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DESIGN, ANALYSIS, AND TEST VERIFICATION OF ADVANCED
ENCAPSULATION SYSTEM

MASTER

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1.0 SUMMARY STATEMENT

Two strawman designs have been devised to aid in the development of analytical techniques for evaluating advanced encapsulation systems designs. The optical model for a multi-layer system in which reflection, absorption, and transmission may occur between layers, was completed and analytically verified. An expression giving the electrical safety criteria for a multi-layer dielectric system has been derived. A thermal analytical analysis program has been developed which will accommodate up to six different material layers for the determination of NOCT. MSC/NASTRAN has been selected as the primary structural analysis computer code. A matrix of materials and properties has been prepared. Work has begun in finding the necessary material properties.

2.0 INTRODUCTION

The objective of this program is to develop analytical methodology for advanced encapsulation systems designs and to determine optimum systems for meeting the Low Cost Solar Array Project goals. The program consists of three phases. In Phase I, analytical models will be developed to perform optical, thermal, electrical, and structural analyses on candidate encapsulation systems. From these analyses an optimum candidate system will be selected based on cost per watt over the life of the module.

During Phase II, modules of this optimum system will be constructed and tested to determine the validity of the analysis methodology developed in Phase I.

In Phase III, a finalized optimum design based on any iterations in Phase II will be developed and delivered to JPL.

3.0 TECHNICAL DISCUSSION

3.1 DESIGN CONCEPTS

Two strawman designs have been devised for use in the development of the analytical techniques and are described in Table 1. Figure 1 shows a plan view of the module design concept that will be under consideration during this program. The module dimensions will be 1.2 x 1.2 square meters, and is comprised of 121 four inch square cells. The two strawman designs are presented in Figures 2 and 3. The Hughes Electro-Optical and Data Systems Group have begun analytical modeling work on designs #1 and #2.

The following sections of this report present a discussion of the work performed to date on:

- (A) Optical, thermal, electrical, and structural analysis based on the strawman designs.
- (B) Material properties which are necessary to quantify these analyses.

Table 1

TASK III PRELIMINARY DESIGNS

<u>Layer</u>	<u>Material</u>	
	<u>#1</u>	<u>#2</u>
Surface	AR Coat	None
Top Cover	Tempered Glass	Korad
Pottant	EVA	EVA Crane Glass
Spacer	Crane Glass	Crane Glass
Substrate	None	Wood Product
Back Cover	Al Foil	EVA Crane Glass

Figure 1. TASK III MODULE CONCEPT

Figure 2

TASK III PRELIMINARY DESIGN NO. 1

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ESTIMATED DIMENSIONS

MATERIAL

3.175 mm [0.125 IN]

TEMPERED GLASS
A-R COATED

0.127 mm [0.005 IN]

EVA

0.254 mm [0.010 IN]

CELLS

0.127 mm [0.005 IN]

CRANE GLASS- EVA

0.0254 mm [0.001 IN]

ALUMINUM FOIL

Figure 3

TASK III PRELIMINARY DESIGN NO. 2

	ESTIMATED DIMENSIONS	MATERIAL
0.127 mm [0.005 IN]	KORAD
0.0762 mm [0.003 IN]	CRANE GLASS-EVA
0.254 mm [0.010 IN]	CELLS
0.1778 mm [0.007 IN]	CRANE GLASS-EVA
6.35 mm [0.25 IN]	WOOD PRODUCT
0.127 mm [0.005 IN]	CRANE GLASS-EVA

3.2 OPTICAL MODEL

The optical model is for a multi-layer system in which reflection, absorption, and transmission may occur between layers. This model was completed, and analytically verified. A FORTRAN computer algorithm is currently being developed and will be incorporated in the near future in the CINDA* program used for thermal analysis. The purpose of the optical analysis is to predict both the effective transmittance of sunlight through the encapsulation layers to the solar cell surface and the fraction of the incident solar radiation which is absorbed and converted into heat in each layer of the encapsulation system.

Propagation of solar energy through a series of dielectric layers is an extremely complex phenomenon. In order to simplify the problem, it was assumed that (1) all the absorbed solar radiation is converted to heat and is conducted to the module surfaces (and then lost to the environment through convection and infrared radiation), and (2) all material properties are independent of temperature. Thus reradiation and scattering phenomena within the encapsulant layers are not taken into account in this analysis. The validity of these assumptions cannot be determined until more information on material optical properties becomes available.

The model does allow for many parameter variations, including the following:

- A. Spectral variation of solar intensity due to the time of day and weather conditions (i.e., turbidity and air mass).
- B. Spectral variation of solar cell efficiency. The decrease in solar cell efficiency with increasing temperature is assumed to be $.5\%/^{\circ}\text{C}$ and is assumed to be independent of wavelength. By changing these parameters cell materials other than silicon may be easily studied.

