Decision Support System for Design of AEPS Modules

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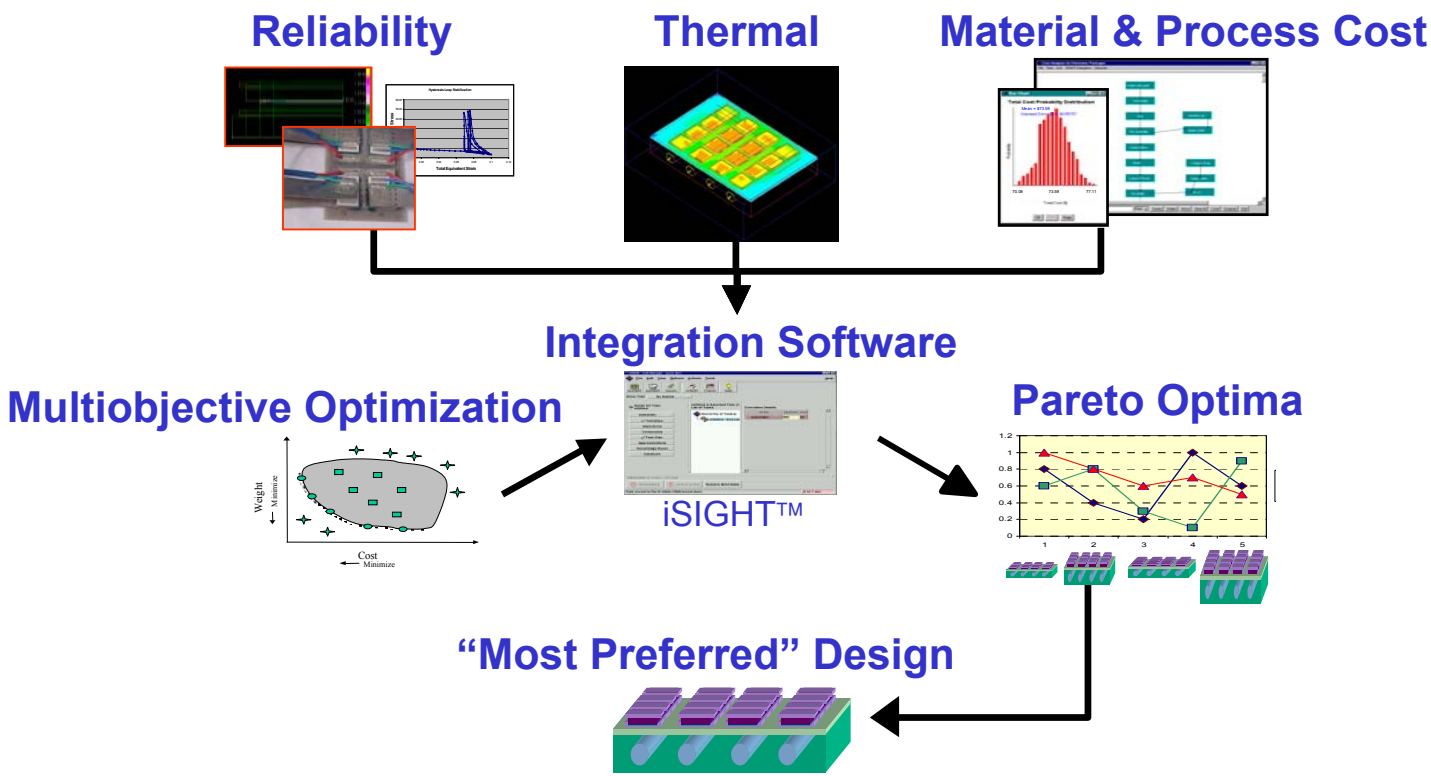
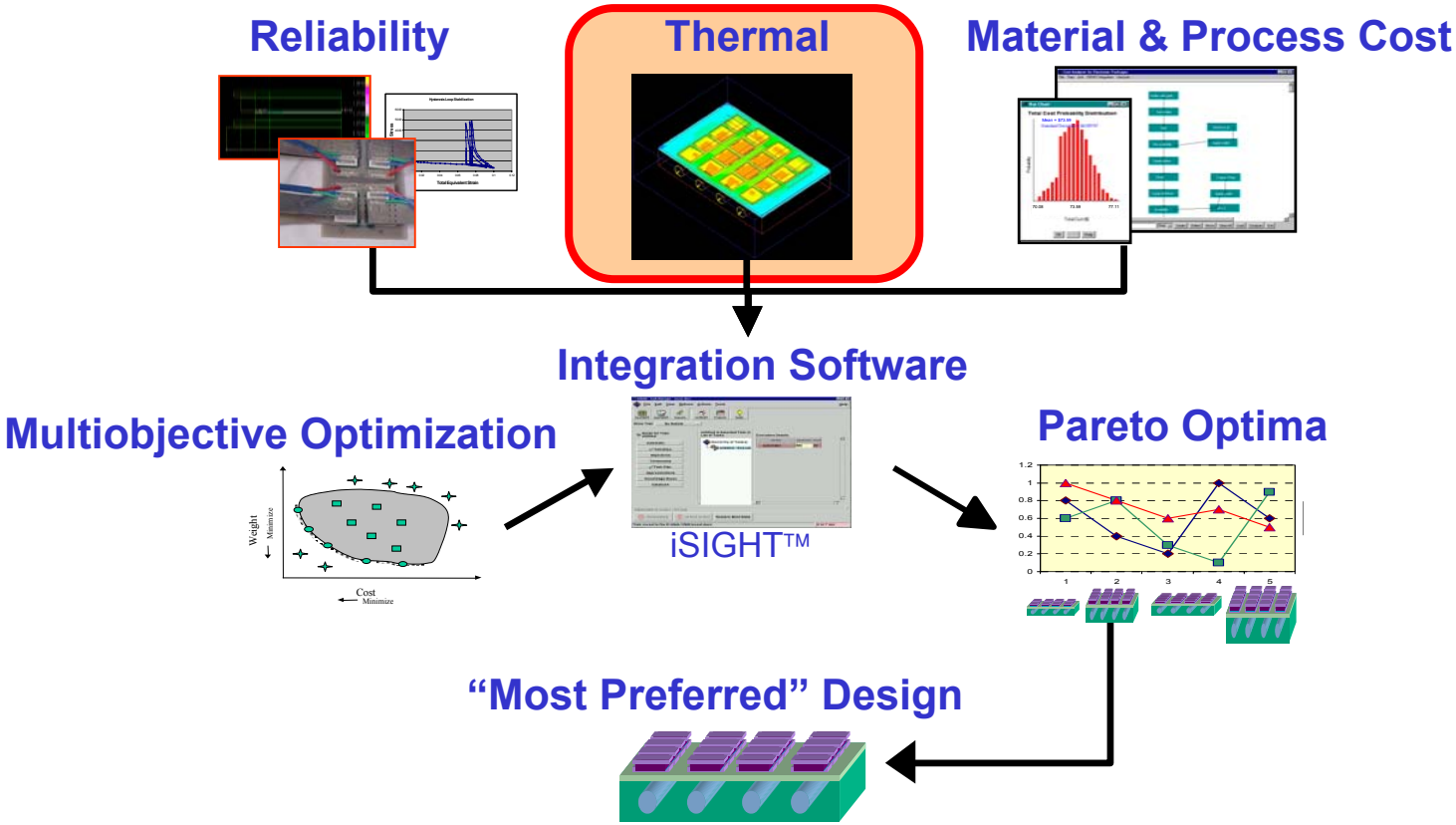
Overall Objective



Objective: Develop a decision support system for design of AEPS modules that facilitates optimized tradeoff explorations of thermal, reliability, and cost at the earliest stages of the development

Thermal: Objective

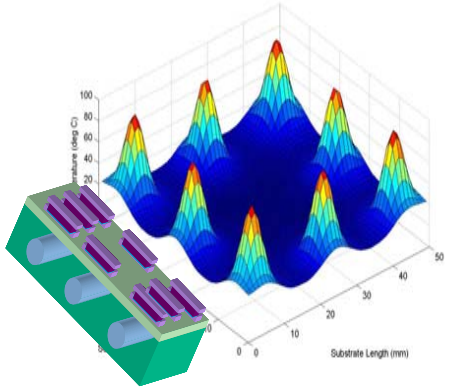


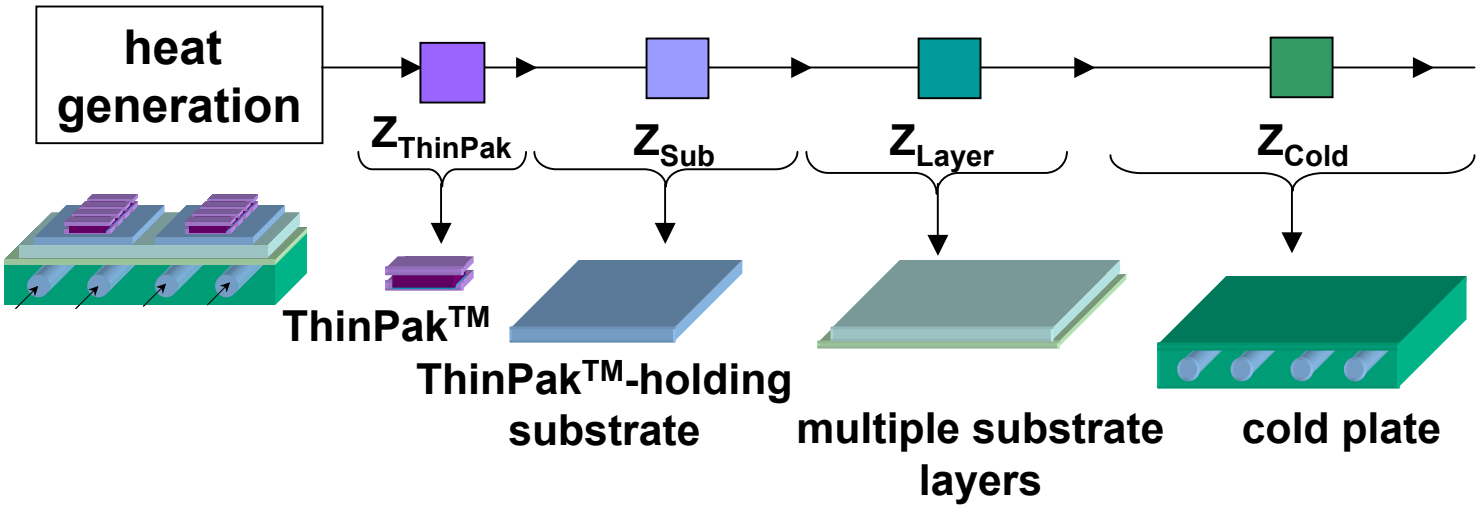
Objective: Develop a computationally efficient model for predicting and optimizing transient thermal performance of liquid cooled AEPS modules

