In: *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, California, June 1, 1983, pp. 337-378.

FATIGUE OF SOLAR CELL INTERCONNECTS

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Interconnects, metallic ribbons connecting and providing electrical continuity between photovoltaic cells, have been observed to fracture in terrestrial applications environments (Figures 1 and 2). The degradation mechanism has been identified as mechanical fatigue resulting from diurnal thermal variations that can impose large cyclical strains upon poorly designed module/interconnect systems (Figure 3). Good design techniques--for example, providing adequate stress relief loops and matching substrate-cell-interconnect thermal expansion coefficients, etc.--will minimize interconnect fractures, but only a systematic design algorithm using life-cycle energy costing to effect the many cost-performance trade-offs will result in optimal (long life, minimum cost) performance. Such an algorithm has been developed by the Engineering Sciences Area of the Flat-Plate Solar Array Project at the Jet Propulsion Laboratory (Figure 4).

The optimization algorithm features three computational procedures, each of which is discussed briefly. The first procedure (Figure 5), called "Interconnect Failure Prediction Algorithm," calculates the strain in interconnects from module geometry and materials data (Figure 6) and site temperature histories (Figures 7 through 9). Strain computations (Figure 10) are facilitated by the use of nomographs that incorporate the results of computer-generated finite element solutions (Figure 11). The computed strains are used in conjunction with interconnect material statistical fatigue curves to estimate the expected fraction of failed interconnects at the end of the operational life of the array field.

The material statistical fatigue curves are obtained experimentally. Candidate interconnect materials (Figure 12) were tested in several geometries (Figure 13) on an apparatus (Figure 14) designed to simulate mechanically the cyclical strain cycles induced by diurnal thermal cycles in the field. Raw data are gathered in the form of curves of fracture probability versus cycles to failure at the constant test strain (Figure 15). A global least-squares minimization routine is used to fit a suitable function to these data; the resulting set of curves are the material fatigue (strain-cycle) curves parameterized by failure probability (Figures 16 through 20). A comparison of test results (Figure 21) reveals the fatigue-performance superiority of the clad materials.

The material statistical fatigue curves find use in module design and in interconnect-failure prediction (Figure 22) and in thermal-cycle qualification test design (Figures 23 through 25). In a thermal cycling test, both the strain (temperature) and the cycle rate are accelerated. The material fatigue curves are used to determine the number of test cycles and allowable interconnect-failure rates to guarantee a maximum allowable field failure rate (Figure 25). Results of thermal cycle testing are presented (Figure 26).

Correlation of field failure data and thermal cycling test data with the experimental fatigue data is good (Figure 27).

The second computational procedure associated with the optimization algorithm is the Array Degradation Analysis (Figure 28), which determines the loss of array power, and hence the energy output reduction, resulting from specified levels of interconnect redundancy and failure probability. The power reduction at 20 years (Figure 29) follows from the array circuit configuration (Figure 30) and the appropriate array power loss data (Figure 31).

The final computational procedure comprising the optimization algorithm is the Life-Cycle Energy Cost Analysis (Figure 32). The important parameters influencing the analysis include the (fatigue-related) relative array energy output, interconnect resistivity and shadowing losses, and materials and fabrication costs (Figures 32 and 33). The relative energy output is determined as the area under the array power output curves (Figures 34 and 35). This, together with plant efficiency considerations (Figure 36), interconnect material and fabrication costs (Figures 37 through 41), and other parameter values (Figure 42), when substituted into the life-cycle energy costing equation (Figure 32), yield the solution cost curves for each candidate material (Figures 43 through 47).

The material cost curves have common features. The dotted curves give cost increments due to fatigue-free interconnects. The left ends of these curves reflect I^2R-losses; the right ends, the materials costs. The solid lines indicate cost increments due to fatigue failures. In all cases there exists a critical strain level (thickness) beyond which costs increase rapidly. The curves suggest designing at about half the critical thickness. The curves also suggest using double interconnect redundancy; more redundancy results in higher cost, while use of a single interconnect gives inadequate protection against random (non-fatigue-related) failures, assumed to be 5 per 1000 in 20 years.

The cost solutions for doubly redundant interconnect systems (Figure 48) reveal that OFHC copper and the 33 Cu/33 INV/33 Cu are cost effective, the latter perhaps more so because it provides for a greater thickness design margin.

A final note: the analysis reveals that the increment in life-cycle energy costs due to interconnects may be as much as 15% of the total life-cycle energy cost of the array.

Figure 1. Broken PV Cell Interconnect

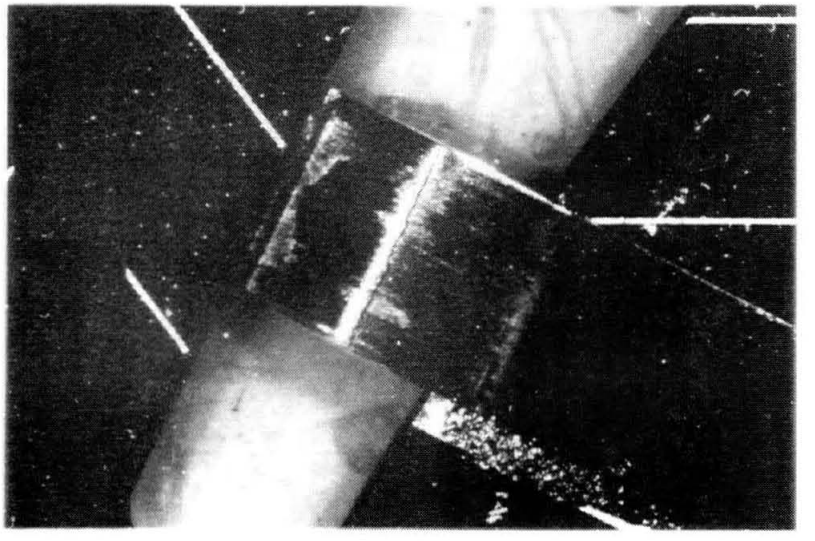
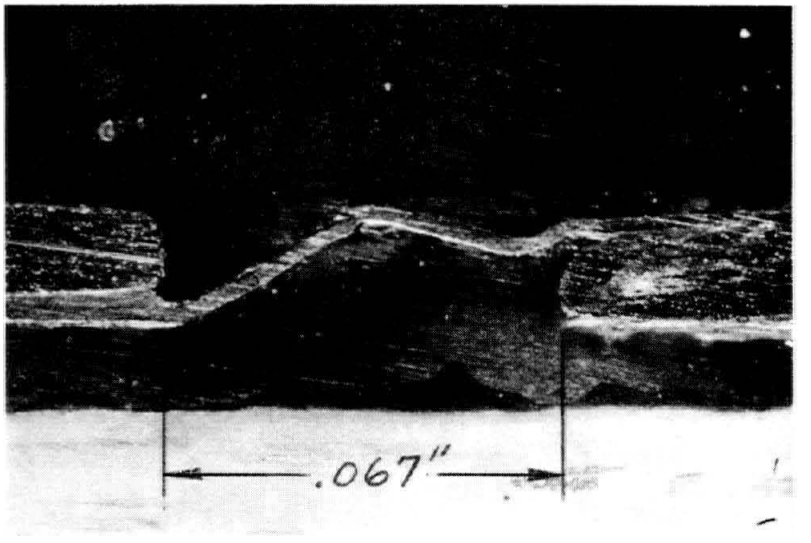
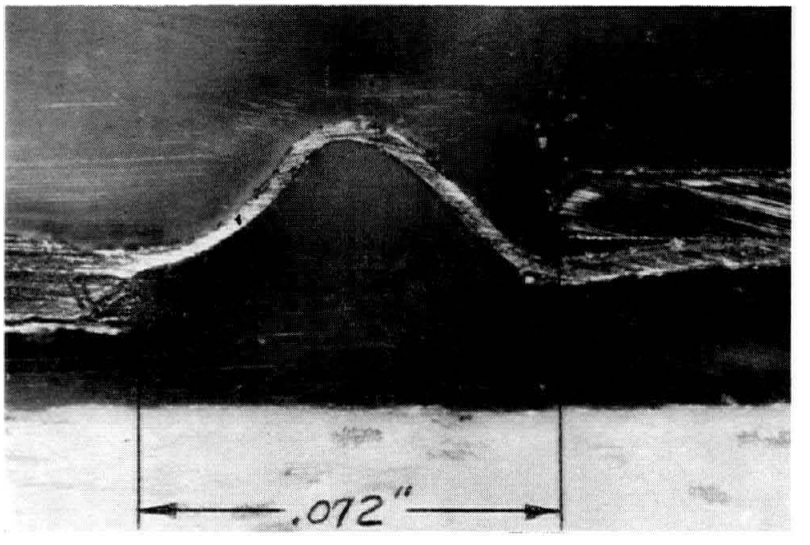


Figure 2. Cell Interconnect Configurations
(Block II Module, Manufacturing Variations)



HIGHEST STRESSED



LOWEST STRESSED

Figure 3. Interconnect Fatigue Failure Mechanism

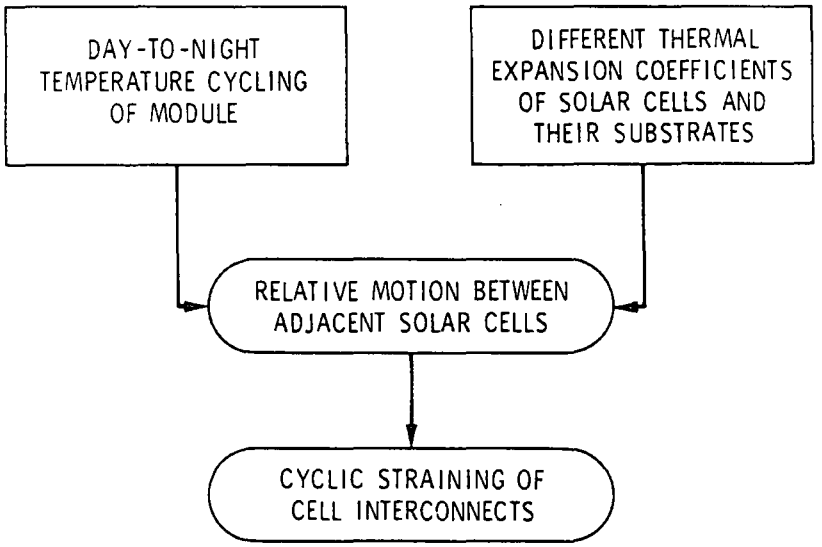


Figure 4. Cost-Optimal Reliability Design Algorithm

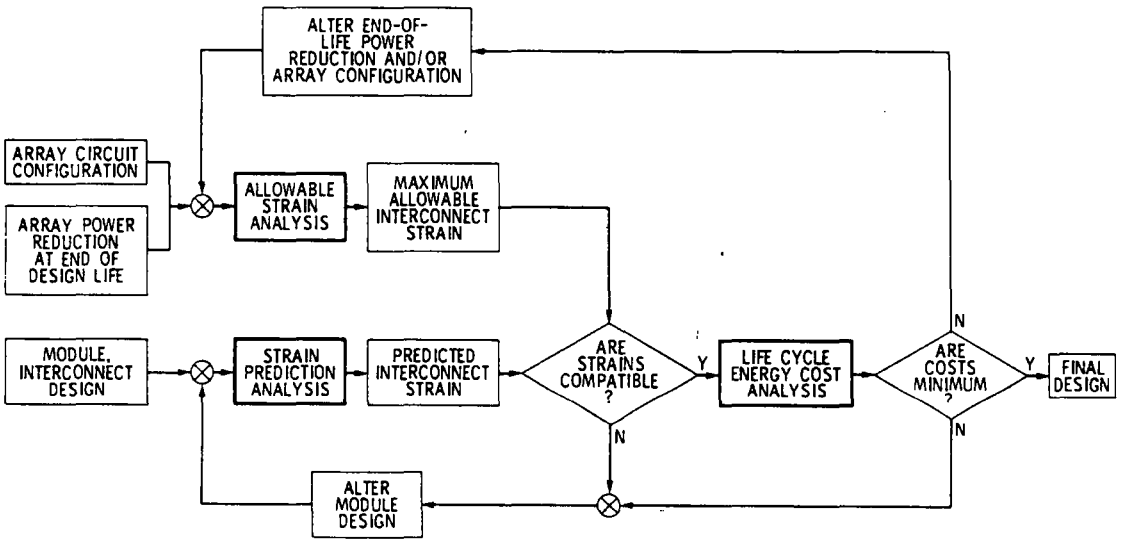


Figure 5. Interconnect Failure Prediction Algorithm

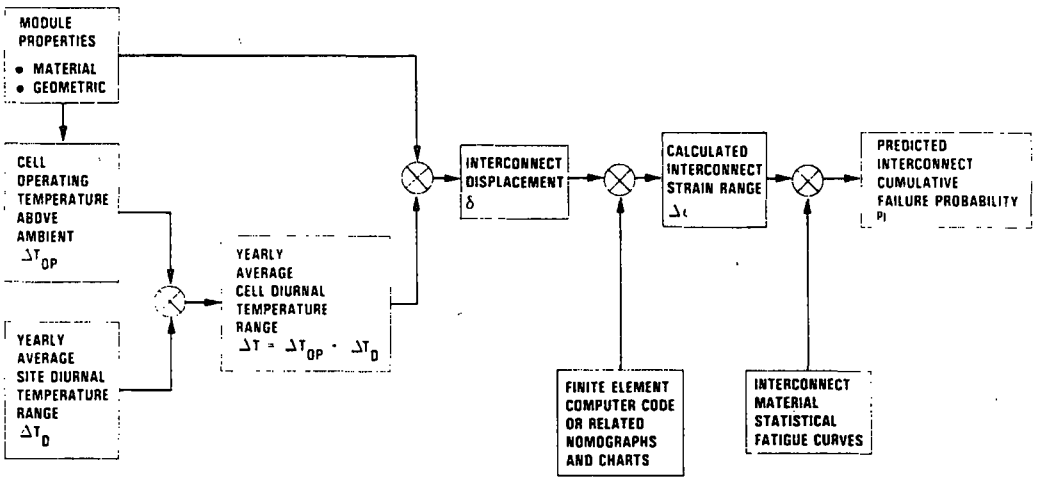
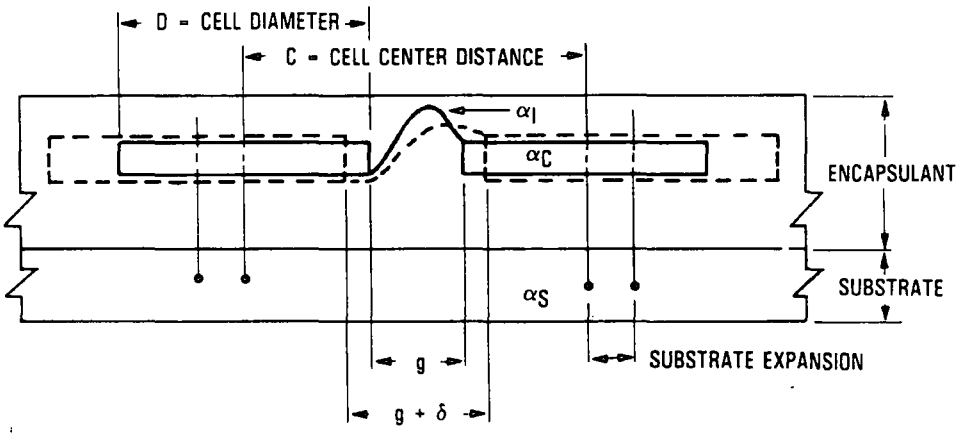


