more) per thruster. Both ion and MPD thrusters can operate at high I_{sp}, although low molecular weight propellants (e.g., H_2) may be required for MPD thrusters operating at an I_{sp} of 10,000 lb_f-s/lb_m. The efficiency and lifetime of ion thrusters (70% to 90% and tens of thousands of hours, respectively) are greater than that of MPD thrusters (40% to 60% and hundreds to thousands of hours, respectively). Thus, there is no clear winner between ion and MPD thrusters; development of both types must continue since one may be favored over the other for some classes of missions, but not for all.

Several other advanced electric thrusters are currently in the research stage. Two examples of these are the electron cyclotron resonance (ECR) thruster and the ion cyclotron resonance (ICR) thruster. In both of these, microwave energy is used to excite and energize the propellant to produce a high-energy plasma which is controlled and directed by externally applied magnetic fields. The more near-term of the two, the ECR thruster, couples the microwave energy to electrons in the plasma. The ECR thruster is potentially scalable over a range of kilowatts to many megawatts per thruster. It can operate at moderate-to-high efficiency (50% to 80%) and high I_{sp}. Interestingly, because it is an electrodeless device (unlike ion or MPD thrusters), it has the potential for very long thruster lifetimes. Also, because it is an electrodeless device, the ECR thruster can use a variety of propellants, including oxidizing propellants such as oxygen derived from extraterrestrial resources.

In the ICR thruster, under development at MIT, microwave energy is coupled to ions in the plasma. This far-term thruster concept would operate at many megawatts per thruster at high I_{sp} (with hydrogen propellants), and at a moderate efficiency (50%). One unique feature of the ICR thruster concept is its ability to continuously vary I_{sp} over the course of a mission so as to optimize vehicle performance (i.e., lower I_{sp} and thus higher thrust for planetary escape or capture followed by higher I_{sp} for the heliocentric transfer). Although most electric propulsion thrusters can also vary their I_{sp}, they typically do so with some loss in performance (e.g., efficiency). The ICR thruster is designed to permit easy and efficient variation in I_{sp} to meet the needs of the mission trajectory.

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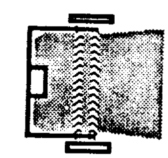
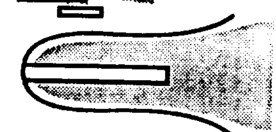
MMW EP THRUSTERS

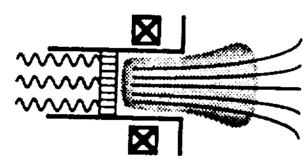
- Various Types of High Power Electric Thrusters in Development
  - Need MW per Thruster
  - High Isp (5,000 - 10,000 lbf-s/lbm) Desirable (Mission Dependant)
  - High Eff. and Long Life Desirable
  - Ability to Use Common or ET-Resource Derived Propellants Desirable
- Near-Term : Ion and MPD Thrusters
  - Ion : Low-to-Medium Power/Thruster, High Isp, High Eff., Medium-to-Long Life



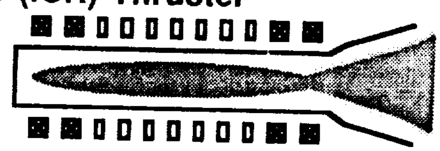
  - MPD : High Power/Thruster, High Isp (w/ H2), Medium Eff., Medium Life (Electrode Erosion)



- Mid-Term : Electron Cyclotron Resonance (ECR) Thruster
  - Microwave Energy Coupled to Electrons in Plasma
  - Low-to-High Power/Thruster, High Isp, Medium Eff., Can Use O2, etc.
  - Long Life (Electrodeless)



- Far-Term : MIT Ion Cyclotron Resonance (ICR) Thruster
  - Microwave Energy Coupled to Ions in Plasma
  - High Power/Thruster, High Isp, Medium Eff., H2 Propellant



MMW EP SUMMARY

Multimegawatt electric propulsion, unlike most near-term Advanced Propulsion Concepts, has the potential for reducing both the IMLEO and trip time for ambitious missions of the SEI. In particular, MMW NEP, because of its ability to provide short trip times, may be enabling for the piloted Mars mission. In terms of overall mission performance, an MMW NEP system is lighter and faster than a similar-power SEP system, but the NEP system does have the added overhead and complexity of nuclear operations and the corresponding infrastructure required to support space-based nuclear power systems. Finally, although 100 MW_e class NEP vehicles are required for piloted Mars missions, NEP or SEP vehicles at power levels of a few tens of megawatts are attractive for the cargo mission where reductions in IMLEO, rather than trip time, are more important.

