NASA Technical Memorandum 103199

An Analysis of Space Power System Masses

(NASA-TM-103199) AN ANALYSIS OF SPACE POWER SYSTEM MASSES (NASA) 3 p CSCL 21H

N90-25184

Unclas

G3/20 0290726

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Prepared for the
25th Intersociety Energy Conversion Engineering Conference
cosponsored by the AIChE, ANS, SAE, ACS, AIAA, ASME, and IEEE
Reno, Nevada, August 12–17, 1990

NASA

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E-5597

ABSTRACT

This paper analyzes various space electrical power system masses with particular emphasis on the power management and distribution (PMAD) portion. The electrical power system (EPS) is divided into functional blocks: source, interconnection, storage, transmission, distribution, system control and load. The PMAD subsystem is defined as all the blocks between the source, storage and load, plus the power conditioning equipment required for the source, storage and load. The EPS mass of a wide range of spacecraft is then classified as source, storage or PMAD and tabulated in a database. The intent of the database is to serve as a reference source for PMAD masses of existing and in-design spacecraft.

The PMAD masses in the database range from 40 kg/kw to 183 kg/kw across the spacecraft systems studied. Factors influencing the power system mass are identified. These include the total spacecraft power requirements, total amount of load capacity and physical size of the spacecraft. It is found a new "utility" class of power systems, represented by Space Station Freedom, is evolving.

INTRODUCTION

A typical space electrical power system (EPS) consists of a power generating source(s), storage (if necessary), power management and distribution (PMAD), and load(s). A survey of existing literature shows that considerable information exists about the source and storage portions of space power systems. Information about the PMAD portion, on the other hand, is scarce. PMAD subsystem mass information is required when performing system trade-off studies for advanced missions. PMAD component masses are readily available, but using component mass alone in system studies is not accurate. Mass data on the PMAD subsystem as a whole is needed but difficult to find. Thus, the primary objective of this paper is to analyze various space electrical power systems to obtain PMAD subsystem masses.

POWER MANAGEMENT AND DISTRIBUTION (PMAD)

A broad definition of PMAD is necessary for the understanding and documentation of its masses for different types of spacecraft. The PMAD subsystem is defined here as performing all electrical power system functions other than generation and storage. Thus, the PMAD subsystem performs the following functions: power conversion, conditioning, transmission and distribution, and power system control. This PMAD definition can be explained by an analogy with the terrestrial utility system which is schematically illustrated in Figure 1. In a terrestrial utility system, power is generated by multiple sources, such as nuclear and coal power plants, and transmitted over a transmission and distribution grid to multiple loads.

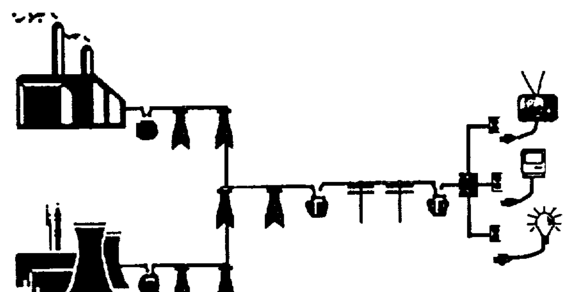

Figure 1 Simplified Terrestrial Utility Power System

The various utility components can be grouped according to their function. The power plant is the electric generating source for the system. Its heat source is converted to electricity by generators typically rated between 14 and 22 kv at 60 Hz. The voltage is stepped up to transmission voltage levels, in the hundreds of kilovolts range, through transformers located just outside the generating station. The backbone of the utility, a flexible transmission grid, interconnects multiple sources and transmits to multiple load locations. Subsequent power distribution is at stepped down voltage levels prior to distribution to load centers. Finally, the loads convert the electricity to the useful function desired by the consumer. Manned control centers tie the whole system together and manage its operation.

Figure 2 shows the functional groupings of the system and the portion defined by PMAD. The functional groupings are power generation, interconnection, transmission, distribution, loads, and system control. The PMAD boundary encompasses the interconnection, transmission, distribution and control center boxes. It also intersects a portion of the source and load boxes. The intersection of the PMAD boundary with the source and loads indicates that there is a PMAD function required within them. The transformers in the source boxes are associated with the generating station, yet they are performing a PMAD function. Likewise, at the load end, most loads do not use 120 volts ac, 60 hz power directly. Some loads have internal conditioning. The computer, for example, has logic chips that operate on +/- 5 volts dc which is derived from the supplied power. This internal conditioning done by the load is actually a PMAD function.

