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NASA PHOTOVOLTAIC RESEARCH AND TECHNOLOGY

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NASA photovoltaic research and technology efforts address future Agency space mission needs through a comprehensive, integrated program. Activities range from fundamental studies of materials and devices to technology demonstrations of prototype hardware. The objectives of the program are to develop and apply an improved understanding of photovoltaic energy conversion devices and systems that will increase the performance, reduce the mass, and extend the lifetime of photovoltaic arrays for use in space. To that end, there are efforts aimed at improving cell efficiency, reducing the effects of space particulate radiation damage (primarily electrons and protons), developing ultralightweight cells, and developing advanced array component technology for high efficiency concentrator arrays and high performance, ultralightweight arrays. Current goals that have been quantified for the program are to develop cell and array technology capable of achieving 300 watts/kilogram for future missions for which mass is a critical factor, or 300 watts/square meter for future missions for which array size is a major driver (space station, e.g.). A third important goal is to develop cell and array technology which will survive the GEO space radiation environment for at least 10 years with 5% or less degradation in power. This paper will describe some of the research and development programs now underway within the agency and show what impact they can be expected to have on space power systems of the future.

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INTRODUCTION

Space power technology has become a pacing item for determining our ability to explore and expand our presence in space. The ability to search, probe, survey and communicate throughout our universe will depend on providing adequate power to the instruments that do these jobs. Power requirements for space platforms are increasing and will continue to increase into the twenty-first century. Photovoltaics arrays have been a dependable power source for space for the last 30 years and have served as the primary source of power on virtually all DoD and NASA satellites. The performance of silicon (Si) solar cells has increased from 10% air mass zero (AMO) solar energy conversion efficiency in the early 1960's to almost 15% on today's spacecraft. Technology development in solar photovoltaic devices and arrays continues to make progress toward high performance solar cells and greater specific power levels, which will enable higher power electrical subsystems at reduced weight for housekeeping and payload power. Problems to be addressed that are unique to space applications include tolerance to the natural charged-particle space irradiation environment, damage from micrometeoroids and space debris impact, increased temperature stability, deployment and dynamic control of large support structures, achieving low atmospheric drag in low earth orbit, pointing and tracking requirements, and ground test qualification of large-area solar arrays.

NASA SPACE MISSION ISSUES AND OPPORTUNITIES

Although most NASA missions usually place a premium on minimizing system mass, particularly in the early stages of an advanced development program, other considerations can often have a significant impact on the technology that is finally selected for flight. An example of the preceding will be investigated later in this discussion. When minimum mass considerations are dominant, however, the discriminator used is power per unit mass, or specific power (W/Kg), whether at the component, subsystem or system level. Generally, only those technologies that can have a major impact at the system level will be developed.

Recently there has been a renewed interest within NASA to extend our physical presence in space, either by a manned visit to Mars, or a return to the moon, or both. Initial activities on either surface would be followed by the establishment of some kind of habitable outpost, which could evolve over time into a permanent manned base of significant size and capability. A new aspect of the attempt to establish this sort of permanent presence is that the mission requirements are no longer fixed, but will evolve over time. Just as the base is expected to evolve in size, complexity, and capability from its initial outpost configuration, the power system will also evolve from an initial few kilowatts to the megawatt range. It now becomes necessary to examine and develop a time dependent set of requirements for the power system, and to put in place a set of advanced R&D programs that are properly phased to produce the needed technology at the right time. In addition to the above manned mission classes, there is also a growing interest in expanding the scope and intensity of those space activities that can help us develop a better understanding of of our own planet and mankind's effect on the global processes that keep it a habitable place to live. The Office of Aeronautics and Space Technology (OAST) within NASA has taken the first steps in both directions with the implementation of its Civilian Space Technology Initiative (CSTI) and Project Pathfinder. CSTI contains the High Capacity Power program, and Pathfinder contains both a Surface Power and a Rover Power program. All three programs are intended to produce a set of technology options for future mission planners that will significantly enhance our capability to accomplish a variety of ambitious space goals, from vigorous manned exploration to intensified science activities.

