ATMOSPHERIC REENTRY SATELLITE ORBITAL STEADY STATE AVERAGE TEMPERATURE EVALUATION

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Abstract. *In this work an orbital steady state thermal evaluation of a mission of the Atmospheric Reentry Satellite (SARA) is presented, comparing the average temperature calculated with SATER-100 and CTSAT-01 computer codes. In this study an approximately equatorial and inertial orbit, was considered. This satellite attitude minimizes the internal forces, so that a micro-gravity environment is obtained for performing the experiences planned for the mission. In this thermal evaluation the satellite steady state average temperatures are calculated as a function of its attitude in orbit, internal and external thermal power, heat transfer external areas and optical properties data.*

Keywords*: temperature, simulation, satellite, heat transfer, energy*

1. INTRODUCTION

A complete satellite mission is composed by several phases, as presented in Fig. 1, besides the phase of preparation of the satellite (at Earth), other 6 phases can be defined: 1 - launch, 2 - orbit insertion, 3 - orbital fly, 4 - reentry, 5 - breaking and 6 - recovery, each one of them with their characteristics and requests thermal, structural, etc., these define the satellite geometry, internal power range, useful load, etc.

This paper presents the results of the orbital phase steady state thermal evaluation of a mission of the Atmospheric Reentry Satellite (SARA in Portuguese), in development in the Institute of Aeronautics and Space (IAE-CTA).

In these simulations SATER-100 and CTSAT-01 computer codes were used to evaluate the orbital average temperatures in steady state of SARA, as a function of its attitude in orbit, the internal and external thermal loads to which it is submitted, the geometric data and the optic properties of the external coatings.

An almost equatorial and inertial orbit was considered (without rotation). This satellite orbital attitude minimizes the internal forces. It is important to obtain a minimum gravity force in the satellite, necessary to the experiences to be accomplished during the mission.

The results of this analysis are important for the evaluation of the mission from the thermal point of view, supplying data to make it possible, as the acceptable thermal power range generated by the internal equipments as a function of the heat transfer area and the type of external covering used.

Important references about satellite thermal control are: NASA (1983), Gilmore (1994) and Karam (1998).

2. SARA PROJECT DATA

To define the satellite mission operational needs it is considered, among other important parameters, the orbit data and attitude of the satellite, its geometric data, mass and power of their internal equipments, etc. All these parameters need to be viable from constructive point of view, launch, operational, thermal, etc.

In these simulations it intends to just evaluate the thermal viability of the orbital phase of SARA mission, it is considered that the total internal power necessary it is between 50 and 120 W. The information used in this study, in regard to the SARA external geometry, as well as attitude parameters in orbit and other relevant data are based on Delpont (1967), Moraes and Pilchowski (1997), Moraes (1998) and Hirdes (2002).

2.1 Satellite geometry

As the objective of this work is SARA orbital phase steady state thermal evaluation, just the relevant parameters for this analysis are considered. Except for the base of the satellite, the whole area is isolated and the external covering has null optic properties. It is noted that is used a material in the cap that should sublimate in the reentry and the cone should be protected of the high resulting temperatures in this phase of the mission, using heat pipes, as proposed by Hirdes (2002) and presented in Fig. 2.

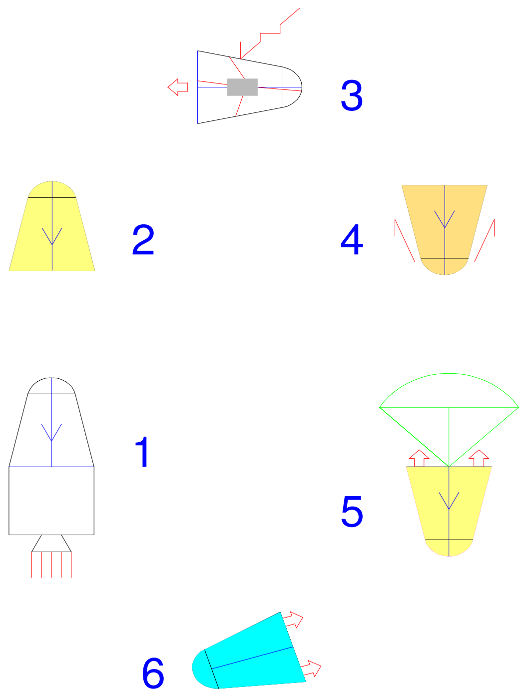

Figure 1: Phases of a satellite mission.