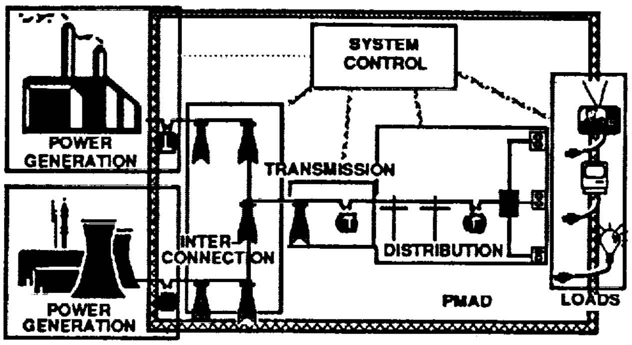

Figure 2 Functional Representation of Terrestrial Utility Power System

A similar functional block diagram of a generic electrical power system is shown in Figure 3. This basic block diagram captures the functions of a terrestrial, satellite, lunar base or Space Station Freedom (SSF) power system. The PMAD functions associated with the source, load and storage are called power conditioning and control (PC&C).

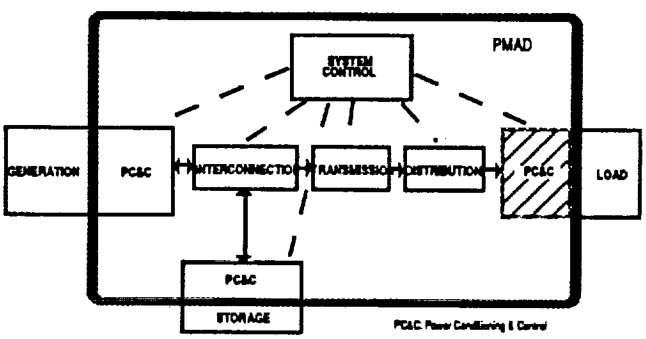

Figure 3 Electrical Power System Functional Block Diagram

In Figure 3 the power conditioning and control (PC&C) block associated with the load is shaded. This is to indicate a "gray" area in the PMAD definition for space power systems. Technically, in terms of function, the equipment in the load PC&C is PMAD and is shown within the PMAD boundary in Figure 3. However, practically, this equipment is almost always a user responsibility, falling completely in the load block and outside the PMAD boundary. The data base reflects this and does not include the load PC&C in quoted PMAD masses. However, in future large power systems trade-off studies, the load PC&C should be included in the PMAD mass estimates. This is based on the potential importance of the interaction between the PMAD design and the load PC&C equipment for the total EPS optimization.

BALANCE OF SYSTEM

Electrical components require supporting components and systems to be able to function properly. In terrestrial power systems, such support takes the form of transmission towers, cooling ponds and towers for the generating stations, and other equipment without which the electrical power could not be generated, transmitted or distributed. In space power systems, such support consists of thermal control to keep the electronics at the proper temperature, structural items such as booms to mount solar array panels or electrical equipment, and mechanisms such as the solar array drive. Thus, the entire electrical power system mass should include not only the source, storage and PMAD, but also the support items necessary for proper EPS function.

"Balance of System" in the equation below captures the concept of the EPS support items:

EPS mass = Source mass + Storage mass+ "Balance of System" mass

"Balance of system" (BOS) is defined to include the PMAD subsystem and the thermal control, structures, mechanisms , etc. necessary for the power system to operate.

DATABASE

With PMAD defined, the question "What does PMAD weigh?" can be investigated. Information on various types of spacecraft was obtained, analyzed and compiled: JPL planetary spacecraft (Mariner R, Mariner C, Ranger Blk III, MV 67, MV 69, MM 71, MVM 73, VO 75, Voyager, Galileo, Magellan), orbiting spacecraft (COBE, Polar Platform), and several Space Station Freedom designs. The data is recorded using a standard spreadsheet program. Each spacecraft has its own spreadsheet with all the available data about the spacecraft recorded there. The parameters of interest are then summarized in one master spreadsheet which is linked to all the individual ones.