High Capacity Power Applications

The High Capacity Power program addresses the development of power system technology for missions requiring 100 kilowatts or more. It is at present focussed exclusively on thermal-to-electric power conversion from either a solar thermal source or a nuclear source. The non-solar baseline technology is the SP-100 nuclear reactor, which will incorporate thermoelectric conversion at a net efficiency in the range of 3% to 4%. The solar thermal conversion system will use heat engine technology, either a free piston stirling engine or an advanced brayton cycle engine. In its advanced version, the SP-100 reactor would use a free piston stirling engine, which would increase that system's efficiency to the mid twenty percent range. It is generally held that photovoltaic power systems will not be competitive on a mass basis with the nuclear/stirling engine system at the higher power levels under consideration, particularly when there is a large energy storage requirement (a lunar base, e.g.), or when there is a high potential for space radiation damage, such as for long duration missions in or through the van Allen belts. That contention will be addressed in the paragraphs that follow.

The issues associated with long duration storage times will be discussed in the section that deals with the new initiative in Surface Power Systems. In the case of orbit transfer missions requiring passage through the van Allen belts, photovoltaic power systems must be capable of specific powers approaching or exceeding 100 W/Kg at end of life to be competitive with the conceptual designs for the thermal-to-electric conversion systems mentioned above. While progress has been made in the development of thin silicon solar cells and lightweight structures, it is still beyond the reach of silicon cell technology to assure long term operation in the van Allen belts. Typical projections from such mission profiles indicate that during the first trip a solar array could be exposed to 1MeV electron equivalent fluences approaching $10^{17}/cm^2$, which would reduce the output of a standard silicon solar array, such as intended for the space station, to less than 10% of its beginning-of-life (BOL) power. There is at present no lightweight silicon solar cell, even with a minimal protective coverglass, which can be incorporated on the most advanced light-weight array structure(s) under development that can meet the above requirement. Acceleration levels associated with electric propulsion booster rockets, although not large, (typically less than 0.1g), still impose a minimum set of requirements on the array structural mass, which will in turn restrict the mass that can be used for physical shielding of the solar cells. It is clear that a new generation of solar cells is needed that are essentially immune to radiation damage, either through some sort of inherent resistance to the effects of space radiation, or through some sort of easily implemented damage removal mechanism. Leading candidates in that regard are InP homojunction cells, particularly in conjunction with concentrated sunlight levels near 100X, and thin film cells such as amorphous silicon and $CuInSe_2$ (2, 3, 4).

Almost all of the information that now exists on the suitability of the above cell types for space applications of any sort, let alone in the high radiation damage orbits, is preliminary in nature. (The first spaceflight data on InP cells, for example, have only recently been reported (5).) Table I provides a comparison of space solar cell performance as determined in laboratory devices for several cell types. A great deal of work yet remains to develop fully space-qualified designs of any of them. The payoff for future mission planners is significant, since such capability provides them with an important additional option to consider as they formulate mission objectives and requirements. The payoff for photovoltaic power system applications is enormous, however, since the technology would open up a whole new set of mission opportunities from which photovoltaic power systems had otherwise been eliminated.

SURFACE AND ROVER POWER SYSTEMS

While the definition of a complete set of time-dependent requirements is an unfinished task, an understanding of key issues has been developed to help guide focussed technology efforts within the Agency. The present discussion will be limited to the case for establishing an evolutionary lunar base, since the same general considerations will apply, but with different associated numbers, to the case for Mars. Technologies intended for a lunar base application will be driven by mass considerations, primarily because of the high cost of payload delivery to the lunar surface. Even if the assumption is made that low operational cost cargo vehicles will be available for transit from low earth orbit (from the space station, e.g.), to the moon, there will still be a high cost for delivery to LEO which must be considered. For comparison purposes the cost can be represented by a payload mass multiplication factor which takes into account the total launch mass required to deliver the intended lunar base elements to LEO. Although a universally agreed-on value for such a multiplier does not exist, primarily because the exact nature of future heavy lift launch capabilities is not known, a value of 5 has been assumed for this discussion, along with an assumed heavy lift vehicle capability of 91,000 kg (200,000 pounds) to LEO. No further justification will be given for using them, except to mention that they have been used in advanced technology planning exercises within NASA, and that doing so allows a quantitative comparison of power system alternatives in terms of their "operational" impact - i.e., the number of launch vehicles required to deliver the system elements to LEO for subsequent transport to the lunar surface.