Thermal Model

Thermal model has two main parts:

- **1st part*: obtains transient surface temperature based on ThinPak™ transient heat dissipation**
- **2nd part: impedance network, using maximum surface temperature obtains maximum junction temperature**



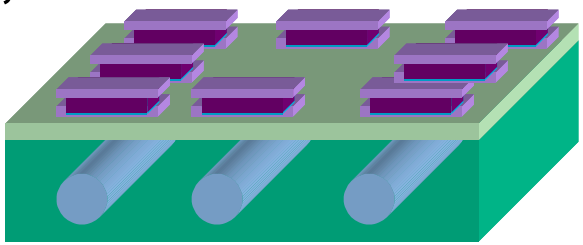


* Kokkas, A. "Thermal Analysis of Multiple-Layer Structure," *IEEE Transactions on Electron Devices,* 21(11), pp. 674-681, 1974

Thermal: Case Study

Problem: Optimize ThinPak™ locations:

- Minimize "maximum junction temperature"
- Minimize "overall coolant pressure drop"



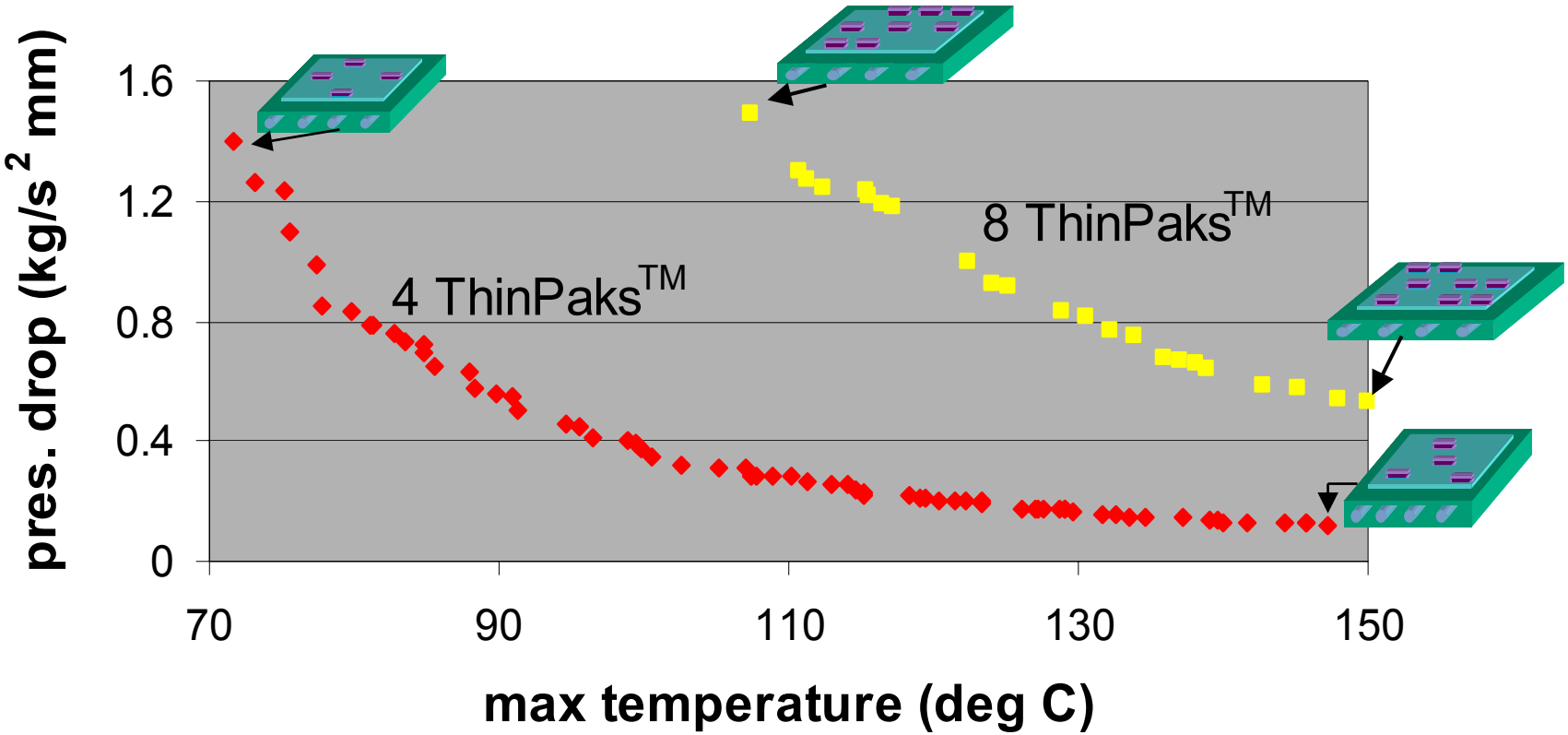
Assumptions:

- Uniform heat distribution for ThinPaks™
- Adiabatic open surfaces for the module
- Thermal properties of module independent of temperature
- Initially, module and coolant with same temperature
- Heat generation only from ThinPaks™
- ThinPak™: 5 mm x 5 mm x 2 mm, dissipates 200 W for 5 sec
- 50 mm x 50 mm < (substrate & cold plate) < 100 mm x 100 mm

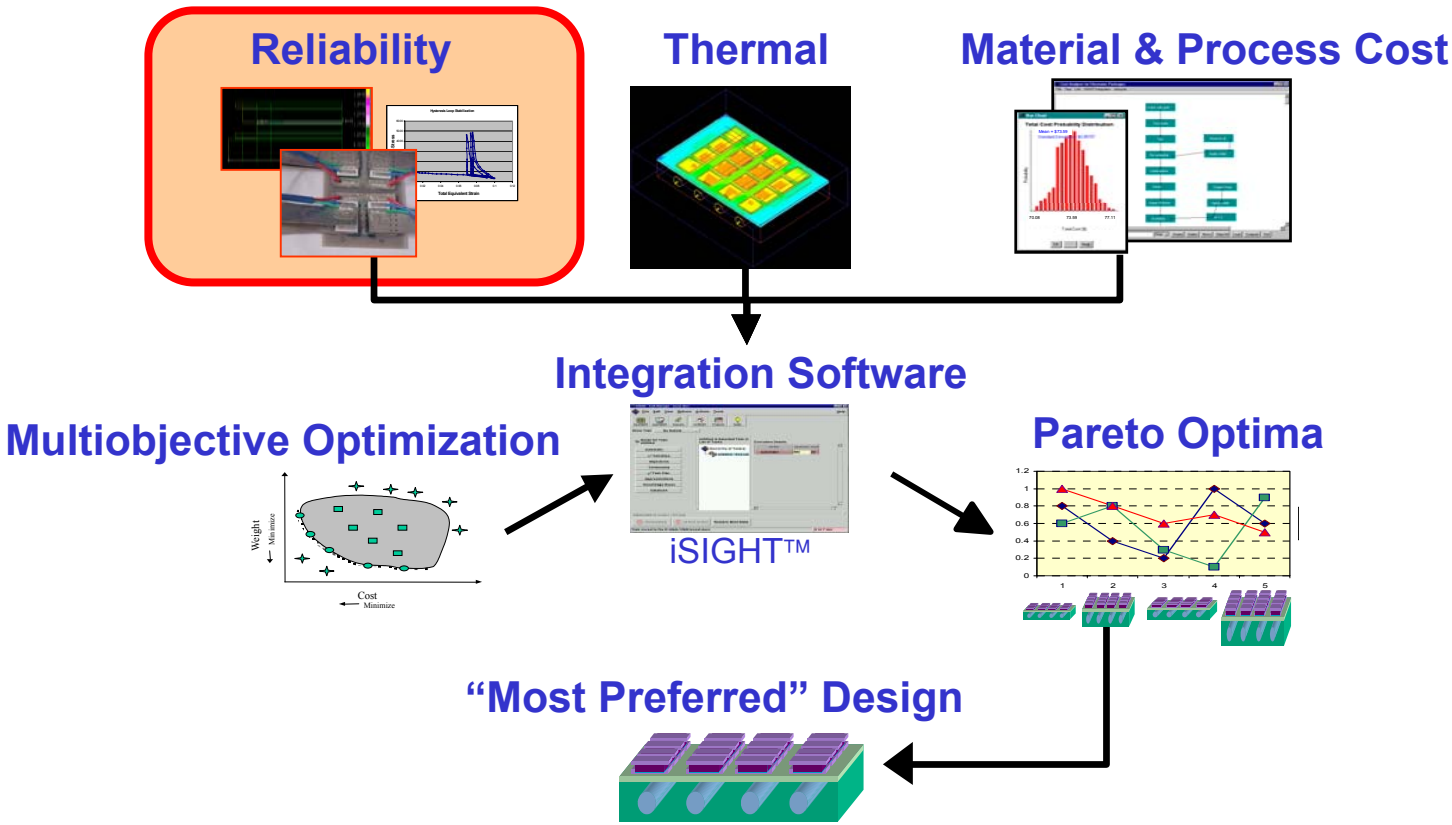
Kaczorowski, P.R., Y. Joshi, and S. Azarm, "Thermal-Based Multi-Objective Optimal Design of Liquid Cooled Power Electronic Modules," *19th Semiconductor Thermal Measurement and Management Symposium* ("SEMITHERM"), San Jose, CA, March 11-13, 2003 (submitted)

Thermal: Case Study Results

Pareto optimum locations of ThinPaks™ on a single substrate attached to a cold plate:



