TIME-INTEGRATION OF ENVIRONMENTAL LOADS AND STRESSES FOR CORRELATING FIELD EXPOSURE AND ACCELERATED TESTING

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An important consideration in the design and understanding of accelerated tests is correlation with field-exposure stress levels and durations. Ideally, a given duration of accelerated testing is quantitatively equatable to a much longer duration of field-application exposure. The accelerated environment generally involves higher environmental stress levels, but may also eliminate some synergistic degradation mechanisms by limiting the range and number of environments present.

The correlation of accelerated stress testing with field exposure is addressed by this author as a three-phased problem. The first phase is to identify the key operating-environment stresses and the rate dependencies of the significant degradation mechanisms on these stress levels. This can be based upon a fundamental understanding of the underlying physical degradation mechanisms, as with metal fatigue, or based upon parametric testing of the test article at various stress levels.

The second phase of the correlation problem deals with characterizing the time-integrated stress associated with the expected field or operating environment. Because the field environment is constantly varying, field exposure is not immediately definable as a known time at a known stress level as is an accelerated test. This prevents direct application of the rate-dependence model defined in the first phase. To allow correlation with the accelerated test environment, it is useful to first reduce the field exposure to an equivalent duration at a simplified or constant stress level approximating the field-stress level. This requites using the previously developed rate dependence to translate each time increment of field exposure to an equivalent exposure duration at the chosen constant-stress level. This process is reasonably accurate if the extrapolating distance between the instantaneous field-stress levels and the constant-stress level is modest, and rate dependence is reasonably well quantified.

The last step is to correlate the equivalent field exposure to the accelerated test exposure. This step rests heavily on the accuracy of the rate-dependence model and the spread between the accelerated-stress level and the field-stress level.

The paper presents the above concepts in a generic context, and then illustrates their application using temperature-humidity testing of photovoltaic modules as an example. Equivalent field environments are computed for both roof-mounted and ground-mounted arrays at a variety of sites in the U.S. using computer analysis of SOLMET hourly weather data.

Proceedings of the Flat-Plate Solar Array Project Research Forum on Quantifying Degradation
December 6-8, 1982, Williamsburg, Virginia, JPL Publication 83-52, JPL Document 5101-231, DOE/JPL-1012-89,
Jet Propulsion Laboratory, Pasadena, CA, June 1, 1983, pp. 223-231

Objective and Approach

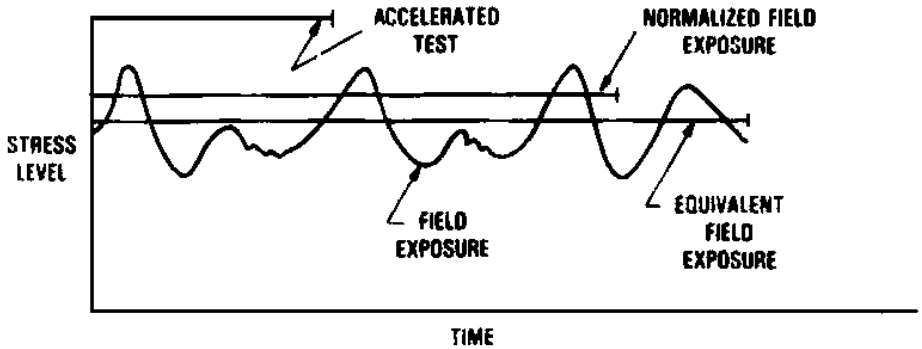
Objective

- Provide an analytical structure for interpreting (correlating) various field and accelerated test exposures

Approach

- Reduce complex field exposure to a simplified exposure (normalized or equivalent) that can be easily assessed in terms of established failure-mechanism parameter dependencies

Exposure-Level Definitions



Field exposure

- Multiple stresses
- Time-varying levels
- Given duration

Accelerated test

- Selected stresses
- Selected fixed levels
- Duration (TBD << field)

Normalized field exposure

- Selected stresses
- Fixed levels ≈ field
- Duration (TBD ≈ field)