Figure 6. Effective Interconnect Displacement Due to Differential Thermal Expansion



——— AT TEMPERATURE T

– – – – AT TEMPERATURE T + ΔT

$$\delta = (\alpha_S C - \alpha_C D - \alpha_I g)\,\Delta T = \left[(\alpha_S - \alpha_C)\,C + (\alpha_C - \alpha_I)\,g\right]\Delta T$$

Figure 7. 1979 Temperatures at New River, Arizona

MONTH	TEMPERATURE, °C AVG. HIGH	AVG. LOW	ΔT_D
JANUARY	11.7	2.8	8.9
FEBRUARY	18.3	5.0	13 3
MARCH	20.6	7.8	12.8
APRIL	27.2	10.6	16.7
MAY	31.1	16.7	14.4
JUNE	38.9	22.8	16 1
JULY	41.1	25.0	16.1
AUGUST	38.9	23.3	15.6
SEPTEMBER	38.9	24.4	14.4
OCTOBER	30.6	16.1	14.4
NOVEMBER	20.0	7.2	12.8
DECEMBER	19.4	6.7	12.8
		AVERAGE ΔT_D =	14.0 °C

Figure 8. Module Operating Temperature (Block II Fiberglass Substrate Module)

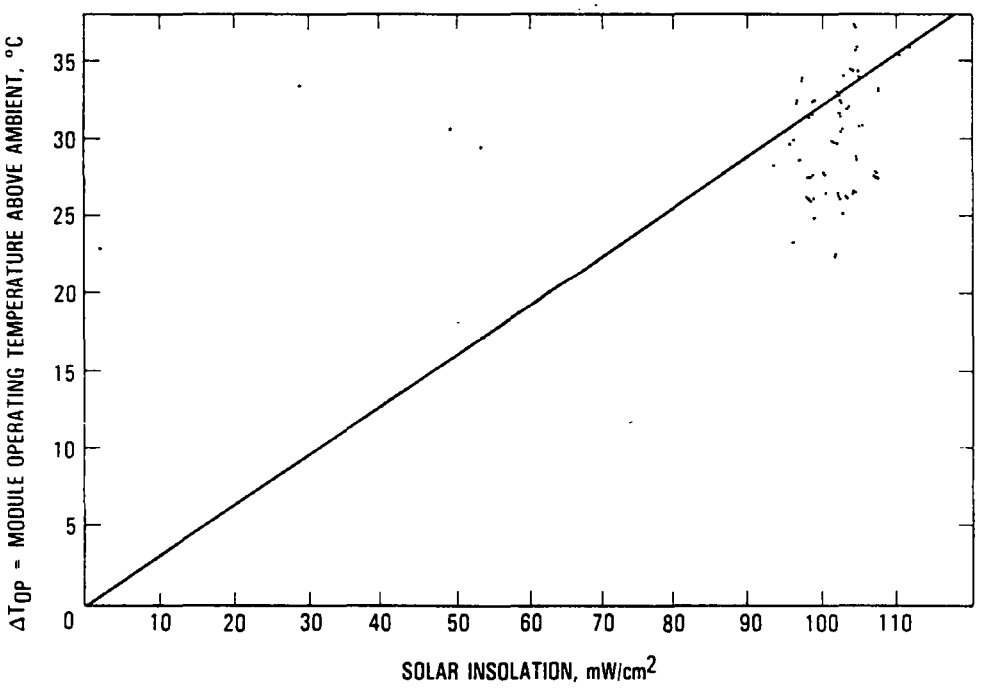


Figure 9. Cell Interconnect Deflection

- **Total Temperature Excursion**

  ΔT_{DN} = 14°C (Yearly Average)

  ΔT_{OP} = 32°C (At 100 mW/cm^2)

  ΔT = 46°C (Yearly Average)

- **Thermal Expansion Coefficients**

  $\alpha_S = 2.78 \times 10^{-5}$/°C (Fiberglass Substrate)

  $\alpha_C = .29 \times 10^{-5}$/°C (Silicon Solar Cell)

- **Cell Interconnect Deflection**

  $\delta = (\alpha_S C - \alpha_C D)\,\Delta T$

  = .0035 in.

Figure 10. Deformed Shape and Strain for Typical Field-Stressed Interconnect

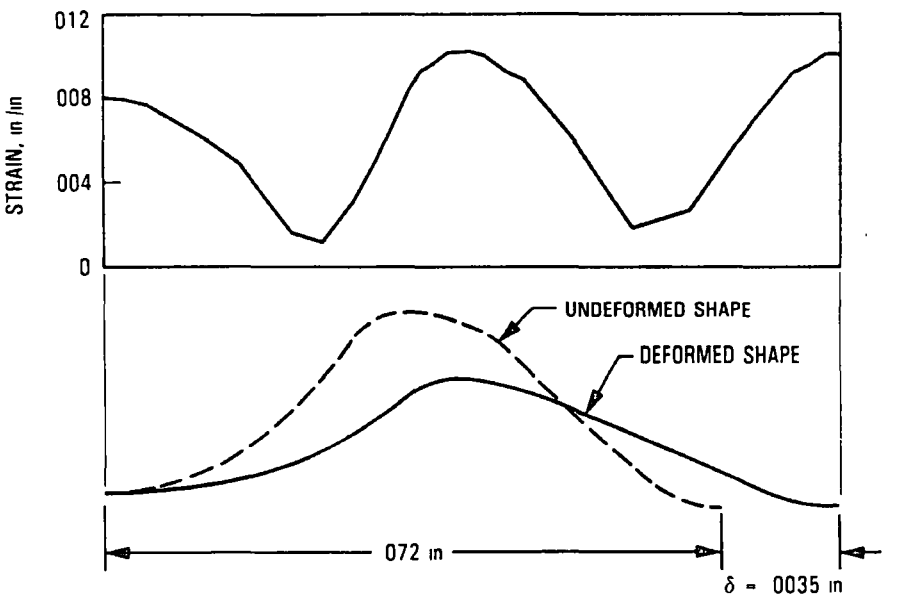
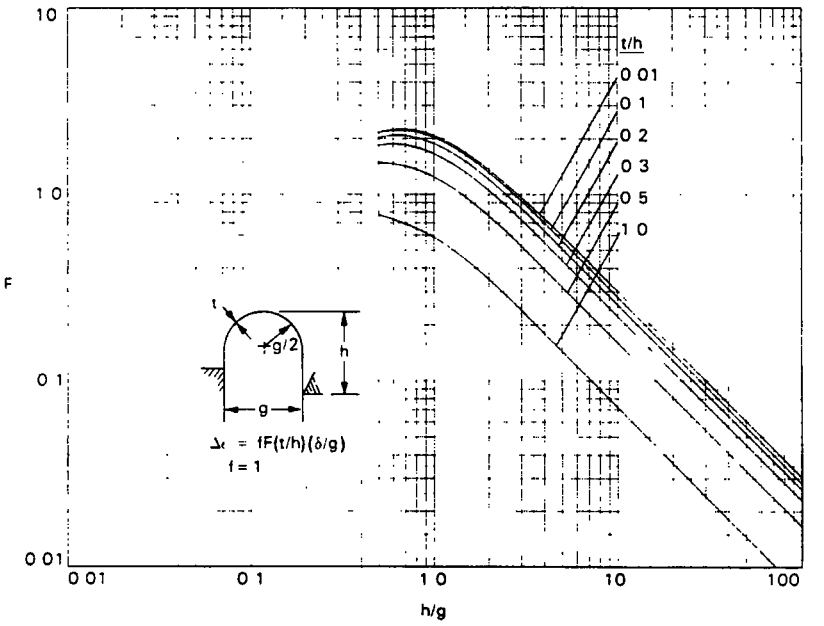


Figure 11. SC-Interconnect Nomograph



Note g is the Horizontal Distance Between Interconnect Attachment Points

Figure 12. Candidate Interconnect Materials

- **Homogeneous Materials**
  - **1100 aluminum**
  - **OFHC 1/4-hard copper**
- **Clad Materials**
  - **33.3 Cu/33.3 INV/33.3 Cu**
  - **12.5 Cu/75.0 INV/12.5 Cu**
  - **16 Cu/68 SS/16 Cu**

