Solar Thermal Systems Analysis

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National Renewable Energy Laboratory

U.S. Department of Energy
Solar Energy Technologies

Presentation Outline

- Systems analysis tools used in solar heating R&D
  - Thermal system performance analysis
  - System cost analysis
  - Material durability analysis
  - Market analysis
- Example of systems analysis tools applied to the management of the innovative, low-cost solar water heater R&D project
- Use of systems analysis in the development of solar heating R&D goals

Presentation Acknowledgements

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- **University**
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  - Bill Beckman, Univ. of Wisconsin

System Analysis Tools

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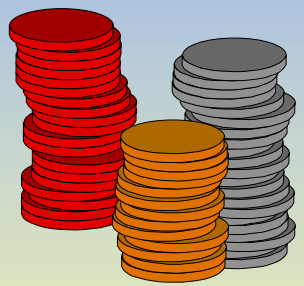
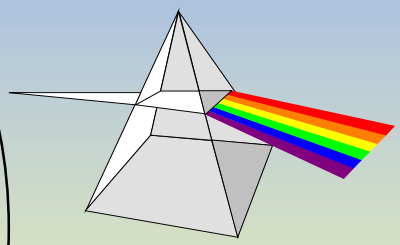
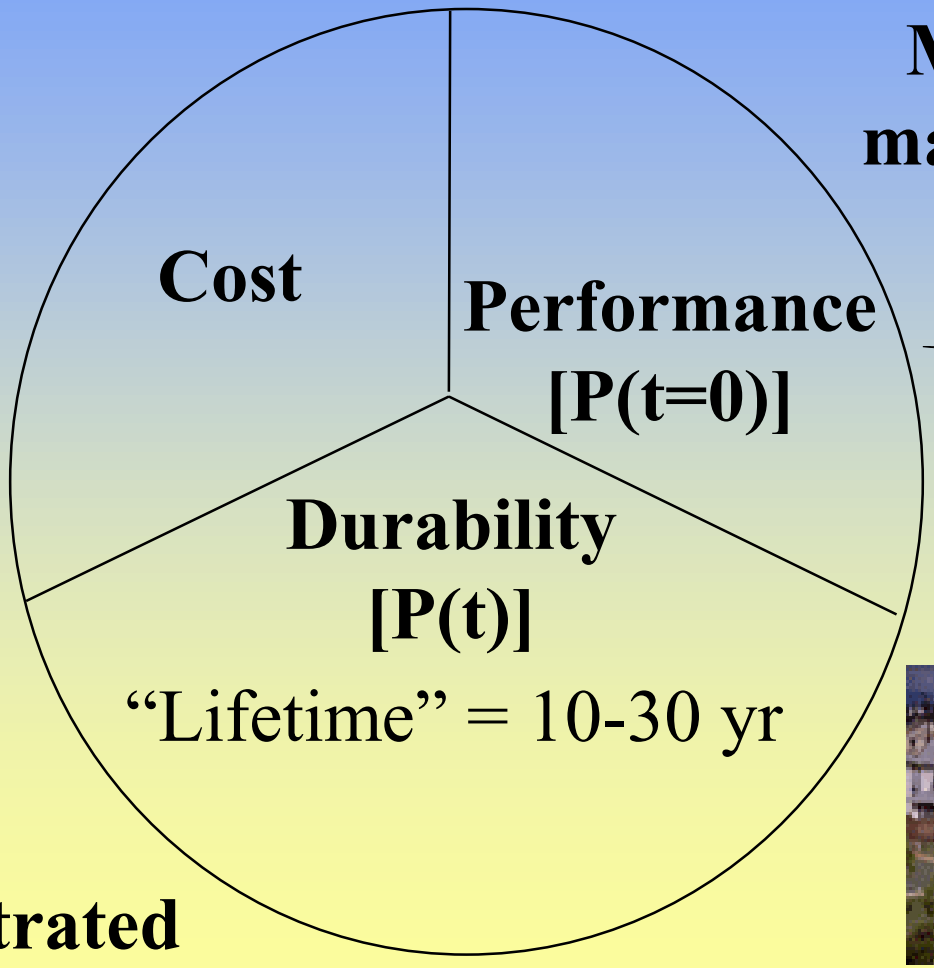
The Product Requirement Triad