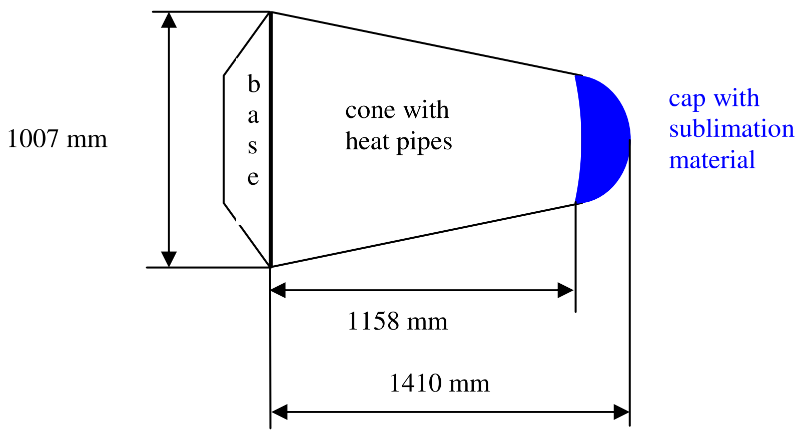

Figure 2: Geometric and constructive parameters of the SARA satellite.

2.2 Orbital parameters

The information regarding the SARA attitude in orbit and other important data to the thermal analyses are available in Tab. 1.

Table 1: SARA orbital attitude parameters.

Parameter	Characteristic
Orbit type	Circulate
Orbit inclination	Equatorial plane
Orbit period	5400 s
Ecliptic	23.5 deg
Orbit altitude	300000 m
Earth radius	6378155 m
Solar constant (S)	1395 [W/m^2]
Average Albedo	0.35

3. SATER-100 COMPUTER CODE

SATER-100 is a software capable to simulate problems to involve transport phenomena, convection and radiation simultaneously, in arbitrary three-dimensional geometries, in steady state and transient regimes.

SATER-100 is capable to make the geometric modeling, to accomplish the thermal simulation and to present results in a graphic way. The numerical method is based on a composition of the methods of finite volumes and finite elements (CVFEM).

The orbital module was specifically developed for space area users. The code allows the calculation of the external surfaces thermal loads of a body in orbit, coming from the Sun, through the planetary reflection (Albedo) and of the radiation emitted by the planet.

3.1 Theoretical modeling

In the thermal project of a satellite it is necessary to use a model to allow calculating the temperature of each equipment of the system or area, of their internal and external surfaces, and the thermal changes among them, as it is done in SATER-100.

Usually the satellites present a quite complex geometry, what impedes the obtaining of it distribution of temperature in an analytical way. To outline this difficulty the nodal method can be used, that consists in subdividing the domain in a finite number of isothermal areas, called knots, with uniform thermal-physics properties and internal dissipation. Soon afterwards, the temperature is calculated for each one of them, through the energy equation, as presented in Cardoso (2003).

For each one of these areas, it is established an energy equation, considering the heat transfer with the other knots and the environment. The simultaneous resolution of these equations, in all the knots, allows the obtaining of the temperature distribution in the domain. Eq. (1) expresses mathematically the energy equation for a generic knot *i*:

$$m_i c_i \frac{\partial T_i}{\partial t} = \alpha_i A_i Q_{si} + \alpha_i A_i Q_{ai} + \varepsilon_i A_i Q_{Ti} + P_i + \sum_{j=1}^{n} C_{i,j}(T_j - T_i) + \sum_{j=1}^{n} R_{i,j}(T_j - T_i) + \sum_{j=1}^{n} H_{i,j}(T_j - T_i) + \sum_{j=1}^{n} D_{i,j}(T_j - T_i) \quad (1)$$

where, to knot i:
m_i : mass
c_i : specific heat
T_i : absolute temperature
α_i : solar absortivity
ε_i : emissivity
A_i : area
Q_{si} : thermal load directly of the sun
Q_{ai} : thermal load the reflection of the radiation of the sun for the earth
Q_{Ti} : thermal load directly of the earth
P_i : power; and:
t : time
$C_{i,j}$: conductive joining among the knots i and j
$R_{i,j}$: radioactive coupling among the knots i and j
$H_{i,j}$: convective joining among the knots i and j
$D_{i,j}$: advective joining among the knots i and j.

