Appendix E: Documented SP-210
(To be updated by LTTT Team over FY03)

Title: **"Electric Propulsion Mission Analysis: Terminology and Nomenclature", 1969, J. P. Mullin, et al, ... J. M. Horsewood, ... C. G. Sauer Jr.** (10-page booklet)

Purpose: Review and add any necessary updates to NASA SP-210 to get a start on our standard variables/ datasets, standard mission definitions, standard data dictionary, and reflect any changes in current standard low thrust conventions used in state-of-the-art analyses and tools.

Updated by the

Intercenter (MSFC, GRC, JPL, JSC)

Low Thrust Tool Development Team

for the

NASA In-Space Propulsion Project Office
and Code S, SSE Office

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NASA SP–210

Electric Propulsion Mission Analysis

Terminology & Nomenclature

Prepared by
NASA Office of Advanced Research and Technology
NUCLEAR ELECTRIC PROPULSION SYSTEMS ANALYSIS TASK GROUP

Scientific and Technical Information Division
OFFICE OF TECHNOLOGY UTILIZATION 1969
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FOREWARD

During the past decade, a large number of low-thrust mission studies have been carried out both in the United States and abroad. For a variety of reasons, these studies have displayed an imaginative diversity in terminology-placing an additional burden on the reader. When, in the spring of 1968, NASA established a task group on nuclear electric propulsion systems analysis, which involved the rapid exchange of large quantities of information, the need for a common terminology became more sharply focused. The results of the efforts of that task group to establish such a language are displayed in this document with the suggestion that active workers in the field consider its adoption in their future work.

The International System of Units, as defined in NASA SP-7012, was used throughout. Where considerations of tradition or under-standing were felt to predominate, other units were added in parentheses.

The members of the task group who developed, adopted, and agreed to promulgate this information are listed on the following page. Suggestions for future revisions should be directed either to the secretary or to the chairman of that group.

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INTRODUCTION

In establishing a set of system parameters for use in mission studies, it is first necessary to define a consistent set of terms and basic relations for reference. Since many groups perform such studies, and since electric propulsion hardware development is intimately associated with software development and mission design, it is prudent to agree on a common terminology. What is attempted here is the formulation of one such language.

SPACECRAFT MASS

Spacecraft initial mass m_o is defined as consisting of the sum of the following masses: low-thrust propulsion system m_{ps}, expendable low-thrust propellant m_p, tankage m_t, retro system m_r, net spacecraft m_n, and structure m_s. Refer to Figure 1 for a typical example of spacecraft mass allocation.

Net spacecraft mass, m_n, is the quantity that has been most often maximized in low-thrust trajectory studies. Net spacecraft mass includes various engineering systems such as guidance, thermal control, attitude control, telecommunications, and supporting structure, as well as mission or science payload mass, m_L. Net spacecraft mass is also occasionally, and somewhat ambiguously, identified as "payload mass." The ambiguity arises in missions where m_n is equivalent, for comparison purposes, to a ballistic spacecraft which is in turn viewed as "launch vehicle payload." We shall, here, demand only that the relationship $m_n \geq m_L$ holds, and that m_L, when used, be carefully defined.

The structural mass, m_s, definition may contribute to the ambiguity of the net spacecraft mass definition in the previous paragraph. In some cases, it is assumed proportional to m_o or m_n and handled separately in the analyses; in other cases, it is not explicitly considered. Because structural mass is inherently included in most subsystem mass allocations, for example, $m_{ps}(\square)$, $m_t(k_p)$, $m_r(k_r)$, and $m_n(k_n)$, the latter approach avoids a double penalty. Therefore, the task group recommends that in future work m_s be set equal to zero.

That portion of the initial mass defined as propulsion system mass, m_{ps}, includes both the power, m_w, and the thrust, m_{ts}, subsystems, not including propellant tankage but including all internal structure, mechanisms, cabling, thermal control, and so forth. Refer to Figure 2 for a system schematic of the propulsion system. Defined in this way, m_{ps}, m_w, and m_{ts} are ordinarily considered directly proportional to power, the proportionality constant, $\square$, being a figure of merit in hardware development. The power subsystem mass, m_w, includes primary power, conversion system, structure, mechanisms, shielding, cabling, mission-peculiar thermal control, and the like. This mass is usually treated as a direct function of power level but may include mission-peculiar anomalies. The mass of the thrust subsystem, m_{ts}, includes thrusters, power-conditioning, vaporizers, isolators, actuators, structures, and so forth. This mass is also a function of power level.

