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PREDICTING PHOTOTHERMAL FIELD PERFORMANCE

JET PROPULSION LABORATORY

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Objective and Approach

- **Extrapolate photothermal accelerated test data to simulate 30-year field exposure**
  - **Develop an analytical model incorporating the measured dependency between transmittance loss and UV and temperature exposure levels**
  - **Exercise the model using SOLMET weather data extrapolated to 30 years for various sites and module-mounting configurations**

Analytical Model Assumptions and Characteristics

- **Encapsulant optical transmittance can be expressed as a function of the concentration of a given reactive species, Q**
- **Rate of variation of concentration, Q/t, is a reaction rate**
- **Standard reaction-rate equations, Arrhenius and power-law relationships are used to relate Q/t to the stress levels**
- **Two competing reactions occur simultaneously, one causing the increase of yellowing and one bleaching out the yellowing**
  - **Principle of superposition is assumed; order in which environmental levels occur not important**
- **Arbitrary constants a_1 to a_{10} determined by least-squares fitting of experimental optical transmittance (as a function of temperature and UV) versus time data**

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Analytical Model

- **Two equations developed:**

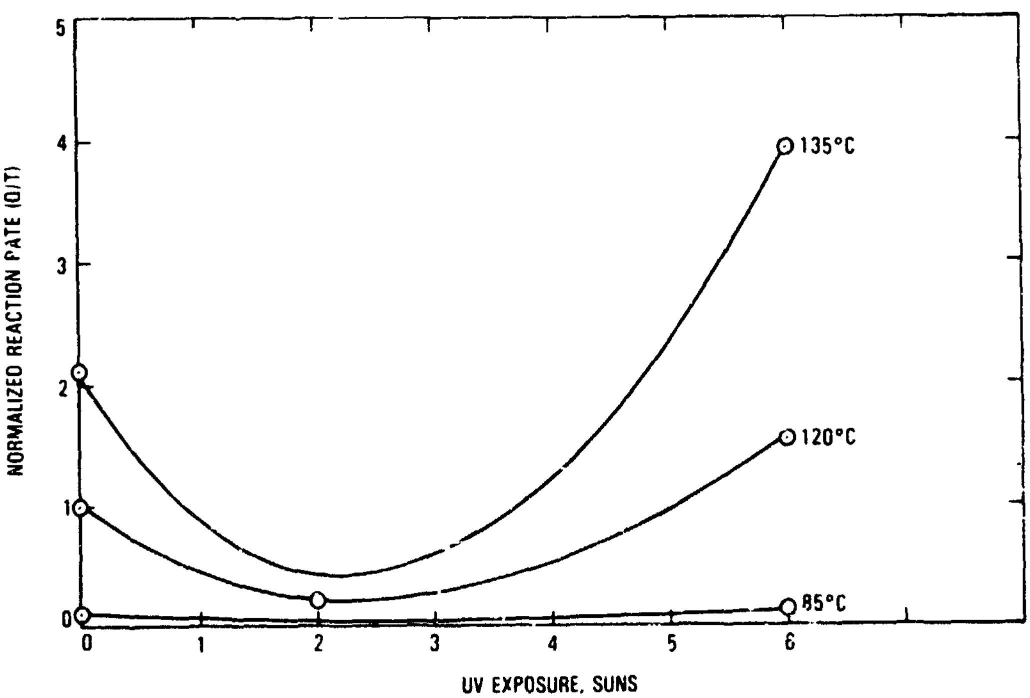
$$\tau/\tau_0 = 1 + a_1 Q + a_2 Q^2 + a_3 Q^3$$