At present, the master file parameters include spacecraft source, storage and PMAD masses, power levels, orbit parameters, date of launch, and length of life. Parameters for the master file can be added or deleted as necessary with the corresponding links to the individual files adjusted. This makes the database flexible so additional data (volume, for example) can be added as it becomes available.

More detailed information about a particular spacecraft can be found in the individual spreadsheets. The original data from a mass data report is entered by spacecraft subsystem. Component mass data in EPS subsystems is also entered. The components are then classified as source, storage, or BOS based on the earlier definitions. BOS components are further classified as PMAD, structures or thermal. The component masses are then reorganized and added together, based on their classification, to find the total PMAD, source, storage, and BOS masses. Spacecraft power data, if available, is also entered in the spreadsheet. In summary, subsystem and component masses are entered as shown on the original mass data reports [1-6], then classified and regrouped as necessary to conform to the PMAD and BOS definitions.

Table 1 Summary of Spacecraft EPS Mass

Spacecraft	Mass Accuracy*	PMAD (kg/kw)	Source (kg/kw)	Storage (kg/kw)	BOS (kg/kw)**	Peak Power- kw	Average Power- kw	orbit***	launch year
Polar Platform	E	70	69	67	102	N/A	6	LEO	N/A
SSF-- Current Design	E	144	99	111	346	100	75	LEO	1996
SSF-- AC-DC Design	E	183	67	101	405	100	65.4	LEO	1996
SSF-- 20 kHz design	E	125	57	86	264	100	77.1	LEO	1996
Mariner R	A	72	142	101	N/A	.15	N/A	P	1962
Mariner C	A	73	151	62	N/A	.25	N/A	P	1964
Ranger Blk III	A	80	143	158	N/A	.15	N/A	P	1965
MV 67	A	67	87	60	N/A	.25	N/A	P	1967
MV 69	A	40	118	37	N/A	.44	N/A	P	1969
MM71	A	43	133	62	N/A	.48	N/A	P	1971
MVM 73	A	63	74	64	N/A	.46	N/A	P	1973
VO 75	A	61	127	109	N/A	.6	N/A	P	1975
Voyager	A	51	234	0-- RTG	N/A	.48	N/A	P	1977
Galileo	A	77	196	0-- RTG	129	.57	N/A	P	1989
COBE	A	155	58	38	293	1.02	.73	LEO	1989
Magellan	A	114	44	113	295	.64	.55	P	1989

*E = Estimated mass
*A = Actual mass
**N/A = Not Available
*** LEO = Low Earth Orbit
*** P = Planetary spacecraft

DATA ANALYSIS

The data from the master spreadsheet is summarized in Table 1. The values shown are all dimensioned as kg/kw. That is, the mass of the subsystem divided by the total system power. This allows some comparison between various spacecraft. Comparisons must be made with caution, however, because it is often difficult to determine the appropriate kw divisor. The generated power and load power both vary over the life of the system. The solar array output power changes over its life, the load power requirements vary, and some systems have peaking capability where they use power from both the solar array and the batteries for a short period. In COBE, for example, the power varies from 688.9 watts required by the load to 1020 watts available from the solar array at beginning of life (BOL) [3]. Some systems quote an average power. For example, Magellan quotes a "time-weighted average power" [6], and Space Station Freedom (SSF) quotes "continuous power rating" [1,2]. The exact load power requirements were not available for some systems, so source specifications were used. For example, Galileo has a 568 watt radioisotope thermoelectric generator (RTG) at BOL [4]. Generally, when the information is available, average power is used to obtain the kg/kw dimension. This is due to the fact that this work is geared toward supporting future system designs which are often specified with an average user power level. (Using average power may not be the best procedure, and alternatives are discussed in the Spacecraft Attributes section.)