The propellant tankage mass, m_t, follows the classical definition of propulsion inerts, being directly proportional to propellant mass. It includes tankage, residuals, reserves, and propellant expulsion elements. In mission performance analysis, expendable propellant mass is evaluated for each specific mission and does not include propellant reserves or residuals. Propellant boil-off, if any, must be included at some point in the analysis as part of the expendable propellant mass.

In many of the missions to be considered, a chemical retro-propulsion system may be required. If included, retro-propulsion system mass, m_r, is made up of two components: first is a

FIGURE 1. Typical Mass Allocation

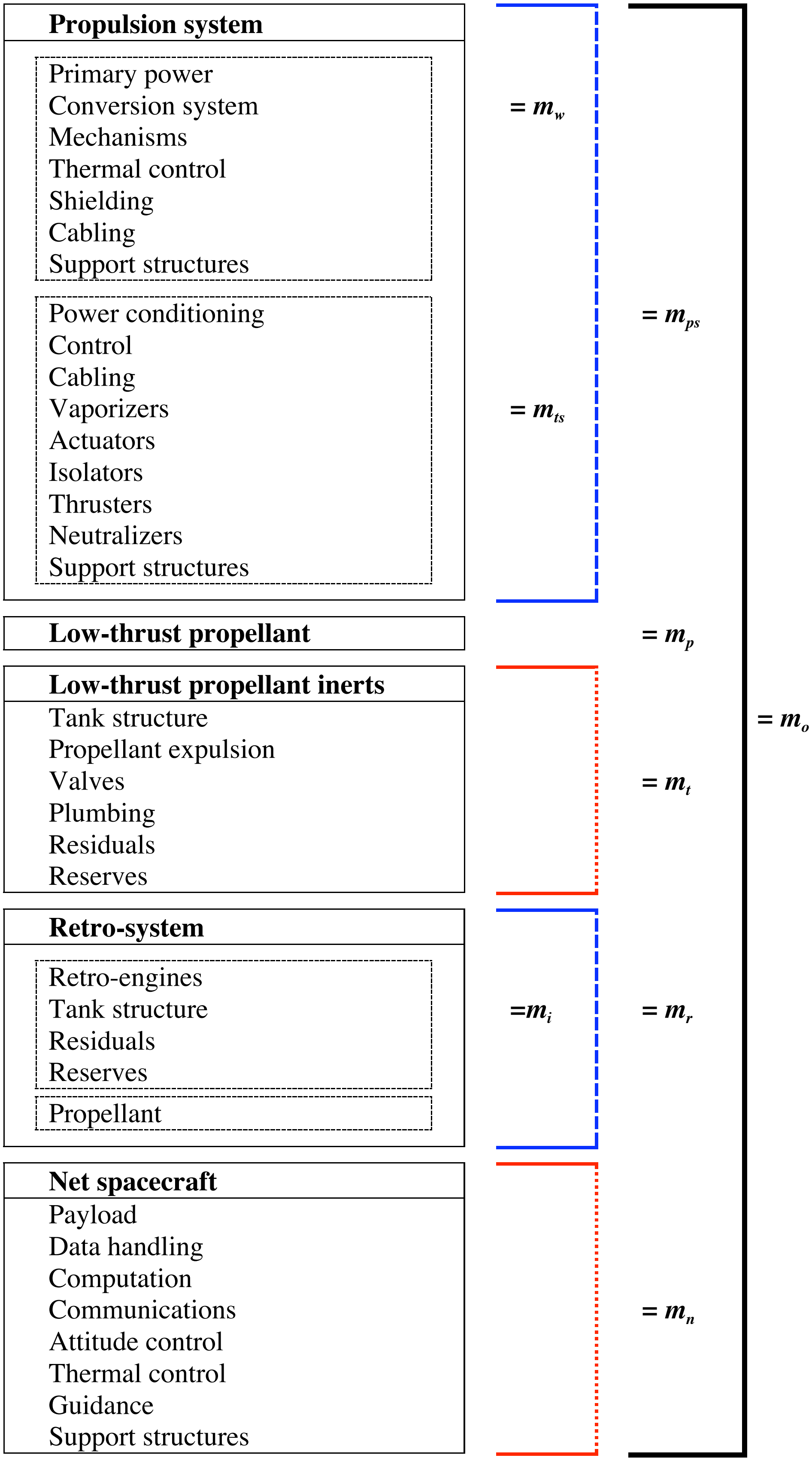
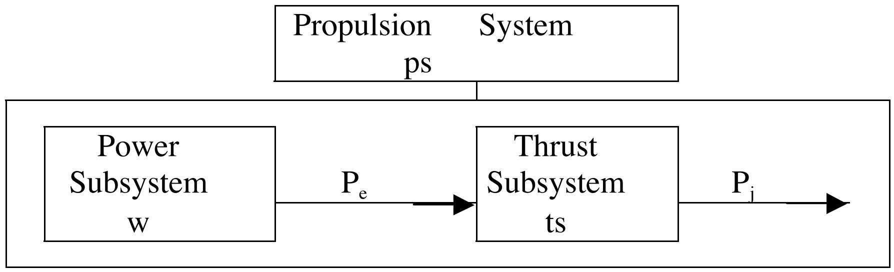