$$Q/t = e^{(a_4/T)} + a_5 e^{(a_6/T)} S^{a_7} - a_8 e^{(a_9 T)} S^{a_{10}}$$

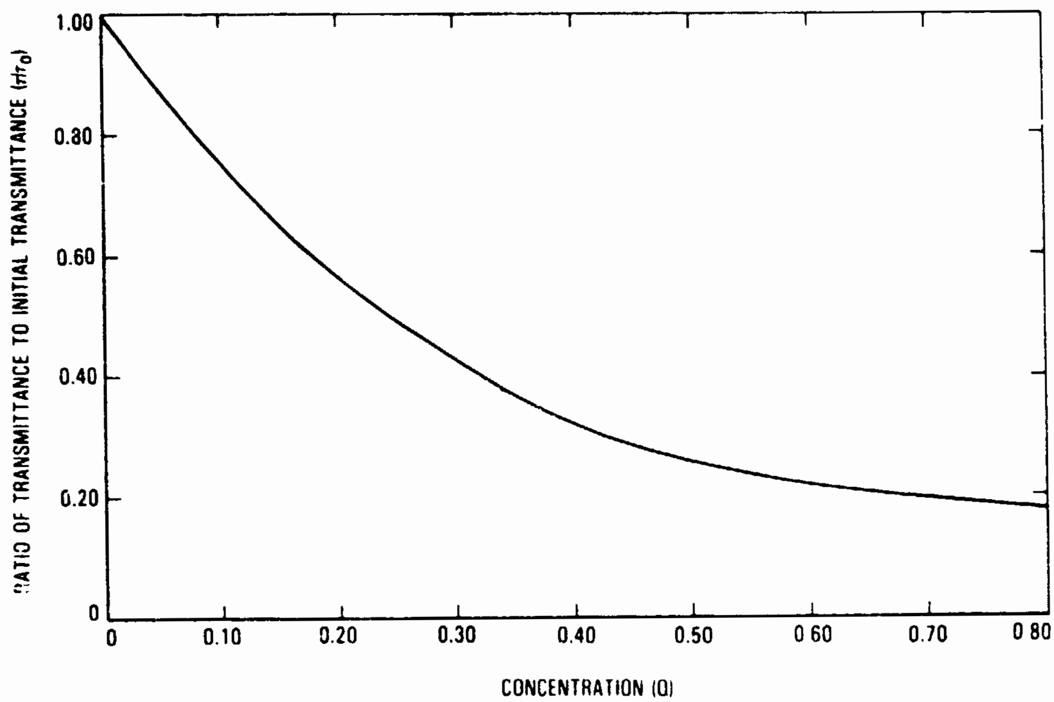
Where:

- τ = transmittance at 440 nm
- τ_0 = initial transmittance at 440 nm
- Q = concentration
- a_i = constant
- t = time
- T = temperature in °K
- S = UV level in suns

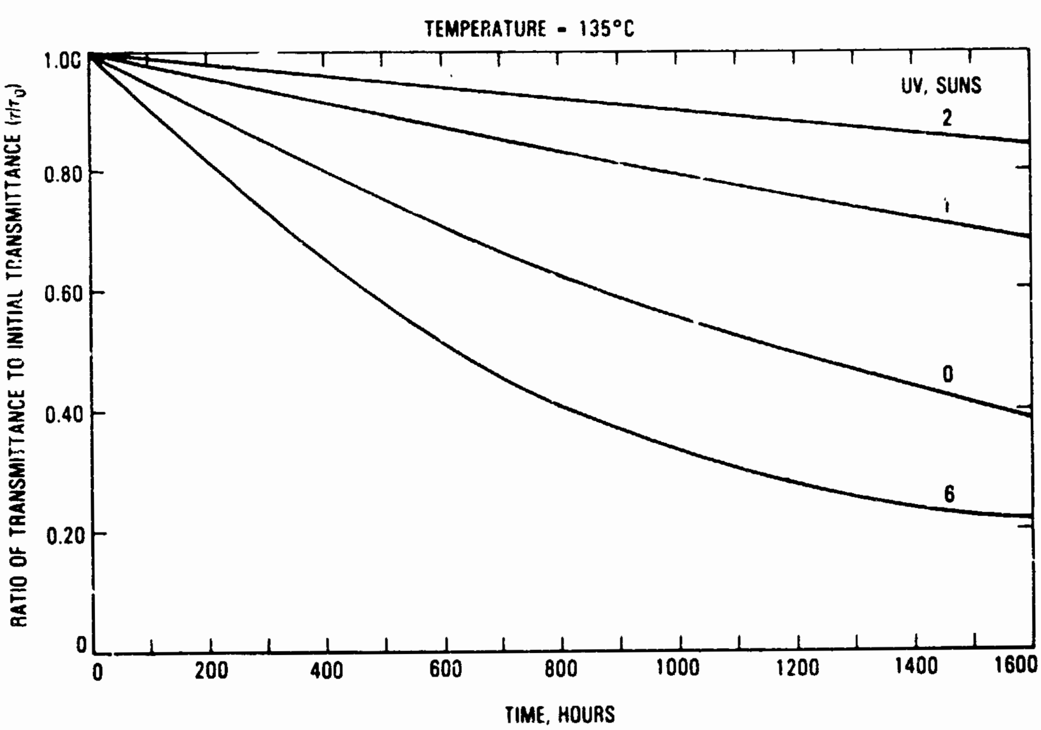
Reaction Rate (Q/Time) vs UV Level As a Function of Temperature (EVA)