Must be minimized

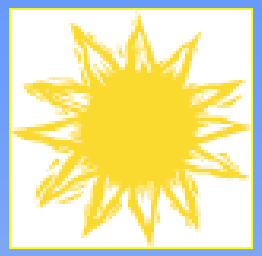


Must be maximized





Must be demonstrated



Systems Performance Analysis

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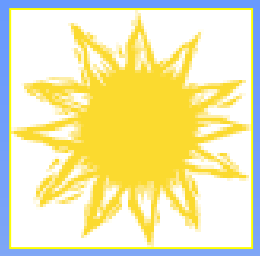
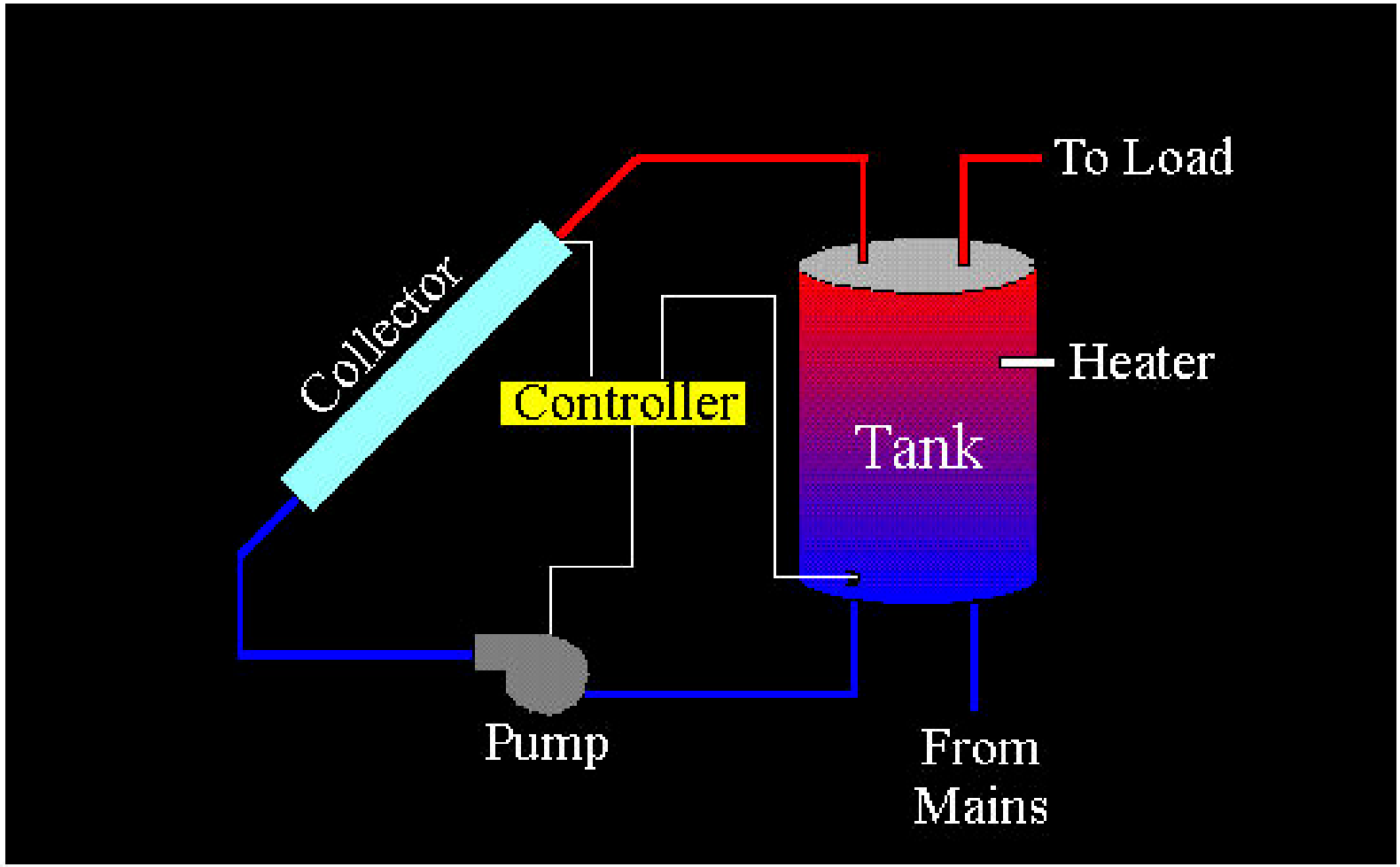