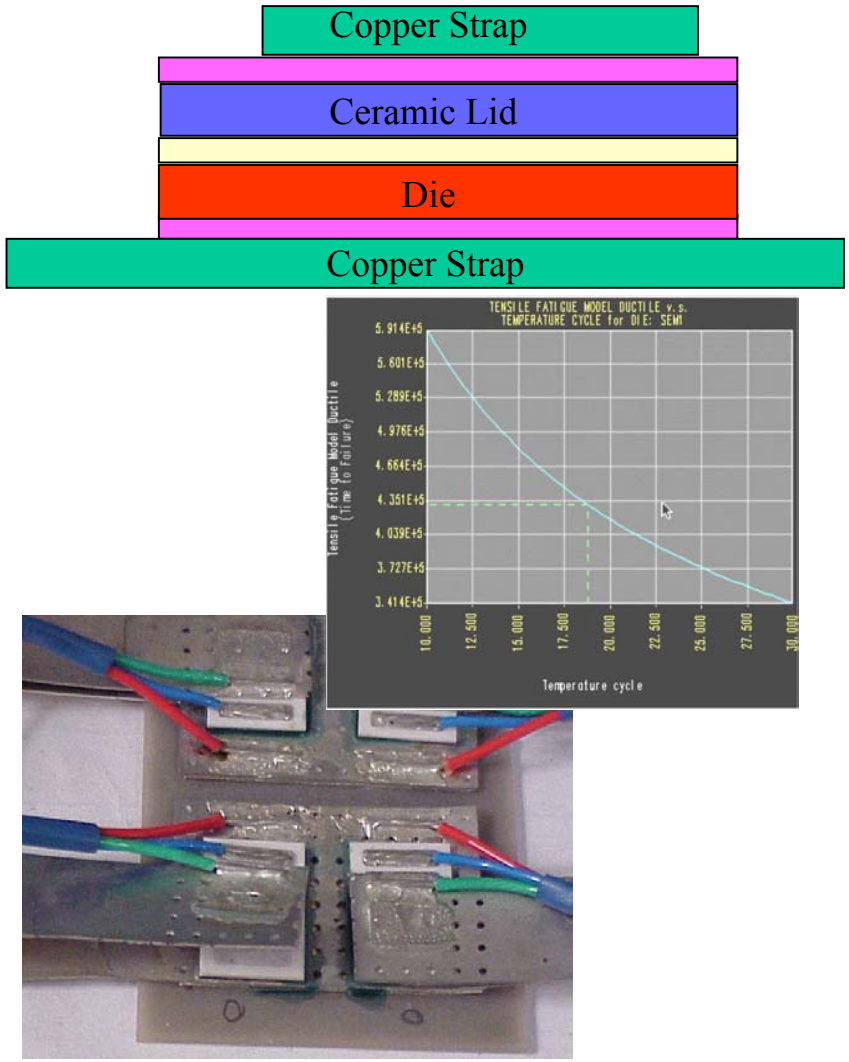
Reliability: Objective



Objective: Develop models for critical failure mechanisms of AEPS modules

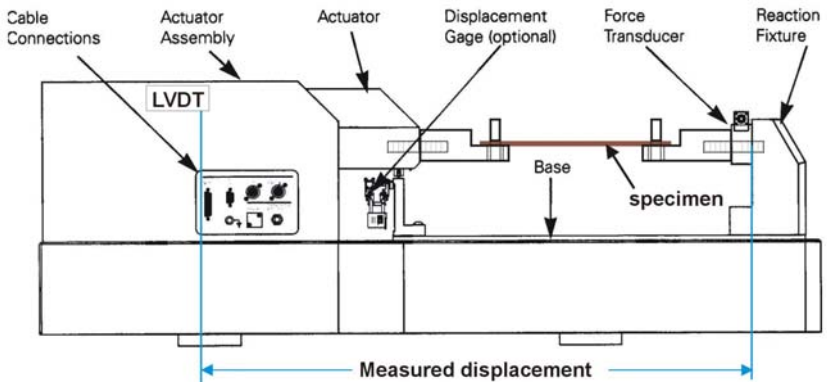
Reliability: Attach Modeling

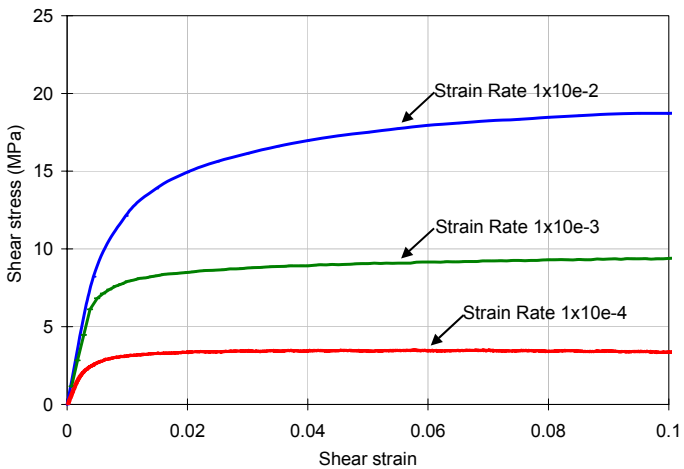
- Developed viscoplastic semi analytical model for fatigue of attach in ThinPak™ modules
- Developed iterative crack propagation model for fatigue of attach in multi-layer modules
- Validated models against -55°C to 150°C thermal cycling results for ThinPak™ modules
- Revealed dominant failure mechanism to be attach fatigue at the copper strap leading to design modification



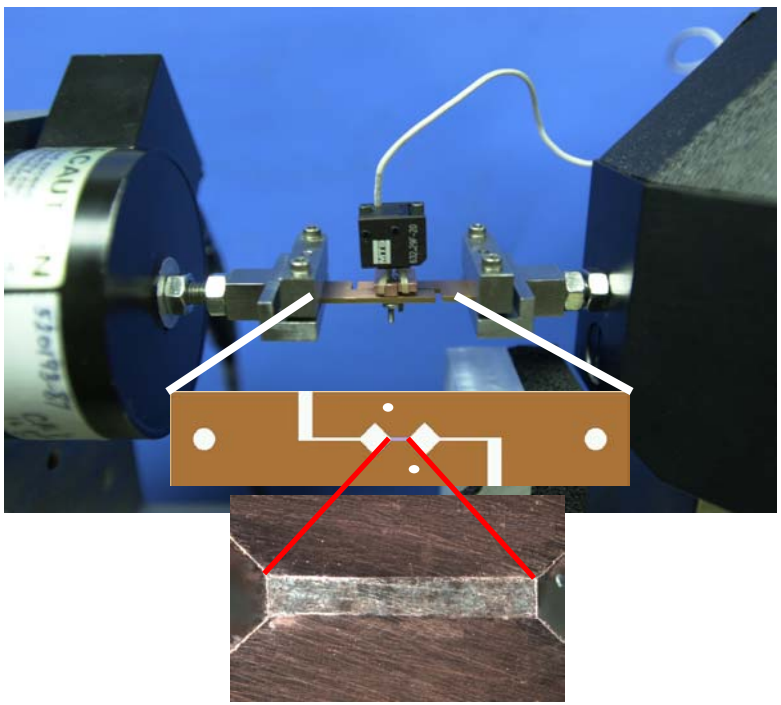
Reliability: Attach Properties

- Determined constitutive properties for attach materials to assess the fatigue resistance of the attach
- Developed test sample configuration and protocol for determining the fatigue coefficients for attach materials



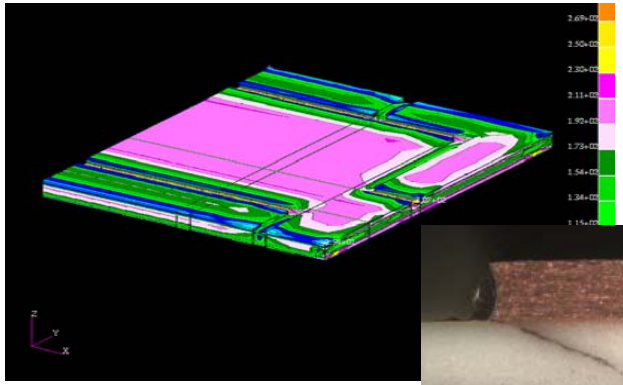


Constitutive properties for Pb2Sn2.5Ag



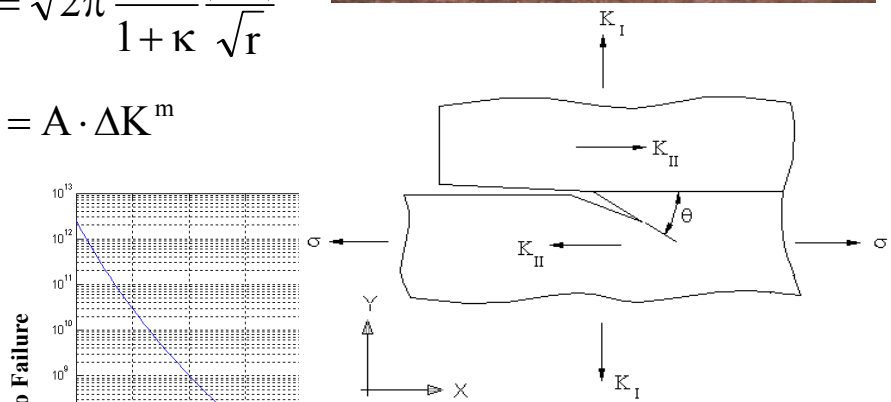
Reliability: DBC-AlN Cracking

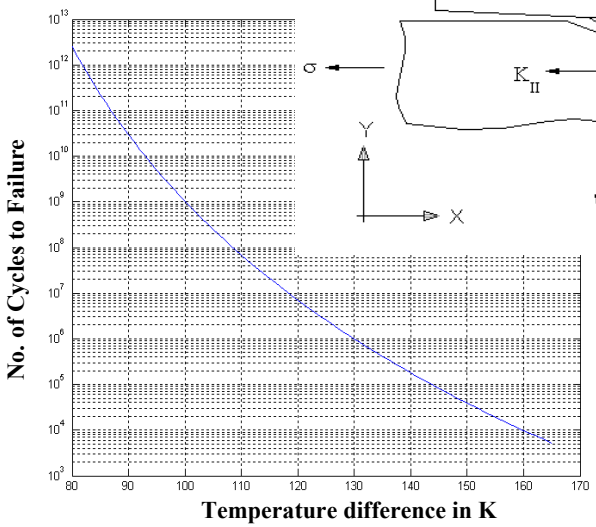
- Determined crack initiation site in DBC-AlN to be at edges of the copper using FEM and experimental observation of thermal shock test results
- Developed an analytical model for copper edge cracking of DBC using Paris' law and the method of Drory for calculating K_I and K_{II}
- Confirmed the analytical model for copper edge cracking using FEM for determining K_I and K_{II}