Current technology programs are addressing several of the technologies of interest here. However, in several cases, only low power applications are being pursued; these programs will need to be extended to cover the MMW regime. The DoE is evaluating several MMW nuclear power system concepts for the SDIO. Steady-state systems (rather than burst-mode systems) are of special interest to the MMW NEP vehicle concept. For SEP, both the Lewis Research Center (LeRC) and the Jet Propulsion Laboratory (JPL) are investigating high-power solar arrays. Both ion and MPD thrusters are being developed at LeRC and JPL, although little work has been done on megawatt-class ion thrusters. Finally, the two advanced thrusters discussed earlier are in the basic research stage; the ECR thruster is being studied at JPL and Caltech, the ICR thruster at MIT.

Technology needs for MMW EP include those of large space structures, power, and thrusters. For the nuclear systems, the required technologies include MMW reactors, dynamic power conversion systems, and lightweight radiators. Note that there may be some significant differences between power systems designed for SDI applications and NEP vehicle applications, such as in the area of "hardness" or vulnerability. In the area of solar power systems, there is a need for lightweight, high-efficiency, radiation-degradation resistant cells and substrates. High-temperature, high-efficiency cells are also important in the laser-electric propulsion concept, in which a laser beam (rather than sunlight) is used to power an SEP-type vehicle.

For ion thrusters, there is a need to develop thrusters with a high power (megawatts) per thruster. There is also a need to demonstrate high-I_{sp} and high-efficiency operation of ion thrusters using common propellants such as argon or krypton, since the xenon currently used is very expensive and may not be available in the quantities required for the Mars SEI. There is also a need to demonstrate high power-per-thruster operation of MPDs, although this is currently more a facilities limitation than a thruster limitation since the MPD is intrinsically a high-power device. Also, MPDs are currently limited in their lifetime due to erosion of the electrodes; both lifetime and efficiency need to be improved. The high I_{sp} (up to 10,000 lb_f-s/lb_m) that may be required for Mars missions will require development of MPDs that can operate on low molecular weight propellants such as hydrogen. Finally, advanced thruster concepts, such as the ECR and ICR thrusters, require continuing basic research to demonstrate and characterize their performance.

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MMW EP SUMMARY

- Potential for Both Reduced IMLEO and Short Trip Time
  - Short Trip Times May Be Enabling for Piloted Mars Mission
- Mission Benefits Issues :
  - High Power (100 MWe Class) NEP Needed for Piloted Mars Missions
    - High Power NEP Lighter & Faster Than Similar Size SEP, but NEP Requires Nuclear Operations & Infrastructure
  - Medium Power (10-100 MWe) Attractive for Cargo Missions
    - NEP and SEP Both Contenders
- Current Work :
  - Nuclear : DoE/SDIO
  - Ion : JPL and LeRC
  - ECR : JPL/Caltech
  - Solar : LeRC and JPL
  - MPD : JPL and LeRC
  - ICR : MIT
- Technology Needs :
  - Large Space Structures
  - Nuclear : MMW Reactor, Dynamic Conversion, Radiators
  - Solar : Lightweight, High Eff., Radiation Resistant Cell Blankets
  - Ion : High Power/Thruster, Ordinary Propellants
  - MPD : Lifetime (Erosion), Eff., High Isp
  - ECR, ICR : Basic Research to Demonstrate/Characterize

SOLAR SAILS

Solar sails operate by using momentum exchange with solar photons; this amounts to a force of 9 Newtons/km^2 at 1 AU. As such, a solar sail has "infinite" specific impulse, because it requires no propellant, but it has a low acceleration resulting in long trip times. Also, solar sails are typically large, gossamer structures with dimensions of kilometers; for example, a typical solar sail has an area of 4 km^2. Because of their light weight and "infinite" I_{sp}, solar sails represent the lightest advanced propulsion concept. Solar sails are also potentially one of the most near-term of the APCs, having been extensively analyzed in the past. The primary disadvantage of solar sails is their low acceleration, which results in very long trip times. Thus, solar sails are suited only to cargo missions, although for these missions they can provide major reductions in IMLEO.

From a mission performance perspective, the long trip times of solar sails represent a significant issue which must be resolved by mission planners. For example, the long trip times affect not only the sail's lifetime requirements, but also the storage life requirements of the cargo. Scheduling of departure/arrival dates may also be complicated by the long trip times.