Thermal Performance Analysis

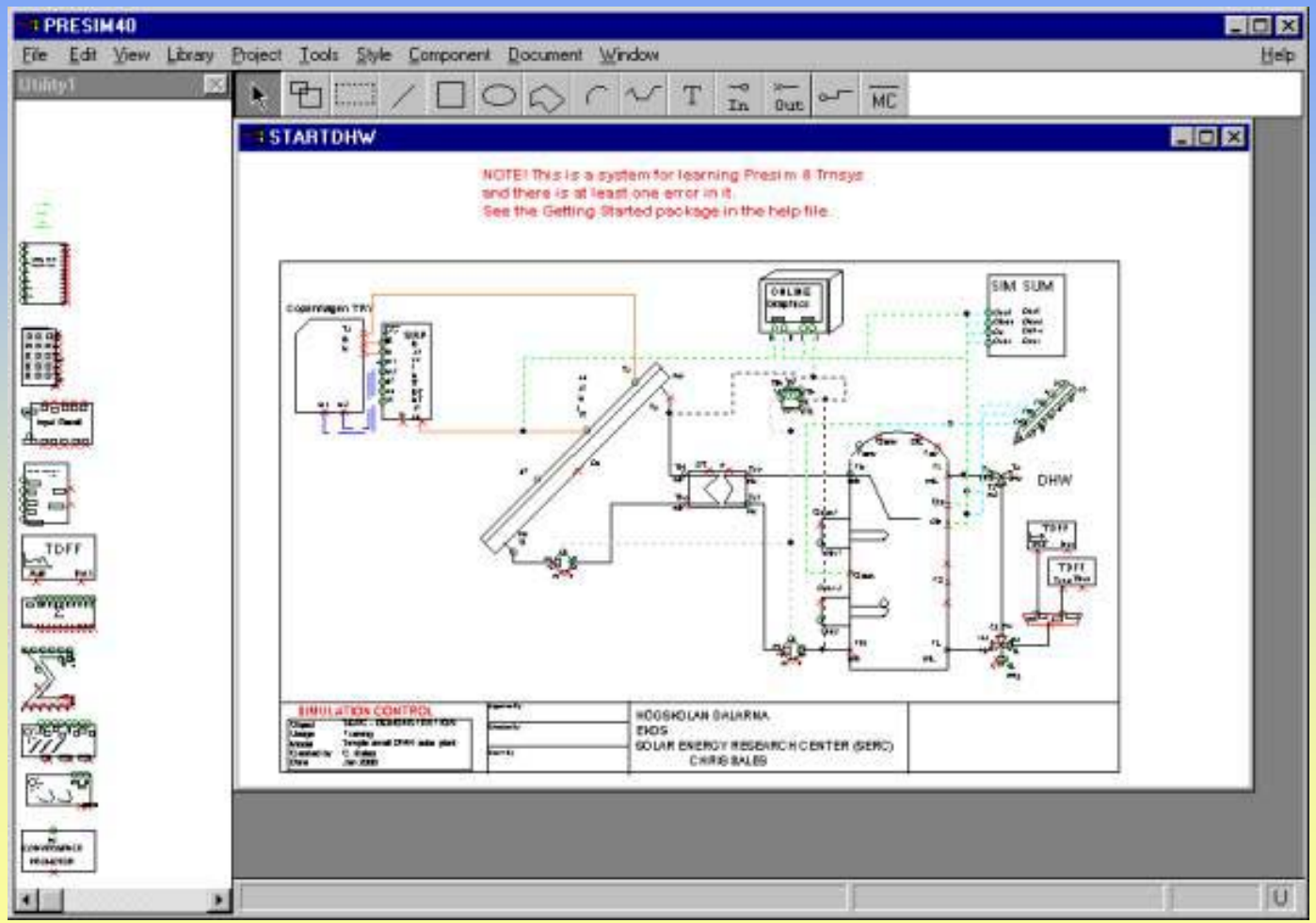
TRNSYS (Transient System Simulation):

- Modular program written in FORTRAN
- Mathematical models of individual system components are connected together to form a complete system for simulation
- TRNSYS solves the set of algebraic and differential equations that describe the system at a user-selectable timestep