As mentioned, the key figure of merit for a photovoltaic array is the power per unit mass in watts per kilogram (W/kg). For a storage system the appropriate figure of merit is the amount of available energy per unit mass in watt-hours per kilogram, (W-hr/kg). The advanced power system uses an ultralightweight photovoltaic array and an advanced hydrogen-oxygen regenerative fuel cell (RFC) for storage. The figures of merit for both systems are listed in Table 2. Table 3 compares the system masses for a state-of-the-art photovoltaic generation/battery storage system sized to deliver 100 kW to a lunar base to that performance projected for an advanced version of such a system. Two cases are considered for the 336-hr lunar night: a 100% duty cycle and a 20% duty cycle. Also shown is the mass saved in delivering the advanced system to LEO, along with the resulting number of HLV launches saved, under the assumptions given above. The final column of the table shows the additional number of HLV launches that would be saved by using the SP-100 nuclear power system currently under development, and intended to have a specific power of 33 W/kg. The table provides compelling evidence that there is a substantial payoff to be had in developing the advanced PV/RFC technology, particularly when placed in the "operational" context of the weight saved at LEO. A third case also exists, that in which the astronauts' stay would be limited to the 336-hr lunar day with a night duty cycle of zero, or close enough to zero so that lander energy storage would be sufficient. In this scenario, only a photovoltaic array would have to be delivered to the lunar surface. A state-of-the-art PV array to supply 100 kWe has a mass of 1515 kg, while an advanced array would weigh only 333 kg, a significant savings under a restricted mass budget.

Figure 1 provides a more graphic comparison between the mass of a SOA photovoltaic/battery system, the advanced photovoltaic/ regenerative fuel cell system, and the SP-100 nuclear power system. As can be clearly seen, the advanced PV/RFC technology has the potential to reduce the mass of a 100 kWe lunar surface power system using state-of-the-art technology by more than a factor of 45, to a value less than 2.5 percent of the mass of the latter. (The SP-100 system, even though projected to be lighter than the advanced PV/RFC system by a factor of 10, will only save a little more than another 2 percent of the SOA system mass.) The long lunar night is clearly the major issue in determining the mass of the lunar base photovoltaic/electrochemical storage system. The key feature that allows such a large mass reduction is that the stored energy in an advanced regenerative fuel cell system is in the form of gaseous reactants stored in high pressure tanks, with the result that the RFC can approach 1000 W-hr/kg, a factor of 4 or 5 better than that projected for advanced batteries, and a factor of more than 60 better than SOA batteries (NiH, for example.)

The program objective in the Pathfinder Surface Power program is an array specific power of 300 W/kg at Air Mass Zero (AMO) insolation (solar insolation at 1 A.U.). At present, lightweight photovoltaic arrays have been demonstrated on a Space Shuttle experiment (OAST-1) at 66 W/kg. A recent design, under development at the Jet Propulsion Laboratory for OAST, was established at 130 W/kg. This design, the Advanced Photovoltaic Solar Array (APSA)(1), is based on 2 mil thick silicon cells. These two array designs are intended for the zero gravity conditions of LEO and GEO (Geosynchronous Earth Orbit). For lunar base applications, the array structure must be rugged enough to withstand the 1/6 g of the lunar surface.

To achieve the 300 W/kg specific power goal, two solar cell technologies have been identified for further development. These candidate cell types are ultrathin gallium arsenide (GaAs) and amorphous silicon (a-Si). Table 4 summarizes the technologies to be developed for a lunar base power system and their current performance. GaAs cells are currently manufactured for space use at an average efficiency of 18 percent, with research devices achieving 21 percent. However, the current cell is too thick at 200 to 250 microns to give the performance needed for lunar base applications. Fortunately, because it is a direct gap semiconductor, GaAs absorbs all photons available for energy conversion within 3 to 4 microns of the illuminated surface. This allows for an ultrathin, high efficiency cell to be produced. Thin (5.5 microns) GaAs cells have been fabricated utilizing the CLEFT (Cleaved Lateral Epitaxy for Film Transfer) (6) process, a technique in which a single crystal thin GaAs layer is grown on a masked GaAs substrate and mechanically removed.

Other processes, such as chemical thinning of the substrate, have also been successfully demonstrated as capable of producing high quality, ultrathin layers and cells (7). Basic research and development in cell interconnectors and cell incorporation into a space compatible blanket will be critical because of the fragile nature of the ultrathin GaAs cells. Figure 2 shows one approach outlined by NASA toward a 300 W/kg zero-g array based on a thin GaAs solar cell. Improvements in the structure and cell interconnector wiring, coupled with the high efficiency, thin GaAs cell, will enable attainment of this performance level. These improvements, as well as the overall design experience gained with zero-g arrays, can be incorporated into the lunar base array structure.