One way to reduce the trip time is by eliminating the long planetary escape/capture spirals by basing the sail at a high altitude, but this then requires an infrastructure of OTVs to ferry cargo from LEO (or low Mars orbit) to the sail's orbit. In fact, this is required at Earth since a sail cannot achieve sufficient thrust to overcome air drag at altitudes less than about 2000 km. Thus, the IMLEO shown in the figure includes the OTV infrastructure required to transport sails and cargo from LEO to the sail's operational altitude (2000 km).

Another significant issue affecting the sail's performance is its method of construction, since this affects the average areal density (grams per square meter) and ultimate acceleration of the sail. For example, current sail technology, studied extensively by JPL for a Halley's Comet rendezvous mission, involves the use of sails which would be deployed (un-folded) in orbit. This requires the use of a relatively thick sail and heavy support structure (booms, etc.), with a fairly high areal density (5 g/m^2), to survive folding on the ground, packaging for launch, and un-folding in orbit. If, however, the sail is assembled in orbit, the sail film and support structure need not be as thick or heavy, since they do not need to survive the folding and un-folding of a sail assembled on the ground. This can result in a roughly five-fold reduction in areal density, but only with the addition of the additional infrastructure of a sail construction facility in LEO.

Finally, if the sail material is fabricated in orbit, zero-gee manufacturing techniques can be used to produce ultra-thin materials and provide a twenty-five fold reduction in areal density as compared to a deployable Halley's Comet class sail. However, although deployable and assemblable Halley's Comet class sails are near-term, sails fabricated in orbit are mid- to far-term, since the technology for zero-gee sail fabrication is yet to be developed.

As mentioned earlier, deployable sails were studied extensively by JPL in the late 1970's for use in a Halley's Comet rendezvous mission. The only current solar sail technology work being pursued is by the World Space Foundation (WSF), a private organization. This group has built upon the work done by JPL, using many of the engineers involved in the earlier JPL activity. The WSF has constructed an engineering prototype square sail of 880 m^2; they are in the process of securing space on a launch vehicle to perform a demonstration flight of their prototype sail.

In the area of technology needs, deployable solar sails are relatively mature. There are still issues of dynamics and control of large space structures to be resolved. These issues would need to be resolved for two types of potential sails: the square and the heliogyro sail, both of which were studied by JPL. The square sail is simply a square film of sail material supported by booms and guy wires; the heliogyro sail operates like a propeller with "propeller blades" of sail material unrolled from a central hub and stabilized by the centrifugal force of the spinning system. Both types of sails have different advantages and disadvantages that must be resolved by further study.

A second area of technology need is the development of on-orbit assembly techniques, since assemblable sails provide such significant performance advantages over deployable sails. Finally, in the far-term, the technology of on-orbit zero-gee fabrication of sails from advanced materials will be required to realize the ultimate in solar sail benefits.

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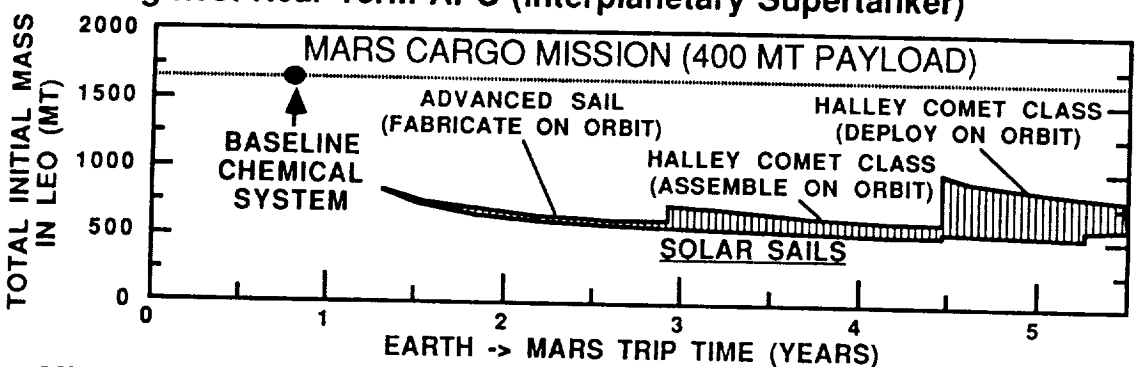
SOLAR SAILS

- Reduces IMLEO Since Infinite Isp, but at Cost of Long Trip Times
  - Lightest Near-Term APC (Interplanetary Supertanker)