Developed at University of Wisconsin Solar Energy Laboratory:
http://sel.me.wisc.edu


To Load
Collector
Controller
Heater
Tank
Pump
From
Mains

TRNSYS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File Edit View Library Project Tools Style Component Document Window Help
Utility1
STARTDHW
NOTE! This is a system for learning Presim & Trnsys
and there is at least one error in it.
See the Getting Started package in the help file.
SIM SUM
DHW
TDFF
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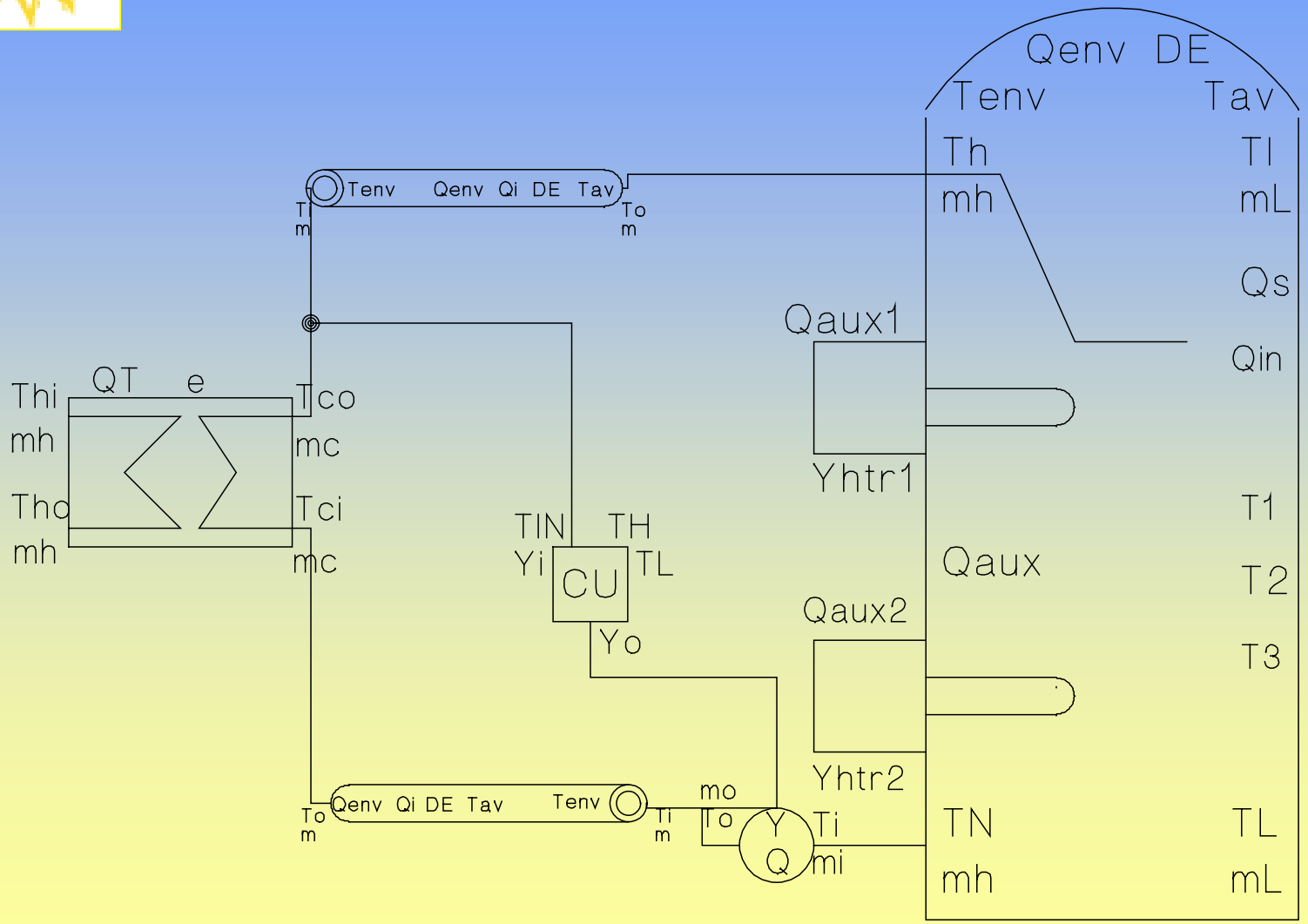
HOGSKOLAN GAVARNA
EIOS
SOLAR ENERGY RESEARCH CENTER (SERC)
CHRIS BALES