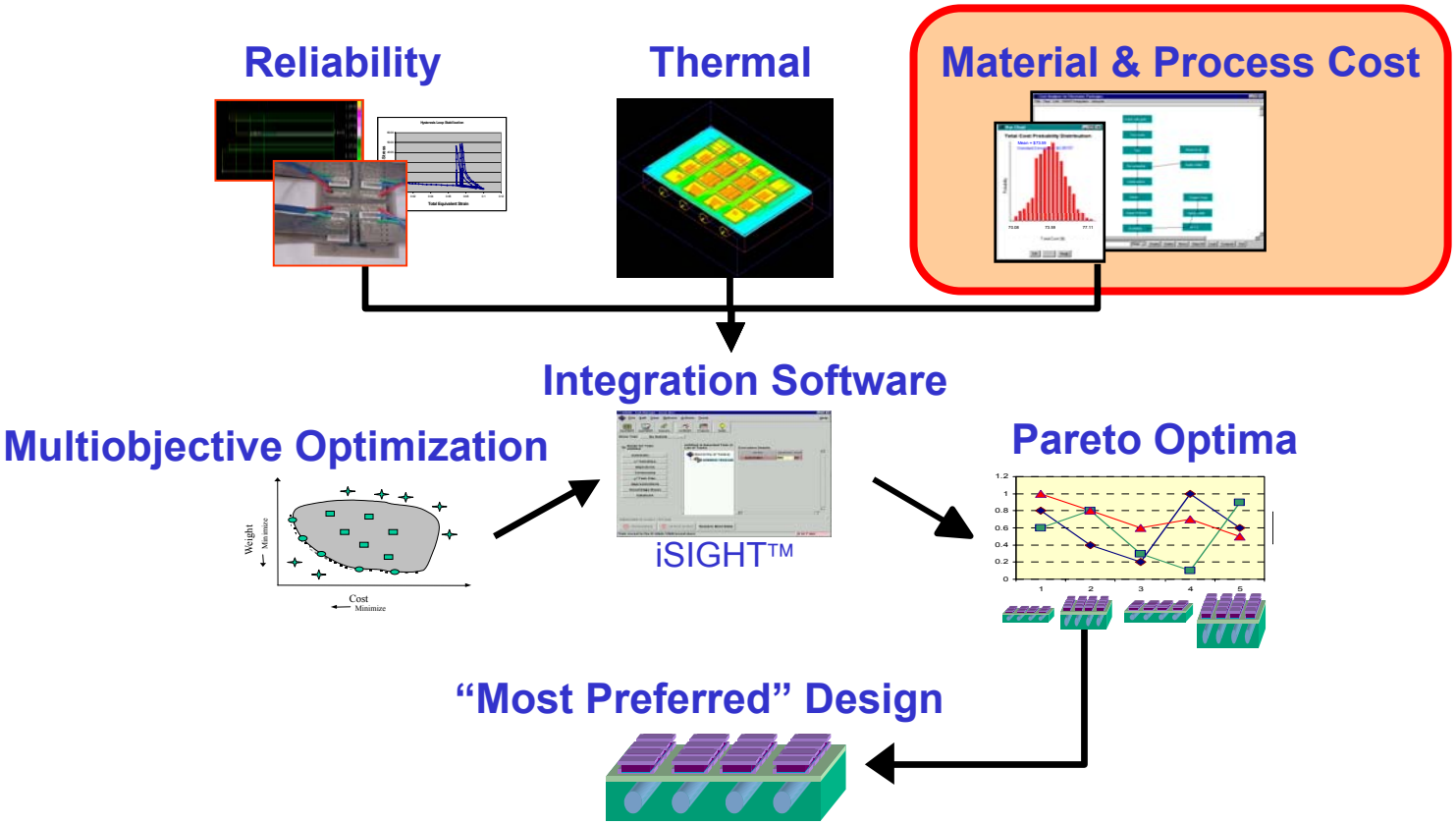
$$K_I = \sqrt{2\pi}\,\frac{G}{1+\kappa}\,\frac{|\Delta\upsilon|}{\sqrt{r}}$$

$$\frac{da}{dN} = A \cdot \Delta K^m$$



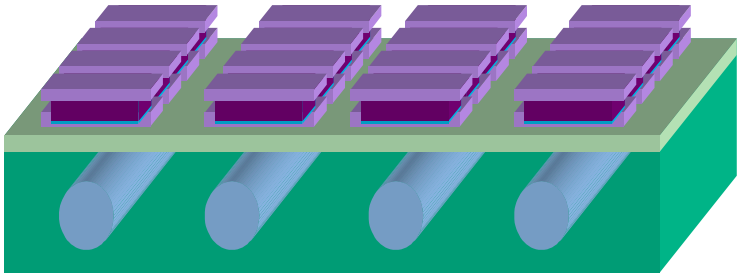


Cost: Objective

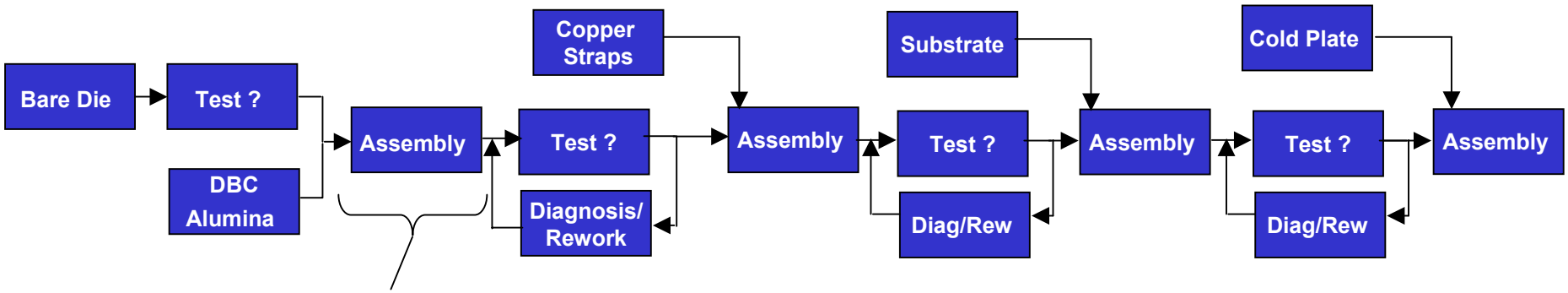


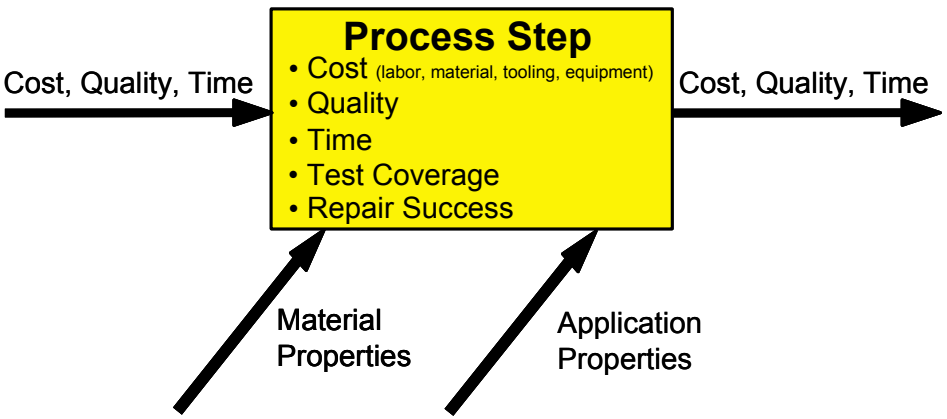
Objective: Develop an economic analysis tool that can be used concurrently with thermal and reliability analysis for optimization of AEPS modules

Cost: Process-Flow Modeling



Developed process-based model that simulates manufacturing and life cycle operations to estimate cost and yield

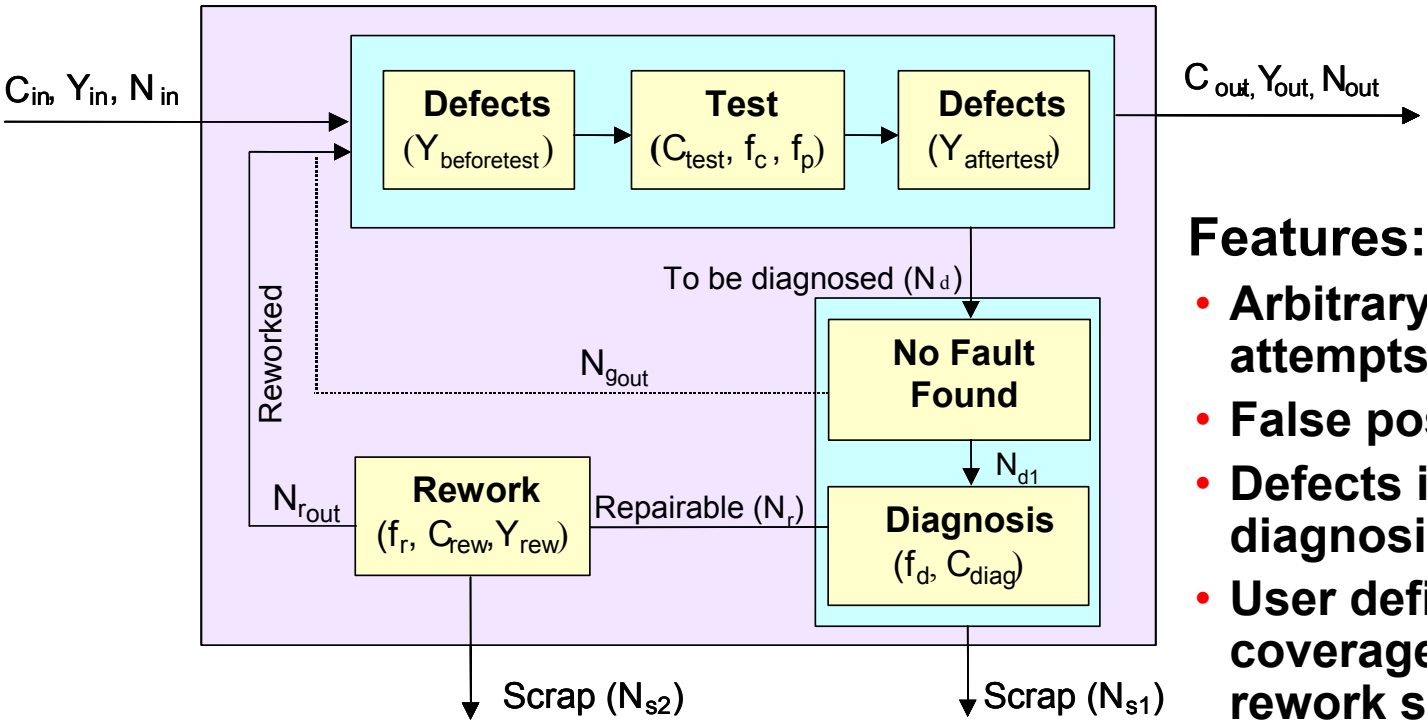




- **Models varying designs and process flows**
- **Accounts for uncertainties in all of the input data**
- **Accommodates detailed test/rework economics**

Cost: Test/Diagnosis/Rework

Developed a new test/diagnosis/rework model that can be used with process flow based cost modeling



Features:

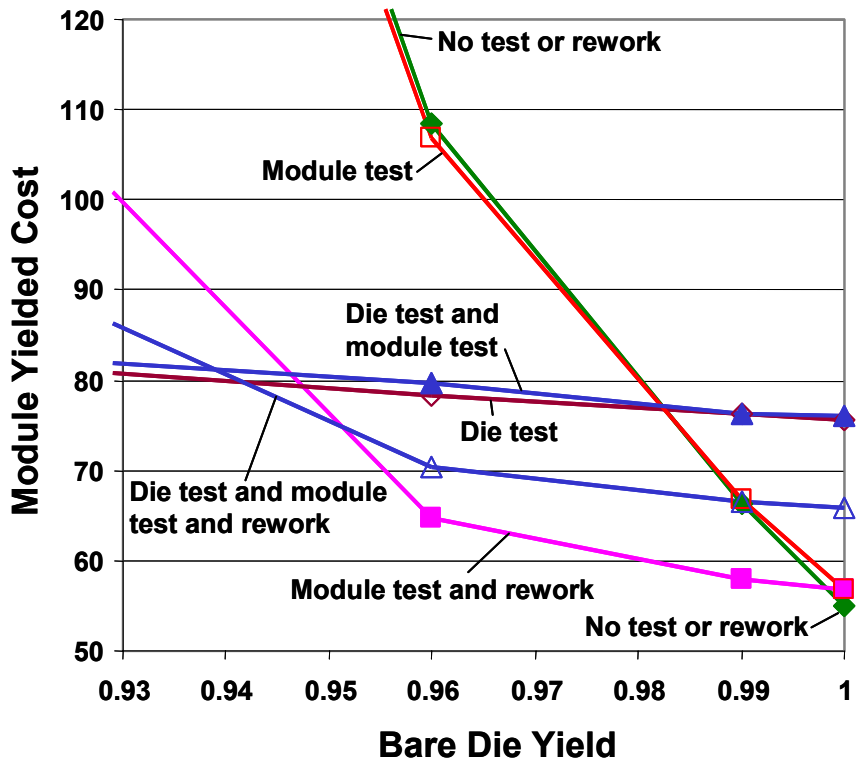
- Arbitrary number of rework attempts
- False positives in testing
- Defects introduced by test, diagnosis and/or rework
- User definable fault coverage, diagnosis and rework success rates
- Variable rework costs
- Accommodation of data input uncertainties

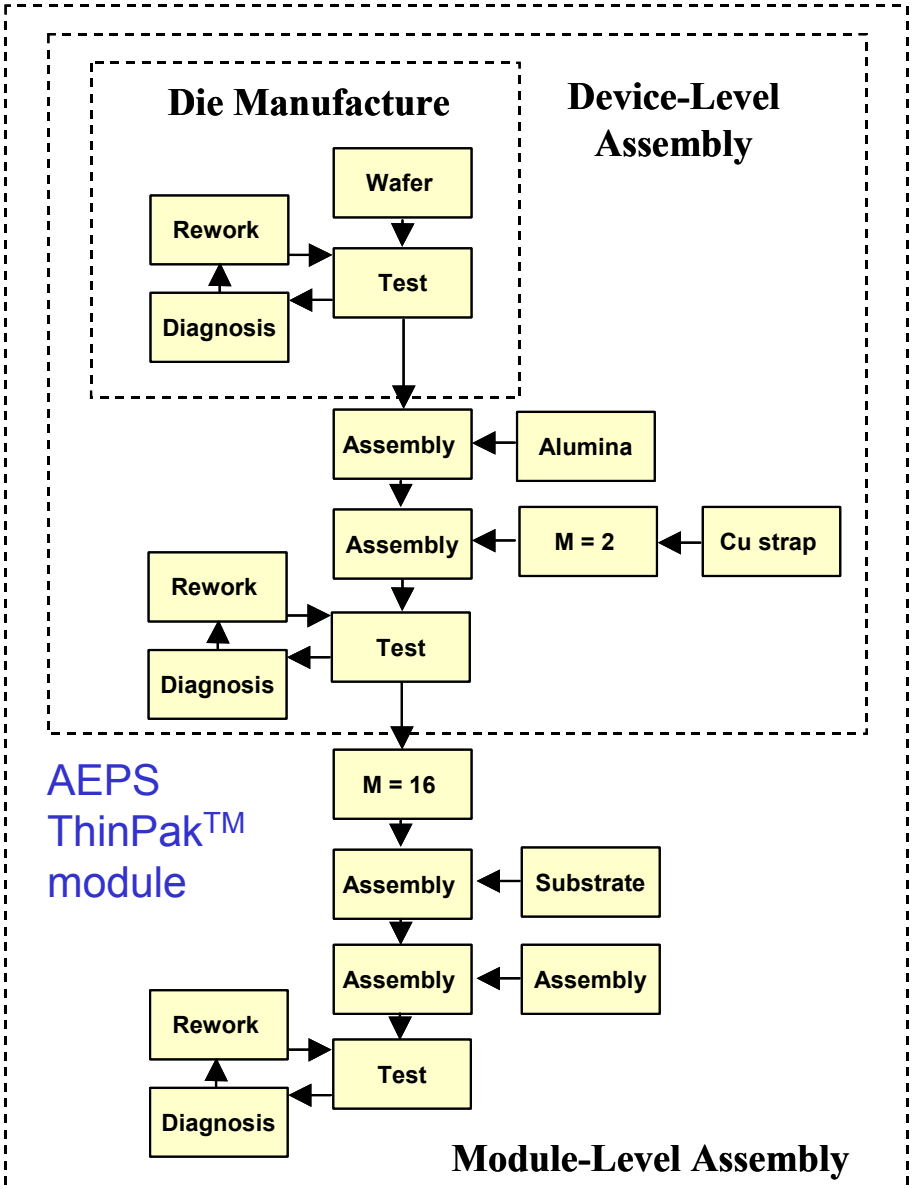
T. Trichy, P. Sandborn, R. Raghavan, and S. Sahasrabudhe, "A New Test/Diagnosis/Rework Model for Use in Technical Cost Modeling of Electronic Systems Assembly," *Proceedings of the International Test Conference*, pp. 1108-1117, November 2001

Cost: Test Location Optimization

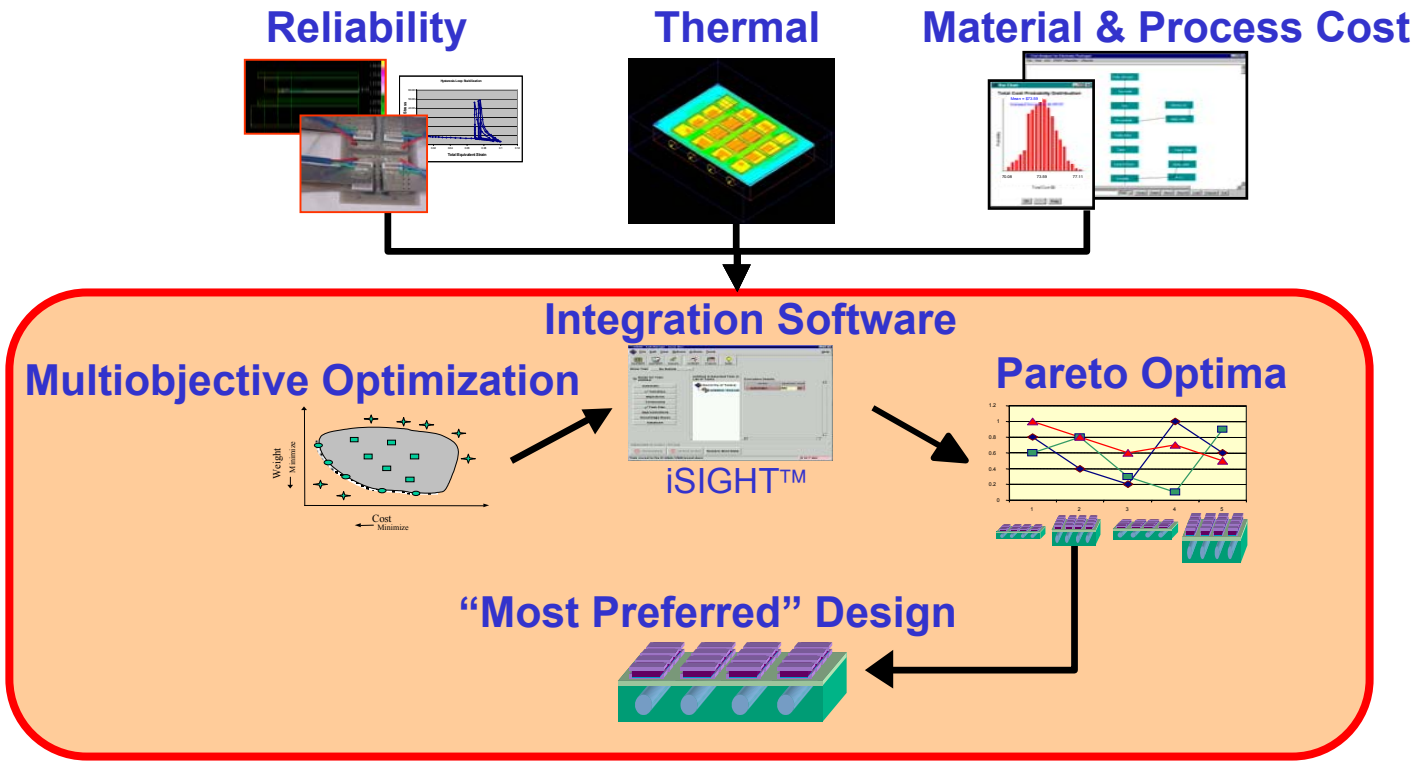
Which test/diagnosis/rework steps should be included to minimize yielded cost?