- Mission Benefits Issues :
  - Long Trip Time (Lifetime)
  - Large Structure Deployed Versus Assembled On-Orbit
    - Impacts Sail Areal Density -> Trip Time

- Current Work :
  - Extensively Studed by JPL for Halley Comet Mission (1978-79)
  - World Space Foundation Engineering Prototype Sail (880 m2)

- Technology Needs :
  - Dynamics / Control (Square Versus Heliogyro Sails)
  - On-Orbit Deployment Versus Assembly Versus Fabrication
  - Materials for Advanced Sails

TETHERS

Tether concepts for propulsion and power have been investigated within the last decade for a variety of space missions. Two classes of tether systems are electrodynamic tethers, which interact with a planetary magnetic field, and non-conducting tethers which interact with the gravitational field. The latter type, which can be used for orbit raising and lowering or planetary escape and capture will be discussed below.

Tethers can reduce IMLEO for the lunar and Mars SEI by reducing or eliminating the propellant required for propulsive maneuvers. For example, rotating tethers can be used in a transportation system in cis-lunar space that requires no propellant. In this system, the orbital angular momentum lost by transferring cargo "up" out of the Earth's gravity well from LEO to the Moon is balanced by shipping lunar materials "down" to LEO. (The rotating tether in lunar orbit rotates at a speed such that its tip has zero velocity relative to the lunar surface, so that payloads can be dropped off or picked up on each cycle.) For Mars missions, tethers can be employed on Deimos and Phobos to lower incoming traffic to lower orbits, or to raise outgoing traffic to higher orbits. In fact, a 6100-km long tether on Deimos can provide an outbound vehicle with Mars escape velocity.

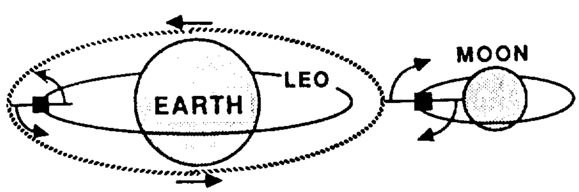
In terms of mission performance, one of the key issues associated with tether systems is the mass of the tether "stations" used to raise or lower the tether for orbital deployment/retrieval. These "stations" typically consist of a power system, tether reel drive motors, structure, and so on. Also, if the station is in a free orbit, rather than based on a moon, propellant is required to re-position the tether station in the proper orbit after each cycle. For example, the tether station would drop to a lower orbit after deploying a spacecraft outward. Typically, the infrastructure represented by the tether stations, their re-boost propellants, as well as the mass of the vehicles used to transport the stations to their final basing location (i.e., lunar orbit, Martian moons, etc.) must be amortized over many payload delivery cycles in order to show a benefit in IMLEO.

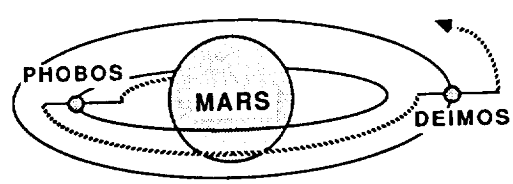
Tethers can be used for a variety of applications. One system currently in development for a Space Shuttle flight in the late 1990's will use a downward-deployed tether to lower a probe into the upper atmosphere. For this mission, as well as most of the applications currently considered, no advanced materials technology is required. State-of-the-art materials like Kevlar or Spectra have the physical properties required for tethers in cis-lunar or Martian space. One area that does require further work is that of the dynamics and control of large, flexible systems like tethers.

JPL

TETHERS

- **Reduces IMLEO by Reducing / Eliminating Propulsive Maneuvers**
  - **Orbit Raising / Lowering and Planetary Escape / Capture**





- Rotating Tethers Can Function as Cis-Lunar Transportation System That Needs No Propulsion
- Tethers on Phobos & Deimos Can Capture / De-Orbit Landers and Pick-Up / Inject Return Vehicles

- **Mission Benefits Issues :**
  - **Infrastructure Set-Up for Tether "Stations" Must be Amortized Over Many Cycles**

- **Current Work :**
  - **STS Demo for Upper Atmosphere Probe**

- **Technology Needs :**
  - **Dynamics / Control**
  - **Materials are SOA Kevlar or Spectra**

EXTRATERRESTRIAL RESOURCE UTILIZATION

Extraterrestrial resource utilization (ETRU) can provide major reductions in IMLEO by producing propellants and other materials (e.g., structures, shielding, etc.) from extraterrestrial resources. ETRU can be used for both lunar and Mars missions. For example, several processes have been investigated for producing oxygen from lunar soil (regolith). One extensively studied concept uses the mineral ilmenite ($FeO \cdot TiO_2$), which is about 10% of the lunar regolith, at feedstock. The ilmenite is chemically reduced by hydrogen, producing water, iron, and titanium dioxide. The water is electrolyzed to produce oxygen and hydrogen, and the hydrogen is re-cycled.

