PROGRESS IN SPACECRAFT ELECTRIC POWER SYSTEM TECHNOLOGIES FOR DEEP SPACE MISSIONS

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Abstract

Planetary missions place unique demands on spacecraft systems and operations in terms of lifetime and autonomous operation. At the same time, the new "faster, better, cheaper" environment requires more technological innovation than ever before to enable us to continue to explore the planets with the same successes that we have enjoyed in the past. This paper discusses new electric power system design and component technologies that provide the basis for planetary exploration in the 1990's and far beyond, especially for small spacecraft. We discuss new concepts in power management and distribution technology, followed by an assessment of the status of photovoltaic and nuclear power source technologies, and we conclude with a discussion of advanced battery technologies for small spacecraft.

Introduction

Detwiler, et al.[1] recently described the prospects for new power technology insertion into planetary science exploration missions. Brandhorst, et al.[2] have described some of these technologies in greater detail. When those papers were first presented in 1995, the last deep space launches by the United States had been in 1989 (Magellan to Venus and Galileo to Jupiter), 1990 (Ulysses solar polar, joint with Europe), 1992 (the failed Mars Observer), and 1994 (Naval Research Laboratory/Ballistic Missile Defense Organization's Clementine, placed in lunar orbit in 1994). In 1996, however, there has been a revival of interplanetary launches, with the Near Earth Asteroid Rendezvous (NEAR) in February, Mars Global Surveyor in November, and Mars Pathfinder (lander and rover) in December, all launched in 1996. With two or three launches now planned every year for the foreseeable future, the opportunity for new technology to have an impact on deep space missions is now great and the planned use of new technologies on upcoming space missions is impressive.

These impacts are being felt in all areas of the power system, from source to load. In fact, mission designers have begun to rely upon technological advances in order for program managers to be able to meet cost and schedule goals, while maintaining high levels of performance. Also, as Detwiler[1] emphasized, the trend continues to dictate that spacecraft be reduced in size and mass, with some "micro-spacecraft" concepts having a wet mass as low as 10 kg[3]. At the same time, power technologies must meet the higher power requirements demanded by electric propulsion thrust stages.

This paper will serve as an update to Reference 1, and report on progress toward insertion of new technologies into deep space science missions. Finally, an updated prognosis for the future is provided.

Power Sources

Photovoltaic Power Sources

Most interplanetary missions for the foreseeable future will be solar-photovoltaic powered. Furthermore, recent technology developments have resulted in the widespread introduction of GaAs/Ge solar cells in planar arrays as the power source for the majority of deep space applications. For example, the Mars Pathfinder cruise stage, lander and Sojourner rover are all powered by 18.5% efficient (AM0, 1-sun) GaAs/Ge solar cells. Similarly, the Mars Global Surveyor is powered by four panels, two-silicon and two-GaAs, and the NEAR spacecraft is powered by GaAs. GaAs has become the technology of choice due to its high efficiency in comparison to silicon. While costs remain somewhat higher, the need for power has become the driving requirement due to constrained packaging volumes that limit the area of solar cells available for power generation. The Mars 1998 orbiter and lander spacecraft will also make use of GaAs/Ge. The Mars lander missions will also provide the opportunity to characterize the performance of photovoltaic cells in dusty environments having wide temperature swings (-110° to +50° C). Finally, the NEAR solar cells were characterized for their low intensity-low temperature (LILT) effects, inasmuch as it will swing as far out as 2.2 AU on its way to its rendezvous with the asteroid 433 Eros in February 1999. This is the most distant use of solar arrays ever attempted in a space mission.

Other developments are now also beginning to have an impact on solar powered mission planning. The imminent commercialization of multi-band gap solar cells will be marked by the almost immediate use of $GaInP_2$/GaAs/Ge dual band gap cells in a linear refractive concentrator array on the New Millennium Deep Space 1 spacecraft.[4] These cells are expected to produce power at efficiencies in the low-20's% (15X concentration at AM0 and 1 AU) in a 2.6kW array. The advantages of the concentrator array are associated with the reduction in cells required for a given array area, as well as mass savings for arrays that must be designed for high radiation environments, since only a relatively small fraction of the exposed surface need be shielded. Also, the high concentrator cell efficiencies will lead to reduced total surface area of the array. The mass of these arrays are unlikely to compete with planar, flexible blanket arrays for some time, and thus concentrator systems should be expected to have an impact primarily on science spacecraft having power requirements demanding large array structures of several kilowatts or more.