*Chrysler Improved Numerical Differential Analyzer

- C. Internal reflection of solar radiation within the encapsulation system. This also includes taking into account solar energy reflected off the intercell interstices back on to the cells. This second effect, also referred to as "internal enhancement" or the "zero-depth concentrator phenomena", leads to a nonuniform radiation pattern on the cell surface and may give rise to delamination problems in the encapsulant.
- D. Spectral variation of encapsulant optical properties such as transmittance and absorption coefficient. This is necessary since many organic polymer materials are known to have absorption bands in the infrared region of the electromagnetic spectrum. (The index of refraction of each encapsulant layer is assumed to remain invariant with wavelength).

The model makes use of a radiosity-irradiation network analysis. This allows a straightforward evaluation of specular radiant energy exchange between several surfaces and absorbing media. The mathematical solution requires solving a set of simultaneous algebraic equations.

3.3 ELECTRICAL ANALYSIS

An expression giving the electrical safety criteria for a multi-layer dielectric system has been derived by assuming that the encapsulation system can be treated as a simple one-dimensional capacitor as shown in Figure 4:

$$E_k = \frac{V_o}{t_k + \gamma_k \sum_{i \neq k} \frac{t_i}{\gamma_i}} \quad (1)$$

where E_k = electric field strength in layer k, volt/cm
 γ_i, γ_k = dielectric constants of layers i and k, respectively
 t_i, t_k = thickness of layers i and k, respectively, cm
 V_o = voltage across capacitor

The design criteria is

$$E_k < S_k \text{ for all layers when } V_o = 3000 \text{ Vdc (LSA requirement)}$$

where S_k = dielectric strength, volt/cm

This expression does not take into account the influences of bubbles, cracks, or the crowding of electric field lines near the corner of a solar cell.

The electrical analysis task has begun for design #1. The breakdown voltage was calculated to be 2629 volts for the Crane-Glass/EVA layer between the silicon solar cell and the aluminum foil layer on the back face of the module. This is somewhat below the LSA breakdown voltage requirement of 3000V, but it should be noted that a dielectric strength of 2.07×10^5 volt cm^{-1} was used for EVA in this calculation and that the accuracy of this value is unknown at the present time.

Figure 4
SIMPLE CAPACITOR MODEL

3.4 THERMAL ANALYSIS

The thermal models for determination of NOCT can accommodate up to six material layers with different thicknesses and physical properties.

Figures 5 and 6 and Table 2 show the results and input data for preliminary thermal analyses of encapsulation designs #1 and #2 for NOCT (i.e., open circuit) conditions. These analyses were performed using a time share option (TSO) version of the CINDA* 3G thermal analyzer program. Use of the TSO allows for faster job turn-around. The results here should be considered preliminary in that thermal and optical properties of EVA (ethylene vinyl acetate) and KORAD (an acrylic film made by XCEL Corporation, Newark, New Jersey) are not available at this time. As a first estimate, the thermal properties of low density polyethylene and plexiglass, were assumed to approximate those of EVA and KORAD respectively. Since the optical properties of the required materials are as yet unknown and since the optical model is not yet operational, an "optically-hot" case and an "optically-cool" case were arbitrarily defined for these calculations. (Figures 5 and 6 show the cool case.)

The "optically-hot" case is that case where 100% of the incident solar energy reaches the surface of the solar cell. The "optically-cool" case is that case where only 90% (i.e., the minimum LSA design requirement) of the incident solar energy reaches the surface of the solar cell. Edge effects due to framing have not been taken into account and hence, are not reflected in the results shown in Figures 5 and 6.

*Chrysler Improved Numerical Differential Analyzer 3rd Generation

Table 2

INPUT DATA

Convective Heat Transfer Coefficient, $W(m^2 \text{ } ^\circ K)^{-1}$

Top Surface: $h_t = 1.247 (\Delta T \cos \Psi)^{1/3} + 2.685 \text{ V}$

Bottom Surface: $h_b = 1.079 (\Delta T \cos \Psi)^{1/3} + 2.685 \text{ V}$

Emissivity-Top:	.9 (Design #1)	.9 (Design #2)
-Bottom :	.6 (Design #1)	.9 (Design #2)
Velocity (Wind)-V:	1 m/s	
Tilt:	40 [°] from horizontal	
Air Temperature:	20 [°] C	
Ground Temperature:	20 [°] C	
Sky Temperature:	-5.2 [°] C	
Solar Flux, q"	.08 W/cm ²	

Figure 5

SUPERSTRATE DESIGN: PRELIMINARY NOCT RESULTS

Optically Cool Case

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Figure 6

SUBSTRATE DESIGN: PRELIMINARY NOCT RESULTS

Optically Cool Case

In generating the results shown it was assumed that no solar energy was reflected off the module and that 10% of the incident energy is absorbed in the layers above the cell. This absorbed energy was allocated on a thickness basis to these layers. For the intercell region 90% of the impinging radiation is assumed to be absorbed in the layer beneath the (clear) encapsulant; the remaining 10% was allocated to the layers above on a thickness basis.