On Mars, carbon dioxide, the main component in the Martian atmosphere, is broken down into carbon monoxide and oxygen; the oxygen is then extracted from the gas mixture by means of a zirconia membrane. Zirconia (ZrO_2) has the property of transporting oxygen through its crystal lattice when a voltage is applied across the membrane. This technology is currently under development by the DoE for extraction of oxygen from terrestrial air.

If water is available on the Moon (at the lunar poles, etc.) or Mars (permafrost, polar caps), it can be electrolyzed to produce oxygen-hydrogen propellant at an oxidizer-to-fuel ratio (O/F) of 8. On Mars, water can also be combined with carbon dioxide to produce methane and oxygen at an O/F of 4, which is nearly ideal for propulsion applications. Even if water is not available on Mars, the carbon monoxide produced by extracting oxygen (from carbon dioxide in the Martian atmosphere) can be used as a low-performance (but "free") fuel.

As with several of the advanced concepts discussed above, the benefits of ETRU depend heavily on the infrastructure requirements. These include the materials production facilities, their consumables (e.g., chemical fluxes, electrodes, etc.), and the systems required to transport and set up the "factories". The degree of process closure or recycling is also important, since this impacts the amount of imported consumables required. Also, unmanned precursor missions may be needed to map out resource locations on the Moon (ilmenite, water) and Mars (water).

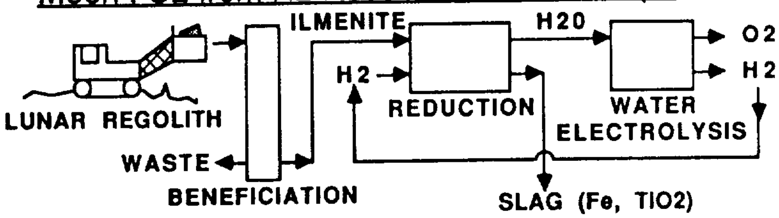
Current work in the area of ETRU processing includes Johnson Space Center (JSC) studies of lunar oxygen production concepts and a University of Arizona project to develop and build a breadboard system to produce oxygen from a simulated Martian atmosphere. Thrusters capable of using propellants derived from ETRU systems (e.g., high-O/F O_2/H_2, O_2/CH_4, O_2/CO, etc.) are under development at LeRC.

Continued thruster development is required to resolve many of the unique technology issues associated with thrusters designed to use unconventional ETRU-produced propellants. These include cooling, coking, and ignition, as well as feed systems, since some potential ETRU-produced fuels are solid materials. For the ETRU production processes, it is necessary to demonstrate the various candidate processes, with the appropriate simulated ET resource, in order to evaluate efficiencies, power requirements, lifetimes, and closure for the various systems. With this information, it will then be possible to select a preferred system for use on the Moon or Mars. For lunar regolith- based systems, it will also be necessary to develop technologies for low- gee soil moving (scooping, digging, etc.) and beneficiation (mineral separation). Finally, ETRU process "factories" will need technologies common to a variety of SEI applications, including power, thermal control (refrigeration), and construction.

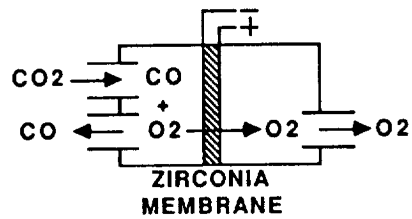
JPL ET RESOURCE UTILIZATION

- Provides Major Reduction in IMLEO by Producing Propellants, etc., from Local Materials

Moon : O2 from H2 Reduction of Ilmenite (FeO•TiO2)



Mars : O2 from CO2



- Mission Benefits Issues :
  - Infrastructure ("Factory"), Closure (Imports)
  - Precursor Missions to Locate Resources (Ilmenite, Water)

- Current Work :
  - ET Propellant Thruster Development at LeRC
  - JSC-Funded Studies of Lunar O2 Production Concepts
  - U of Arizona Breadboard Demo of Mars CO2/O2 System