Figure 13. Geometry of Interconnects

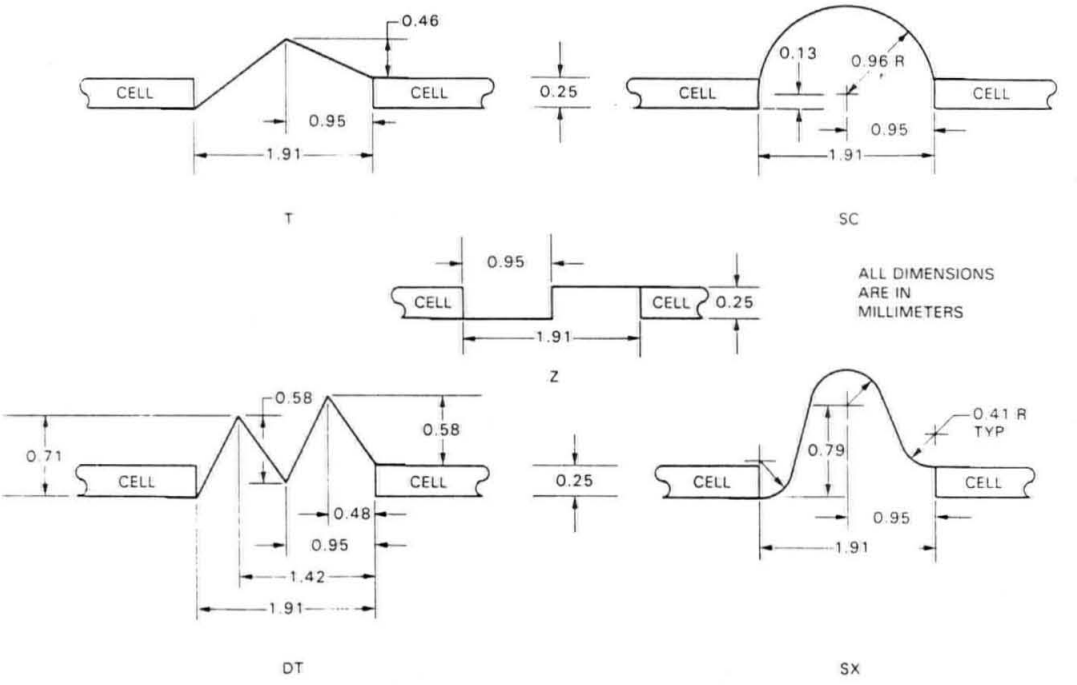


Figure 14. Interconnect Strain-Cycle Apparatus

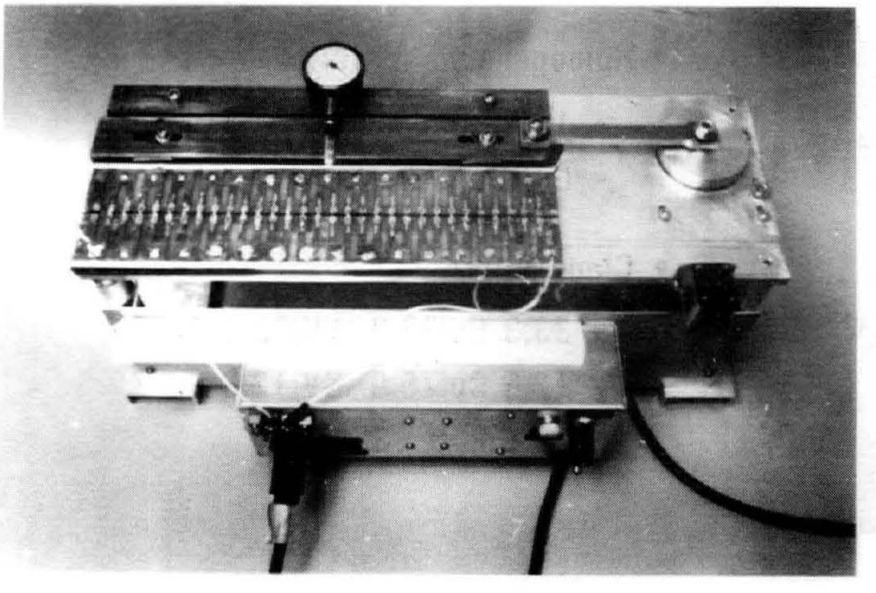


Figure 15. Experimental Data: OFHC Copper Interconnects

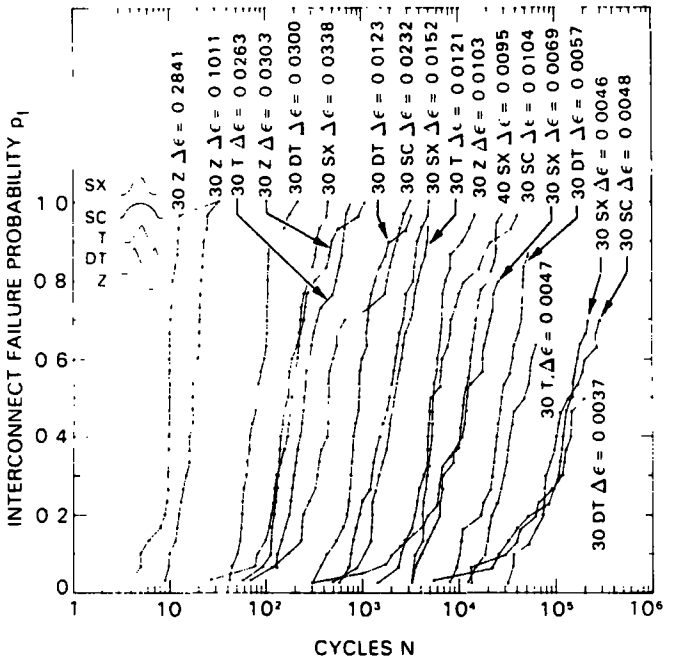


Figure 16. Statistical Fatigue Curves for Tinned, Annealed 1100 Aluminum

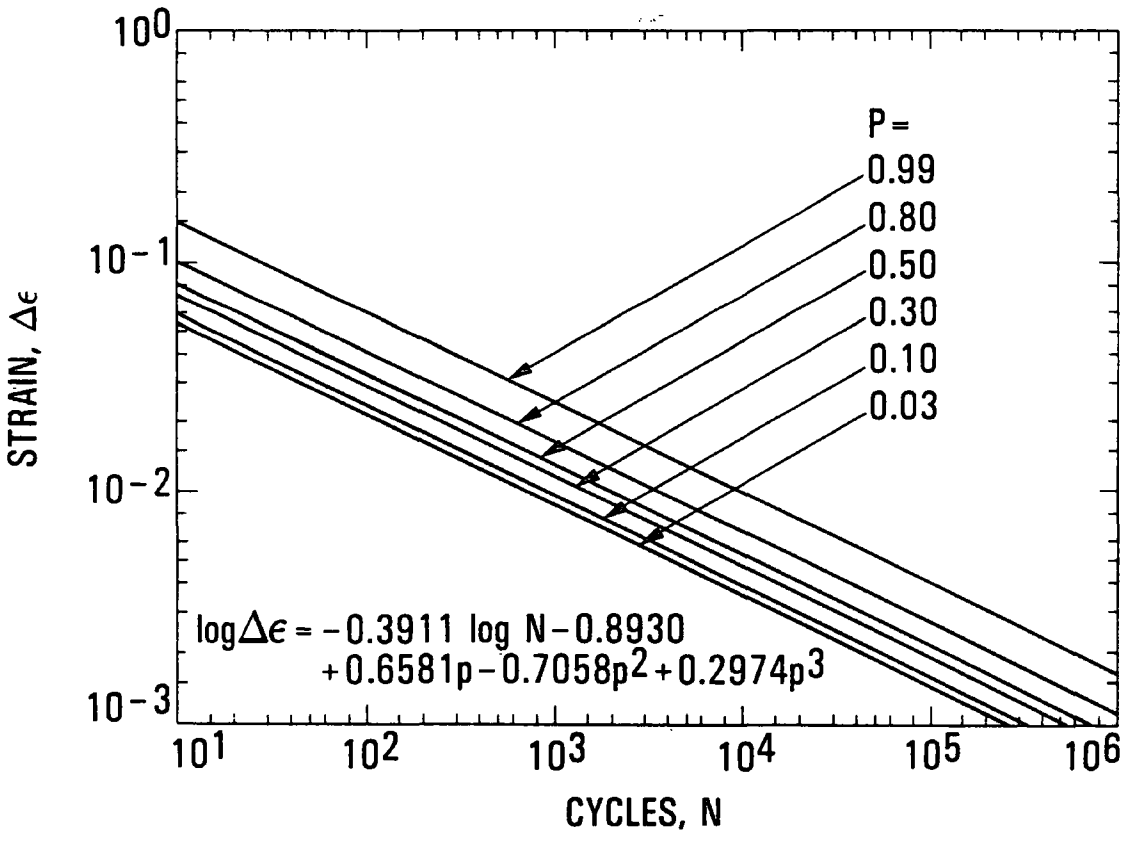


Figure 17. Statistical Fatigue Curves for OFHC ¼-Hard Copper

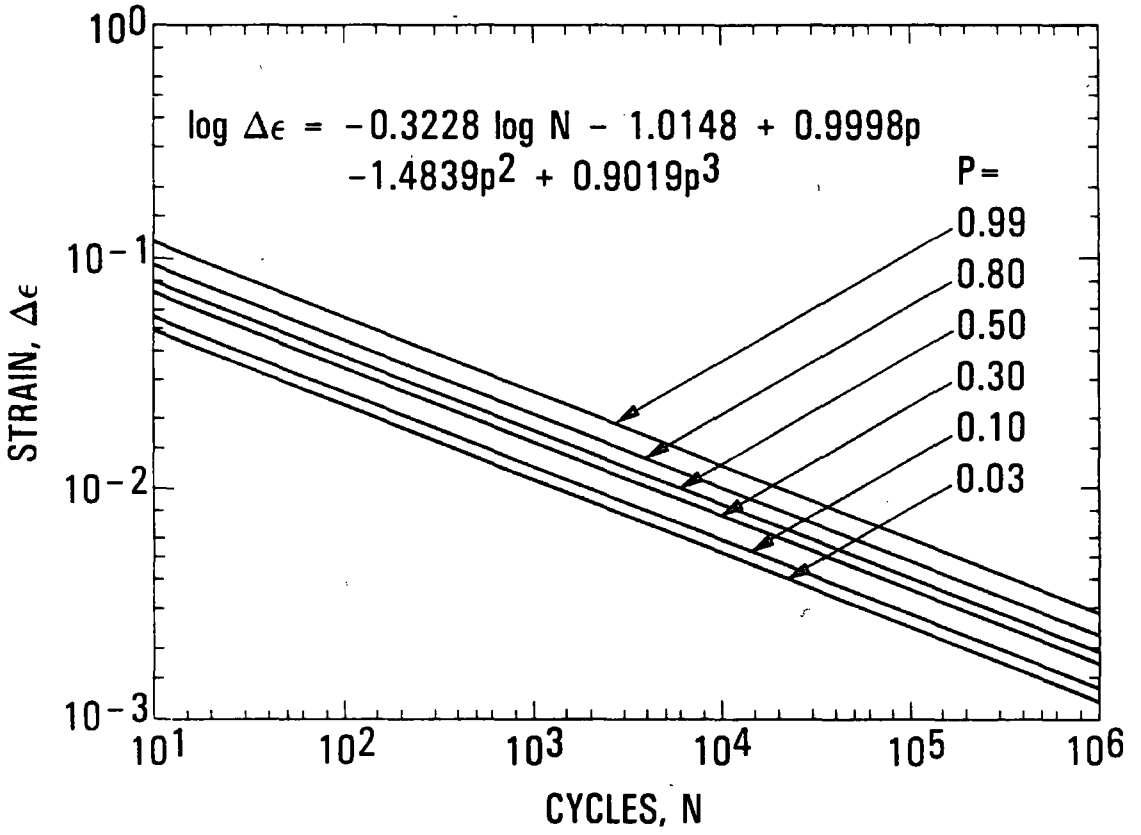


Figure 18. Statistical Fatigue Curves for
33 Cu / 33 Inv / 33 Cu

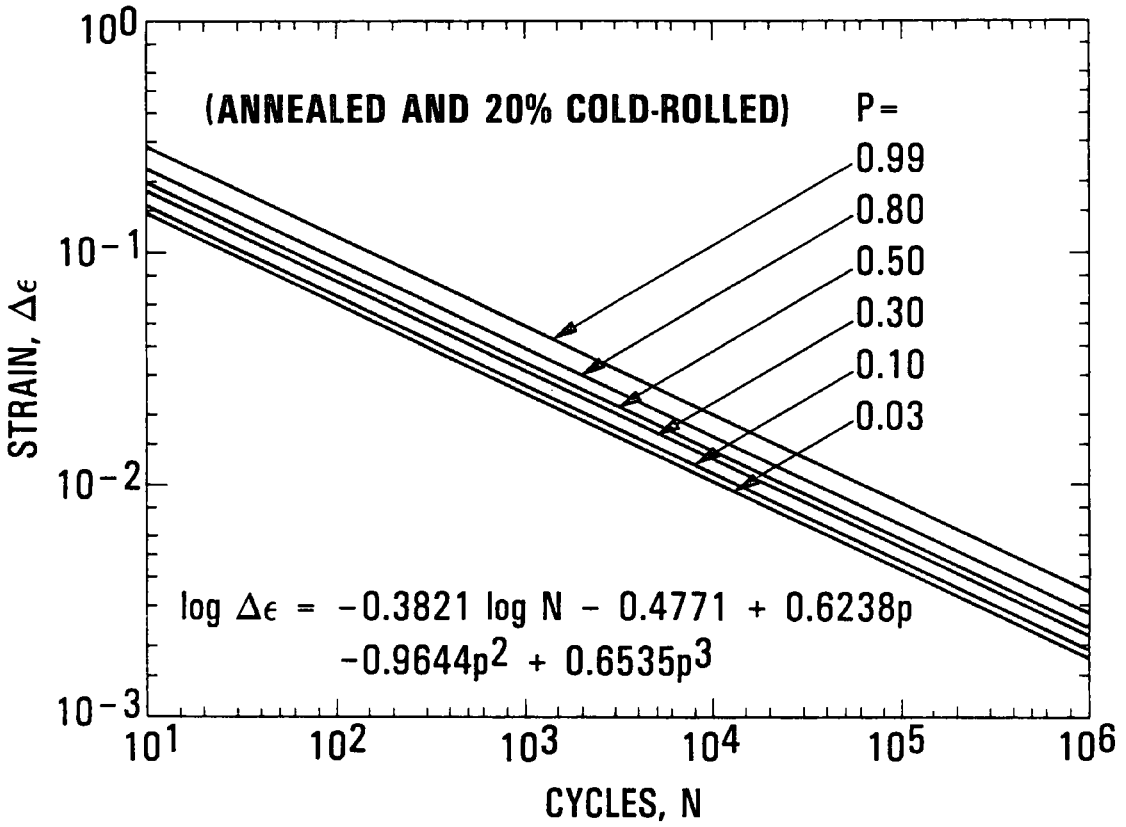


Figure 19. Statistical Fatigue Curves for Cladding, 12.5 Cu / 75 Inv / 12.5 Cu

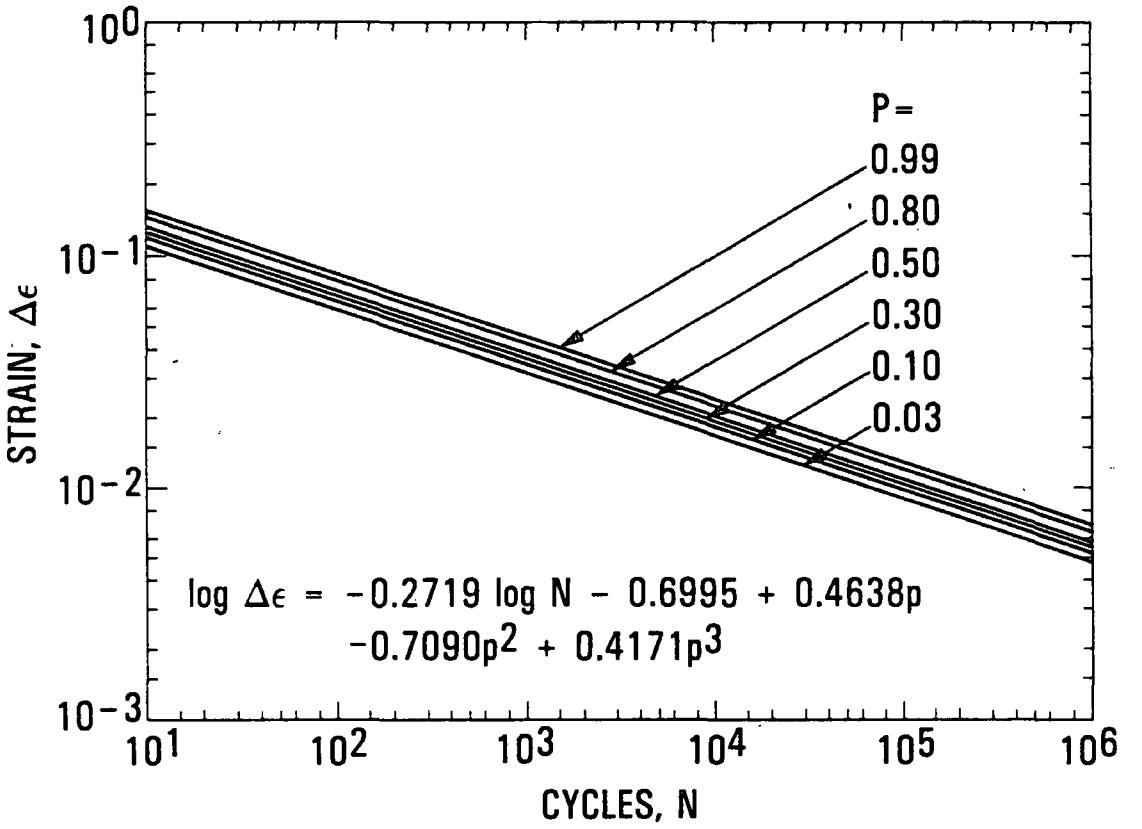


Figure 20. Statistical Fatigue Curves for Cladding (16 Cu / 68 SS / 16 Cu)

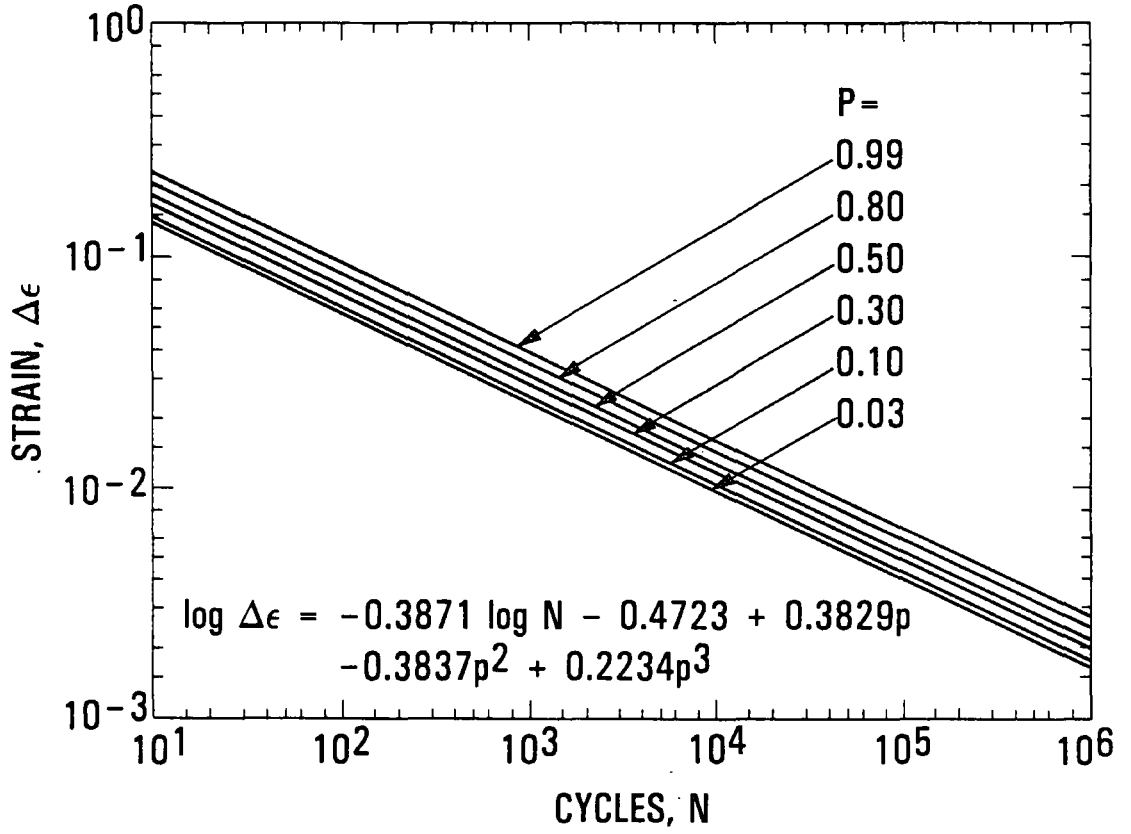


Figure 21. Experiment Fatigue Test Results

- **Comparison at same strain level for which 10% of copper interconnects fail in 20 years**

Material	Years to 10% failures
Aluminum	7
Copper	20
33 Cu/33 INV/33 Cu	106
12.5 Cu/75.0 INV/12.5 Cu	1030
16 Cu/68 SS/16 Cu	85