- Genetic algorithm for placing test steps and selecting fault coverage





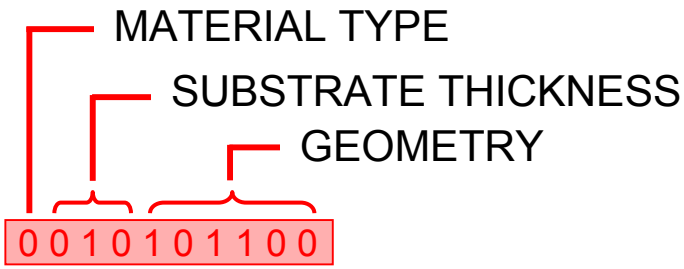
Optimization and Selection: Objective



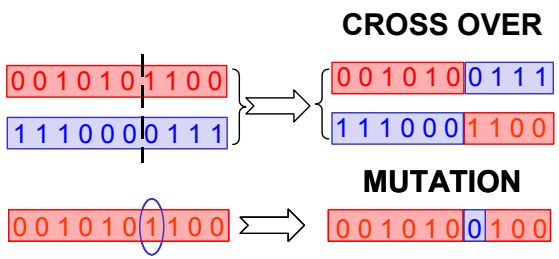
Objective: Develop a decision support system with <u>Multi-Objective Optimization</u> and <u>Selection</u> methods to choose the "most preferred" AEPS module design alternative

Optimization with MOGA
Multi-Objective Genetic Algorithm

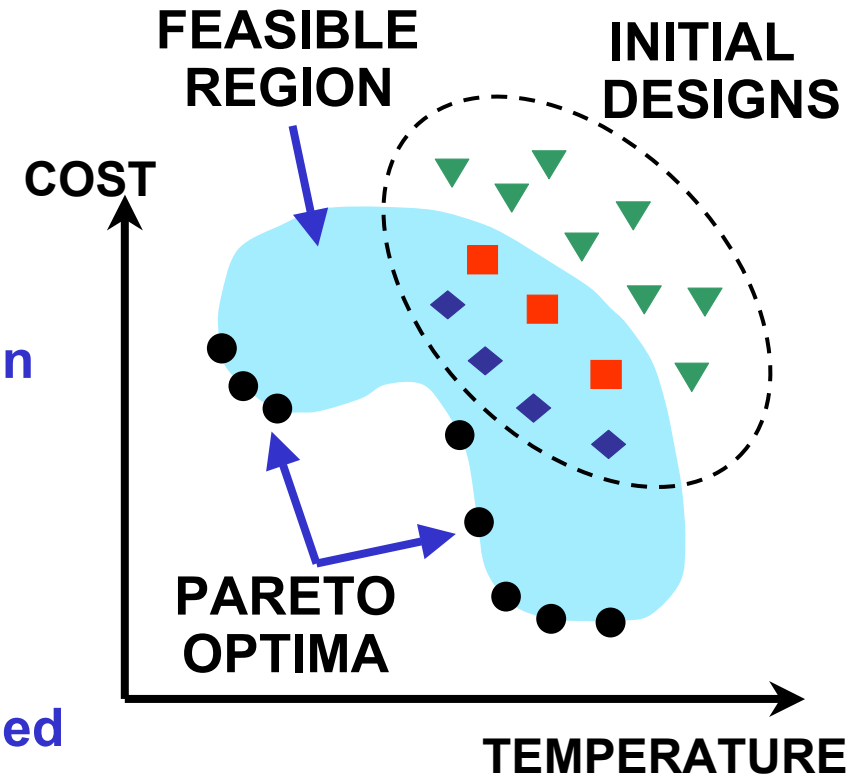
1. Code AEPS module designs into "chromosomes"



2. Generate random initial designs
3. Evolve via crossover and mutation



4. Fitness of a design evaluated based on "multi-objective dominance"



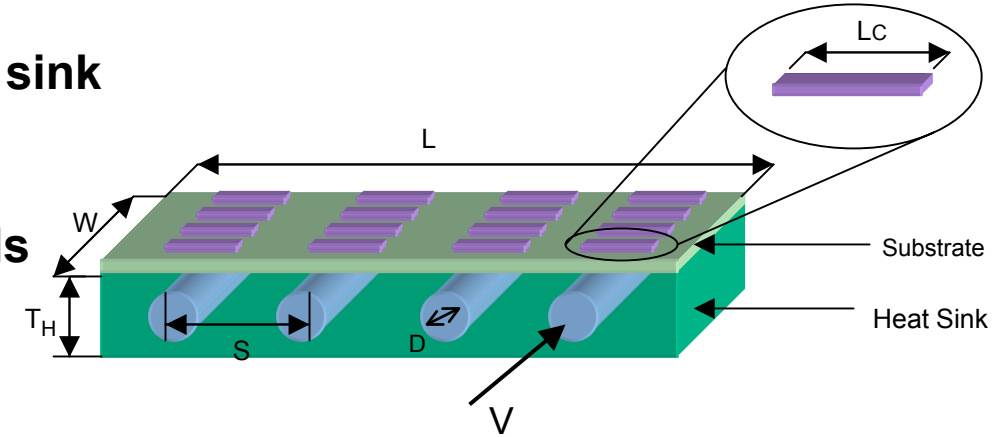
Farhnag-Mehr, A., and S. Azarm, "Entropy Based Multiobjective Genetic Algorithm for Design Optimization," *Structural and Multidisciplinary Optimization*, 2002 (in press)

Reynold, B., and S. Azarm, "A Mutiobjective Hybrid Heuritic-Based Genetic Algorithm," *Mechanics of Structures and Machines*, 2002 (in press)

Optimization: Case Study

Variables:

- L,W : Length and Width of heat sink
- T_S : Thickness of Substrate
- T_D : Thickness of Die attach
- S : Spacing between channels
- D : Diameter of channels
- V : Inlet velocity
- K_H : Heat sink material
- K_S : Substrate material
- K_{so} : Solder Material



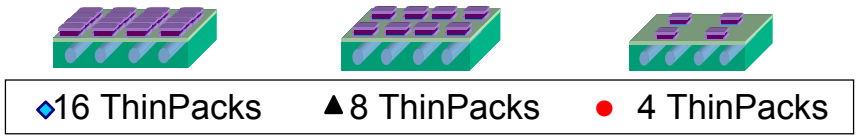
Constants:

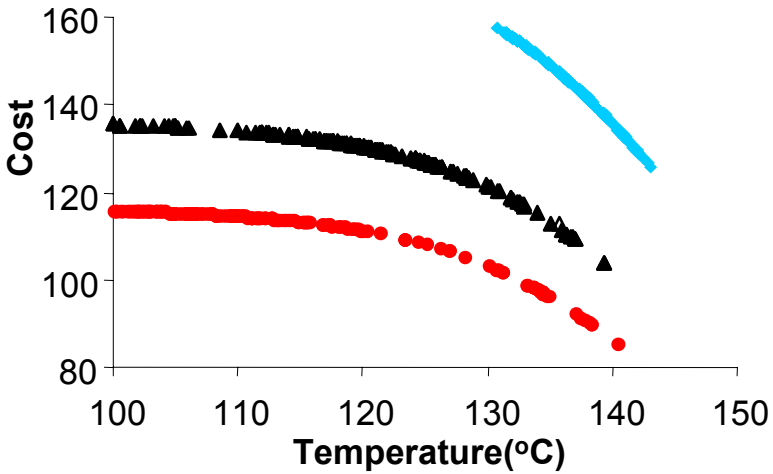
- N : Number of devices
- L_C,W_C : Length and width of ThinPack™
- T_H : Thickness of sink
- T_C : Thickness of copper layer
- T_{so} : Thickness of solder layer
- Q : Power dissipated by device

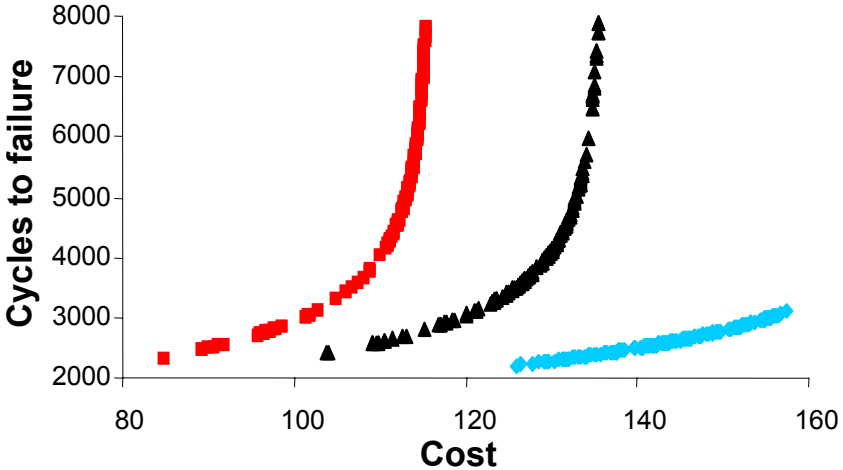
Design objectives:

- Maximum junction temp ⬇
- Cost ⬇
- Cycles to failure ⬆

Optimization: Case Study
Pareto Optimum Solutions

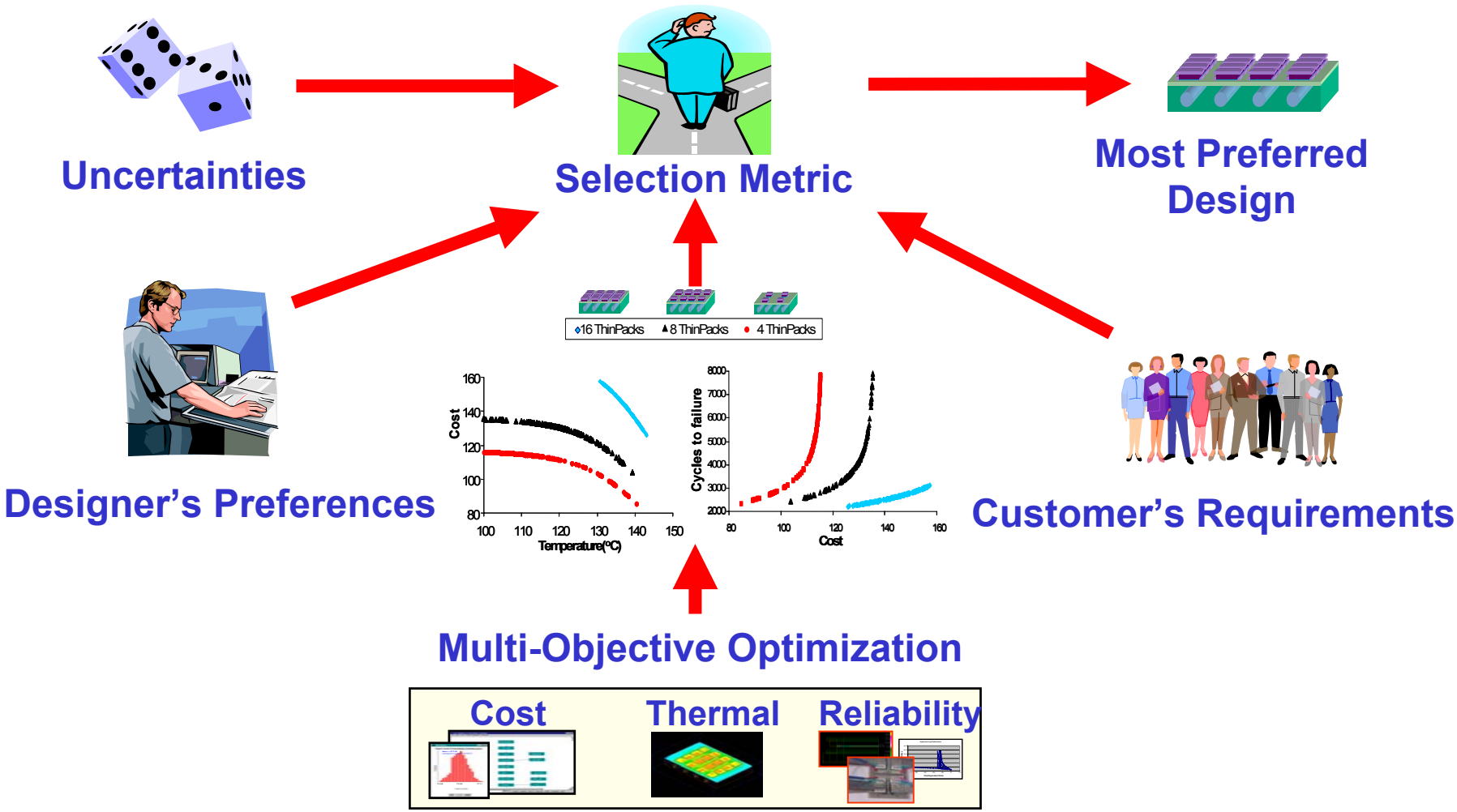






Which AEPS module design alternative, among Pareto solutions, is the "most preferred"?

