ANGLE-OF-INCIDENCE EFFECTS ON MODULE POWER AND ENERGY PERFORMANCE

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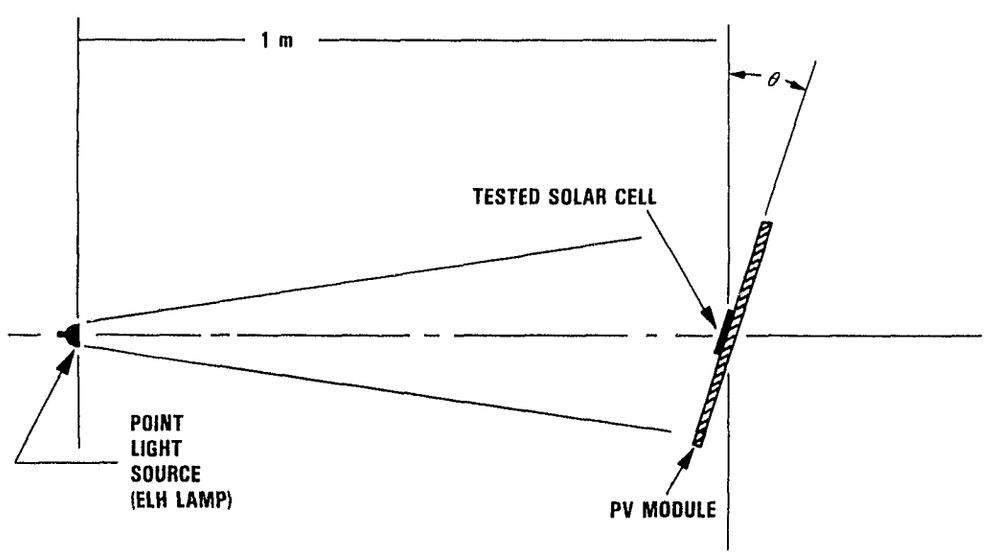
Study Objective

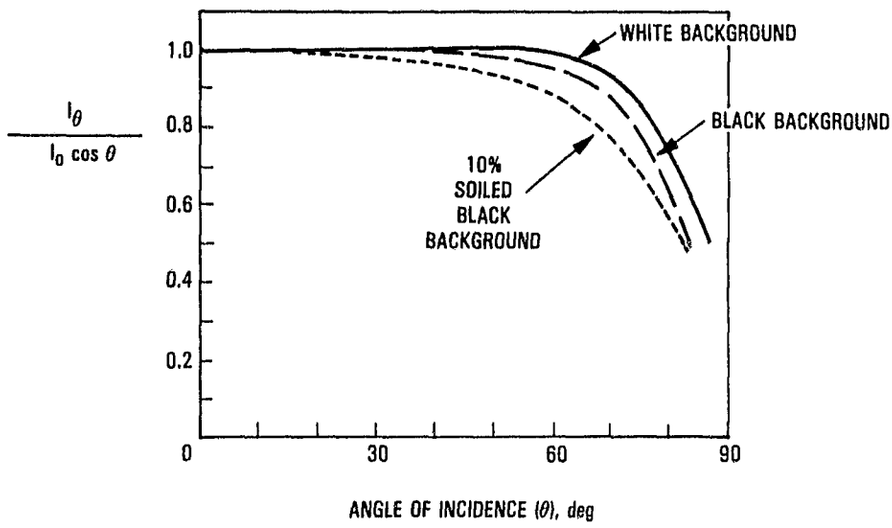
- **Measure effects of steep angles of incidence on photovoltaic (PV) power output including:**
  - **Cell background reflectance**
  - **Glass surface (smooth vs stippled)**
  - **Soiling level**
- **Develop analytical expressions for predicting power output vs angle of incidence and optical surface parameters**
- **Compute prediction error in annual energy performance due to commonly assumed pure cosine dependence and improved algorithms**

Test Configuration

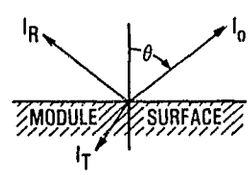


Progress Report 21 and Proceedings of the 21st Project Integration Meeting
Jet Propulsion Laboratory, Pasadena, CA, 1983, pp. 423-426.