Figure 22. Statistical Fatigue Curves for OFHC ¼-Hard Copper

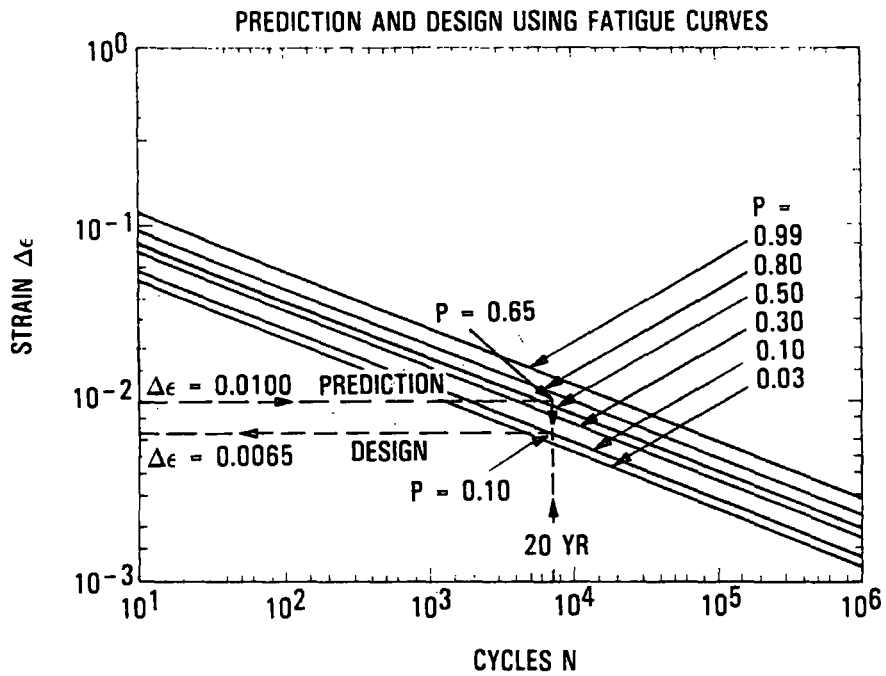
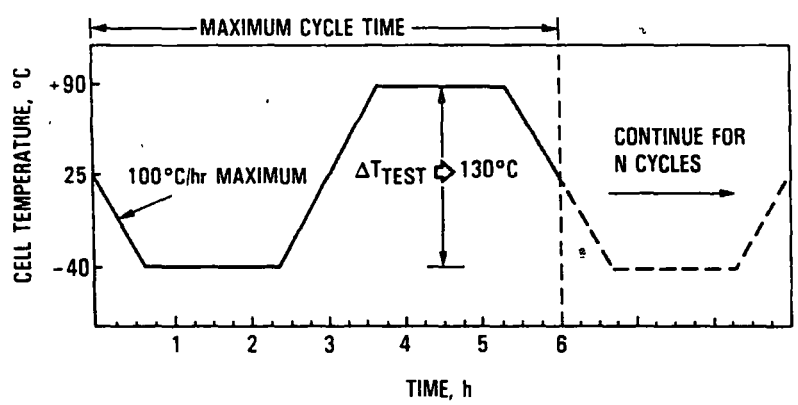


Figure 23. Typical Thermal-Cycle Test Profile and Test Acceleration Factor



Test Profile

- **Amplitude: ΔT_{TEST} = 130°C**
- **Duration: N = 200 cycles**

Test Purpose

- **To qualify modules for typical field application (ΔT_{FIELD} = 46°C)**

Test Acceleration Factor

- **Since interconnect strain varies linearly with temperature change,**

$$\frac{\Delta\epsilon_{TEST}}{\Delta\epsilon_{FIELD}} = \frac{\Delta T_{TEST}}{\Delta T_{FIELD}} = \frac{130}{46} = 2.83$$

Figure 24. Statistical Fatigue Curves for OFHC ¼-Hard Copper Thermal-Cycle Test Design

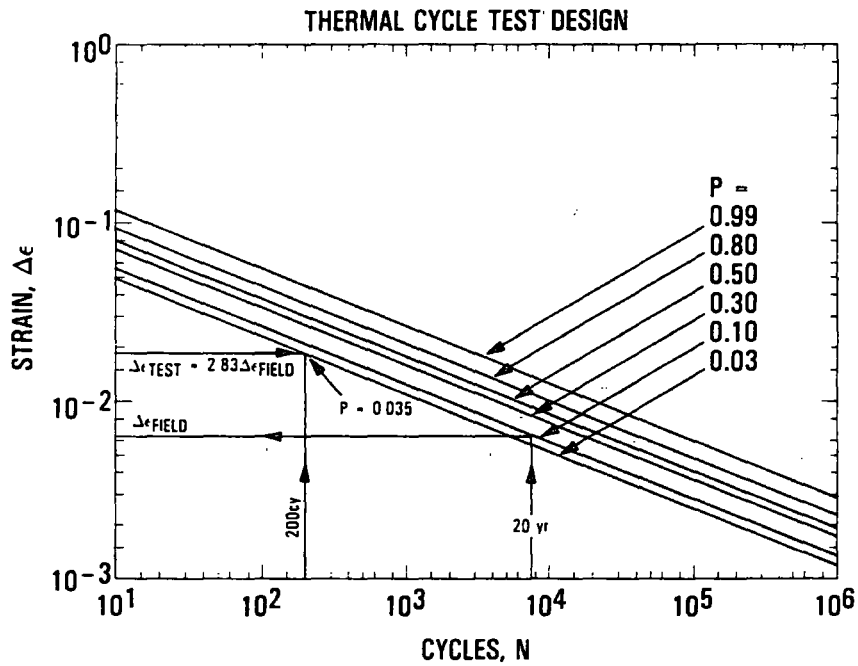


Figure 25. Thermal-Cycle Qualification Test Design

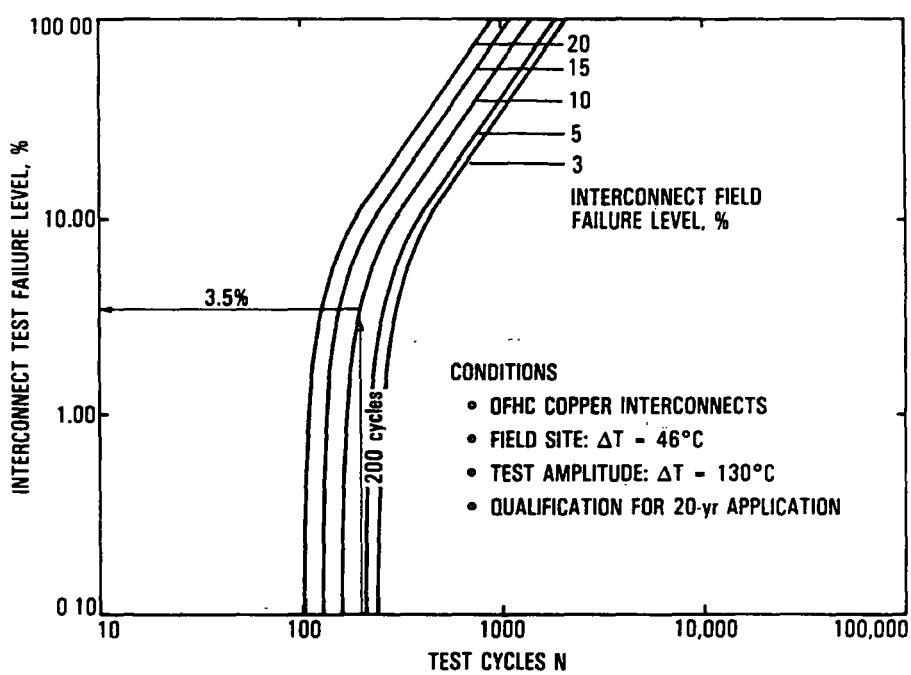


Figure 26. Module Qualification: 20-Year Service ΔT ≈46°C
Thermal-Cycle Test Results

Type of Module	Number of Thermal Cycles (ΔT = 130°C)	Observed Interconnect Test Failure Level, %	Qualification for 10% Field Failure Level		Qualification for 3% Field Failure Level	
			Maximum Allowable Test Failure Level, %	Judgement	Maximum Allowable Test Failure Level, %	Judgement
Randomly Oriented Glass Fiber Substrate	297	67	10.0	Failed	3.2	Failed
	575	69	27.0	Failed	15.0	Failed
	297	36	10.0	Failed	3.2	Failed
	575	69	27.0	Failed	15.0	Failed
	297	31	10.0	Failed	3.2	Failed
Superstrate	247	0	7.2	Passed	3.3	Passed
Superstrate	446	3	18.4	Passed	10.4	Passed
Superstrate	397	0	15.5	Passed	8.2	Passed
Substrate	547	6	25.0	Passed	14.0	Passed
	547	10	25.0	Passed	14.0	Passed
Substrate	497	0	21.0	Passed	12.0	Passed
	497	7	21.0	Passed	12.0	Passed

Figure 27. Statistical Fatigue Curves for OFHC ¼-Hard Copper
Correlation With Field and Thermal Cycle Test Failure Data

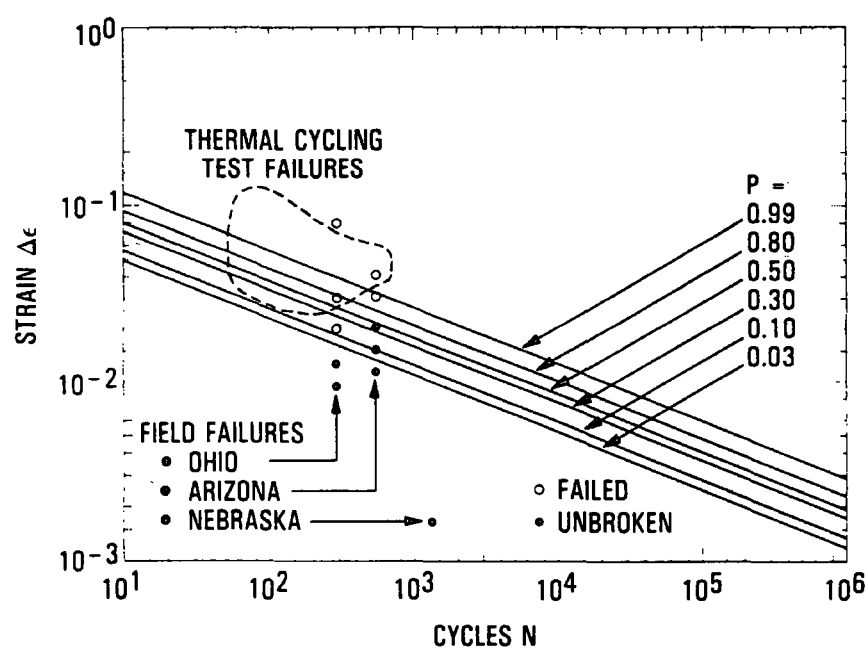


Figure 28. Array Degradation Analysis Algorithm

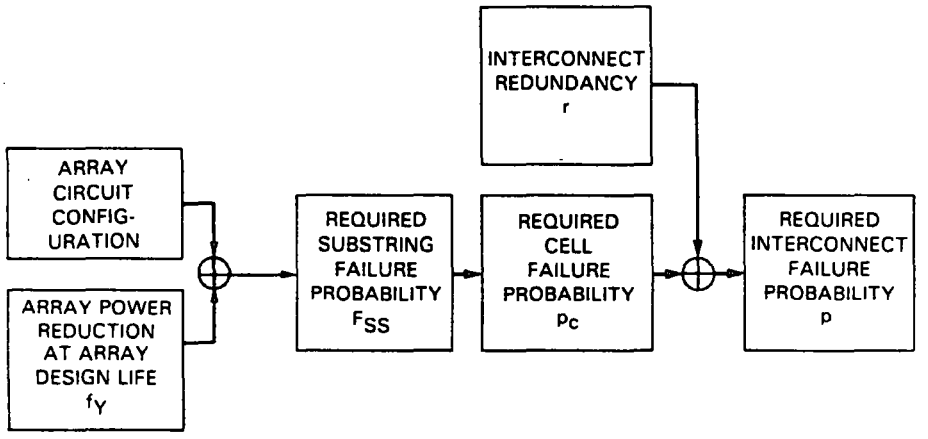


Figure 29. Array Power Reduction at 20 Years

20-YEAR INTERCONNECT FAILURE PROBABILITY P_I	ARRAY POWER REDUCTION AT 20 YEARS f_Y					
	r = 1	2	3	4	5	6
0.005	0.125	0.0018	0	0	0	0
0.010	0.240	0.0059	0	0	0	0
0.050	0.71	0.05	0.0070	0.0004	0	0
0.100	0.96	0.24	0.029	0.0055	0.0007	0
0.150	1.00	0.31	0.054	0.019	0.005	0.0013
0.200	1.00	0.57	0.19	0.038	0.013	0.003
0.300	1.00	0.90	0.46	0.20	0.048	0.023
0.400	1.00	1.00	0.90	0.45	0.26	0.085
0.500	1.00	1.00	1.00	0.80	0.53	0.32

Figure 30. Example Design Parameters

Array Configuration:

- **8 parallel by 11 series cells per series block**
- **57 series blocks per branch circuit**
- **One series block per diode**
- **V_{ARRAY} = 250 volts**