Improved dual band gap cells and triple band gap cells are anticipated in the next few years, with efficiencies above 25% projected.[5,6] Such developments will further enhance the functionality of science spacecraft, however, it is clear that a practical limit to solar array efficiencies near 30% will be reached in the near future. Thus, future solar power technology performance advances may depend on array and system level developments. For example, concepts such as a combined radio frequency-photovoltaic array system will be important in the future if significant advances in performance and/or functionality are to be expected in the period ten years or more from now. By combining or integrating more than one spacecraft function, mass reductions and increased functionality may be realized.

Finally, solar photovoltaic systems of the future will also be required to withstand extreme environments. Bankston, et. al,[8] described some of the challenging environments that may be encountered by photovoltaic systems in the future. Temperature extremes (as low as 100K in some missions, as high as 700K in others), dust, and high radiation environments are examples of the problems that will face cell and array developers in the future. Successful solutions to such requirements will be enabling for missions to the vicinities of both the inner and outer planets. These requirements will also likely include the need to withstand high-G (10's of thousands) impacts, while being tightly packaged in extremely small volumes. Insofar as radiation is concerned, various multi-cell combinations incorporating InP show promise.[7]

Radioisotope Power Sources

Recent advances have led to opportunities to significantly increase the performance of radioisotope systems for deep space missions. While considerable effort is being devoted to extending the applicability of solar photovoltaic systems, studies continue to show that radioisotope power sources will continue to be required for future deep space missions. Here the relative insensitivity to the local environment and distance from the sun are the prime factors favoring radioisotope power for certain mission scenarios.

Specifically, the alkali metal thermal-to-electric converter (AMTEC), thermophotovoltaics (TPV), and the Stirling engine have received considerable attention in recent years for possible use in radioisotope systems. All three technologies have the potential to produce electricity from a radioistope source at approximately 20% or greater. The goal continues to be to optimize the use of the $Pu^{238}O_2$ fuel while significantly reducing the size and mass of the power source for future small planetary spacecraft.

Multi-tube AMTEC cells are now being designed, fabricated and tested.[9] These designs are now considered near-flight prototypical and the optimization of system designs incorporating the latest cell technology is continuing. Accelerated lifetime test programs have been initiated and an AMTEC technology flight experiment is manifested on STS-88 scheduled for December of 1997. Work on TPV has been characterized by continued progress in the development of a narrow band-pass filter.[10] More experimental data on these filters are now available for input into systems studies, providing greater confidence in the projected performance of TPV radioisotope systems. These projections show that efficiencies near 20% in a radioisotope power source of approximately 80W (compared to the General Purpose Heat Source-Radioisotope Thermoelectric Generator[11] (GPHS-RTG) efficiency of 6-7%) are possible.[12] Stirling engines, still the more mature of the three radioisotope converter technologies, also continue to be studied, albeit at a lower level, continued design enhancements and lifetime demonstrations being the principal focus of recent attention.[13]

In view of recent technological progress and the prospective need for radioistope power sources for future deep space missions, the Department of Energy has recently announced plans for a program to design and develop an advanced radioisotope power system in the 100W class.[14] The plan includes, following selection of a specific conversion technology, the fabrication of an electrically heated engineering model of the advanced radioisotope power source by July of 1999.

Figure 2 depicts the objectives and future prospects for thermal-to-electric converter performance. Note that for power sources that operate near their peak power point, the relationship given by Curzon and Ahlborn[15] predicts a maximum efficiency of 38% for converters operating between the temperature limits shown (from the GPHS-RTG). Thus, for small power sources, 100W or smaller, we would not expect efficiencies to ever substantially exceed 30%. Most space systems would operate near their peak power point, and while the temperature limits may vary, limitations on heat sources and radiator areas will probably not allow substantial deviation from operating temperatures of the GPHS-RTG.