Selection

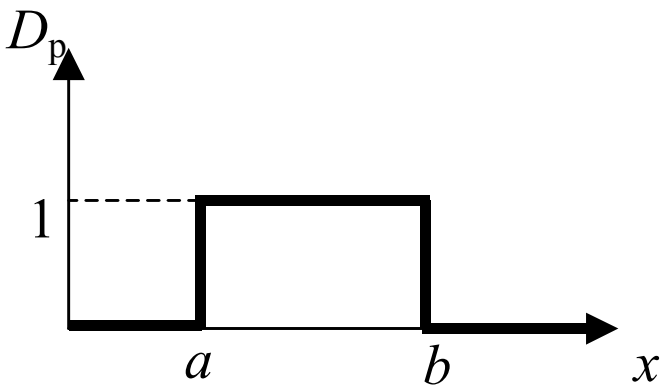


Besharati, B., S. Azarm, and A. Farhang-Mehr, "A Customer-Based Expected Utility Metric for Product Design Selection," CD-ROM *Proceedings of the ASME IDETC*, Montreal, Canada, Sept 2002

Selection: Definitions
Purchase Decision and Demand

- **Customer buys a product if level of attribute x is within customer range: $[a,b]$**

$$D_{\mathrm{p}}(x) = \begin{cases} 1 & \text{If } x \text{ is within customer range} \\ 0 & \text{If } x \text{ is outside customer range} \end{cases}$$

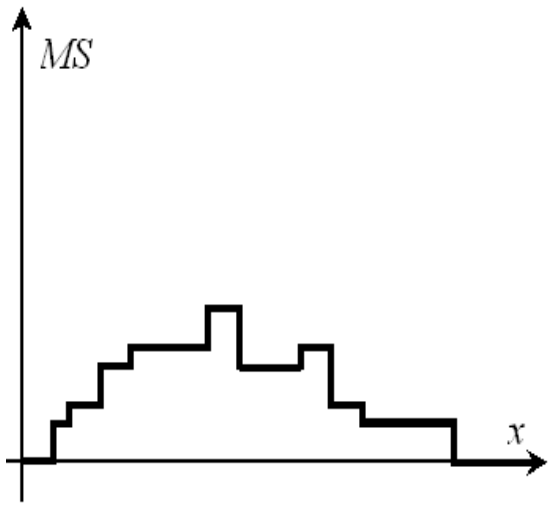


- **Normalized demand (MS)**

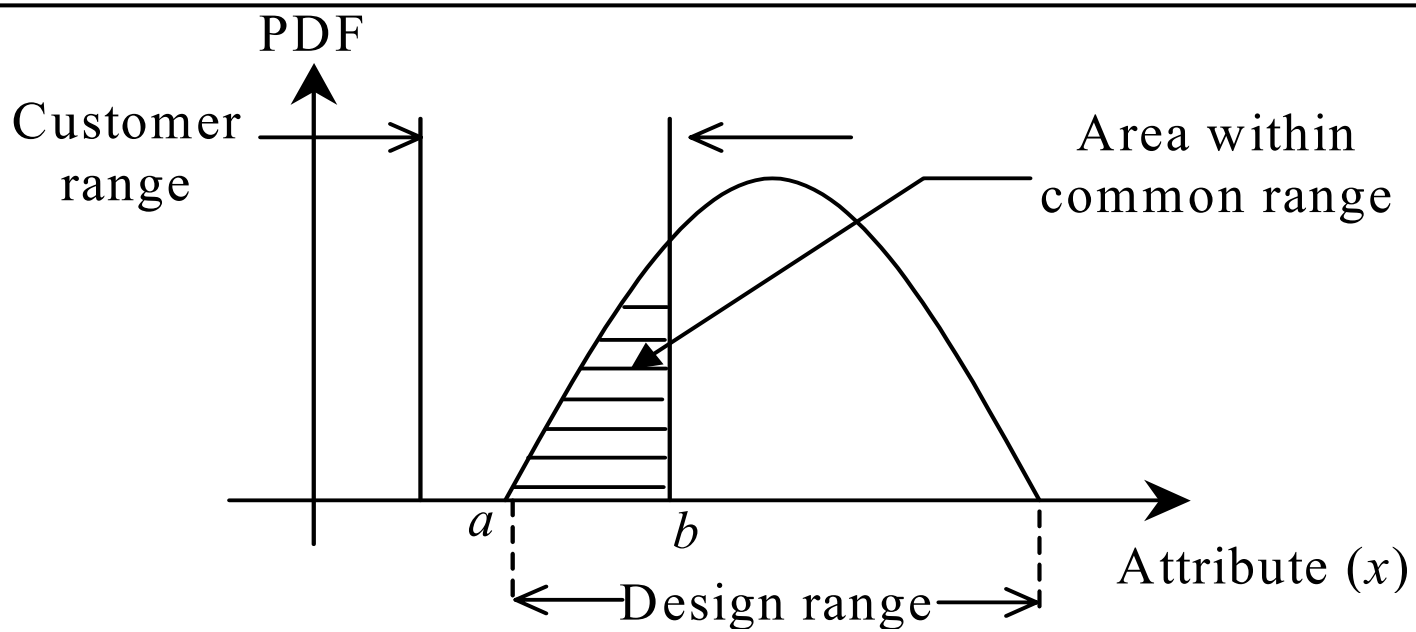
For attribute levels $\mathbf{x}$:

$$MS(\mathbf{x}) = \frac{\sum_{i=1}^{N} D_{\mathrm{p}_i}(\mathbf{x})}{N}$$

N = number of customers in market



Selection: Definitions (cont'd)
Probability of Success (P_s)



$$P_s(x) = \int_a^b p(x)dx = \int D_p(x)p(x)dx$$ single attribute

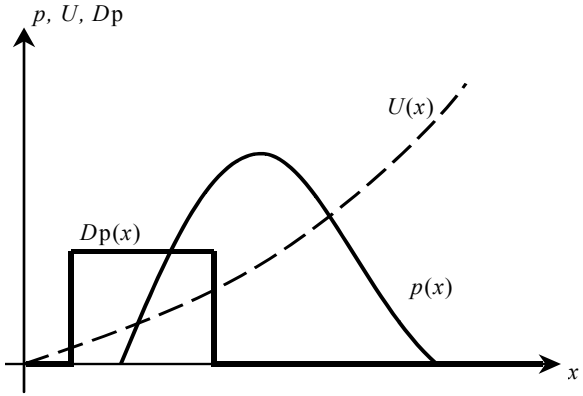
$$P_S(\mathbf{x}) = \int\int\cdots\int D_p(\mathbf{x})\,p(\mathbf{x})dx_1 dx_2 \ldots dx_n$$ multiple attributes

Suh, N. P., Axiomatic Design: Advances and Applications, Oxford University Press, New York, 2001

Selection: Metric
Customer-Based Expected Utility (*CEU*)

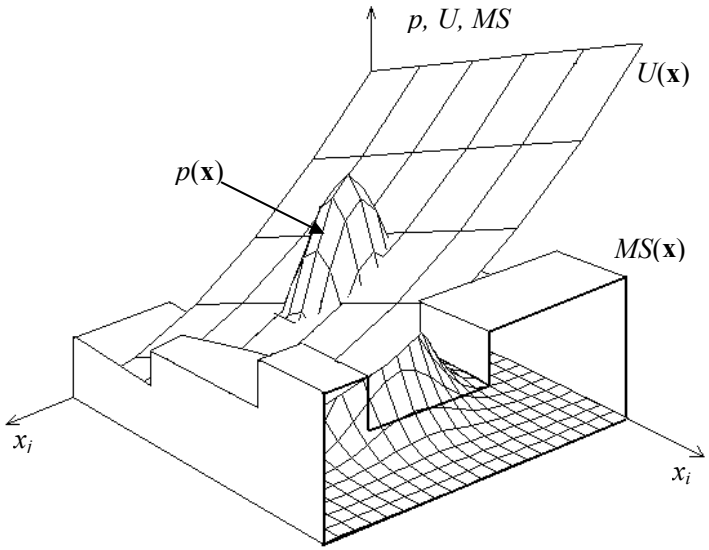
- **Single customer:**

$$CEU(\mathbf{x}) = \int\int\cdots\int D_{\mathrm{p}}(\mathbf{x})\,p(\mathbf{x})U(\mathbf{x})dx_1dx_2\ldots dx_n$$