Figure 31. Array Power Loss

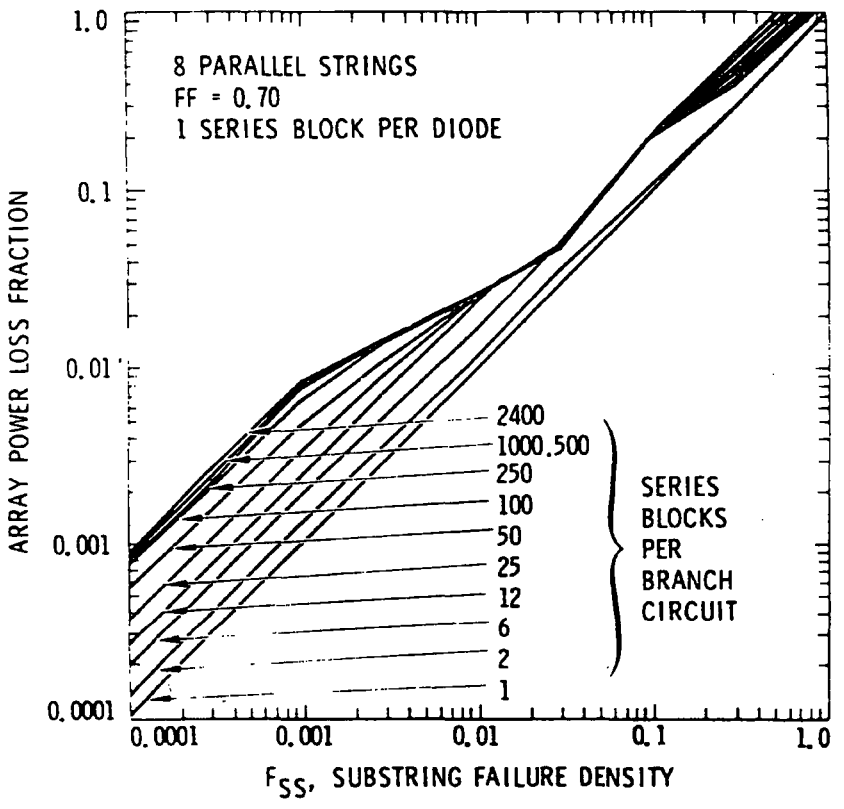


Figure 32. Effect of Material Properties on Life-Cycle Energy Costs

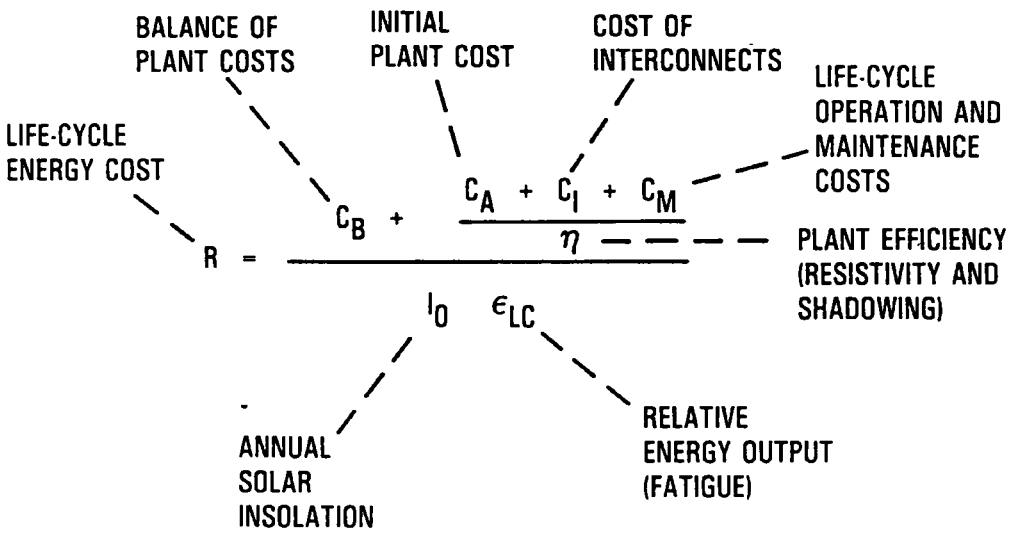


Figure 33. Module Interconnect Assessment Algorithm

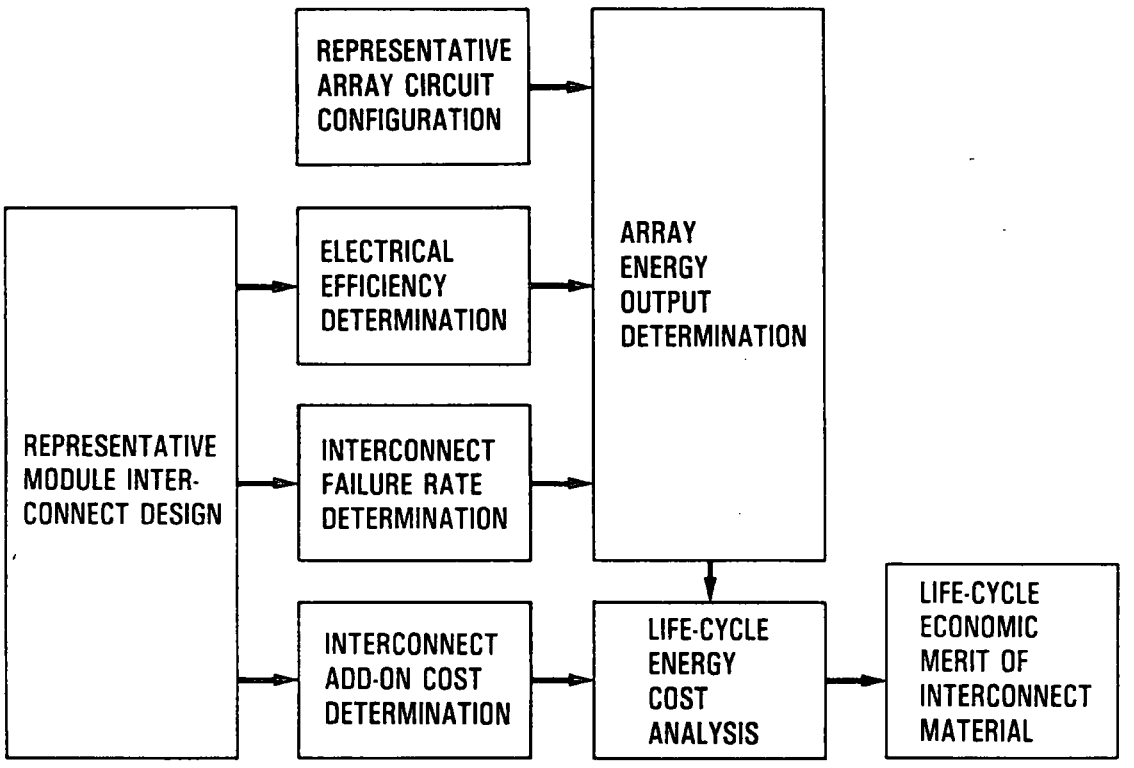


Figure 34. Array Power Output Fraction vs Years of Operation

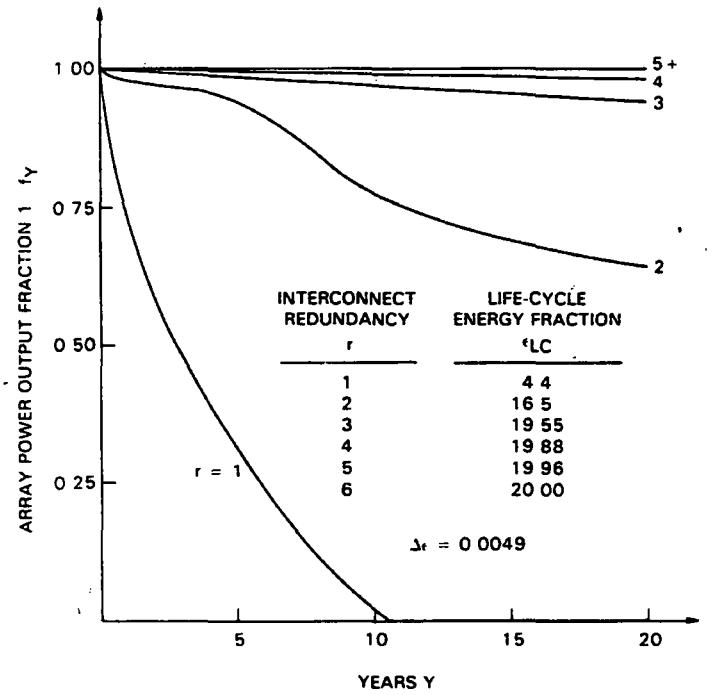


Figure 35. Life-Cycle Energy Fractions

20-Year Cumulative Interconnect Failure Probability	Life-Cycle Energy Fraction ϵ_{LC}					
P_I	r=1	2	3	4	5	6
0.005	17.8	19.95	20	20	20	20
0.010	16.6	19.90	19.96	20	20	20
0.050	11.7	19.45	19.89	19.98	20	20
0.100	7.7	18.2	19.76	19.92	19.98	20
0.150	4.4	16.5	19.55	19.88	19.96	20
0.200	2.25	13.2	18.47	19.55	19.88	20
0.300	1.74	11.2	17.1	18.65	19.66	19.91
0.400	1.60	9.9	15.17	17.1	18.7	19.15
0.500	1.5	8.9	13.2	15.6	17.4	17.9

Figure 36. Total Plant Efficiency η

Equations:

$$\eta = \eta_0 \left(1 - \frac{LW}{A}\right)\left(1 - \frac{I^2\Omega}{P_0}\right)$$

$$\Omega = \frac{\ell\rho}{wt}$$

$$\rho = \rho_x \frac{1}{2x + y\left(\frac{\rho_x}{\rho_y}\right)}$$

Symbols:

ρ = electrical resistivity of cladding
x/y/x = thickness ratio of claddings
$\rho_{x,y}$ = electrical resistivity of materials x,y
ℓ,w,t = length, width, and thickness of interconnect
Ω = resistance of interconnect
I = solar cell current at maximum power
P_0 = cell power output
$\frac{LW}{A}$ = ratio of cell area covered by interconnect to total cell area
η_0 = baseline plant efficiency

Figure 37. Add-On Cost for Interconnects vs Thickness With Interconnect Redundancy as Parameter (Tinned, Annealed 1100 Aluminum)

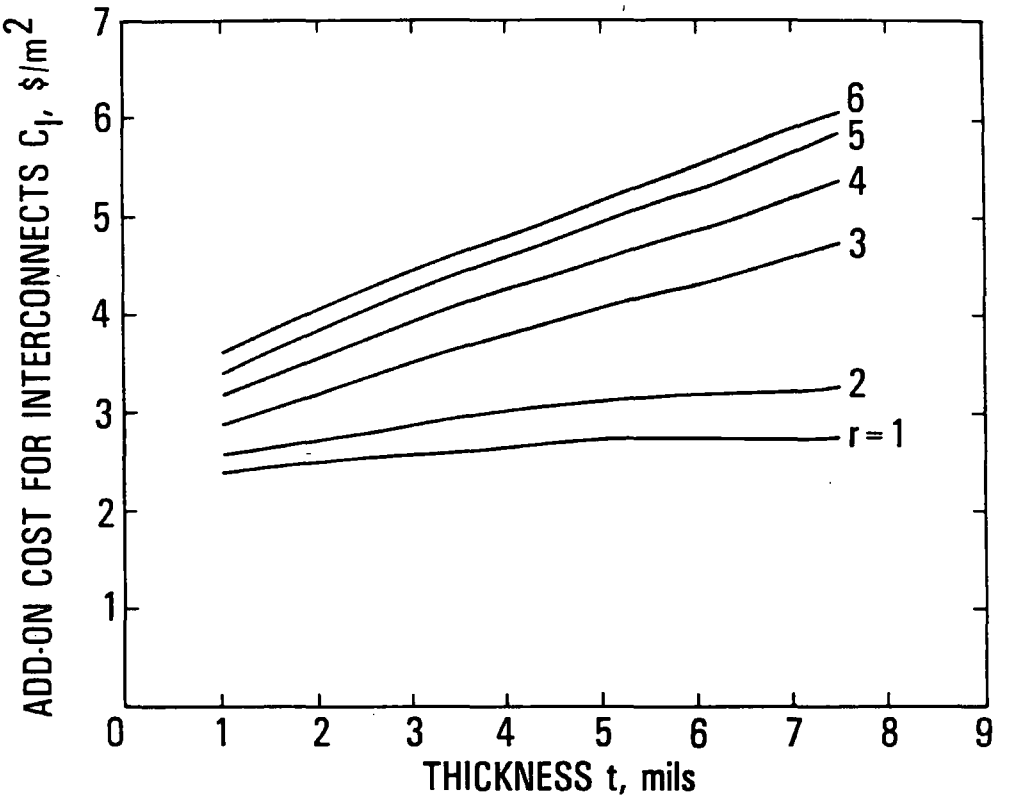


Figure 38. Add-On Cost for Interconnects vs Thickness With Interconnect Redundancy as Parameter (OFHC ¼-Hard Copper)

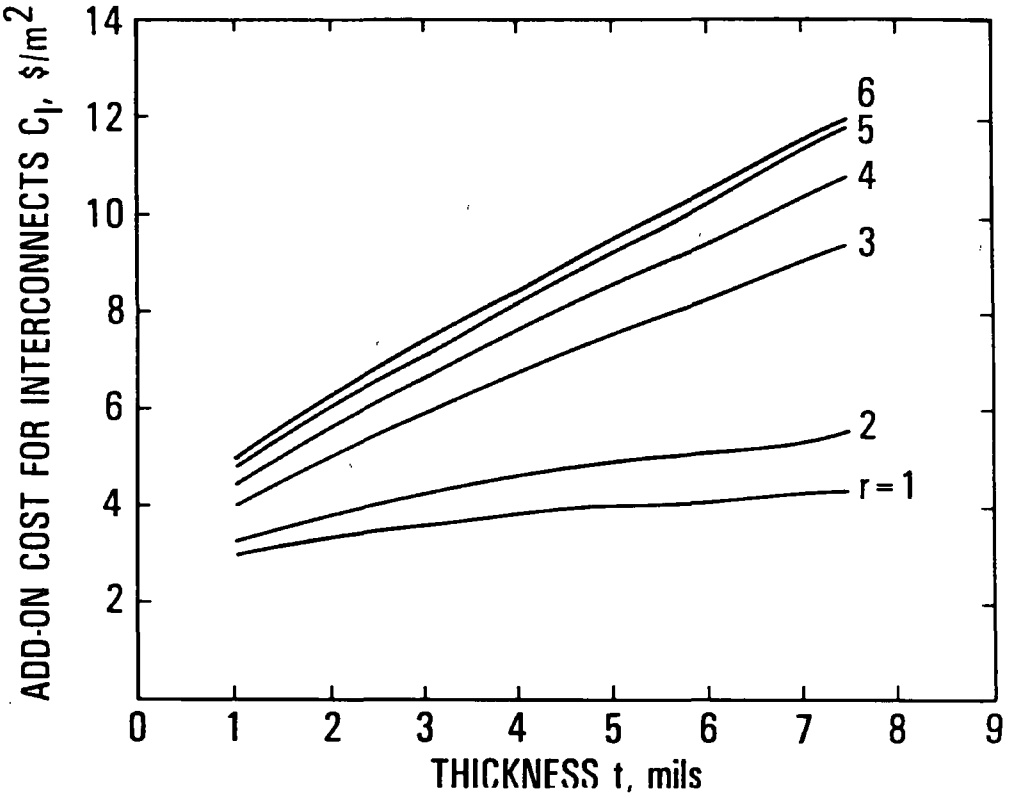


Figure 39. Add-On Cost for Interconnects vs Thickness With Interconnect Redundancy as Parameter (33 Cu / 33 Inv / 33 Cu)

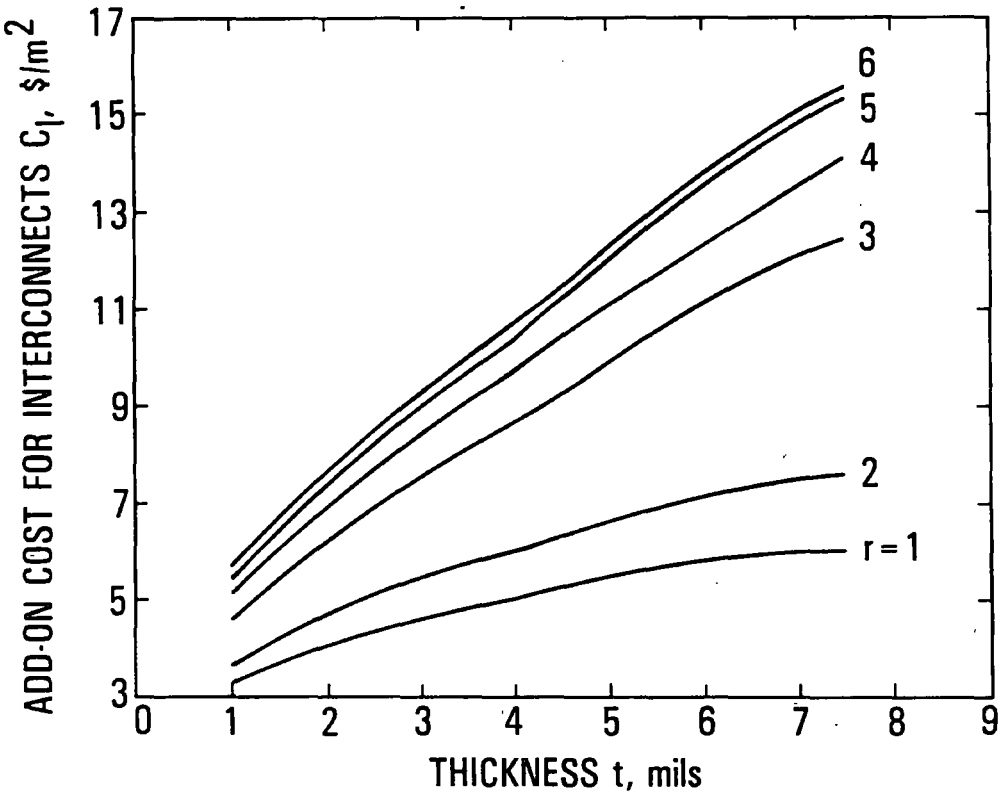


Figure 40. Add-On Cost for Interconnects vs Thickness With Interconnect Redundancy as Parameter (12.5 Cu / 75 Inv / 12.5 Cu)