The conclusion, then, is that assuming successful development of one of the candidate technologies (or some other as yet unidentified converter), we will soon be reaching a practical limit on the efficiency of thermal-to-electric converters for radioisotope power sources. However, future challenges remain. The environments that may be encountered by photovoltaics, described previously, would also be encountered by the radioisotope power source. Planetary atmospheres, wide temperature ranges, high-G impacts, dust, etc., are a few. Also, the need for even smaller power sources, from 10's of milliwatts to 10's of watts are envisioned for small landers, probes, and microspacecraft.

Energy Storage

Major progress has occurred in the area of energy storage. 1996 saw the first planetary launch of the two-cell common pressure vessel nickel-hydrogen battery on the Mars Global Surveyor. This design[16] has now been selected for the New Millennium Deep Space 1, Mars '98, and Discovery-Stardust missions. Its design has been found to be well suited for the small, mass constrained spacecraft now in development, requiring 10-25 Ahr capacity cells, and desiring long cycle life. They have been deemed capable of functioning in a low-earth orbit-type duty cycle for 20,000 cycles or more. These developments, along with the launch of the 22-cell single pressure vessel battery on Clementine in 1994, made nickel-hydrogen the rechargeable battery of choice for recent mission planners that provided mass savings and enabled mission functionality otherwises unavailable from conventional nickel-cadmium.

While, nickel-hydrogen technology has become accepted for deep space missions, rechargeable lithium cell technology has been advancing rapidly. Lithium-ion cells have now been scaled up to 20 Ah, cell level specific energies of more than 100 Wh/kg. Cycle life demonstrations for small cells (~1Ah) have now exceeded 5000 cycles. Lithium-ion-polymer systems are also in development with the potential for specific energies of more than 150 Wh/kg. These cells are destined for use on planetary landers and probes, and for orbiters as LEO-type duty cycles are demonstrated. Lithium-ion cells could be candidates for the Mars missions to be launched in 2001.

In addition to normal, ambient temperature requirements, rechargeable batteries will be expected to withstand extreme temperatures in many cases. At JPL, we are currently developing lithium-ion cells that will charge and discharge at -20°C or lower for use on the surface of Mars. Missions to Venus or Mercury may require rechargeable batteries that are operable at very high temperatures. Furthermore, primary lithium cells are now being developed to function down to -80°C for use on the New Millennium Deep Space 2 Mars penetrators to carried on the Mars '98 mission. The penetrator batteries are required to provide 10's of milliwatts of power for relatively short periods of time. As discussed previously, both primary and secondary lander-type batteries will be required to withstand high-G (10's of thousands) impact loads.

Figure 3 illustrates the trends in battery development. As rechargeable lithium technology matures and if more than 150 Wh/kg can be achieved by lithium-ion-polymer systems, with high cycle life, then we will be reaching a limit stored energy density from electrochemical systems for small spacecraft applications, since options for high density energy storage materials are limited. (Fuel cells are unlikely to be applied to small spacecraft for the foreseeable future, due to the disproportionalte mass and volume penalties paid for hydrogen and oxygen stowage.) The next advances could thus be at the payload or system level, where energy storage devices are integrated directly with various spacecraft elements. Innovative concepts that lead to the integration of energy storage with sensor heads, solar cells, or "on-chip" storage for processors or data storage could have wide application in future microspacecraft systems.

Power Electronics

Klein, et. al,[17] recently described expectations for the electronics required to distribute, condition and control power onboard the spacecraft. Plans to fly advanced power electronics technologies onboard the New Millennium Deep Space 1 mission have proceeded. These plans are based on the concept of integrating all spacecraft electronics into a 3-D, multi-chip module stack. Figure 4 shows the power electronics modules, to be flown as an experiment, now in design. They comprise advanced elements, including solid state switching, mixed signal ASIC's, High Density Interconnects, and high efficiency synchronous rectifier-base DC-DC conversion that are being developed by a Boeing-Lockheed Martin team. Integration of these components with the remaining avionics is the next step in implementing this approach, with thermal management being one key element.

In addition, technological advances in digital systems foreshadow other needs from the power electronics community. For example, an increasing use of optical data transmission and storage will probably require the development of triple-mode (digital/analog/optical) ASIC's.