Amorphous silicon is primarily a terrestrial photovoltaic material. However 9 percent efficiency at AMO has been measured.(3) The electronic structure of amorphous silicon allows for total cell thickness of less than 1 micron along with the use of flexible substrates. This is compatible with very high blanket specific power and low volume storage requirements. Although an extensive terrestrial solar cell manufacturing base already exists for a-Si terrestrial solar cells, several major hurdles must be overcome before it can be considered a viable space cell candidate. Among these are low conversion efficiency and cell performance degradation under constant illumination. In addition, even though some terrestrial modules are manufactured on flexible, rugged substrates, few of the materials used are compatible with space requirements, necessitating basic studies in lightweight blanket materials and design.

Research and development on the array structure is also warranted by the need, for the first time, for a space solar array to operate in a continuous gravity field. An APSA wing is pictured in Figure 3 along with the detailed cross-section of its blanket. Its design specific power of 130 W/kg is met with 13.5 percent efficient, 63 micron thick silicon cells. Replacing the silicon cells with GaAs cells of 25 percent efficiency, assuming the same blanket mass and eliminating the 10% mass contingency built into the design, yields a specific power of 260 W/kg, quickly approaching the lunar base goal. This also assumes that a reduced gravity structure will require no more mass than the zero-g APSA structure. The latter may be quite possible, since the APSA structure, blanket box and deployment mechanism constitute more than fifty percent of the mass of the entire array.

At present only primary fuel cells exist and regenerative fuel cells, which do not limit mission time or power availability by the amount of hydrogen and oxygen that can be carried along, have not yet been demonstrated. The primary focus of RFC research for a lunar base power system will be on fuel cell stack configurations including oxygen electrode catalysts, thermal and gas management and lightweight, high pressure, robust tank technologies. The principal effect of the 336 hr duration of the lunar night is the requirement for a very large fuel cell reactant mass. Therefore, significant mass gains can be made by reduction of the storage tank mass. Figure 4 illustrates the effect of storage duration on RFC system energy density for several tank types (personal communication with L.H. Thaller of NASA Lewis). For the high pressure gas storage system chosen for the lunar base, the use of filament wound tanks enables the storage system energy density to approach 1000 W-hr/kg. This can be significantly exceeded by cryogenic reactant storage which at present has application for primary fuel cells only. Feasibility studies being conducted within NASA for using this technology with an RFC on the lunar surface have not yet been completed, but early results look promising, with the potential for 1500 W-hr/kg.

The question naturally arises concerning the relative impact of ultralightweight array technology versus that of advanced RFC technology for the lunar base. The severe storage requirement (336 hours) means that the batteries comprise over 98 of the mass of the SOA system in Table 3. Hence, even if no lightweight array development work occurred, a 97% reduction in system mass could still be achieved with the RFC technology alone. The answer is that at present there is simply no suitable solar array technology for this application, and given the mass constraints of such missions, it is imperative to develop the lightest weight version that is possible. Added to the above are the as yet undefined requirements for minimum stowage volume during earth-lunar transport and for fast, easy deployment and/or erectability. The situation illustrates the point made at the beginning of the section on NASA mission issues and opportunities. Although total system mass considerations usually predominate, other mission requirements will often have as big, if not bigger, an impact on the technology selected for advanced development and flight. In this case, the need for stowability, transportability, and deployability are at least as important as minimum mass.

SUMMARY

The intent of the preceding discussion has been only to highlight some of the space power issues currently of high visibility within NASA's advanced planning horizon. There are a number of very legitimate concerns that have not been mentioned that have to do with the more "routine" uses of spacecraft for communication, earth observation, and so on, as well as the myriad of issues associated with development of the solar array for the space station. What has been shown is that there is a growing interest in lightweight concentrator arrays with high levels of radiation resistance for orbital applications, and in a totally new generation of solar array technology for terrestrial-like applications in a non-terrestrial environment. While it is generally true that orbital missions require both minimum mass and minimum area (thereby implying high efficiency), advanced development of photovoltaic power systems for operation on the lunar or Martian surface is driven as significantly by other requirements. This new scenario makes it possible for the terrestrial thin film technologies to compete effectively with the high efficiency solar cell technology that has been traditionally pursued in the space program, and is an important new thrust for space solar array development.