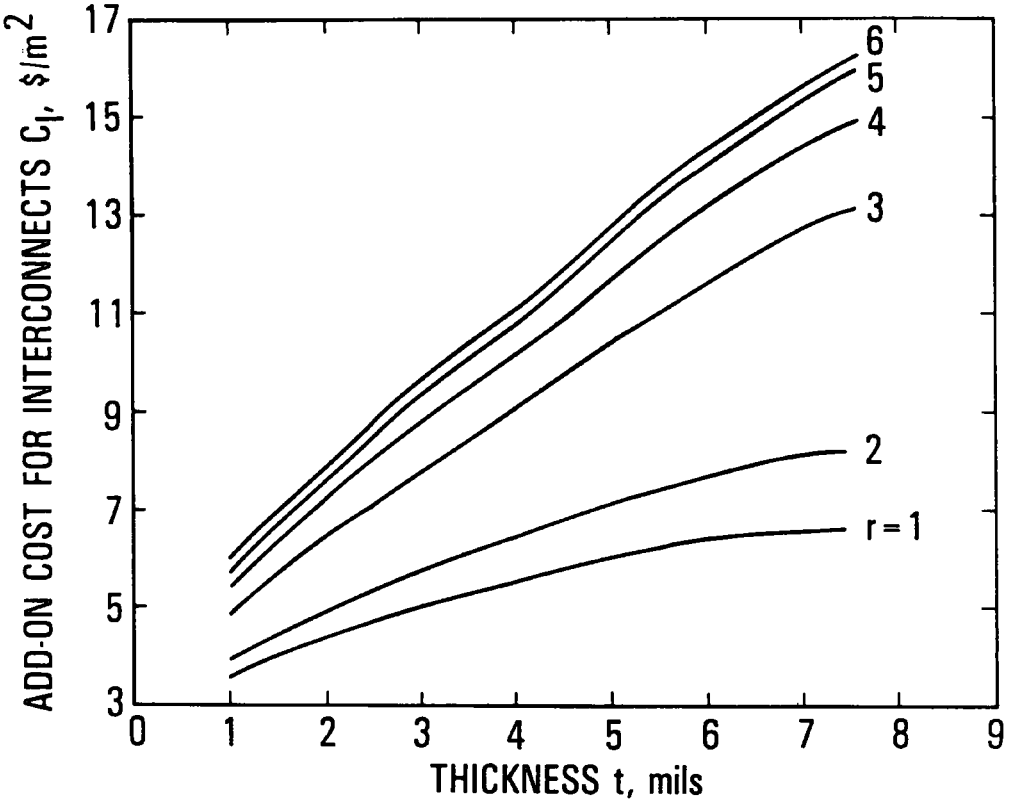


Figure 41. Add-On Cost for Interconnects vs Thickness With Interconnect Redundancy as Parameter (16 Cu / 68 SS / 16 Cu)

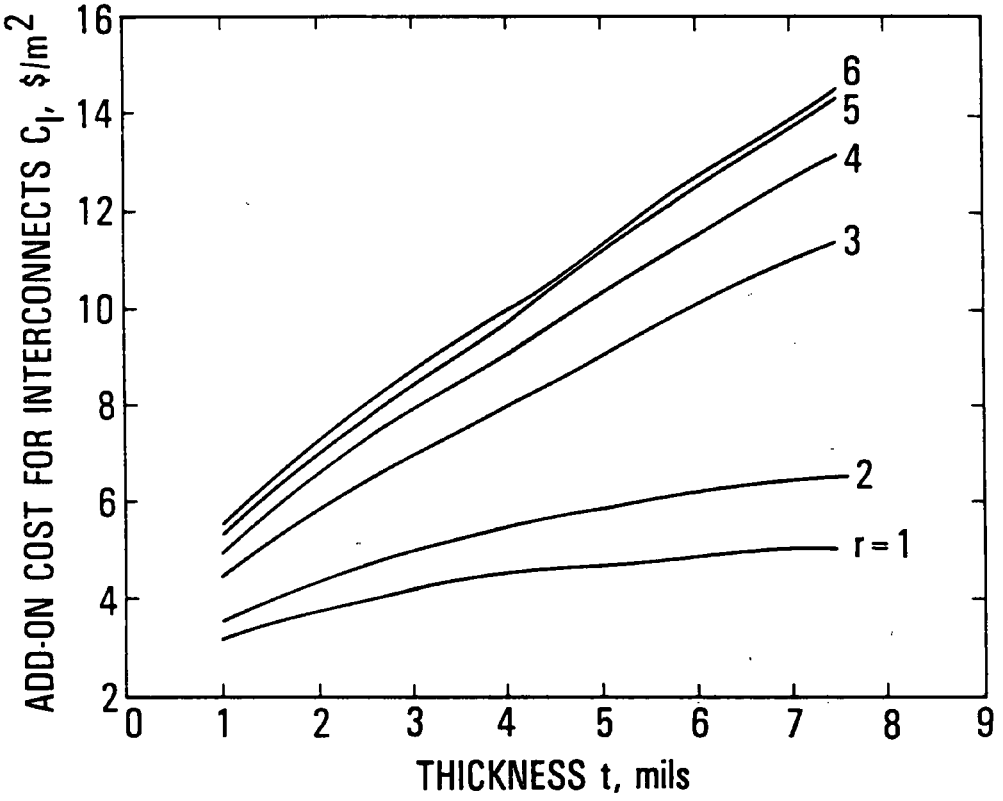


Figure 42. Parameters Used in Life-Cycle Energy Cost Analysis

C_B = 250 \$/kW

C_A = 113 \$/m^2

C_M = 0

I_0 = 2000 kWh/m^2/yr

$\eta_0(1 - \frac{LW}{A})$ = 0.092

I = 2.0 amps

P_0 = 1.2 watts

ℓ = 3.0 in.

W = 0.2 in.

Figure 43. Fractional Increment in Life-Cycle Energy Cost Due to Interconnects vs Thickness, With Interconnect Redundancy as Parameter (Tinned, Annealed Aluminum)

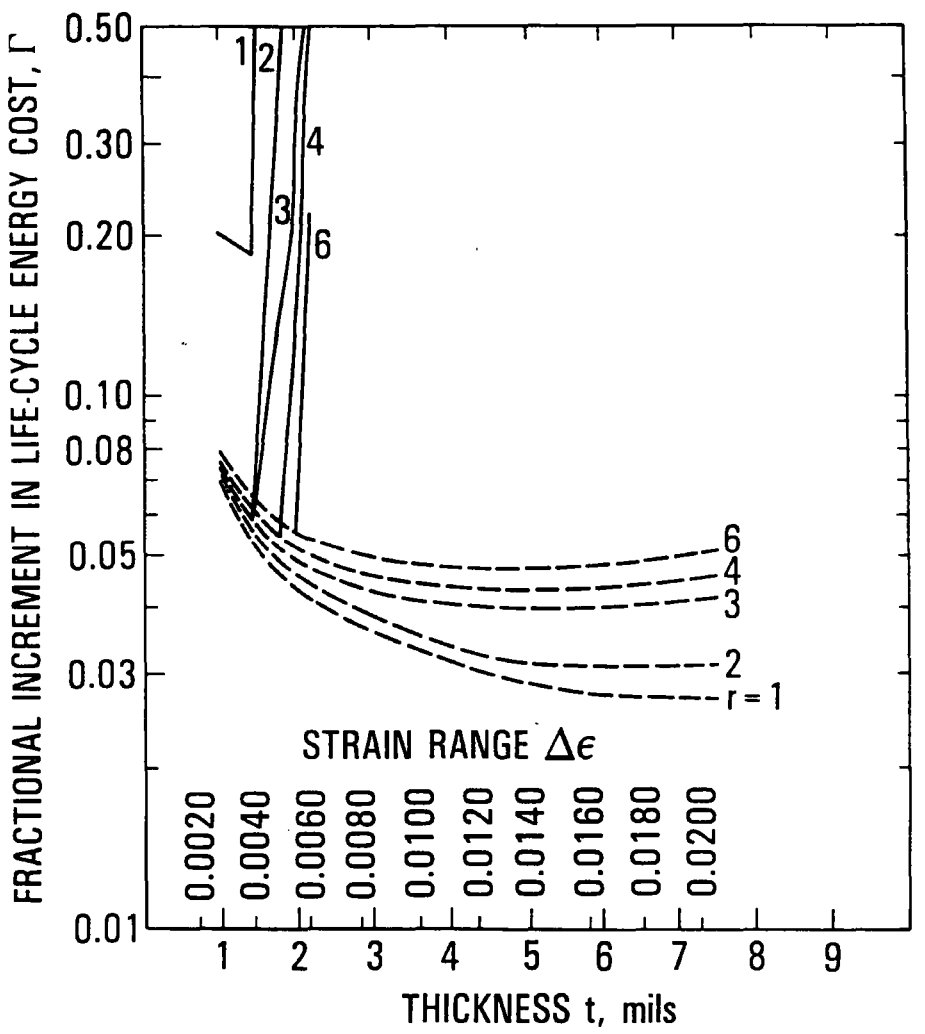


Figure 44. Fractional Increment in Life-Cycle Energy Cost Due to Interconnects vs Thickness, With Interconnect Redundancy as Parameter (OFHC ¼-Hard Copper)

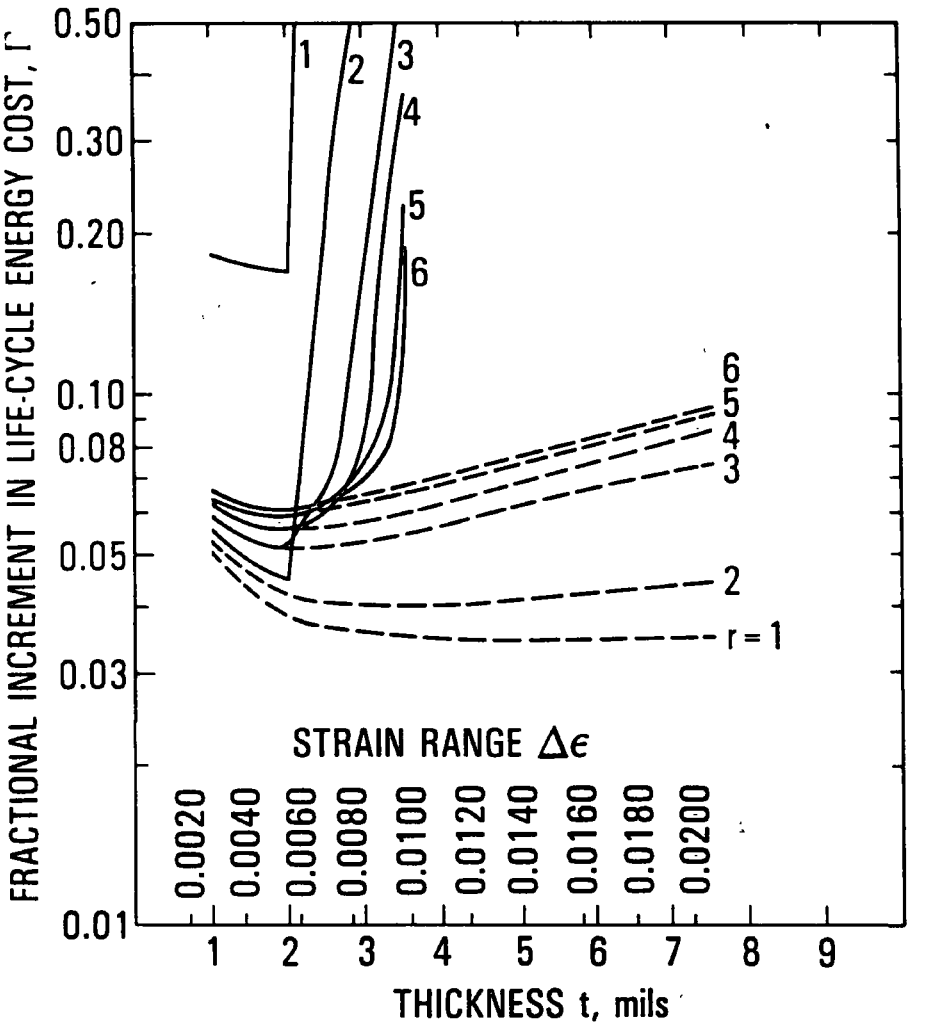


Figure 45. Fractional Increment in Life-Cycle Energy Cost Due to Interconnects vs Thickness, With Interconnect Redundancy as Parameter (33 Cu / 33 Inv / 33 Cu)

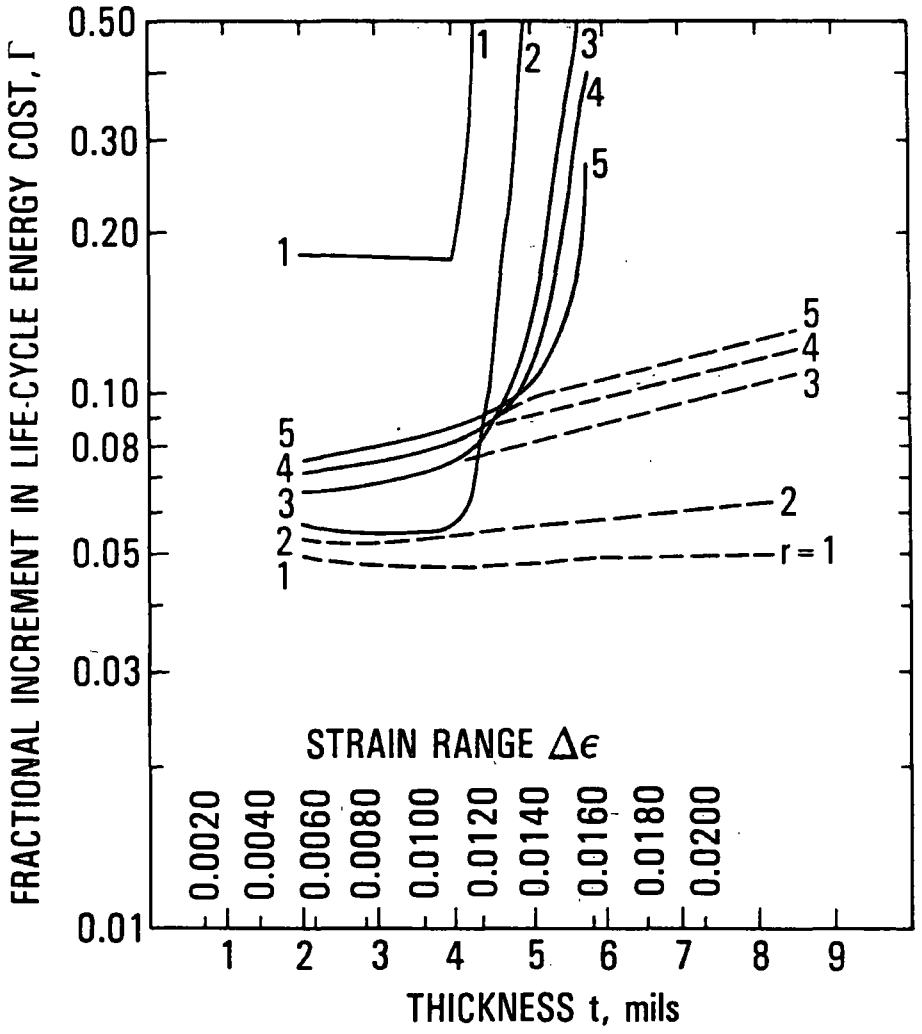


Figure 46. Fractional Increment in Life-Cycle Energy Cost Due to Interconnects vs Thickness, With Interconnect Redundancy as Parameter (12.5 Cu / 75 Inv / 12.5 Cu)