Conclusions

The insertion of new technology into deep space science missions is accelerating rapidly. Virtually all missions have been found to be utilizing recent innovations that are either providing essential mass or volumetric margin or enabling greater functionality or performance. However, for power sources and energy storage, we appear to be converging on thermodynamic and materials' limits that will prevent further major improvements beyond those projected for systems currently in development. Accordingly, the next breakthroughs will come from innovative system level developments that combine other spacecraft systems with elements of the power system. Examples include the combination of solar power generation with the radio frequency system, integrating small radioisotope power sources with energy storage, or integrating energy storage with elements of sensors or data systems (so-called "on-chip storage"). Finally, technology challenges remain in developing systems to withstand the extreme environments that will be encountered in deep space.

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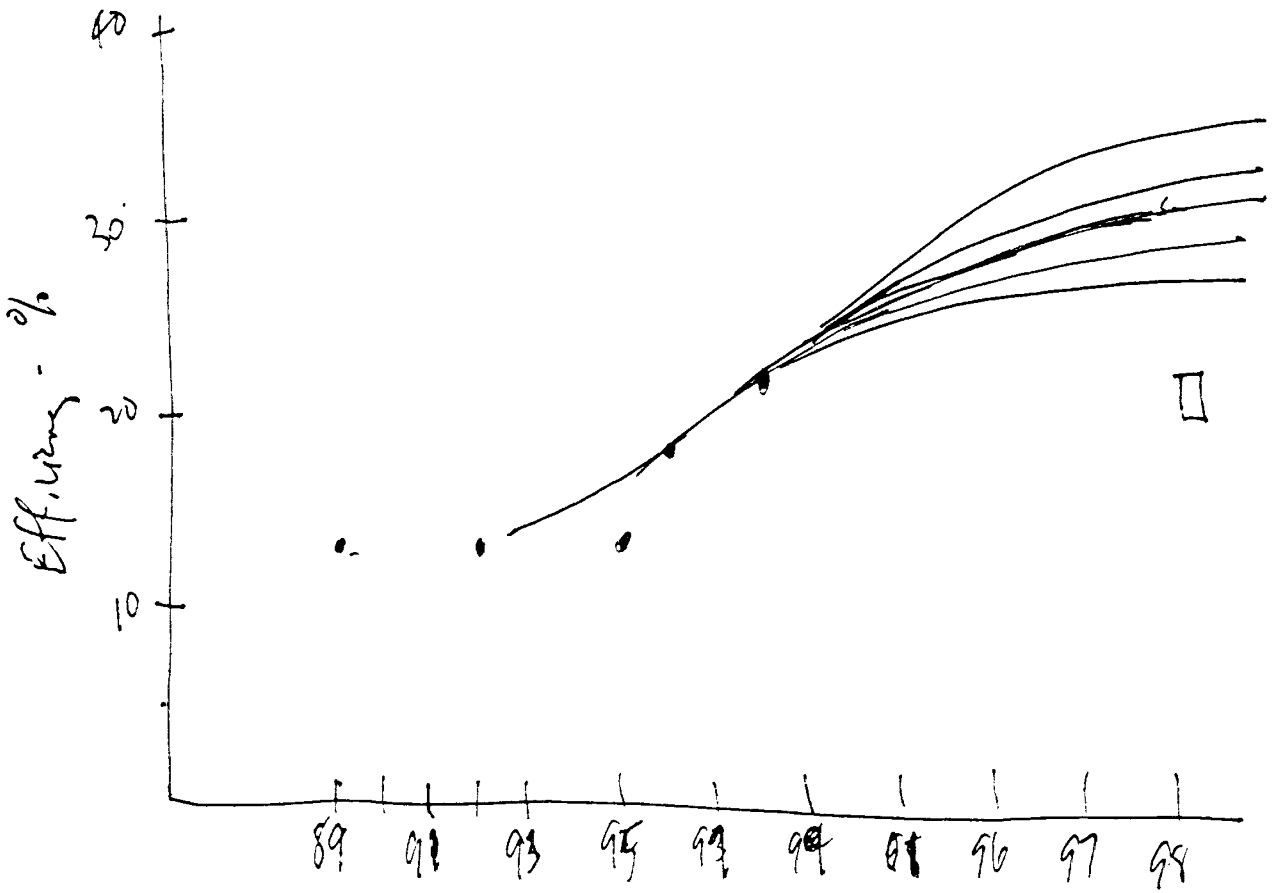
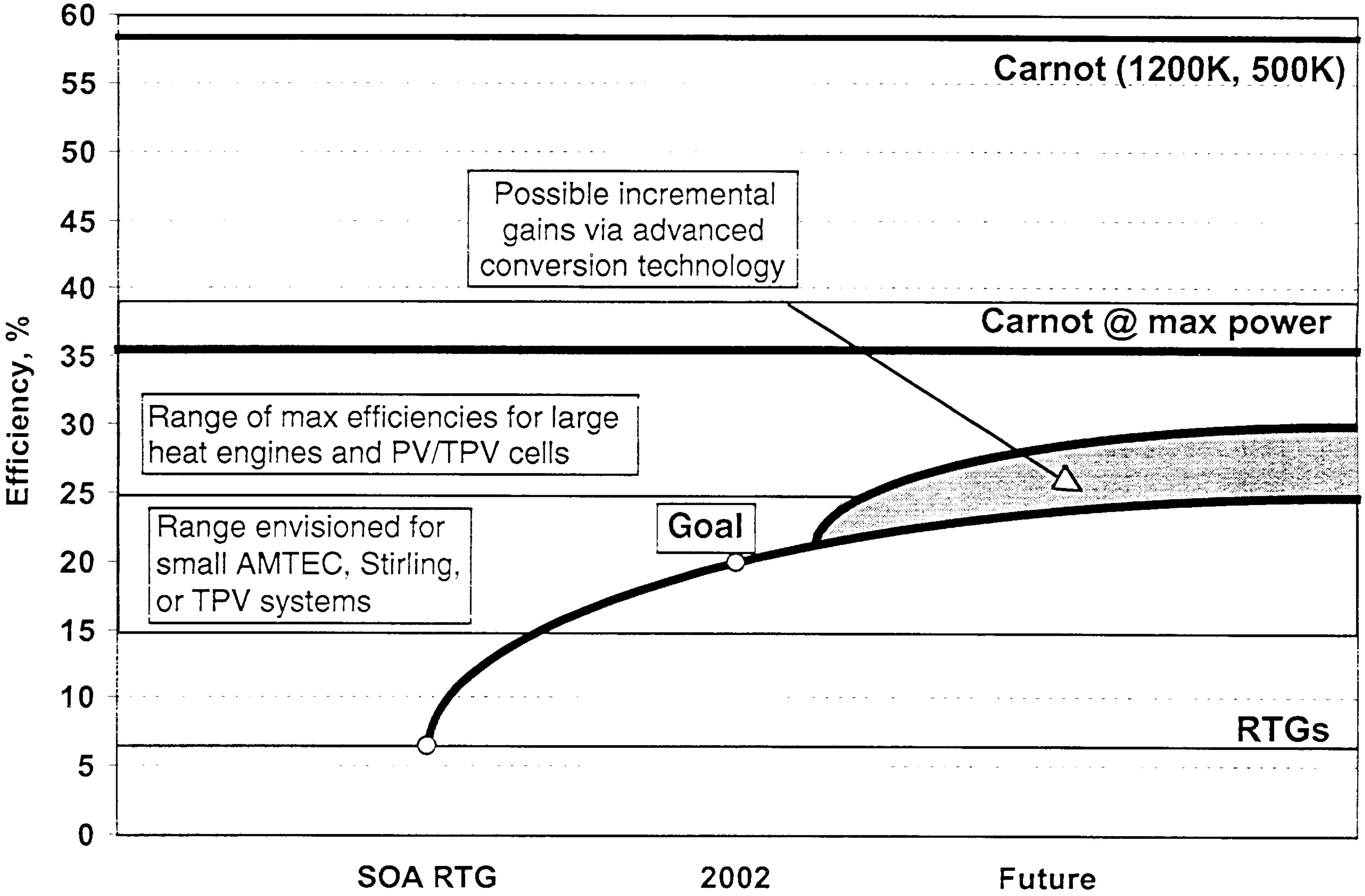
F1