- Technology Needs :
  - Demo Thrusters With Unconventional ET Propellants
  - Demo Processes w/ Simulated Resource
    - Efficiencies, Power, Closure
  - For Moon : Demo Digging, Scooping, Beneficiation, etc.
  - Related Technologies : Power, Refrigeration, Construction

SUMMARY

To summarize the advanced propulsion concept discussed in this presentation, MMW class NEP and SEP, solar sails, tethers, and ET resource utilization can have a significant impact on the lunar and Mars SEI. 100 MW_e class NEP is the only near-term concept that appears capable of providing the one-year round-trip time that may be required for a piloted Mars mission. At powers of tens of megawatts, NEP and SEP are both attractive for Mars Cargo missions. The benefit of MMW NEP and SEP is strongly dependent on the power and propulsion system performance; low specific mass is essential and high I_{sp} (up to 10,000 lb_f-s/lb_m) is highly desirable. Finally, development of the NEP vehicle nuclear power system may gain a significant input from the DoE/SDIO MMW space nuclear power program.

Solar sails are the lightest, but also slowest transportation system for cargo missions. Their benefit will be a function of the relative importance of IMLEO as compared to trip time. Interestingly, deployable (Halley's Comet class) sails are potentially the most near-term of the APCs discussed here.

Tethers and extraterrestrial resource utilization can show significant benefits for both lunar and Mars missions. However, their benefit does depend on the infrastructure (tether stations, process factories, initial transportation and set-up) required for their operation. In both cases, the infrastructure must be amortized over many usage cycles. For the ETRU processes, propellants, especially oxygen, will be produced in the near-term. As the technology matures, other materials (structures, etc.) can be produced. However, because of the need to manipulate large quantities of lunar regolith, the technology for lunar oxygen production will tend to be more complex than that for martian oxygen production which requires only atmospheric carbon dioxide as its feedstock.

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SUMMARY

- 100 MWe Class NEP May Enable 1-Year Round-Trip for Piloted Mars Missions
  - NEP and SEP Competitors at < 100 MWe Levels for Cargo Missions or Split Piloted Missions
  - Benefit Depends on Power System and Thruster Performance
    - Low Specific Mass Needed; High Isp Desirable
  - NEP Synergistic with DoE/SDI MMW Space Nuclear Power
- Solar Sails Lightest Transportation System, but also Slowest
  - Benefit Depends on Importance of IMLEO Versus Trip Time
  - Deployable (Halley Comet Class) Sails Very Near Term
- Tethers May Show IMLEO Benefits for Large Missions
  - "Amortize" Infrastructure Over Many Operational Cycles
- ET Resource Utilization Can Provide Propellants in the Near Term and Other Useful Products in the Far Term
  - Lunar Process Complex, Mars Process Simple

CONCLUSIONS

The advanced propulsion concept discussed above can be developed to meet the schedule of SEI missions in the first quarter of the 21st Century. Out of all of these concepts, MMW space power (solar and nuclear) and high- power electric thrusters stand out as two technologies that can significantly enhance and potentially enable a wide variety of piloted SEI missions. However, a major study effort is needed soon to characterize and compare these concepts for SEI missions. This will make it possible to select the best concept(s) and plan the technology development effort required to meet the SEI schedules. Once selected, the total technology development cost for any one concept is likely to be in the $100M to $1B range. Although this is a non-trivial development cost which may be necessary for several technologies, it should be remembered that the savings in IMLEO made possible by this advanced technology will off-set these costs. For example, at a launch cost of $1M per metric ton to LEO (one-tenth the current launch costs), a single Mars cargo mission would save as much in launch costs using an advanced propulsion concept as the costs of developing that concept. Finally, continuous support at the $1M to $5M per year level is essential to maintain basic research on the very advanced concepts which will be required for large-scale solar system exploration and exploration missions in the post-2025 era.

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CONCLUSIONS

- The Advanced Propulsion Concepts Discussed Above Can Be Developed in Time for SEI Missions in the First Quarter of the 21st Century
- MMW Space Power and Advanced High-Power Electric Thrusters Stand Out as Important Technologies That Can Enable a Wide Variety of SEI Missions
- A Major Study Effort Is Needed Soon to Select Among the Concepts and to Plan the Technology Development Effort
- Once Selected, the Total Technology Development Cost for Any One Concept Likely to Be in the $0.1-1B Range
- Support at the $1-5M per Year Level Needed for Basic Research on the Very Advanced Concepts Which Will Be Required for Missions in the Post-2025 Era

SECTION 1.5

FOREIGN TECHNOLOGY

PRESENTATION 1.5.1

JAPANESE TECHNOLOGY