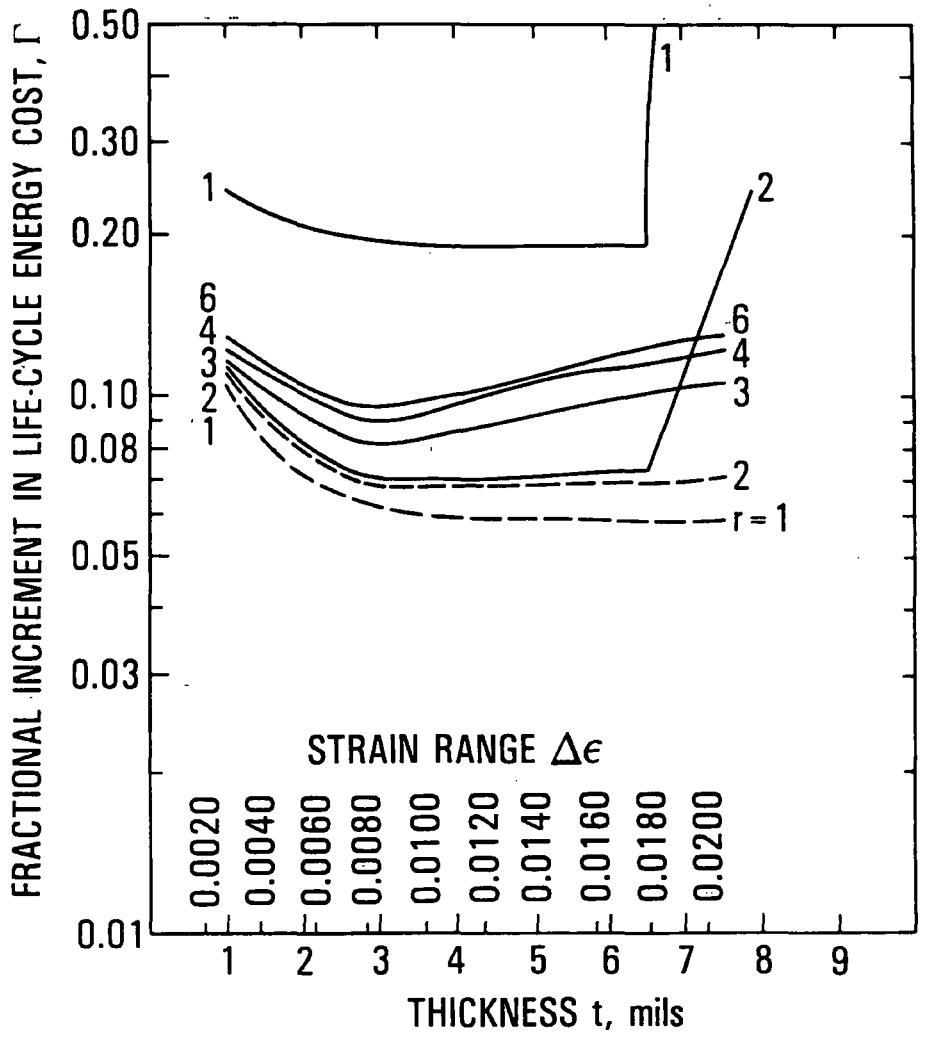


Figure 47. Fractional Increment in Life-Cycle Energy Cost Due to Interconnects vs Thickness, With Interconnect Redundancy as Parameter (16 Cu / 68 SS / 16 Cu)

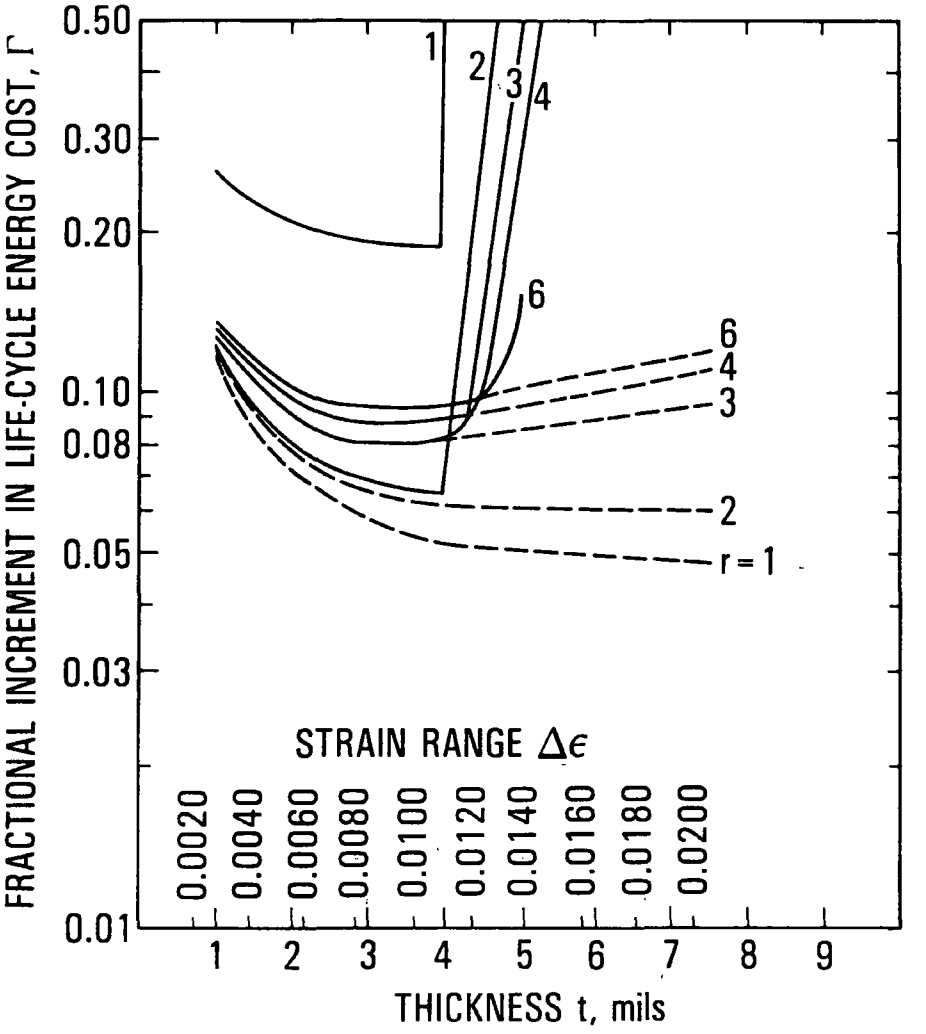


Figure 48. Percentage of Life-Cycle Energy Cost Increment Due to Doubly Redundant Interconnects

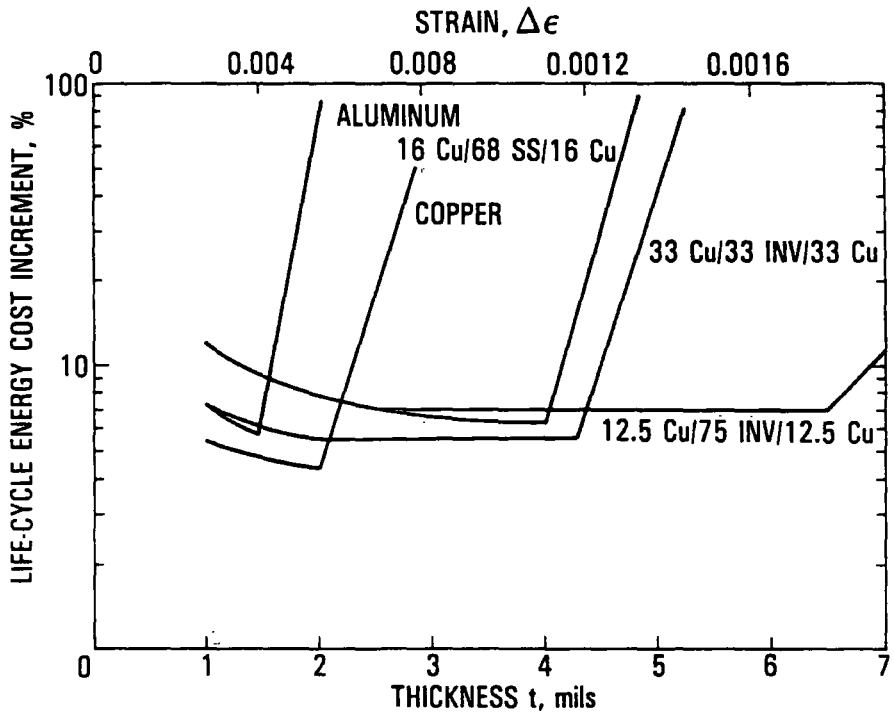


Figure 49. Conclusions

- Copper is a good interconnect material because of its low cost and high electrical conductivity
- Aluminum ranks poorly because of its disappointing fatigue performance
- Claddings offer improved performance due to substantially enhanced fatigue behavior; in particular, 33 Cu/33 INV/33 Cu exhibits superior overall performance
- Developed design algorithm provides an effective means of assessing the economic merits of candidate interconnect materials and module designs

Figure 50. Crack Propagation Across Fatigued Interconnect
(12.5 Cu / 75 Inv / 12.5 Cu, Top View)

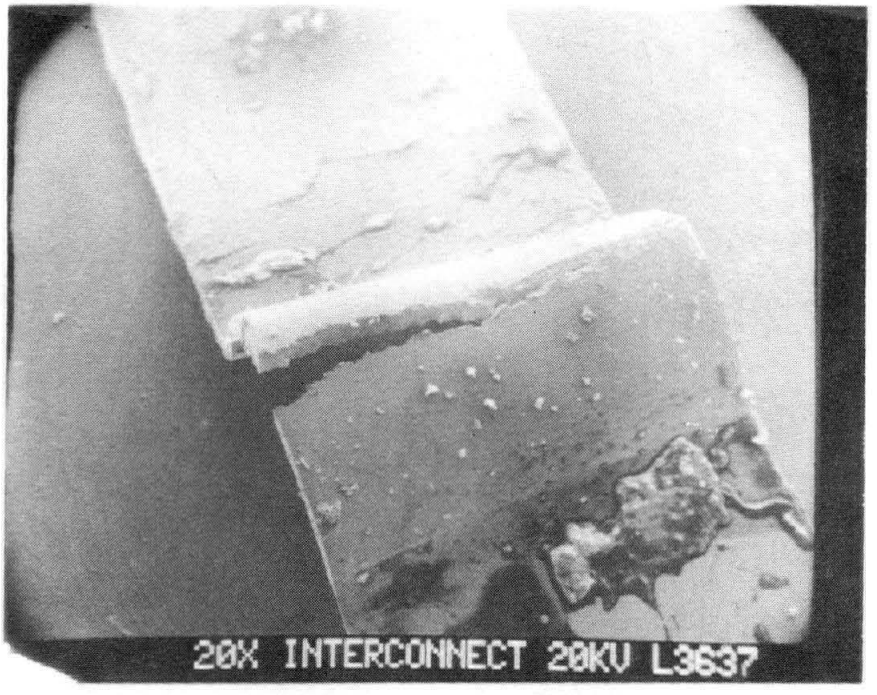


Figure 51. Crack Propagation Across Fatigued Interconnect
(12.5 Cu / 75 Inv / 12.5 Cu, Bottom View)

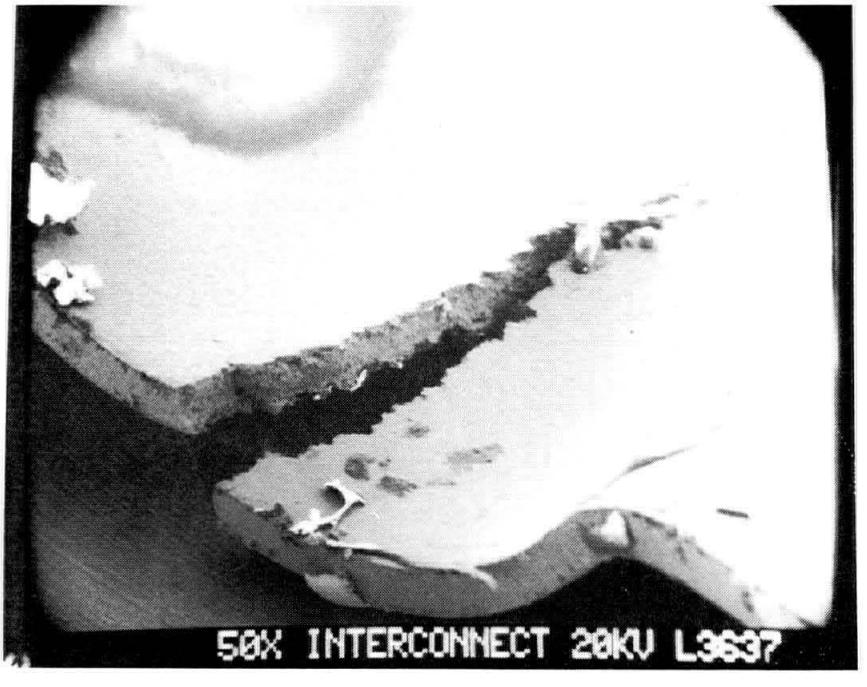


Figure 52. Crack Propagation Across Fatigued Interconnect (Annealed OFHC Copper, Top View)