Equivalent field exposure

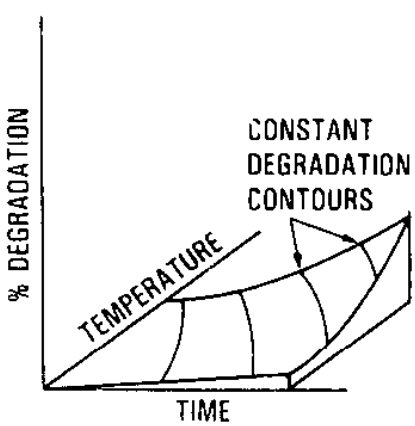
- Selected stresses
- Fixed levels (TBD ≈ field)
- Duration equal to field

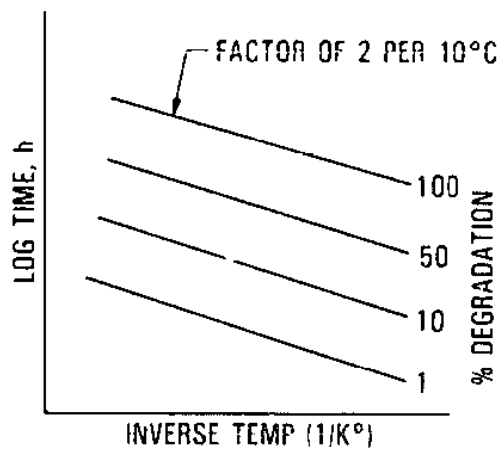
Computational Steps

- Obtain failure-mechanism stress-parameter dependencies
- Obtain detailed characterization of field/operational environment over time (e.g., SOLMET)
- Compute product mechanism-specific stress levels versus time over use duration
- Select normalized field-exposure (fixed-stress) level
- For each time interval of field exposure, use stress-parameter dependencies to compute time increment at normalized field-stress level which causes same incremental degradation as actual field-stress level
- Sum computed time increments to establish duration of normalized field exposure
- Use stress-parameter rate dependencies to:
  - Compute fixed-stress level corresponding to equivalent field exposure
  - Compute accelerated-test durations corresponding to field exposure

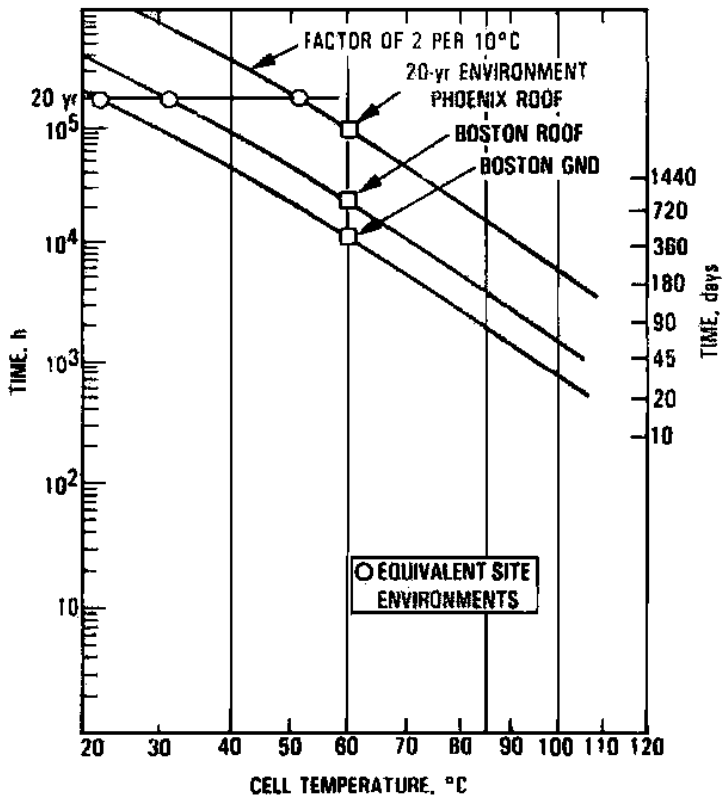
Example: Temperature-Accelerated Degradation of PV Cells and Modules

DEGRADATION PARAMETER DEPENDENCY:





Arrhenius Plot for Time to Degradation vs Cell Temperature



Example Computations

Operational environment characterization (SOLMET weather data tapes):

- Hourly ambient temperature (T_a, °C)
- Hourly solar irradiance (S, mW/cm^2)
- Hourly wind velocity (V, m/s)

Hourly stress (temperature) computation:

- $T = T_a + (0.3 - 0.01\ V)\ S$ (ground mounted)
- $T = T_a + (0.5 - 0.01\ V)\ S$ (roof mounted)