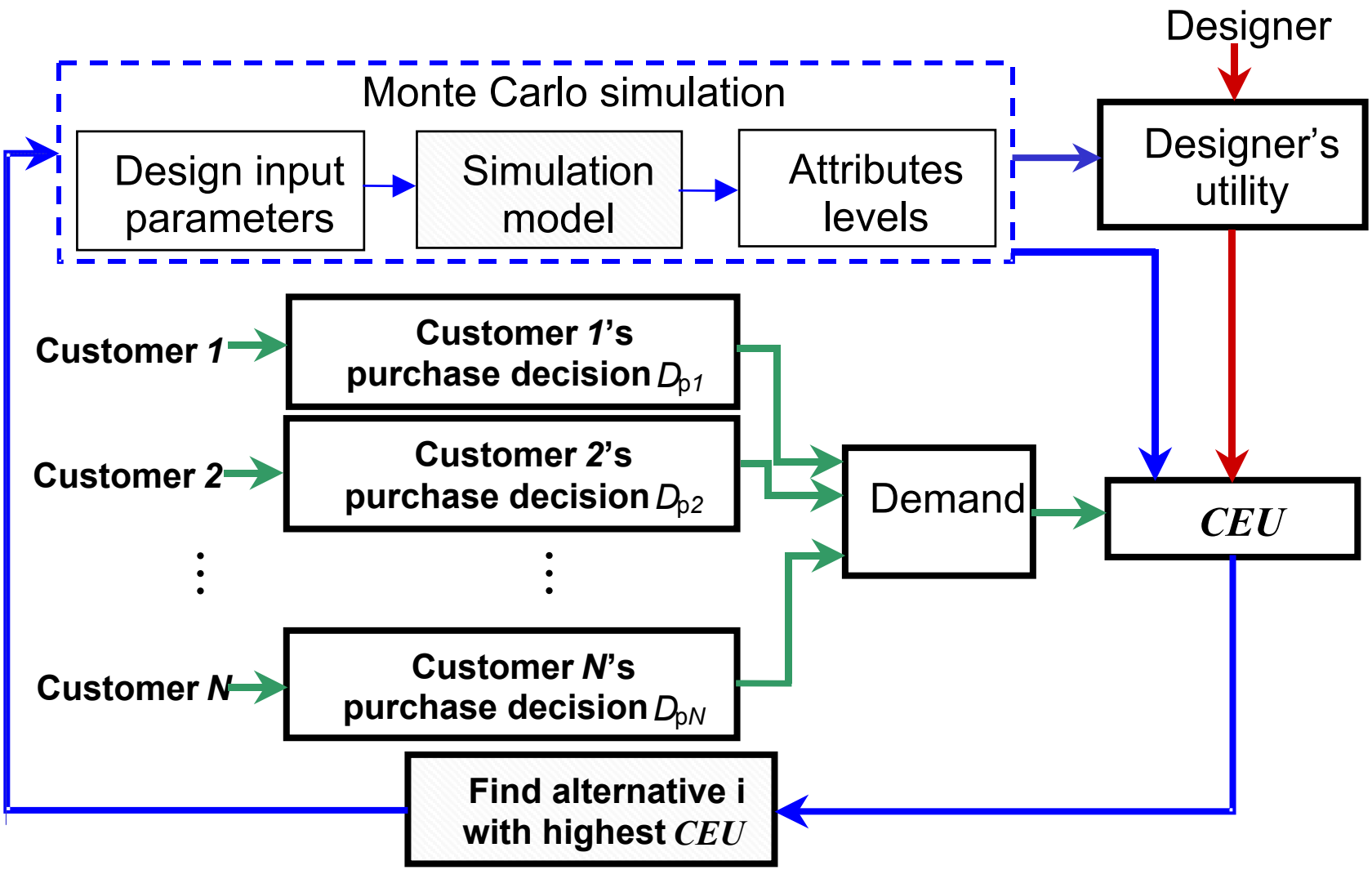


- **Multiple customers:**

$$CEU(\mathbf{x}) = \int\int\cdots\int MS(\mathbf{x})\,p(\mathbf{x})U(\mathbf{x})dx_1dx_2\ldots dx_n$$



Selection: Methodology



Selection: Case Study

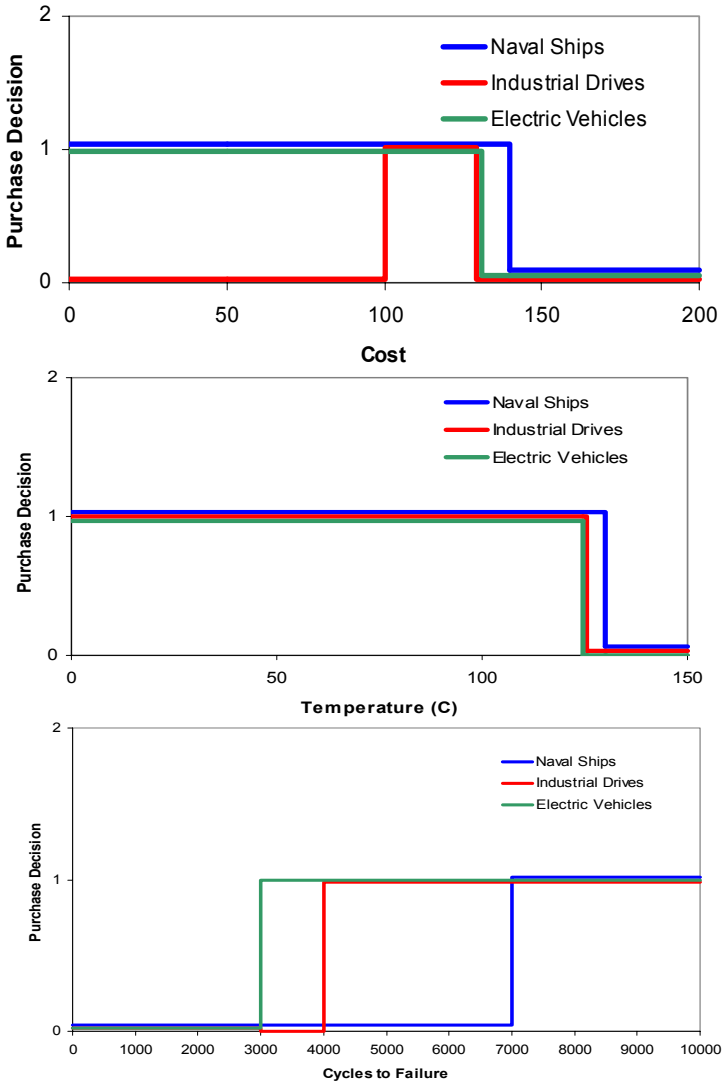
Problem: Select AEPS module design from the Pareto solutions, given purchase decision profiles:

- Single customer: Navy Ships
- Multiple customers: Navy Ships; Industrial Drives; and Electric Vehicles

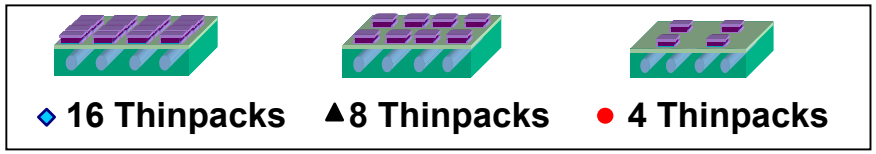
Designer's utility:

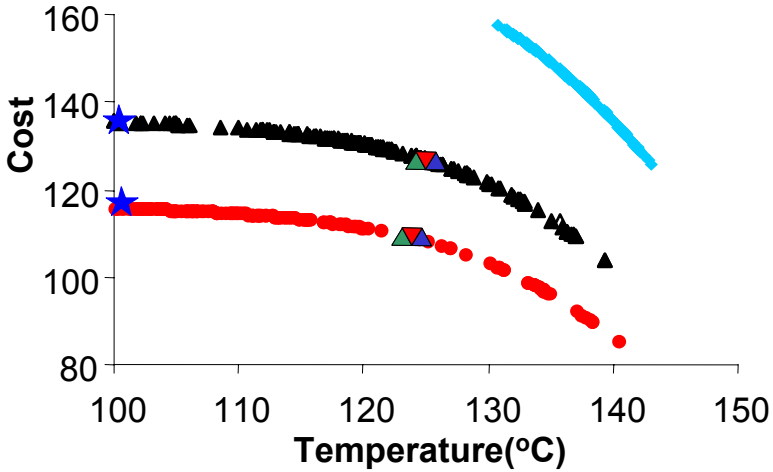
- Temperature and reliability are more important than cost
- Reliability is more important than temperature

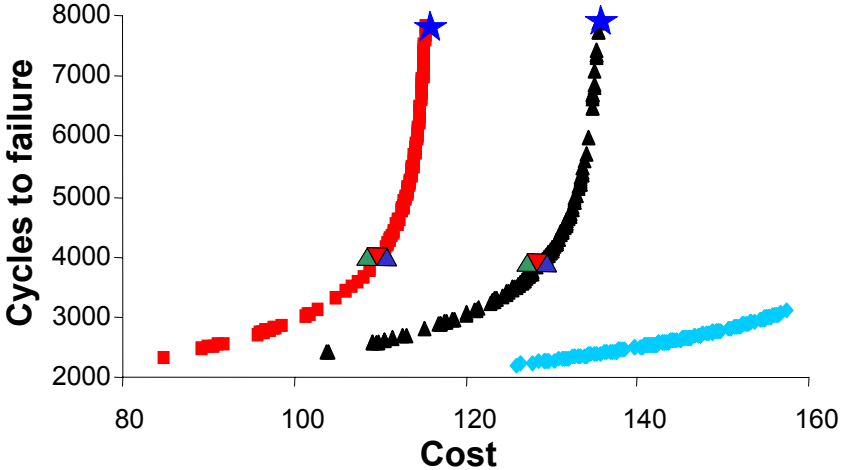
Purchase Decision Profiles



Selection: Case Study Results







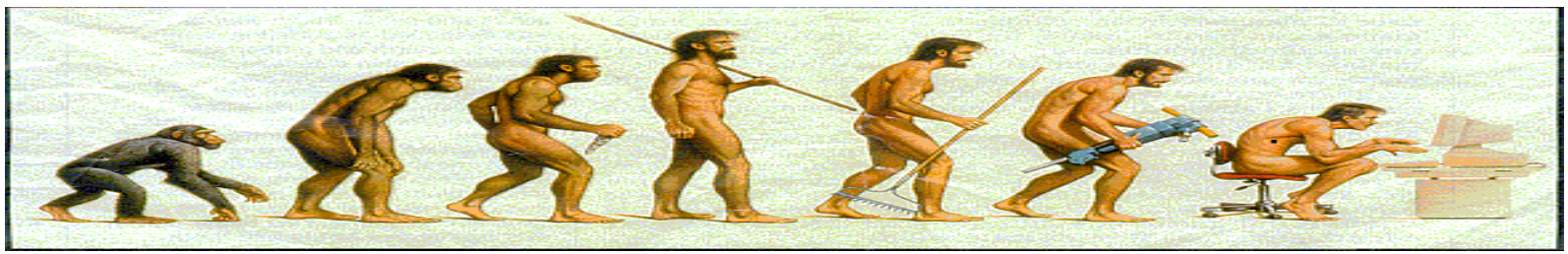
The *CEU* metric:

- Penalizes alternatives falling outside customer's requirements
- Selects, among alternatives within customer's requirements, the alternative with highest designer's utility

Summary

Developed for AEPS module architectures:

- Transient thermal compact model with multiple device interactions
- Failure mechanisms, including attach fatigue and substrate fracture models
- Process flow based cost model with test/diagnosis/rework capabilities
- Multi-objective design optimization and selection methods



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Aug'98 Nov'99 May'01 Aug'02