The PMAD kg/kw values in Table 1 range from 40 for a planetary probe to 183 (estimated) for an SSF design. The PMAD and BOS mass estimates for the three SSF designs include only Work Package 4 items, namely, only the equipment from the source to the entrance to the modules). PMAD equipment inside the modules is a Work Package 1 responsibility [8]. Therefore, the PMAD mass for the entire SSF, source to load, will be greater than that shown in Table 1. In addition, the three SSF mass estimates are each taken at a different time, at a different stage of design. Therefore, these mass estimates are not necessarily a good indicator of the "best" design.

SPACECRAFT ATTRIBUTES

Space Utility

Some preliminary observations can be made about the causes of the wide range in PMAD masses. One of the first and most obvious observations is the difference between the various types of spacecraft. The planetary probes are small in size and have power capabilities of less than 1 kw. Space Station Freedom, on the other hand, is large in size and rated at 75 kw. With its multiple sources (8 solar array panels), multiple loads, and large physical size, the SSF power system is more like a terrestrial utility system than a traditional spacecraft power system.

In the typical earlier spacecraft (Figure 4), the most obvious PMAD elements are contained in the PC&C blocks, either associated with the source, storage or load. A source regulator and the battery charge and discharge regulators are all that are shown on a typical spacecraft power system block diagram [7]. The other functional blocks, interconnection, transmission and distribution, exist, but are not as readily obvious as PMAD elements. For example, the cabling for the power system (a transmission or distribution element) is often grouped with other types of cabling (data handling, communication) on the mass data report [3]. This makes it difficult even to account for power cable as part of the PMAD mass.

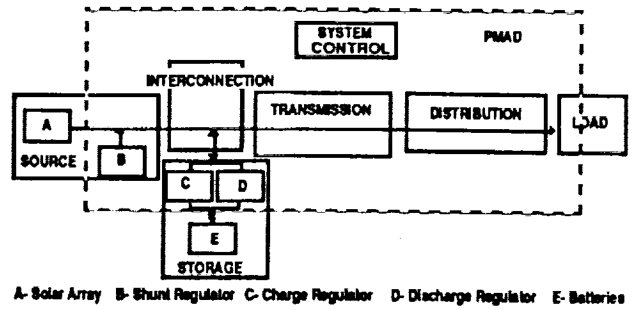

Figure 4 Satellite EPS Block Diagram

For the SSF, however, the interconnect, transmission and distribution blocks become very important. The SSF design must interconnect eight solar array panels and twenty-four battery charge-discharge units. Then it must transmit the power 50 to 60 meters from the solar arrays to the main bus switching units (MBSUs). Finally, the power must be distributed to many users in many locations. As a result, the transmission and distribution blocks account for 60% of the PMAD mass (Figure 5). Transmission includes the four MBSUs, and PMAD cabling outboard of the alpha gimbal. Distribution includes the PMAD cabling inboard of the alpha gimbal, the thirty-two DC to DC converter units (DDCUs) for the modules, nodes and pallets, and the remote power controllers (RPCs) which will be installed in the modules and nodes.

There are other new features of the SSF which add requirements and mass to the PMAD subsystem. The SSF EPS is required to grow to a higher power level. It must be maintainable over a long life (30 years). Finally, it must be adaptable to many different users during that time.

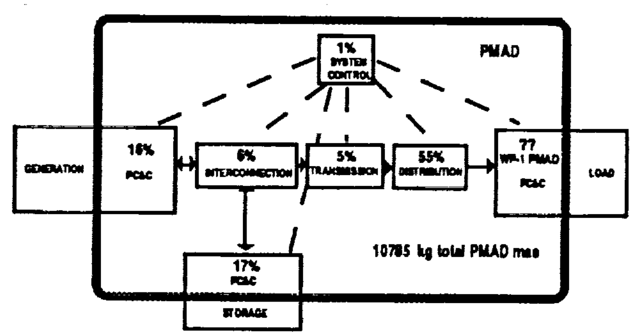

Figure 5 SSF EPS Block Diagram and PMAD masses

Load Capacity

Another feature of the SSF electrical power system is the physical availability of power to many places on the station. Many users can be connected to the power system, but only an average of 75 kw worth of load may operate at any given time. This arrangement of sharing the power saves mass in the power system as a whole. At the load end, though, there is enough remote power controller (RPC) capability to connect approximately 2 Mw worth of loads [2]. By loads sharing power, the source and storage can be sized to provide much less than the load capacity of 2 Mw. Although mass is saved in the power system in the source and storage areas, PMAD becomes quite large to provide the wiring and components for 2 Mw of loads.