Selected normalized field-stress level: 60°C

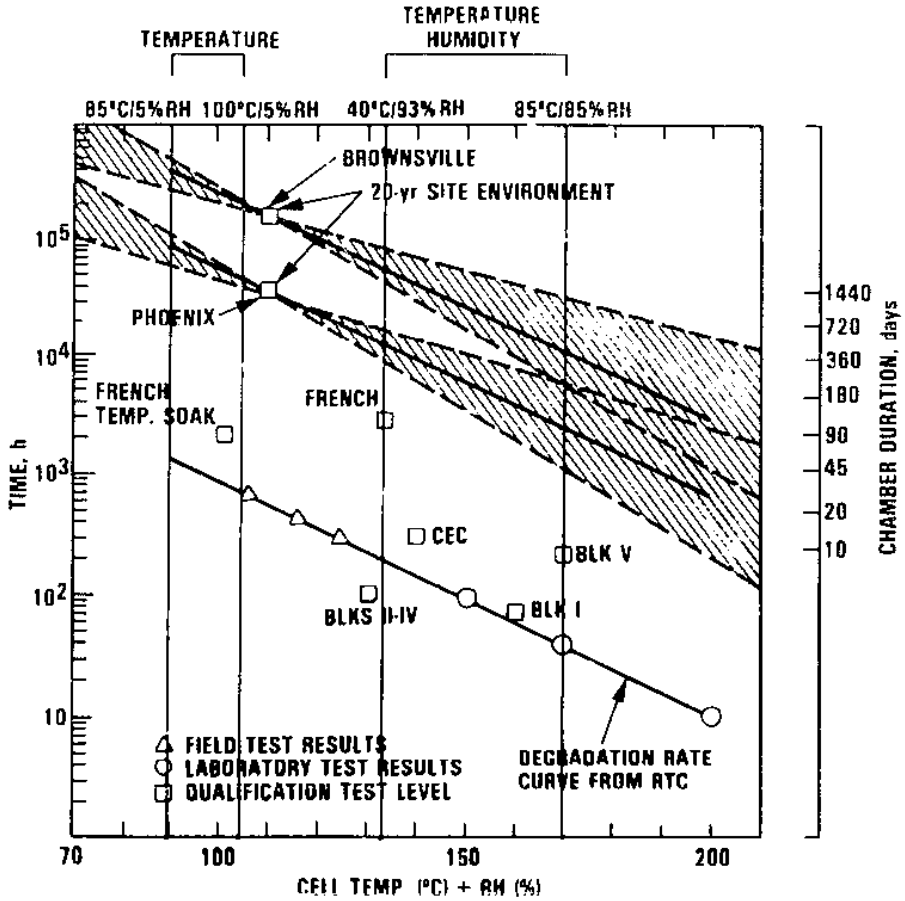
Computation of normalized time increments:

$$\Delta T_i = \Delta t_i \times 2^{\left(\frac{T - 60}{10}\right)},\ \Delta t_i = 1\ h$$

Normalized field exposure duration:

$$T = \sum_i \Delta T_i,\ (i = 1 \text{ to use duration})$$

Comparison of Temperature-Humidity Exposure Environments for PV Modules



Summary and Conclusions

Requires detailed knowledge of failure-mechanism stress dependencies and site stress levels:

- **Mechanism specific**
- **Site specific**

Provides a useful means of comparing and correlating:

- **Site environments**
- **Operating conditions**
- **Test environments**

DISCUSSION

WHITE: I understand from a previous Bell Labs paper that for certain things like your atmospheric pollutants, when you are doing an accelerated test, you have to normalize for the different temperatures. I don't really know why but you have to change your actual concentrations at higher temperatures and I was wondering how that would change your plot. Would it make it nonlinear? It seems as you go up the temperature scale your concentrations would change and your amount of degradation would change.

ROSS: I don't pretend to know anything about the effect of pollutants in concentration. This is a diagram here that is without pollutants added to it; it doesn't have SO_2, chlorine or anything added to it. So someone else will have to answer that question.

ROYAL: Would anyone like to add to that?

LANDEL: Ron, one thing didn't come out to me very clearly and that was what is it a time to what--you see, we are interested in a failure time and we have these times.