FIGURE 2. System Schematic



retro-propulsion fuel mass, m_{pr}, which does not include propellant reserves or residuals, and second is the retro-propulsion system inert mass, m_i, which includes the retro-engines, propellant tankage, and fuel reserves. The latter mass is taken to be proportional to the retro-propulsion fuel mass.

From the viewpoint of the mission analyst, the two elements of the low-thrust electric propulsion system of major consequence are thrust magnitude, F, and the propellant mass flow rate, $\dot{m}_p$. The thrust acceleration of an electric-propelled spacecraft at any time, t, is related to its initial mass, m_o, by the expression

$$a(t) = F(t) / \left(m_o - \int_o^t \dot{m}_p dt\right) \tag{1}$$

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EXHAUST JET VELOCITY

We here adopt the convention of defining propulsion exhaust or effective jet velocity as the ratio of thrust to mass flow rate:

$$V_j = F/\dot{m}_p = c \tag{2}$$

(V_j or c can be used interchangeably for velocity).

Historically, comparative analyses of propulsion systems have been made with a figure of merit defined as “specific impulse”, I_s. This parameter has the dimension of time because of the consideration of propellant "weight" flow rather than mass flow in equation (2). Specific impulse is, therefore, related to jet velocity by the constant of Earth's gravity, g_o:

$$I_s = V_j / g_o = c/g_o \tag{3}$$

Defined in this way, either specific impulse or jet velocity may be used as a figure of merit in the comparison of electric-propulsion thrust systems.

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POWER AND EFFICIENCY

The effective jet velocity has been defined as a function of thrust and propellant mass flow rate. It is also possible to define an effective jet power of the propulsion system:

$$P_j = {}^1/_2\, \dot{m}_p V_j^2 \tag{4}$$

The effective jet power can then be referred to any other point in the propulsion system by introducing an appropriate efficiency function. This efficiency is ordinarily expressed as a function of I_s and is useful in defining electrical power level, P_e, via the expression

$$\eta_{ts} = P_j / P_e \tag{5}$$

Further breakdown of this efficiency, which is itself the product of the thruster efficiency and the power conditioning efficiency, into its constituent elements inside the thrust subsystem is of value to hardware developers, but is of little consequence to the mission analyst. There can be interminable dispute regarding the "best" point at which to measure P_e -- the choice again being of some interest only to hardware developers. We shall here adopt, however arbitrarily, the convention that electrical power, P_e, is defined as that total electrical power delivered to the input terminals of the power-conditioning assemblies (i.e., into the thrust subsystem) at a fixed reference condition. For nuclear reactor power systems this reference condition is design power level, for radioisotope systems the reference condition is start of mission power, and for solar power systems the reference condition is power at 1 A.U. The power variation of the solar and radioisotope systems should be identified so that the system analyst may design for the maximum and minimum power along the mission.

Electrical power level may sometimes be closely related to the spacecraft initial mass. For this reason it is useful to define a normalized power level proportional to initial spacecraft mass. Termed "specific power", P^*, this normalization may be expressed as

$$P^* = P_e / m_o \tag{6}$$

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SPECIFIC MASS

A convenient figure of merit of electric propulsion technology is the ratio of propulsion system mass to power. This quantity is defined as specific mass α or α_{ps}:

$$\alpha = (m_w + m_{ts}) / P = \alpha_{ps} \tag{7}$$

Specific mass may be expressed in terms of either jet power or electrical power:

$$\alpha_j = (m_w + m_{ts}) / P_j \tag{8}$$

$$\alpha_e = (m_w + m_{ts}) / P_e = \alpha \tag{9}$$

To avoid confusion, the appropriate subscript could be used; however, from common practice, the lack of a subscript shall only refer to electrical power. The specific mass can also be separated into a power subsystem specific mass, α_w, and a thrust subsystem specific mass, α_{ts}:

$$\alpha_w = m_w / P_e \tag{10}$$

$$\alpha_{ts} = m_{ts} / P_e \tag{11}$$

The specific mass of a power system is itself a function of power level. This phenomenon has traditionally been handled by displaying results parametrically for some reasonable range of specific mass. However, alternative approaches using an explicit function to represent the dependence of specific mass upon power may have value in some analyses. For example, the relationship $\alpha = (K_1 + K_2 P_e^N) / P_e$ where K_1, K_2, and N are appropriately chosen constants reflecting technology level, has proved useful in the case of nuclear reactor powered systems.

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NOMENCLATURE

a	Thrust acceleration, m/s^2
c *or* V_j	Effective thruster jet/exhaust velocity, m/s
F	Thrust force, N
I_s	Effective thruster specific impulse, seconds (s)
k_n	Net spacecraft structure proportionally constant
k_o	Structural proportionality constant (k_s?)
k_p	Propellant inert proportionality constant
k_r	Retro-system inert proportionality constant
m	Instantaneous mass of spacecraft, kg
m_f	Final spacecraft mass, kg
m_i	Retro-system inert mass, kg
m_L	Payload mass, kg
m_n	Net spacecraft mass, kg
m_o	Initial spacecraft mass, kg
m_p	Low-thrust propellant mass, kg
m_{pr}	Retro-propulsion fuel mass, kg
m_{ps}	Propulsion system[1] mass, kg
m_r	Retro-system mass, kg
m_s	Structural mass, kg
m_t	Low-thrust propellant tankage or inert mass, kg
m_{ts}	Thrust subsystem mass, kg
m_w	Power subsystem mass, kg
P_e	Electrical power to thruster subsystem, kW or kW_e optionally
P_j	Kinetic power in jet exhaust, kW_j
t_f	Mission time(s), days
t_p	Propulsion time(s), hours
V_j *or* c	Effective thruster jet or exhaust velocity, m/sec
α *or* α_{ps}	Propulsion system specific mass, kg/kW_e (kg/kW optionally)
α_{ts}	Thruster subsystem specific mass, kg/kW_e (kg/kW opt.)
α_w	Power subsystem specific mass, kg/kW_e (kg/kW opt.)
η_{ts}	Thrust subsystem efficiency ($\eta_{ts} = \eta_{power\_proc\_unit} * \eta_{thruster}$)

[1] "Propulsion system" as used here includes neither propellant nor tankage.

TERMINOLOGY

Initial spacecraft mass[1]

$$m_o = m_{ps} + m_p + m_t + m_r + m_n + m_s$$

($m_s = 0$ preferred, see text)

Propulsion system mass

$$m_{ps} = m_w + m_{ts} = \alpha\, P_e$$

Low-thrust propellant tankage or inert mass

$$m_t = k_p\, m_p$$

Retro-system mass including inerts

$$m_r = m_i + m_{pr} = k_r\, m_{pr} + m_{pr}$$

Structural mass[2]

$$m_s = k_o\, m_o \text{ or } k_n\, m_n$$

(preferred approach is $m_s = 0$)

Payload mass, final mass

$$m_L \leq m_n$$

(m_L and m_f defined by analyst when used)

Thrust subsystem efficiency

$$\eta_{ts} = P_j / P_e = \eta_{power\_proc\_unit} * \eta_{thruster}$$

Thruster jet or exhaust velocity

$$V_j = F / \dot{m}_p = c$$

Thruster specific impulse

$$I_s = V_j / g_o = c / g_o$$

(g_o is a defined constant equal to 9.80665 m/s^2)

Thrust acceleration

$$a = F/m\ ;\ \ a_o = F / m_o$$

Specific mass

$$\alpha_w = m_w / P_e$$

$$\alpha_{ts} = m_{ts} / P_e$$

$$\alpha = (m_w + m_{ts}) / P_e = \alpha_w + \alpha_{ts} = \alpha_{ps}$$

[1] In some circumstances, a retro-system is not included ($m_r = 0$). Structure may not be accounted for explicitly ($m_s = 0$).

[2] It should be recognized that use of the m_s option can cause a double penalty because of the allocation for structure within $m_{ps}(\alpha)$, $m_t(k_p)$, $m_n(k_n)$, and $m_r(k_r)$.