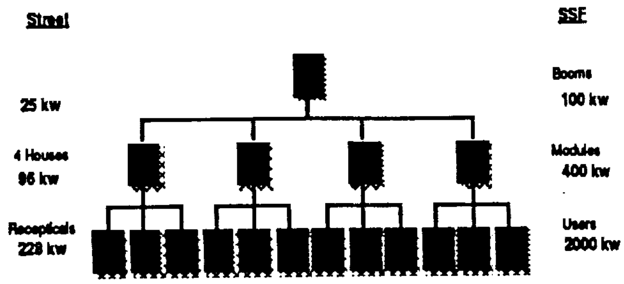

Figure 6 Power Tree

This is not unique to the SSF and may be best illustrated by use of another terrestrial analogy, a residential street power distribution system (Figure 6). Typically, a 25 kva transformer provides 120/240 volt power to multiple houses, four in this example. At the entry point to each house there is a main circuit breaker, typically rated at 100 amps. That gives 24 kw available at each house, or 96 kw available for all four houses. If all the circuit breakers or fuses in the main panel for each house were added together, there would be more power than the main breaker rating, say 57 kw in this example. For all four houses, that would be 228 kw worth of load capacity. In other words, although the street transformer can provide only 25 kva worth of power, each of the houses are provided with enough PMAD equipment for 57 kw, or 228 kw total. For the SSF, the solar arrays and batteries are sized for a peak power output of 100 kw. There are a total of 400 kw of DC to DC converter units (DDCUs) provided at all the nodes and modules and user distribution points. There are 2 Mw of remote power controllers (RPCs) at the user end.

Not all of the user capacity is built into the SSF for convenience and flexibility. Some of the RPCs and DDCUs are required for redundancy. Some are there for future growth of SSF. If that occurs, more source capability will be added, so that more loads could operate at once with the existing PMAD. Finally, some of the 2 Mw of RPCs is due to packaging constraints. An RPC module is designed with one 130 amp RPC, or two 50 amp RPCs, or four 25 amp RPCs, or eight 10 amp RPCs. Hence, even if only three 10 amp RPCs are required in one particular location, eight will be installed since the packaging comes in that form.

Whatever the reasons, the idea of a large "load capacity" seems to be new with the SSF. From discussions with JPL designers and a COBE engineer, their spacecraft basically have the same load as source power. They indicated that perhaps up to twice as much load capacity versus source may occur in some cases, but nowhere near the 20:1 load capacity to source ratio found in the SSF. This idea of connectable load warrants further investigation as more data is gathered on other satellites. A large connectable load to source ratio may be a generic feature of large manned power systems, such as the SSF and others planned for the moon or Mars.

In estimating the PMAD masses for future large power systems, load capacity must be considered. As stated earlier under the "Database" section, it is often difficult to determine what kw value to use as the mass divisor to find a kg/kw value for the PMAD subsystem. It may be more accurate to divide the power system up into sections based on the amount of power each section is required to handle, then estimate each section's mass based on its kw rating. For example, in Figure 5, the first level of the system from the solar arrays and batteries to the interconnection, would be rated at 100 kw, the peak power. The next level would be from the interconnection block through the transmission block to the DC to DC converter units (DDCUs) in the conversion block. This level would be rated at 400 kw since this power level is the total capability of the DDCUs and associated wiring. The user level of the system would be the remainder of the system, from the output of the DDCUs in the distribution block to the load. The user level would be rated at 2 Mw, the amount of load capacity. A PMAD kg/kw value could be used for each section based on the items in the section. Such items may include the RPCs, or RPCs plus cabling and converters, or whatever happens to be in a particular section. The corresponding kw value would be used to determine the PMAD kg/kw mass. Finally, a summation of the masses of all the sections would yield the total mass. This method would be more accurate than just using one overall PMAD kg/kw value and multiplying it by the average required power.