The degree of refinement of the adopted mesh depends as much of the geometry as on the thermal and physical properties of the satellite and the boundary conditions it is submitted. Considering a single satellite model it is possible to make temperature distribution calculations and to identify critical areas, where there are great temperature gradients and thermal flux, etc.

3.1.1 Thermal load modeling

For a satellite in low orbit, there are three main sources of external thermal load: solar direct, Earth radiation, and Albedo. The values effectively incidents on a surface in orbit depend on its orientation, altitude, and relative position Earth - Sun - surface.

The incident direct solar radiation is given by:

$$Q_{si} = S\cos\theta_i \quad , \quad (2)$$

where:
θ_i : angle between the normal to the surface and the Earth - Sun vector;
S: solar constant; and
Q_{si}: incident direct solar radiation in the face i of the object.

Like this, the Albedo value is given by:

$$Q_{ai} = aSF_{oi-Calota} \quad , \tag{3}$$

where:
a: Albedo coefficient;
$F_{oi\text{-}Calota}$: Form factor of the face i of the object for the illuminated cap; and
Q_{ai}: heat flux incident in the face i of the object due to Albedo [W/m^2].

The incident terrestrial radiation is given by:

$$Q_{Ti} = \frac{(1-a)}{4} SF_{oi-Esfera} \quad , \tag{4}$$

where:
$F_{oi\text{-}Esfera}$: Form factor of the face i of the object for the Earth; and
Q_{Ti}: heat flux incident in the face i of the object due to Earth [W/m^2].

3.1.2 Radiation modeling

The radiation heat transfer is a no linear phenomenon, proportional to the body external surface temperature elevated to the fourth potency. In the energy equation, Eq. (1), the term corresponding to the radiation is linear with the Rij coefficients. This term also considers the effect of the multiple reflections, happened due to the reflectivity of the several involved surfaces. In a medium where a great number of surfaces exist, it is impossible to obtain an analytical expression for this coupling. For two surfaces Eq. (5) calculates this value exactly. This expression can be used inside with more surfaces, without great precision loss, since the surfaces have high emissivity.

$$R_{ij} = \frac{\varepsilon_i \varepsilon_j A_i F_{ij} \sigma}{\left[1-(1-\varepsilon_i)F_{ii}\right]\left[1-(1-\varepsilon_j)F_{jj}\right]-(1-\varepsilon_i)(1-\varepsilon_j)F_{ij}F_{ji}} T_m^3 \tag{5}$$

where:

$$T_m = \sqrt[3]{(T_i^2 + T_j^2)(T_i + T_j)} \tag{6}$$

Using the method of Integral of Area, with base in Fig. 3, the form factor is:

$$F_{ij} = \frac{1}{2\pi A_i} \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{\cos B_i \cos B_{j_i} A_i A_j}{r_{ij}^2} \tag{7}$$

4. CTSAT-01 COMPUTER CODE

CTSAT-01 software was developed at the Institute for Advanced Studies (IEAv), in C++ language, to do satellite thermal analysis, calculating average temperature in steady state as a function of the satellite orbit attitude and other parameters supplied by the user, as the value of the solar constant, Albedo, heat transfer areas, internal power, optic properties, etc. Like this, CTSAT-01 calculates, iteratively, the incidents external thermal loads and the total thermal load in [W/m^2], and soon afterwards, it obtains the average temperature of the simulated satellite, as presented in Borges (2004).

In the SARA case, for a given internal power P [W], its generic mission considers that the cap of the cone is always directed for the Sun and that its base should be gone back to the Earth for an enough time for the necessary acquisition and transfer data.