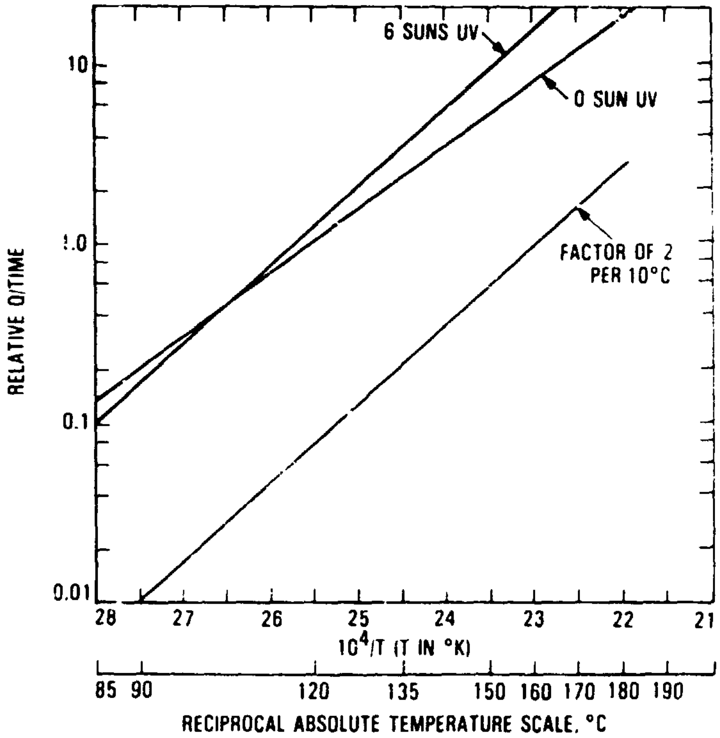
Transmittance Loss vs Concentration, Q (EVA)



Transmittance Loss vs Time (EVA)



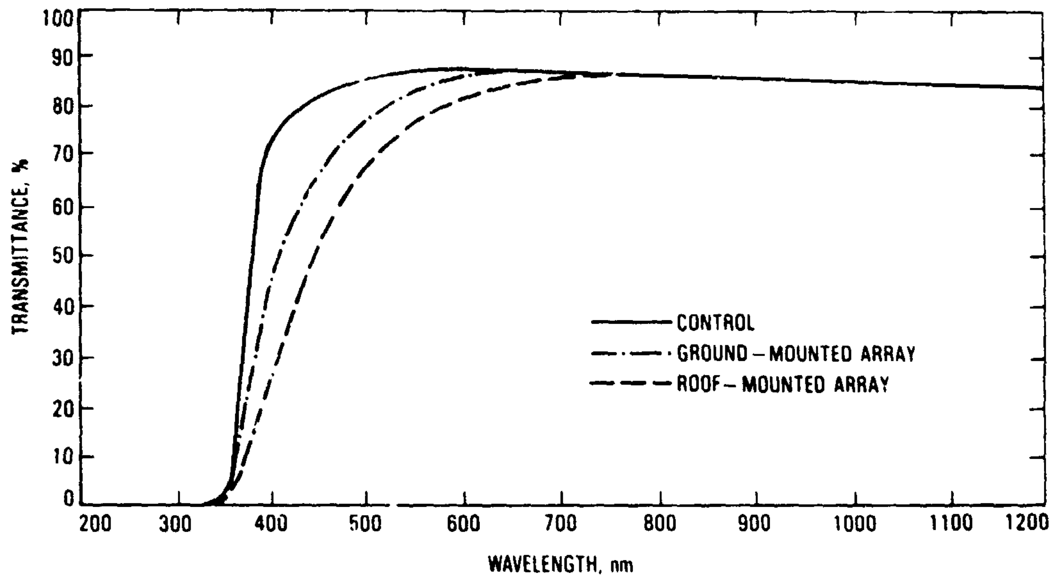
Arrhenius Plot of Reaction Rate (Q/Time) vs Temperature (EVA)