As seen in Figures 5 and 6 module design #2 (wood-product substrate design) runs somewhat cooler than design #1 (glass superstrate design). Thus, the NOCT for design #1 is 52°C, and the NOCT for design #2 is 50.9°C. Additional analysis indicated insignificant differences between "optically-cool" and "optically-hot" conditions.

The results of the analyses so far indicate that NOCT is somewhat sensitive to the emissivity of the aluminum foil on the back (anti-sun) side of module design #1. For instance, if the aluminum foil is treated to raise the emissivity to .9, the NOCT for design #1 drops to about 49.5°C.

3.5 STRUCTURAL ANALYSIS

MSC/NASTRAN (Mac Neil Schwendler Corp., Pasadena, Calif.) has been selected as the primary structural analysis computer code for this program. The ANSYS code (Swanson Analysis Systems, Houston, Pa.) was also considered. Both NASTRAN and ANSYS have equivalent capabilities for heat transfer, thermal-stress, and geometric non-linearity (i.e., large displacements such as those found in wind loading) analyses.

MSC/NASTRAN was selected for the following reasons:

- a) Extensive use at HAC and other aerospace companies.
- b) Less costly to run since NASTRAN is available in-house whereas NASYS is only available through an outside vendor.

A two-dimensional finite-element model has been developed for Design No. 1 utilizing the MSC/NASTRAN structural analysis computer program. The model features detailed resolution of each material layer, including the glass superstrate, EVA encapsulant, crane glass spacer, and aluminum foil back cover. The model will be used for both heat transfer and thermal-structural design studies.

The MSC/NASTRAN heat transfer capabilities include conduction, convection and radiation. The 2-D model is currently operational for both conduction and convection heat transfer mechanisms. Work is proceeding to incorporate the radiation capability. Results of the MSC/NASTRAN and CINDA 3G analyses will be compared in order to verify the accuracy of the MSC/NASTRAN thermal analysis capability. If the results compare favorably, the MSC/NASTRAN model can be utilized for both heat transfer and thermal-structural design studies.

An MSC/NASTRAN finite-element model, suitable for the analysis of solar array panels subjected to wind loading is currently under development. The model will include geometric nonlinear capability in order to properly account for the relatively large displacements which are a characteristic of lateral loading of large panels.

Work is currently underway on models for module designs No. 1 and 2 for the respective temperature distributions shown in Figure 7. For the time being, it will be assumed that the lateral temperature gradients in each material layer are linear. The validity of this assumption will be investigated in the near future.

3.6 MATERIAL PROPERTIES

Table 3 shows the matrix of materials and properties with the most convenient units for the modeling work. Work has begun on filling in the material properties in the matrix. Information from Spring-born Laboratories and JPL is being collected, and samples of certain materials are being prepared for possible testing.

Figure 7
TEMPERATURE DISTRIBUTION, SUPERSTRATE DESIGN

MATERIAL	PROPERTY													
	1 Density g/cc	2 Tensile Strength ² dynes/cm ²	3 Young's Modulus ² dynes/cm ²	4 Shear Strength ² dynes/cm ²	5 Shear Modulus ² dynes/cm ²	6 Poisson's ratio	7 Thermal Conductivity watt-m/°c	8 Specific Heat watt-sec. gm-°c	9 Thermal Expansion Coefficient °c ⁻¹	10 Dielectric Strength volts/cm	11 Emissivity	12 Reflectivity	13 Absorbitivity	14 Refractive Index
Ethylene Vinyl Acetate														
DuPont Elvax 150														
Crane-Glas/EVA														
Ethylene Propylene Rubber														
Nordel 1320														
Poly (Vinyl Chloride) Plastisol														
A-10588-1														
Polyurethane- Mixed Ratio														
K.J. Quinn Q626/Q621 3.86/1														
Silicone Acrylic Copolymer														
Poly (n-butyl acrylate) JPL														
Tedler Polyvinyl Fluoride														
(X00-BG-30-UT)														
Korad 201/R														
Mylar DuPont Type A 3M Co.														
Metalized Mylar 3M Co.														
Porcelain on 1010 steel														
Porcelain on Aluminum 6061T6														
Aluminum Foil														
#1235 Zero Temperature 99.35% Pure														
Particular Board														
Masonite Super Dcrlux														
Tempered Glass														
ASC-Sundex/Solatex														
Silicon														

Table 3

4.0 CONCLUSIONS AND RECOMMENDATIONS

There are no conclusions and recommendations for this period.

5.0 PLANNED ACTIVITIES

During the next four month period Phase I of the program is scheduled for completion. The optical, electrical, thermal, and structural analyses will be completed and an optimum design selected. A test plan for Phase II will also be submitted to JPL for critique.