ROSS: I am not interested in failure times. I am not worried about whether it failed or not. All I am saying is, that is a judgment call that someone else can make. I am going to tell you where the site is. The site is right here.

LANDEL: That's OK, but now you have a locating point labeled Phoenix and Brownsville and which gives you then the starting point, as you said, to draw your band of lines through? How did somebody get a number which came out to be like 5×10^4 for Phoenix? The crossover point for everything that is there?

ROSS: It is not a time, it is an equivalent to 20 years in Phoenix, given the activation energy. It has nothing to do with degradation.

LANDEL: Let me give you a point of reference of (partly) why I am asking the question. In the solid-propellant industry you have this same sort of problem. You put a rocket motor out and the temperature goes up and down a heck of a lot more than it does in the storage environment--there is an environmental load, there is a thermal load. When people were talking about running the MX missile back and forth across the country on trains there was an initial program saying, well we have to know the loads before we can do anything, so let's instrument a train and run it back and forth across the country and find out what the loads are. Well it turns out the railroads had that kind of information. Now you have a statistically varying load which in the mechanical sense says OK, if I put a stress on and the stress is wavering up and down, I know that if I put a constant load on it will last a certain length of time. So there are two parts to the problem. What is the nature of the load and how long would I expect something to last? Or how long would I have to wait before something happens?

ROSS: I am assuming in this example a fairly simplistic model. I am assuming it is an Arrhenius-type temperature acceleration only. We have a fairly simplistic degradation mechanism that is rate-dependent on temperature. First step: obtain the failure mechanism stress parameter dependency. You can't even start the problem until you have that. That is the first step and the dependency we started with--it was an assumed dependency for the example problem--was a pure Arrhenius-type temperature acceleration. We are assuming the humidity had no affect on this reaction or we have a hermetic package so that humidity is prevented from having an affect.

LANDEL: That gives me a temperature dependence of something but I would have to say that something occurs that I am interested in at, let us say 1000 minutes or 1000 hours.

ROSS: No. You don't have to know anything about that at all. All you have to do is know that the rate of that chemical reaction or whatever it is that is taking place has this Arrhenius relationship.

LANDEL: But the Arrhenius relationship gives me a temperature dependence but what I need, in addition, is the time.

ROSS: No you don't need the time.

LANDEL: I have to pick some point on there if I am going to shift some things around.

ROSS: No, I am not going to shift them, I am going to use the slope of this curve. It's the only thing I am going to use.

ROYAL: Let him go through it again and we will stop him at the appropriate times.

ROSS: We have to have, first of all, a degradation mechanism. Clearly, if we are modeling mechanical fatigue, temperature variation isn't important, we are going to be worrying about some kind of loads. By the way, we have done this on fatigue also and it's a real bear because you end up with nonuniform cycles. You can consider that the problem with fatigue is that everybody does fatigue with full typically plus-minus cycles. How do you take a site environment where you have dc stresses and fatigue about dc stresses with a little wind flutter with all sorts of different frequencies and depths? How do you model the equivalent mechanical fatigue due to a wind environment? Well, we have done that on the computer, too. It's a real bear and I didn't want to try to put that in as an example. We are going to pick a simple one, but clearly the model has to reflect the failure mechanism parameter dependencies and so we are going to model fatigue differently from the way we are going to model Arrhenius chemical-reaction-type dependencies. We are going to start out with the example, anyway, with just something that allows us to relate the effect of two different temperatures. That's really all we are interested in. We are going to say right now, during this particular hour, right now it's 100°C on that roof and I want to convert that 100°C on the roof to the equivalent amount of time at 60°C. Well, that is fairly easy and I don't have to know where I am on this degradation rate curve. All I have to know is that this thing has a factor of 2 per 10°C. It says no matter where I am in time through the aging of this product that if it is

100°C, it is 40°C hotter than my reference temperature and I have 2^4, or whatever it is, acceleration. So that hour of 100°C, is equivalent to--whatever it is--16 hours, or whatever the math is--at 60°C.

LANDEL: That is 1 hour base reference time.