TRNSYS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mc
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Qaux
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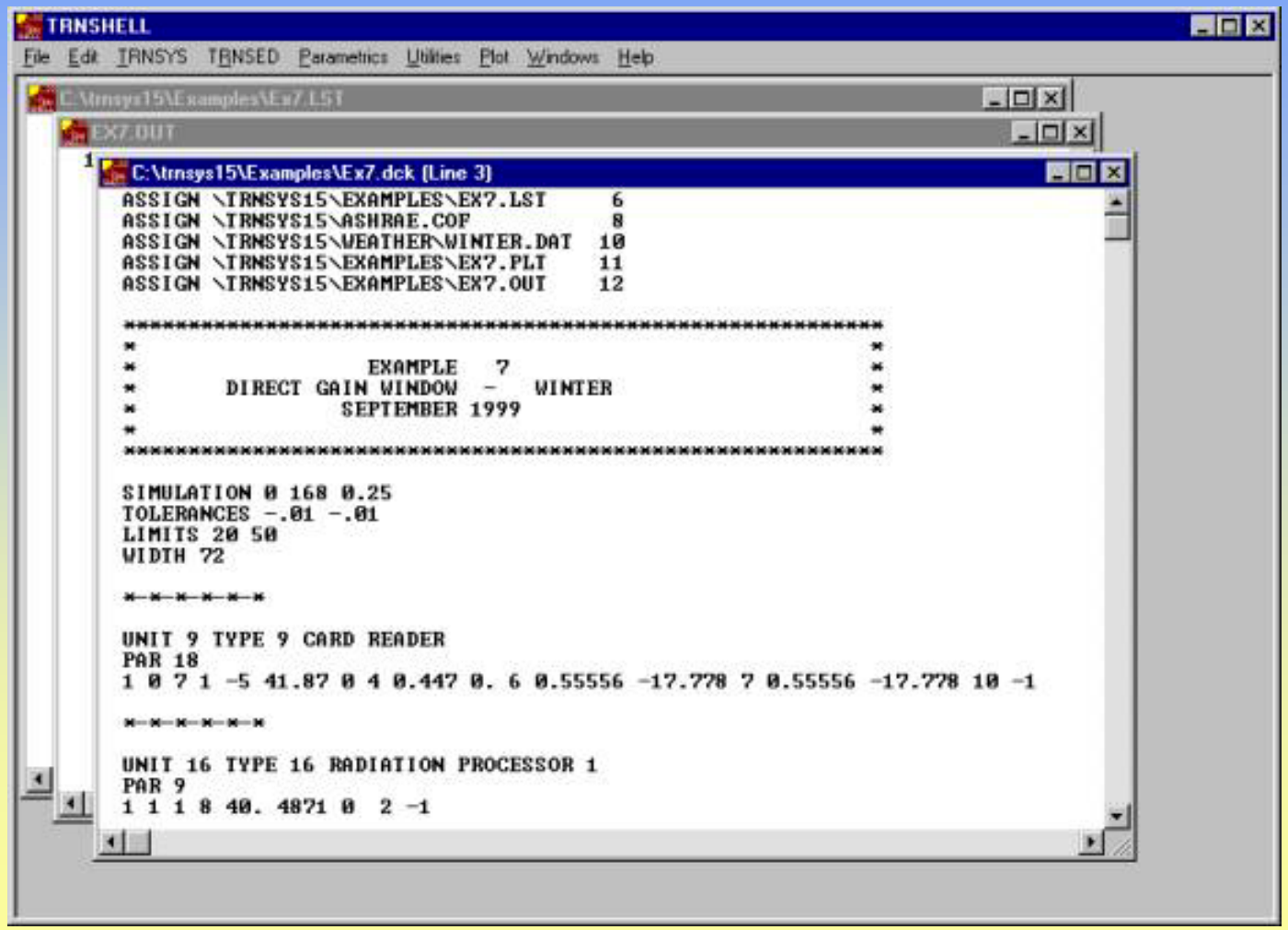
TRNSYS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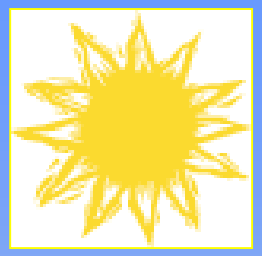
EX7.OUT
C:\trnsys15\Examples\Ex7.dck (Line 3)
ASSIGN \TRNSYS15\EXAMPLES\EX7.LST 6
ASSIGN \TRNSYS15\ASHRAE.COF 8
ASSIGN \TRNSYS15\WEATHER\WINTER.DAT 10
ASSIGN \TRNSYS15\EXAMPLES\EX7.PLT 11
ASSIGN \TRNSYS15\EXAMPLES\EX7.OUT 12
EXAMPLE 7
DIRECT GAIN WINDOW - WINTER
SEPTEMBER 1999
SIMULATION 0 168 0.25
TOLERANCES -.01 -.01
LIMITS 20 50
WIDTH 72
UNIT 9 TYPE 9 CARD READER
PAR 18
1 0 7 1 -5 41.87 0 4 0.447 0. 6 0.55556 -17.778 7 0.55556 -17.778 10 -1
UNIT 16 TYPE 16 RADIATION PROCESSOR 1
PAR 9
1 1 1 8 40. 4871 0 2 -1