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TABLE I - PHOTOVOLTAIC POWER SYSTEMS PV CELL TECHNOLOGY SUMMARY

CELL TYPE	NOW		GOAL	
	Eff., Percent	Rad. Deg., Percent	Eff., Percent	Rad. Deg., Percent[a]
GaAs	21	10 to 15	25.5	10
Tandem Cell	In Dev	In Dev	30	10
InP	19	In Dev	20	0
Thin Film Cells	6	10	10	5

[a] After 10 years in GEO

TABLE II. - FIGURE OF MERIT COMPARISONS FOR PHOTOVOLTAIC/ELECTROCHEMICAL TECHNOLOGY OPTIONS

	State-of-the-art	Advanced
Array	66 W/kg, OAST-1	300 W/kg, ultralightweight
Storage	14 W-hr/kg, NiH battery	1000 W-hr/kg, H-O RFC

TABLE III. - COMPARISON OF CURRENT AND ADVANCED PHOTOVOLTAIC POWER SYSTEMS FOR A MANNED LUNAR BASE

[Instrument shielding only for SP-100.]

Power level, kWe	Night duty cycle, percent	SOA PV/battery mass, kg	Advanced PV/RFC mass, kg	Weight saved at LEO, kg	HLV launches saved	Additional HLV's saved W/SP-100
100	100	1 680 000	34 350	7 910 000	87	1.6
100	20	336 420	7 133	1 580 000	17.4	.2

TABLE IV. - TECHNOLOGY STATUS AND DESIGN PROJECTIONS

	Lunar base design	Current performance
Photovoltaic devices		
Gallium arsenide	25 percent AMO efficiency	21 percent
Amorphous silicon	15 percent AMO efficiency	9 percent
Array structure		
Specific power	300 W/kg (APSA)	66 W/kg (OAST-1)
Energy storage		
High pressure gas	1000 W-hr/kg	300 W-hr/kg (primary fuel cell)
Regenerative fuel cell	60 percent efficiency	60 percent efficiency

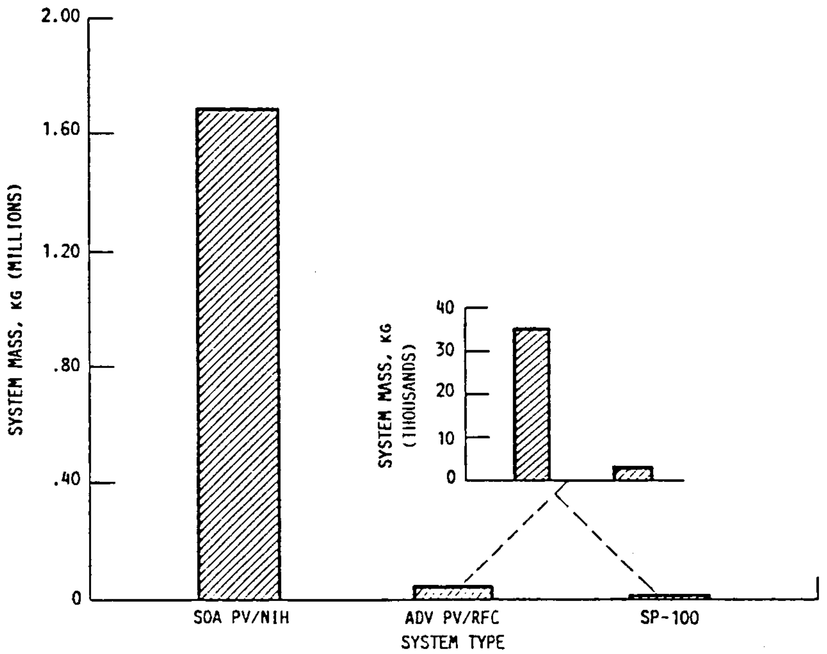

FIGURE 1. - POWER SYSTEMS MASS COMPARISON; 100 kWe LUNAR BASE, 2 WEEK STORAGE.