Balance of System

In the SSF, the BOS mass is significant. In the current design, the BOS is 346 kg/kw, and less than half of that is the PMAD subsystem. The rest of the mass is power system support (Figure 7). The amount of support equipment required appears to increase with the power level of space power systems. Hence, it is anticipated that BOS, rather than PMAD alone, will be important for consideration. System trade-off studies may show that the lightest PMAD for a given application is not neccessarily the lightest BOS or, in turn, the lightest EPS.

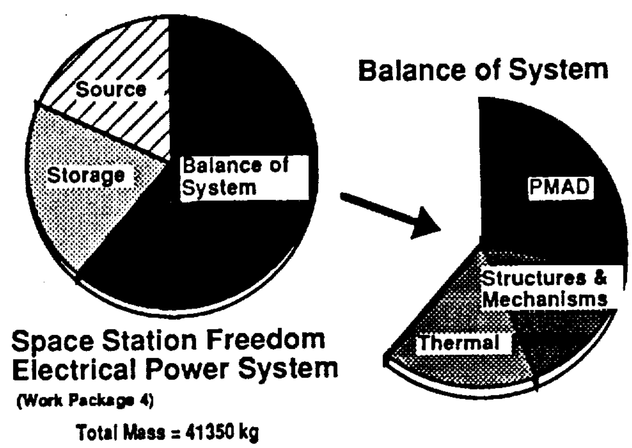

Figure 7 Space Station Freedom Balance of System

Redundancy

Another feature of the SSF is redundancy. Man-rated systems must have a certain level of reliability which can be achieved by the use of redundant components. However, redundancy adds mass to the PMAD subsystem. In one of the earlier SSF designs, there were eight main inverter units (MIU) specified. Each unit was rated at 25 kw and weighed approximately 93 kg [1]. That gives a component unit mass of 3.72 kg/kw. However, there were eight of them specified for a 75 kw load. Therefore, the total system MIU mass was (8x93)/75 = 10 kg/kw.

CONCLUSIONS

EPS mass data from several spacecraft has been obtained, evaluated and entered in a database. An analysis of the PMAD masses in the database leads to the following conclusions:

1. PMAD mass is not insignificant, the smallest value being 40 kg/kw.

2. SSF data shows that a large distributed utility-like power system is evolving. The interconnection, transmission and distribution blocks are much more significant than in a typical low power spacecraft.

3. The "balance of system" (BOS) is becoming more important as the power of the system increases. BOS is almost two-thirds of the Space Station Freedom EPS mass. PMAD is only 50% of the BOS. The rest of the BOS mass is composed of thermal control, structures, and mechanisms.

4. SSF has a large load capacity compared to typical low power spacecraft. This will also probably be a feature of any high power system with growth requirements and a large number and diversity of loads.

5. Man-rated reliability requirements achieved through redundancy contributes significantly to PMAD masses.

In the future, the database will be expanded. Power system masses of various types of spacecraft will continue to be added as the data becomes available. Additionally, other parameters such as life cycle cost, volume and efficiency will be added. This work is being undertaken to better understand how new technology can improve future space electrical power systems.

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This work was supported by the NASA Lewis Research Center under contract NAS3-25266 with Ronald C. Cull as monitor.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-103199		

4. Title and Subtitle

An Analysis of Space Power System Masses

5. Report Date

6. Performing Organization Code

7. Author(s)

Barbara H. Kenny, Ronald C. Cull, and M. David Kankam

8. Performing Organization Report No.

E-5597

10. Work Unit No.

506-41-41

9. Performing Organization Name and Address

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

11. Contract or Grant No.

13. Type of Report and Period Covered

Technical Memorandum

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, D.C. 20546-0001

14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the 25th Intersociety Energy Conversion Engineering Conference cosponsored by the AIChE, ANS, SAE, ACS, AIAA, ASME, and IEEE, Reno, Nevada, August 12-17, 1990. Barbara H. Kenny, Sverdrup Technology, Inc., Lewis Research Center Group, 2001 Aerospace Parkway, Brook Park, Ohio 44142; Ronald C. Cull and M. David Kankam, NASA Lewis Research Center.

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Mass; Space power system Power management and distribution; PMAD; EPS	Unclassified – Unlimited Subject Category 20

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	9	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161