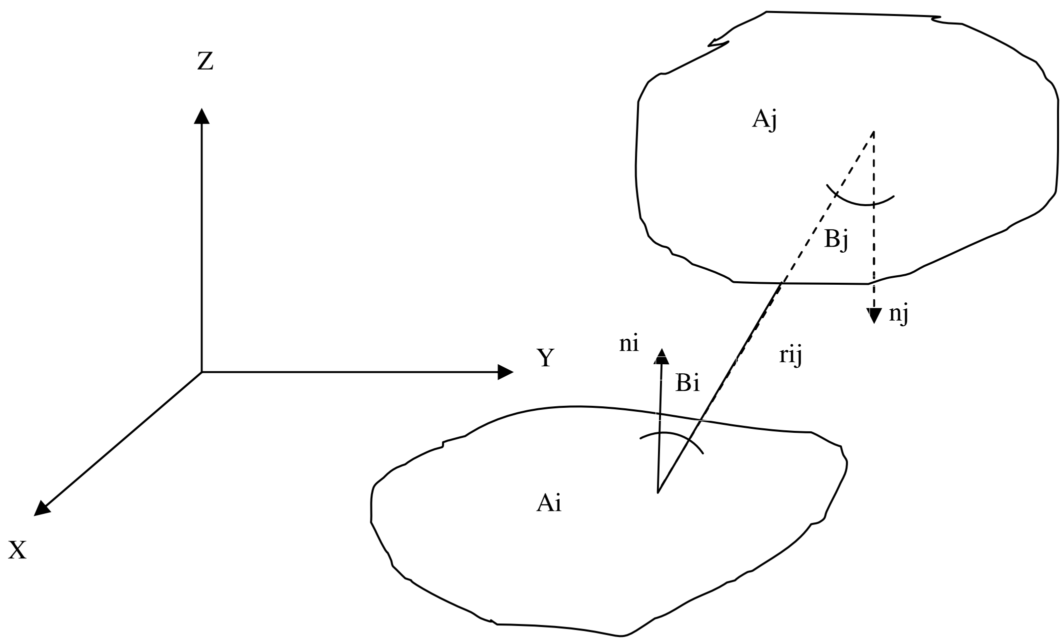

Figure 3: Calculation of the form factor among areas.

Due to its form and this attitude in orbit, it was considered in the SARA case the following external areas: of heat transfer rejection (A_R), of solar ray incidence (A_S), of Albedo incidence (A_A) and of Earth radiation incidence (A_T). Defining the visible spectrum absortivity (α) and the infrared emissivity (ε) the energy equation in steady state is:

$$\alpha A_S qs + \alpha A_A qa + \varepsilon A_T qt + P - \varepsilon A_R \sigma T_{SAT}^4 = 0 \quad . \tag{8}$$

The SARA satellite average temperature is:

$$T_{SAT} = \sqrt[4]{\frac{\alpha A_S qs + \alpha A_A qa + \varepsilon A_T qt + P}{\varepsilon A_R \sigma}} \quad . \tag{9}$$

The average solar thermal load (qs) incident on the satellite is:

$$qs = \Psi\, S \, , \tag{10}$$

where, S is the solar constant [W/m^2] and Ψ is a parameter that depends on the orbit data and it can be calculated by the expression:

$$\psi = \frac{1}{2} + \frac{1}{\pi} \mathrm{sen}^{-1}\left(\frac{\sqrt{1-(R/\rho)^2}}{\cos(\theta)} \right) \quad , \tag{11}$$

where, R is the Earth radius; ρ is the orbit radius that it is obtained as the sum of the Earth radius with the satellite altitude; and θ is the angle between the vector Earth - Sun and the orbital plane.

The Albedo thermal load (qa) incident on the satellite is:

$$qa = \frac{aS}{8}\left(1 - \sqrt{1 - \frac{R^2}{\rho^2}} \right) \quad , \tag{12}$$

where, a is the average Albedo value.

The average thermal load due to the Earth (qt), incident on the satellite is:

$$qt = \frac{1}{2}\sigma T_T^4\left(1-\sqrt{1-\frac{R^2}{\rho^2}}\right) \quad , \tag{13}$$

where, σ is the Stefan-Boltzman Constant [W/m^2K^4] and T_T is the Earth temperature [K].

It is important to note that Eqs. (12) and (13) are used for a spherical form satellite thermal calculations, and they are applied in CTSAT-01 as an approximation to represent the SARA geometry.

5. SIMULATIONS

In this work, the average temperature was evaluated in steady state of SARA satellite as a function of the heating due to the Sun, Albedo and Earth, comparing the results obtained with the SATER-100 and CTSAT-01 computer codes, considering the satellite attitude in orbit, geometry, internal power and optic properties of the external covering in the areas of heat transfer simulated, and the average temperature of the satellite is the average of the temperatures of the areas. The knots and faces used in SARA simulation by SATER-100 are presented in Fig 4.