Measured Angle-of-Incidence Dependence vs Cosine Model



Reflection Loss Dependence on Angle of Incidence



From Fresnel's Law: $\rho(\theta) = \frac{I_R}{I_0} = \frac{1}{2}\left[\frac{\tan^2(\theta - \theta')}{\tan^2(\theta - \theta')} + \frac{\sin^2(\theta - \theta')}{\sin^2(\theta - \theta')}\right]$

where $\theta' = \arcsin\left(\frac{(\sin\theta)}{n}\right)$

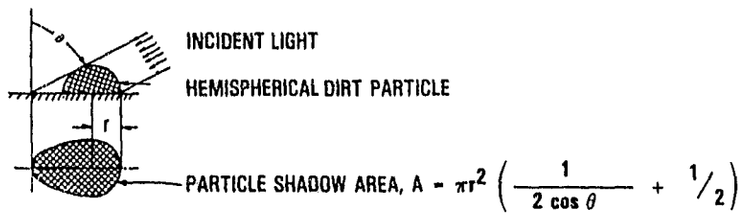
n = index of refraction of optical surface

Define $F_R = \frac{I_T(\theta)}{I_T(0)} = \frac{I_0 - I_R(\theta)}{I_0 - I_R(0)}$

or $\boxed{F_R = \frac{1 - \rho(\theta)}{1 - \rho(0)}}$

where $\rho(0) = \left(\frac{n - 1}{n + 1}\right)^2$

Soiling Loss Dependence on Angle of Incidence



Define

$$F_S = \frac{\text{current with actual enlarged shadowing}}{\text{current with } \pi r^2 \text{ shadowing}}$$

Given fraction soiling loss at normal incidence = f

$$f = \frac{I_0 - I_{SO}}{I_0}$$

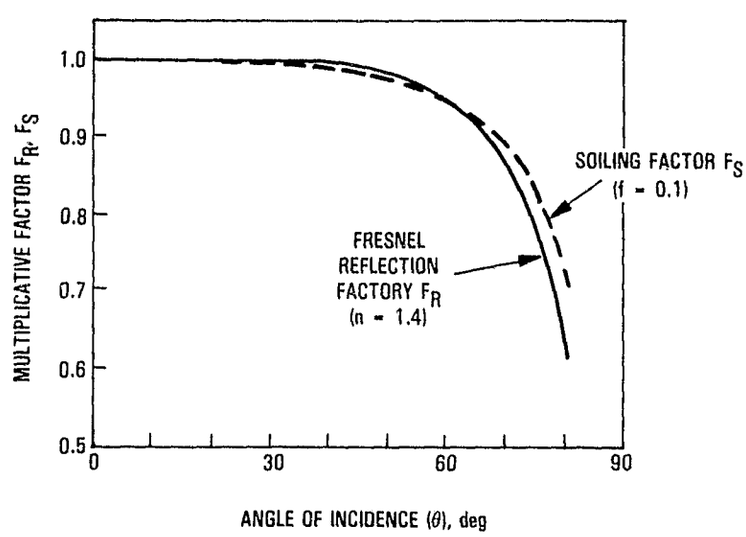
where I_0 = current when $\theta = 0°$ for clean surface

I_{SO} = current when $\theta = 0°$ for soiled surface

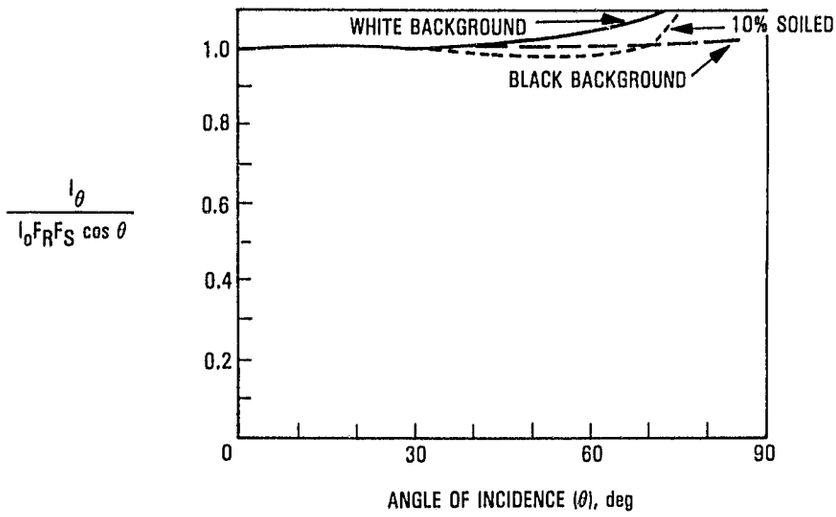
Then

$$F_S = \frac{1 - f\left(\frac{1}{2 \cos \theta} + \frac{1}{2} \right)}{1 - f}$$

Angle-of-Incidence Correction Factors



Measured Angle-of-Incidence Dependence vs Improved Models



Conclusions

- **Angle-of-incidence effects are influenced by:**
  - **Surface index of refraction**
  - **Soiling level**
  - **Surface texture (smooth vs stippled)**
  - **Cell background reflectance**
- **Fresnel reflection and soil shadowing models provide good prediction for these effects**
- **Conventional cosine model provides acceptable accuracy for energy prediction calculations when soiling is low**