Photovoltaic Cell Efficiency - Planetary Missions

F2

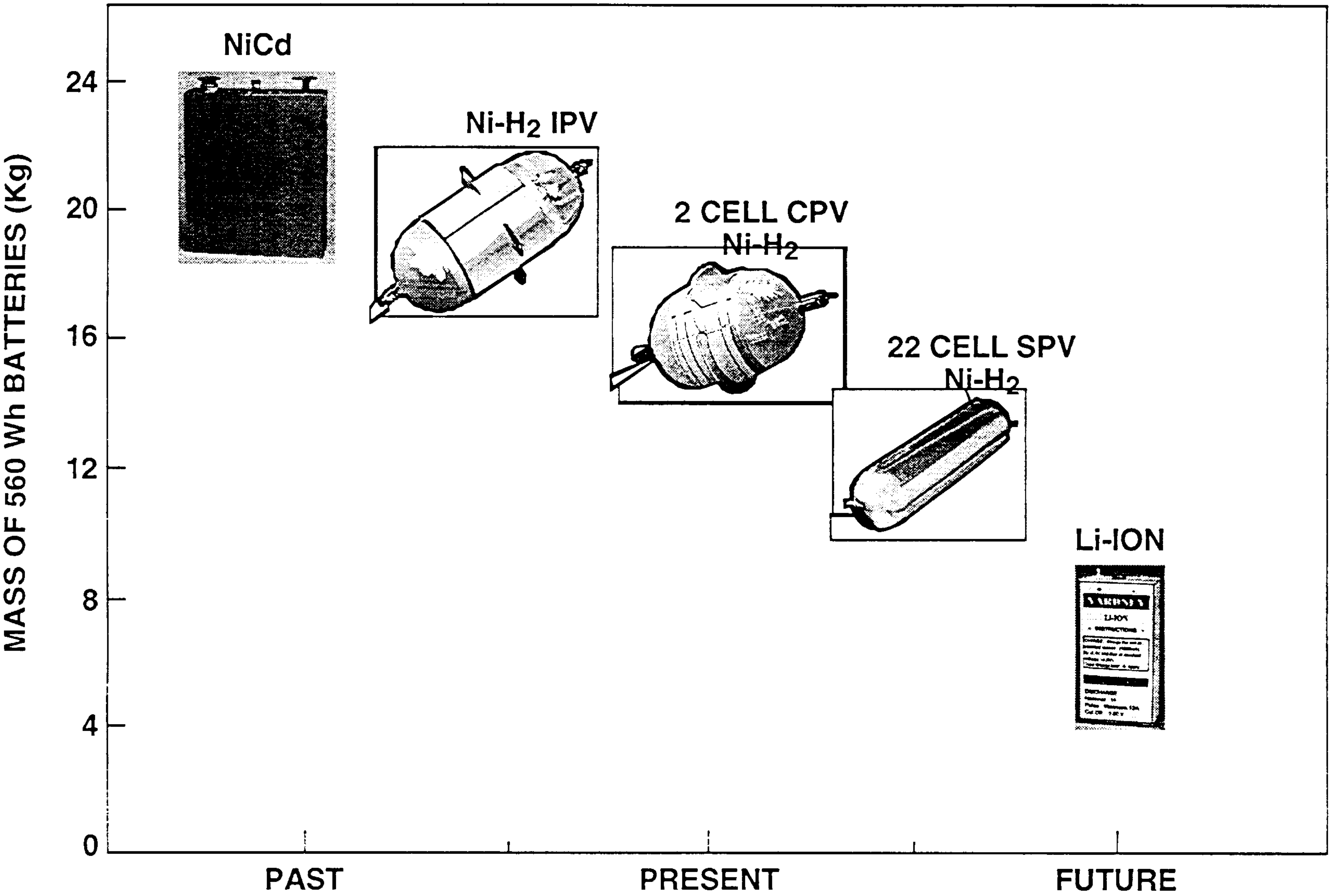
RPS Efficiency Compared to Carnot



F3

JPL

ADVANCED LITHIUM SPACECRAFT BATTERIES



New Millennium Program Office

μElectronics Systems IPDT

Power μElectronics Roadmap Summary

Fig 4