System Cost Analysis

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Residential Solar Water Heating

Common System Types

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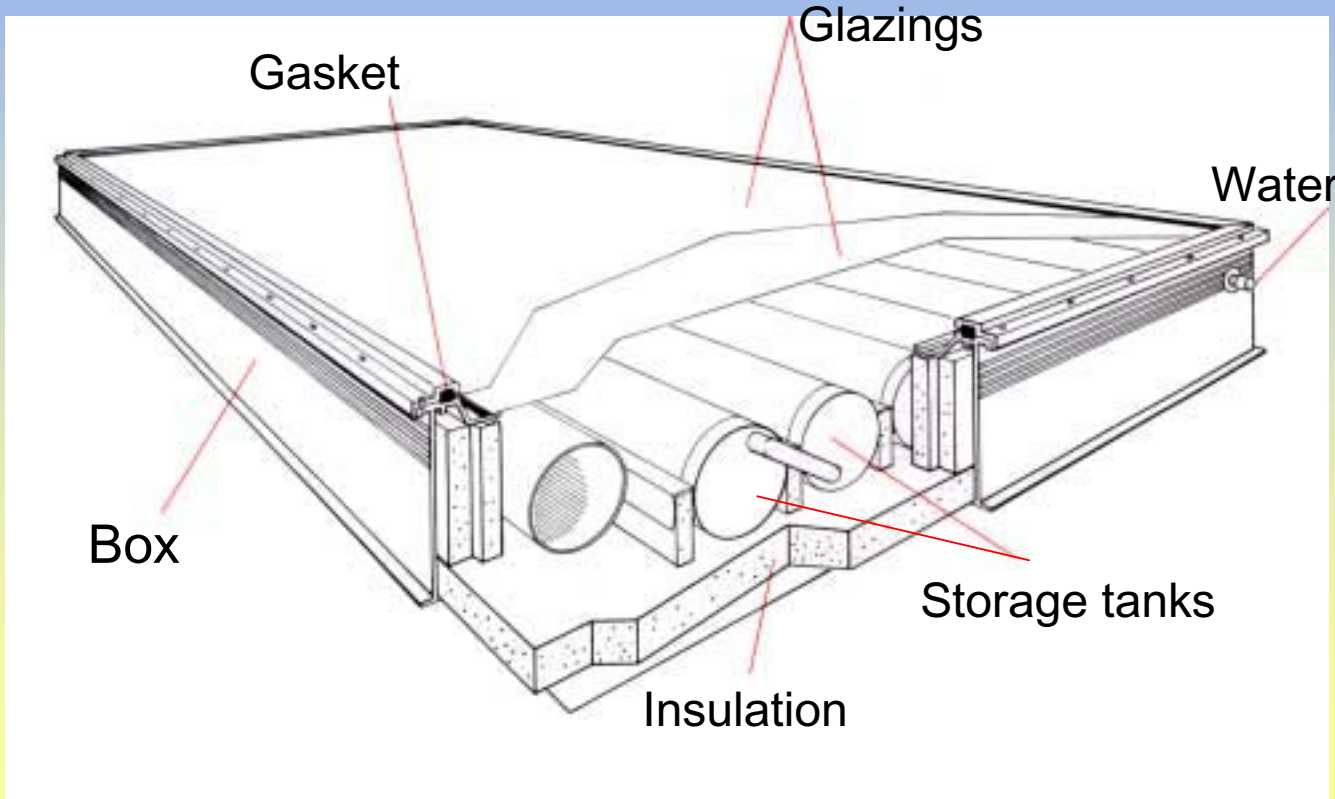
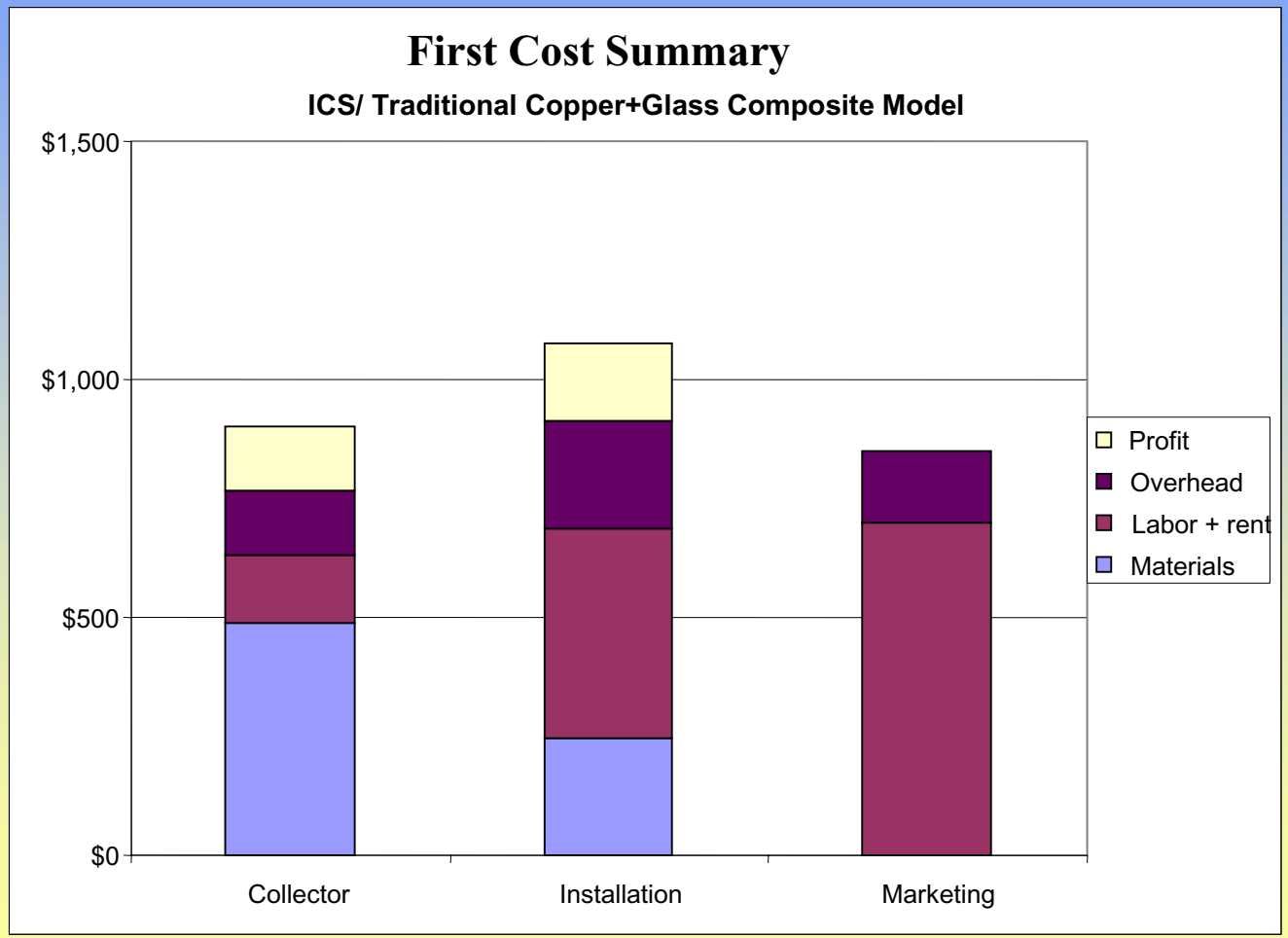
Passive