ROSS: That's right. Now doing that only 1 hour base reference time simply because the SOLMET weather tapes are in 1-hour increments, my data base is in 1-hour increments, so I am taking them an hour at a time. The first thing I had to do, of course, was to compute the actual temperature of the product because the ambient temperature isn't the important thing. The actual temperature was computed each hour using wind velocity, irradiance data and ambient air temperature data and this happens to be an extremely good model. In fact, it is difficult to improve upon it. The scatter in this model has parameters we don't understand. I could have selected this level to be anything I wanted. I could have selected 70° or whatever. What I am trying to do is to depict it at a temperature that is going to cause least extrapolation. Every time I take an hour I would like to have a minimum motion and I know that the higher temperatures are going to be the key ones relative to the degradation. I am going to personally bias it up to about where I know that a lot of the operating hours are going to exist. Then I am going to take each hour starting out January 1st at 1:00 in the morning and it is going to be operating at 10°C or something like that and I am going to plug 10°C in here and I am going to find out that that is only worth 5 minutes at 60°C. Then I am going to go to 2:00 in the morning, and I am going to say, well, at 15°C at 2:00 in the morning it is only another 6 minutes or something equivalent at 60°C. I just keep going all the way through the year and I add up all those incremental times, you know, the 5 minutes plus the 6 minutes, plus the whatever, and that ends up eventually this number of hours of equivalent 60°C and this number (you don't know what it's going to be when you start the computational process) as you go all the way through a year and it's a function clearly of the model. In other words, if I switched the thermal model all of a sudden I have jacked up the temperature when I insulated the back of the array so I ended up with an equivalent to a longer period of time. In the Phoenix environment, of course, the difference there was the fact that Phoenix is just a hotter environment.

LANDEL: I think then that some of the things that led me astray was the title of this plot and the kind of degradation. As you have described it just now, this is the equivalent time for 60°C.

ROSS: I apologize. This is a viewgraph that we happened to have developed that we are actually using. In fact, when we are running chamber tests for our products we plot them on this plot. The title happens to be The Time to Degradation because we are actually plotting failure points on this plot and these other axes up here are reference points to allow us to assess the degradation of that product relative to the actual site environment.

BERNSTEIN: If you didn't know the degradation mechanism but you did know the failure time, could you calculate, could you plot an activation energy and compare two sets of data, like laboratory and field? It might represent a composite mechanism. I wonder what the limits are.

ROSS: Well, if you can compute an activation energy, all I need is the slope which is the activation energy. As long as you can compute the activation energy you can do the computer analysis. If you don't have the faintest idea what the activation energy is, which we didn't when we started our testing, you can do it parametrically. We just did it for a whole variety of activation energies and you end up with a lot of lines here with different slopes and different intercepts. It provides you with a feeling for what it is, even though you don't know much about it. From just a general knowledge of chemical processes you know the activation energies are in general ranges and you can pick with some knowledge the range of activation energies that are appropriate for chemical processes.

BERNSTEIN: What I am driving at, though, is: if you didn't know the mechanism but you knew the failure times, which is more real-world kind of a situation, could you apply this technique?

ROSS: No.

BERNSTEIN: Do you think the data might be too scattered?

ROSS: No. The computer analysis required a knowledge of the rate dependencies times the failure. It is independent totally of what is happening to the product. It is strictly a function of the rate dependencies of the reactions.

If a modulus can survive for 20 years in Phoenix, it is going to be cycling up and down days and nights and if you ask if you sat it in an oven for 20 years, what temperature would you have to run the oven at to have the same environmental stress you had at Phoenix, this would be the oven temperature. It is an equivalent constant-temperature environment to the cyclic environment at Phoenix, and Boston for these.

COULBERT: I am just trying to understand this like everybody else here. In your first question that you posed, that you had to answer--the answer to that question is a factor of 2 per 10°C, right?

ROSS: That was the assumed dependency, parameter dependency of the failure mechanism for this example.

COULBERT: But if we run our material tests and we come out with another answer, such as a factor of 1.5,then you get a new plot but you could go ahead and plot that curve from my answer. Once we get that answer than you could plot the curve.

ROSS: Let me caution you on that. To some extent I can go through and say this point is going to stay right there and I will put a different slope through it but I am making an error now because in the actual weather analysis I am actually using this. But if you are not off by too far, these points won't move too much. We have found that out from experience. We have done this thing parametrically as a function of activation energy. In fact, I chose this 60°C with some prior knowledge of having done this parametrically and I know these curves tend to hinge about this point on the plot. If you came to me I could give you a pretty quick answer but ideally what I would do would be to go back and reexercise the computer model.