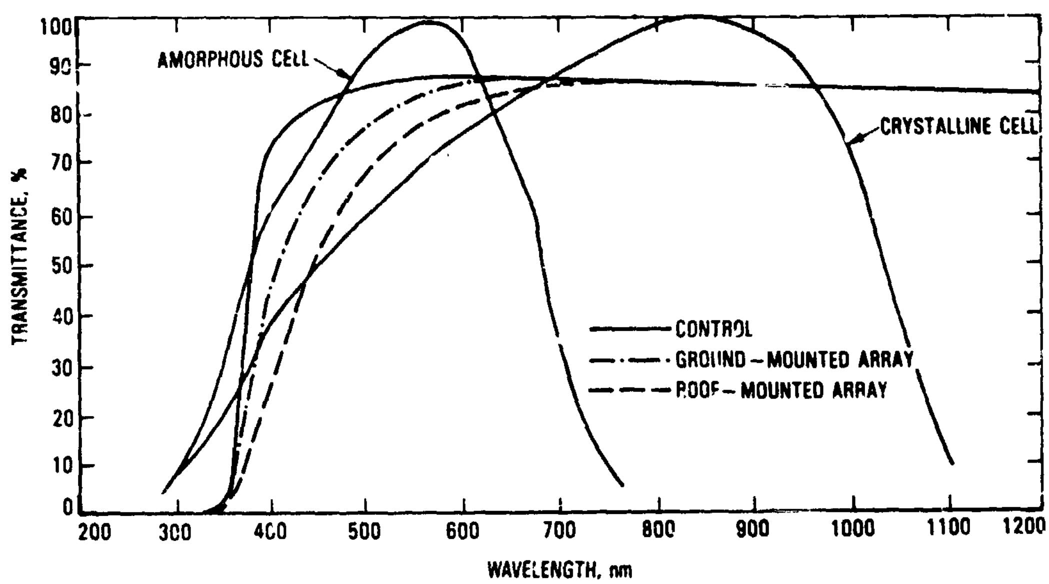
Derivation of Photovoltaic Degradation From 440-m Transmittance Loss

- 440-nm transmittance loss defines unique spectral transmittance curve for encapsulant
- Photovoltaic response requires convolution of encapsulant transmittance curve, cell spectral response curve, and solar distribution curve (global spectrum)
- Two-cell spectral response models used, one for crystalline silicon and one for amorphous silicon cells

30-Year Transmittance, %, vs Wavelength for EVA



Spectral Response Curves of Crystalline and Amorphous Silicon Cells



Determining 30-Year Degradation Using Photothermal Degradation Simulation Model

- Calculate 30-year field exposure environment using hourly SOLMET weather data tapes
  - Encapsulant operating temperatures computed as a function of irradiance level on tilted surface and ambient air temperature
  - UV level computed as a fixed 5% of the solar irradiance level
  - Results presented as matrix of annual number of exposure hours at each combination of temperature and UV level

- Simulate 30-year photothermal degradation using simulation model and environmental stress matrix
  - Matrix of reaction rates, Q/t, determined for temperature and UV levels in exposure-hours matrix
  - The product is taken of the two matrices
  - The sum of the values in each element of the last matrix yields the concentration Q at the end of a year
  - 30-year concentration is 30 times annual value

Annual Hours of Exposure of a Ground-Mounted Array to Various Cell Temperatures and UV Levels (Phoenix)

Cell temperature, °C	Annual hours of exposure											
	UV level in suns											
	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.05	1.15
75	0	0	0	0	0	0	0	0	0	11	4	0
65	0	0	0	0	0	1	17	24	107	294	167	6
55	0	0	0	32	18	56	130	81	201	142	177	17
45	22	74	32	110	62	84	144	73	172	154	55	1
35	134	131	63	124	97	93	113	49	53	17	0	0
25	190	129	92	86	53	21	22	0	0	0	0	0
15	129	94	36	35	8	0	0	0	0	0	0	0
5	55	20	3	0	0	0	0	0	0	0	0	0

Relative Values of Reaction Rates (Q/Time) for Various Cell Temperatures and UV Levels

Cell temperature, °C	Relative values of reaction rates, Q/time											
	UV level in suns											
	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.05	1.15
75	65	61	58	55	52	49	46	44	41	39	37	35
65	33	31	29	28	26	25	24	23	21	20	19	18
55	16	15	14	13	13	12	12	11	11	10	10	9
45	7	7	7	6	6	6	6	5	5	5	5	4
35	3	3	3	3	3	3	2	2	2	2	2	2
25	1	1	1	1	1	1	1	1	1	0.9	0.9	0.9
15	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1

Photovoltaic Power Loss After 30 Years in Phoenix* (EVA)

Cell type	Ground-mounted array	Roof-mounted array
Crystalline cell	3.5%	7.9%
Amorphous cell**	8.1%	17.8%

30-year allocation for this degradation mode is 6%

*Based on assumed UV acceleration factor distribution near one sun

**Only when EVA is between module front surface and cells

Conclusions

- Temperature is key driver to photothermally induced transmittance loss (approximate doubling of rate per 10°C)
- Sensitivity of transmittance loss to UV level is highly nonlinear with minimum in curve near one sun
- EVA results consistent with 30-year life allocation

Future Work

- Refine analytical model using additional data taken in region of one sun
- Repeat the thermal-UV exposure tests with the addition of humidity to study the impact of this variable
- Investigate the use of techniques similar to those discussed here for determining the photothermal degradation of encapsulant mechanical properties over 30-year life