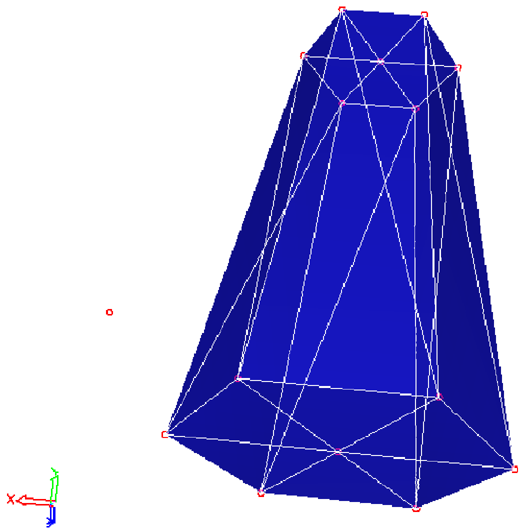

Figure 4: SARA geometry simulated by SATER-100.

Table 2 presents the adopted materials in this analysis as options of external covering and their respective optic properties, as defined by Cardoso (2004). It is noted that Tape Shedal (Cardoso 2004) and Solkote (Solec 1982) are optical coatings specifically formulated for solar thermal applications.

Table 2. Optic properties.

External covering	Type	Absortivity (α)	Emissivity (ε)
Tape Shedal	Plane reflector	0.14	0.12
Solkote	Solar absorber	0.91	0.38
Black paint	Plane absorber	0.90	0.90
White paint	Solar reflector	0.26	0.85

In these simulations two values for satellite heat transfer areas (maximum and minimum) are considered, due to the mission operational needs, such as, space for reception and transmission data antennas, hatchway for parachute opening, etc. The value of the maximum area of heat transfer adopted is equal to one half of the base area and the minimum is equal to one third of the base area. As mentioned in Section 2.1, only in the base of SARA satellite is used the optical properties coating presented in Tab 2. Table 3 presents the adopted area values in these thermal analyses.

Table 3. Values of the satellite heat transfer areas.

Area	Values [m^2]
Maximum	0.400
Minimum	0.267

Figure 5 presents the curves of average temperatures in steady state of the orbital SARA satellite, as a function of the internal power variation for the maximum external heat transfer area and optic properties presented in Tab. 2, obtained with SATER-100 and CTSAT-01 computer codes.

Figure 6 presents the curves of average temperatures in steady state of the orbital SARA satellite, as a function of the internal power variation for the minimum external heat transfer area and optic properties presented in Tab. 2, obtained with SATER-100 and CTSAT-01 computer codes.

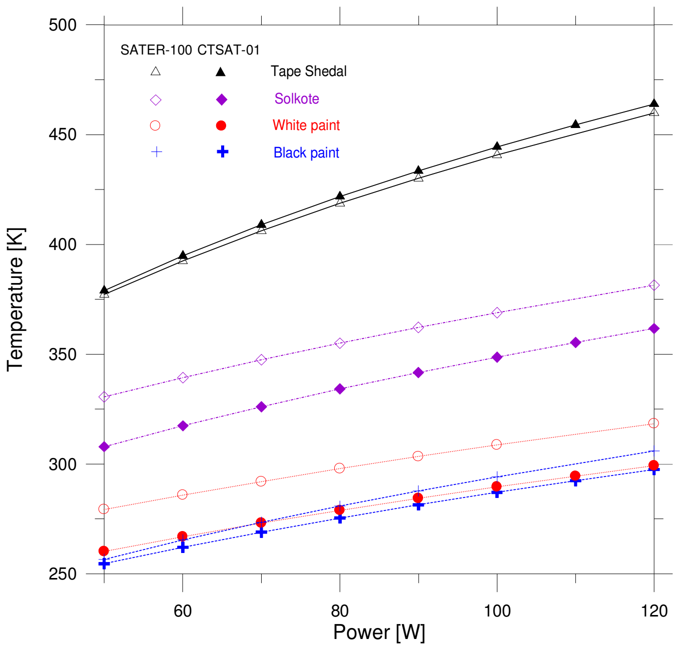

Figure 5: SARA orbital average temperatures for the maximum heat transfer area.