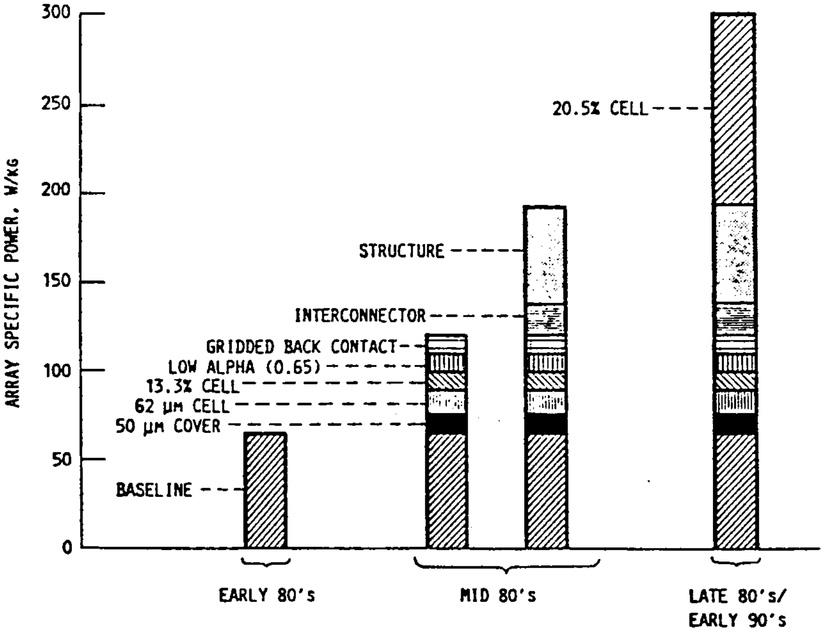

FIGURE 2. - HIGH PERFORMANCE SOLAR ARRAY RESEARCH AND TECHNOLOGY.

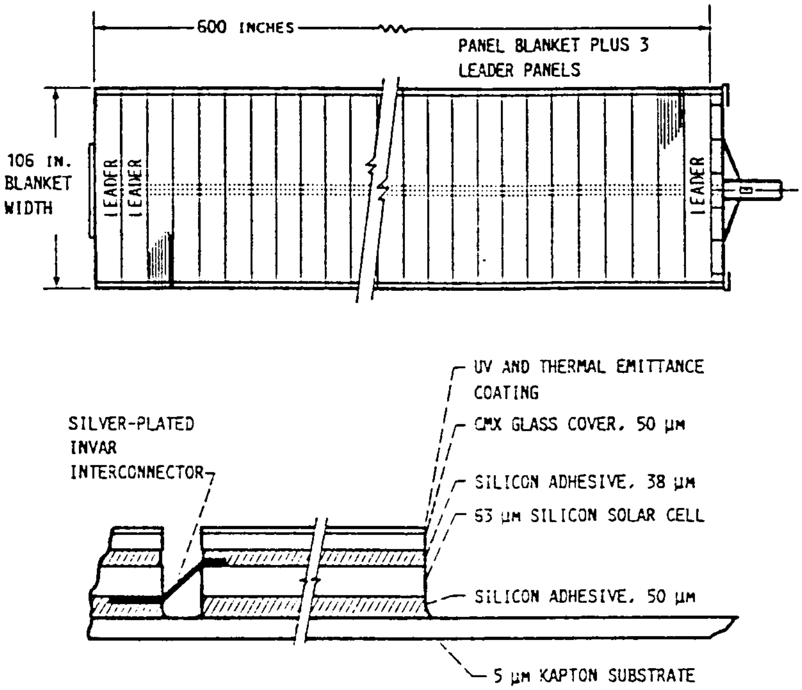

FIGURE 3. - ADVANCED PHOTOVOLTAIC SOLAR ARRAY (APSA) WING AND BLANKET.

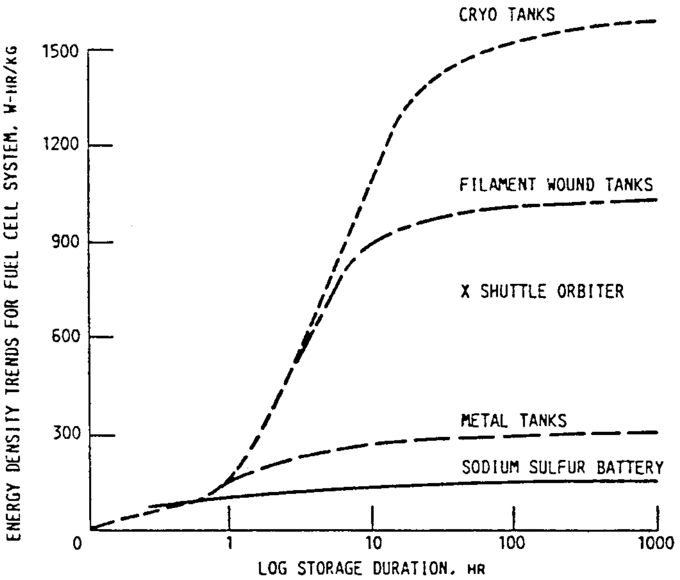

FIGURE 4. - APPROXIMATE ENERGY DENSITY CHARACTERISTIC OF FUEL CELL SYSTEMS AS A FUNCTION OF TANK TYPE AND STORAGE DURATION.

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