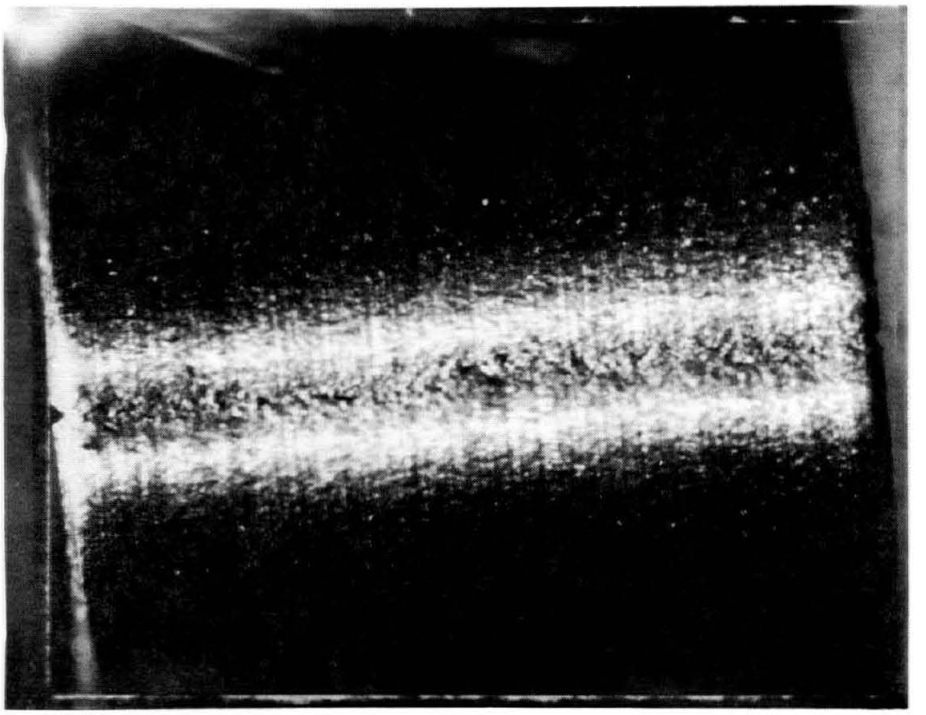


Figure 53. Crack Propagation Across Fatigued Interconnect (Annealed OFHC Copper, Bottom View)

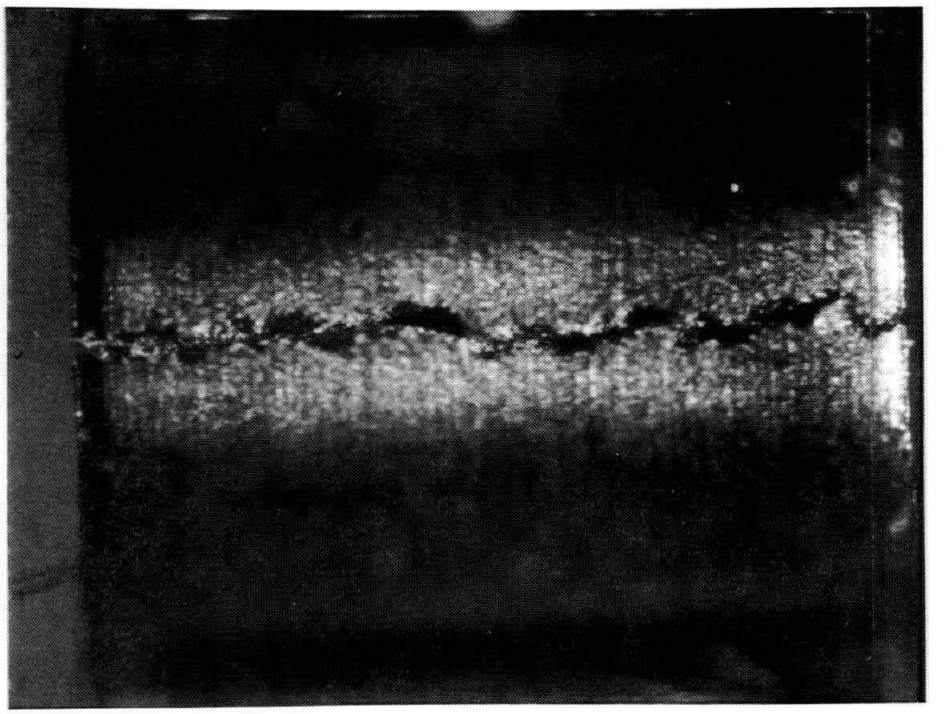


Figure 54. Schematic for Explaining Crack Propagation in Fatigued Interconnects

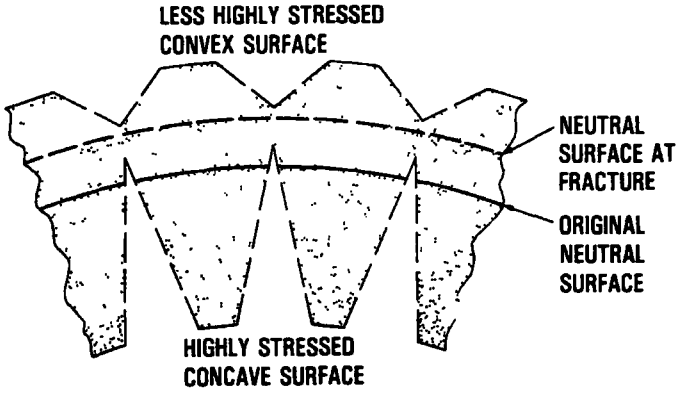


Figure 55. Neutral Surface at Fracture (12.5 Cu / 75 Inv / 12.5 Cu)

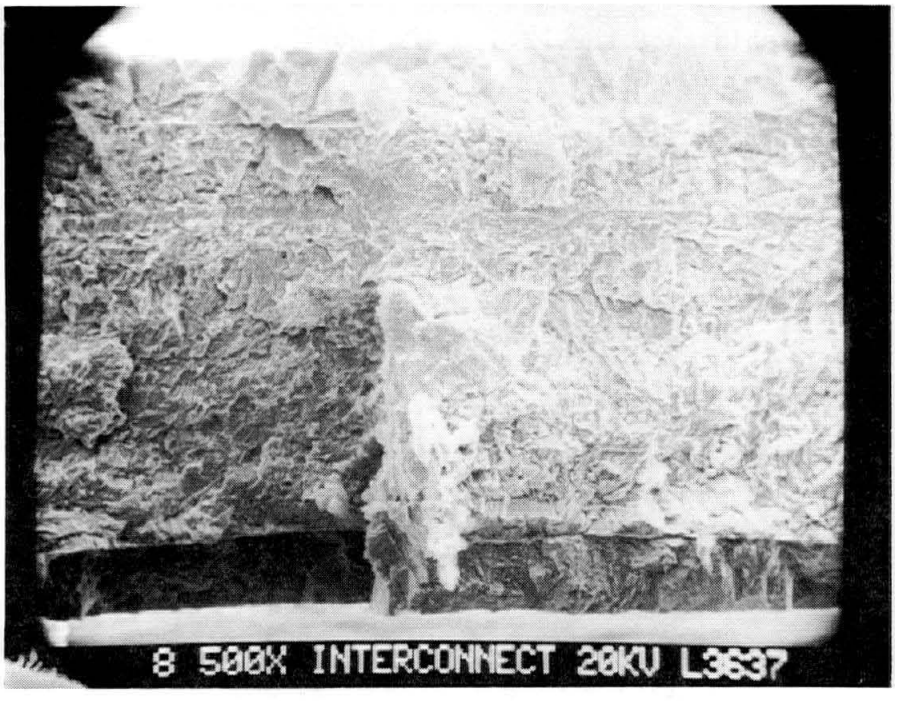
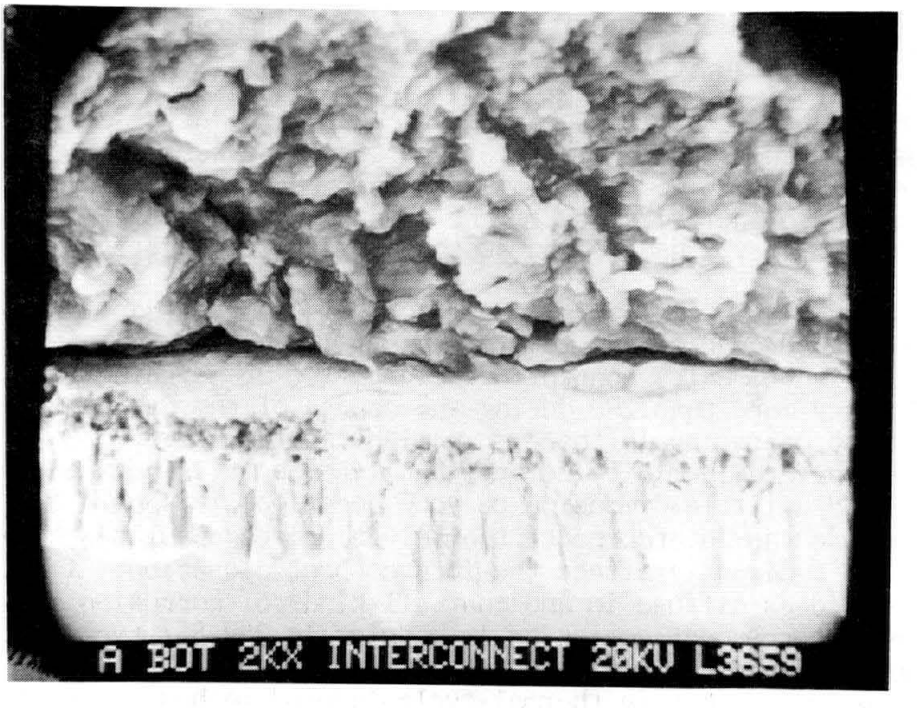


Figure 56. Tinned 1100 Aluminum Showing Region Between Aluminum and Tin



DISCUSSION

JOYCE: At the very end you made two comments about the copper-Invar system. In one case you said that the 12.5 Cu/75 Inv/12.5 Cu was economically favorable.

MON: No, the 33 Cu/33 Inv/33 Cu.

JOYCE: What was it you said about the 12.5 Cu/75 Inv/12.5 Cu, do you recall?

MON: I don't think I said anything about it really. It was less favorable. From a fatigue point of view the 12.5/75/12.5 is the best because it has more Invar in it than anything else and the Invar has much better fatigue characteristics than copper. But when you bring into account the costs, I^2R, resistivity effects and everything else, the 33/33/33 turns out to be superior.

JOYCE: My second question is about the copper. I notice that in each case you refer to the oxygen-free high-conductivity (OFHC) copper. How are its properties different from other copper available and what would be the disadvantage of using a non-OFHC copper for an interconnect?

MON: I don't know if I can totally answer that but OFHC copper, being pure, has the highest conductivity of any copper, so other than that I don't know what the advantage would be of using a less pure copper. Probably, if anything, it would be a disadvantage.

LEE: I may have missed it but did you have any environmental control on your test specimens?

MON: No. They were tested in air. You saw that apparatus? They were mounted between those plates in air.

LEE: We, in conducting fatigue tests, have seen some influence of just the atmosphere on the resultant life, in particular crack-growth rates, depending on whether you use a nitrogen-purged atmosphere or just the normal amount of humidity that might exist in a laboratory environment. Just wondered if you had looked at this in any of your lifes?

MON: No, we haven't. Our laboratory is humidity-controlled, more or less, and temperature-controlled, more or less. I have to say more or less because it isn't really controlled down to 1°C or anything like that but we don't vary more than 2°C during the course of the day even with a lot of equipment operating in there. We might go from 22°C to 24°C. I don't remember the humidity numbers but I think it is between 50% and 60%. To add a little dimension to your question, it should be noted that in actual use the interconnects themselves are encapsulated so atmospheric effects don't directly affect the interconnect operation. I know that water vapor does diffuse in and that all kinds of corrosion can happen. I have seen interconnect corrosion in modules in 85°-85% type humidity tests but we haven't taken that into account. We are strictly looking at one mechanism and that is thermal-cycle-induced mechanical fatigue.

MOORE: I think Gordon mentioned this in his talk but I want to emphasize that the module interconnect design influences where the strain range is placed on the abscissa (thickness) of the graphs that he presented. The module design, I think, can influence the material selection.

MON: That's right. To amplify that, you saw that at 2 mils thick, OFHC copper -- you suddenly got that big increase in life-cycle energy cost. That depends on the strain and what Don is saying is that depending on the design this strain can move back and forth on the X axis, which will likewise move all those curves back and forth.

COULBERT: One of the interconnect designs which has been used, and I am not sure whether it is still in favor or not, is the expanded mesh that has been used on some modules. Is that still a viable design, and does your analysis include aspects of that problem?

MON: Whether or not it is a viable design, I don't know. I have not investigated this. I have only looked at ribbon.

ROSS: I might point out that the algorithm is absolutely applicable as long as you can calculate the strain in that thin mesh. Once you have calculated the strain in the algorithm it will carry you through to an answer as to whether it is cost-effective.

LANDEL: As some of my colleagues know, when I see a nice piece of work I am always one to push it on a little bit further. In conjunction with the discussions which we have heard, then, vis-a-vis corrosion, the question has already been asked, but let's state it specifically: can you estimate how far your strain-versus-cycle (s-n) curves would shift with corrosion, or could someone in the audience shed some light on that?

MON: I have no idea.

WHITE: In the work we have done with some of the modules, I have seen some extensive corrosion on our leads. They have discolored, they got really ugly-looking, but there was no obvious power loss due to that. The only power loss we have seen due to our leads was due to lead breakage caused by pulling too hard on them or something, actually breaking them.

LANDEL: Were these unencapsulated?

WHITE: They were encapsulated.

FEIGE: I assumed you selected the Invar because of its coefficient of expansion, am I correct?

MON: Yes.

FEIGE: I would complement you on the choice. I think you went the right way. I think you are getting enhanced protection with the Invar versus the copper.

MON: If you put the Invar on the outside like Invar/copper/Invar, instead of copper/Invar/copper, that might have a lot of advantages because the Invar would first of all resist fatigue better and it might have a better

corrosion resistance, because we are concerned with corrosion here. Although the copper/stainless/copper proved not be a good material, if you reversed that and made it stainless/copper/stainless you might begin to have a better performance from the point of view of fatigue resistance and corrosion.

FEIGE: OK. I'll buy that.

LEE: Just to follow up on the strain-versus-cycles (s-n) curves: for corrodible material you would see a significant shift in the s-n curves, a significant degradation in the life at a given stress, and in the case of copper that might be the case. We haven't done any work in our lab. We have dealt primarily with steels and stainless steels but you can see an order of magnitude shift in life at a given stress in the presence of a corrosive environment. So you might have some conservative data, having generated the s-n curves in your laboratory air environment. If you looked at a cleaner environment which you might have in the encapsulation, you might actually see a longer life. In terms of the composites or the clad materials you have, if you have the Invar between the copper you may in fact have favorable galvanic relationships because you will have a small cathode and large anode. Similarly with the stainless clad on top of the copper you may have an inherently more corrosion-resistant material with the stainless steel on the surface. But if you do have any perforation of the stainless surface, then you will have very unfavorable relationships with large cathode areas with the stainless steel and very small anode areas with the copper where you have the perforation of the stainless steel. Which would lead to through-penetration.

MON: Looking at the physical side of crack propagation, I think that the material will cycle for 90% of its life before a crack develops. The remaining 10% (and these are rough numbers) the crack will propagate. So I think corrosion would not be a problem because as long as the interconnect is encapsulated, 90% of its life will go by without experiencing much in the way of corrosive environment. Then when it does crack and water or what have you gets in, I don't think there is that much time left for the corrosion to really speed up the final failure. Am I wrong on that?

FEIGE: Corrosion fatigue will be quite a factor. It will rapidly accelerate the rate of failure.

MON: It is clear that we have done nothing on corrosion. We have talked about it a lot but it would be difficult to design this type of test. Encapsulate a material and then shake it back and forth in a shaker. We could put it in a chamber. It's another thing to do.