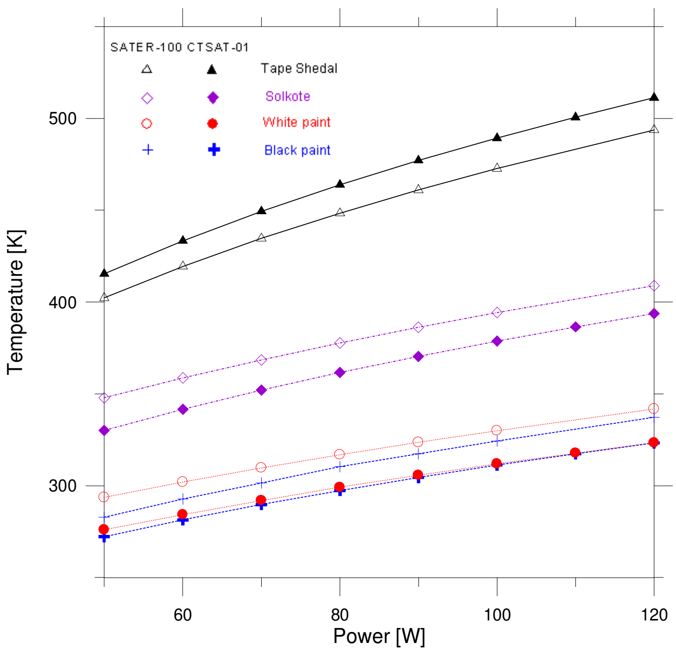

Figure 6: SARA orbital average temperatures for the minimum heat transfer area.

6. CONCLUSION

In this paper a thermal simulation of the Atmospheric Reentry Satellite (SARA), in development in IAE-CTA, comparing the orbital average temperatures, in steady state regime, is obtained with SATER-100 and CTSAT-01 computer codes. Although the mathematical models used are different, the softwares presented very close results for some cases.

Due to the SARA cap and cone thermal isolation used (necessary during the reentry phase), the influence of the solar radiation is minimized and the temperature depends mainly on the emissivity of the base satellite external covering.

Considering the orbital satellite attitude, the important parameters of this analysis are: the base heat transfer area, satellite external covering and internal power necessary for the mission. It is noted that the average temperatures in steady state are dependent on all these parameters, and as result they present a wide range of variation. Therefore, as a function of making possible a given mission, and to reach their objectives, all parameters of interest can be defined and to do again the thermal evaluation, structural, etc.

Wile CTSAT-01 code can be used only to calculate the satellite average temperature, in steady state regime, SATER-100 code could be utilized to evaluate the temperature distribution for each satellite equipment as a function of orbital time.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Borges, E. M, Braz Filho, F. A., e Caldeira A. D., 2004, "Um Projeto Térmico Conceitual Do Satélite De Reentrada Atmosférica - SARA", Nota Técnica CTA/IEAv-ENU/NT-006/2004, São José dos Campos, SP, Brasil.

Cardoso, H. P., 2003, "Projeto Térmico de Satélites Artificiais - Apostila do Curso: Análise Térmica de Satélites", São José dos Campos, SP, Brasil.

Cardoso, H. P., 2004, personal communication.

Delpont, J.P., et al., 1967, "Calculo des Puissances Radiantes Reçues par un Orbite Terrestre", Note Technique 6, CNES, França.

Equatorial Sistemas Ltda., 2001, **"**SATER-100 Sistema de Análise Térmica**.** Manual do Usuário**"**, São José dos Campos, SP, Brasil.

Gilmore, D. G., 1994, "Satellite Thermal Control Handbook", The Aerospace Corporation Press, California, USA.

Hirdes, V., Borges, E. M., Braz Filho, F. A., Hirdes, M., e Cardoso, H. P., 2002, "Tubos de Calor para Satélites de Reentrada", II CONEM, João Pessoa, Pb, Brasil.

Karam, R. D., 1998, " Satellite Thermal Control fo Systems Engineers", American Institute of Aeronautics and Astronautics Inc., Virginia, USA

Moraes Jr., P. e Pilchowski, H. U., 1997, "Plataforma Orbital Recuperável para Experimentação em Ambiente de Microgravidade"**,** XIV COBEM, Bauru, SP, Brasil.

Moraes Jr., P., 1998, "Design Aspects of the Recoverable Orbital Plataform SARA", VIII Congreso Chileno de Ingeniería Mecánica, Concepción, Chile.

NASA, 1983, "Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development",1982 Revision (V.1), TM82478, USA.

www.solec.org/ , 1982.

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