Active

Integral Collector-Storage (ICS) Unit



Solar Water Heating System Cost Model

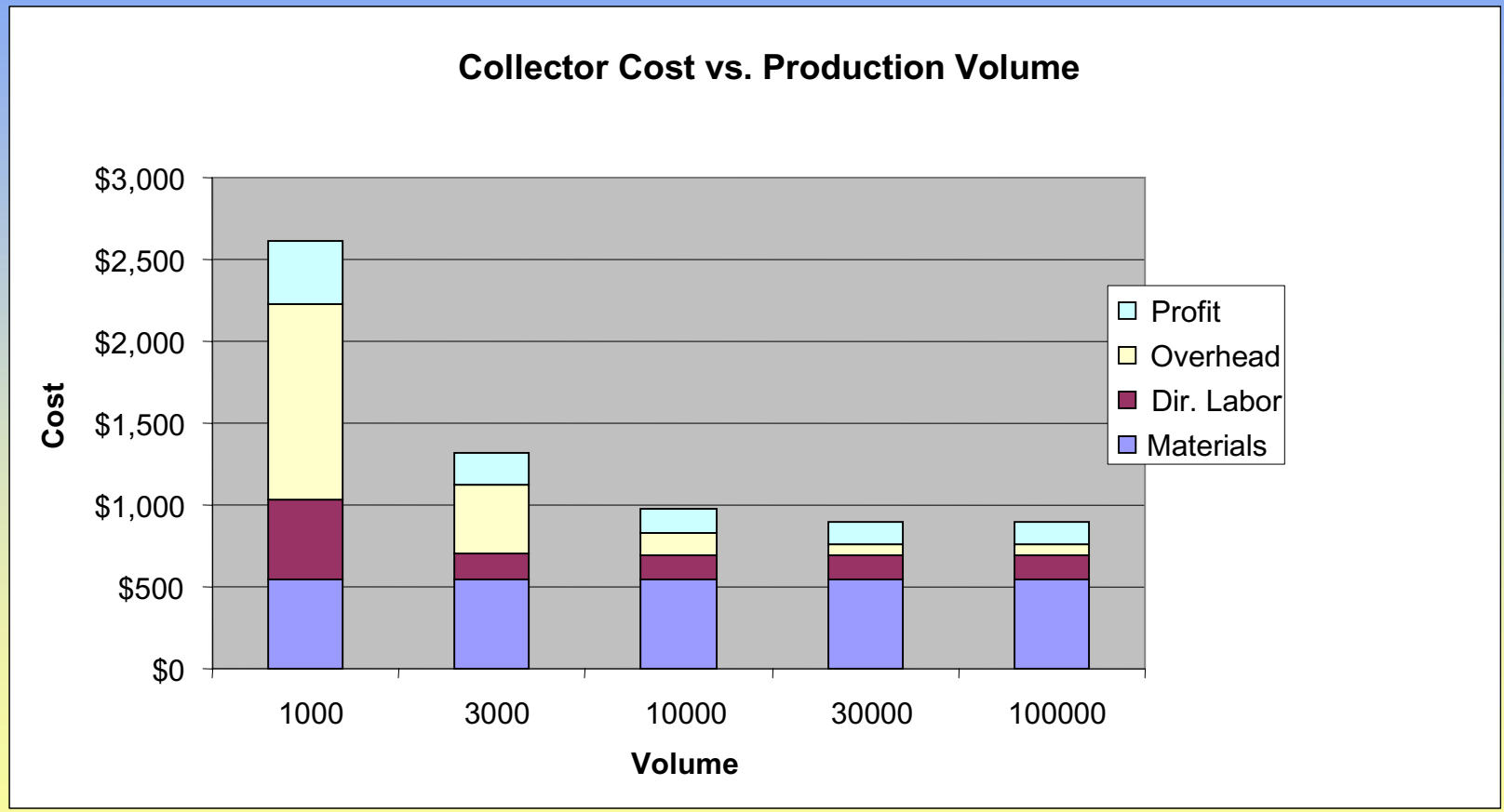


Solar Water Heating System Cost Model

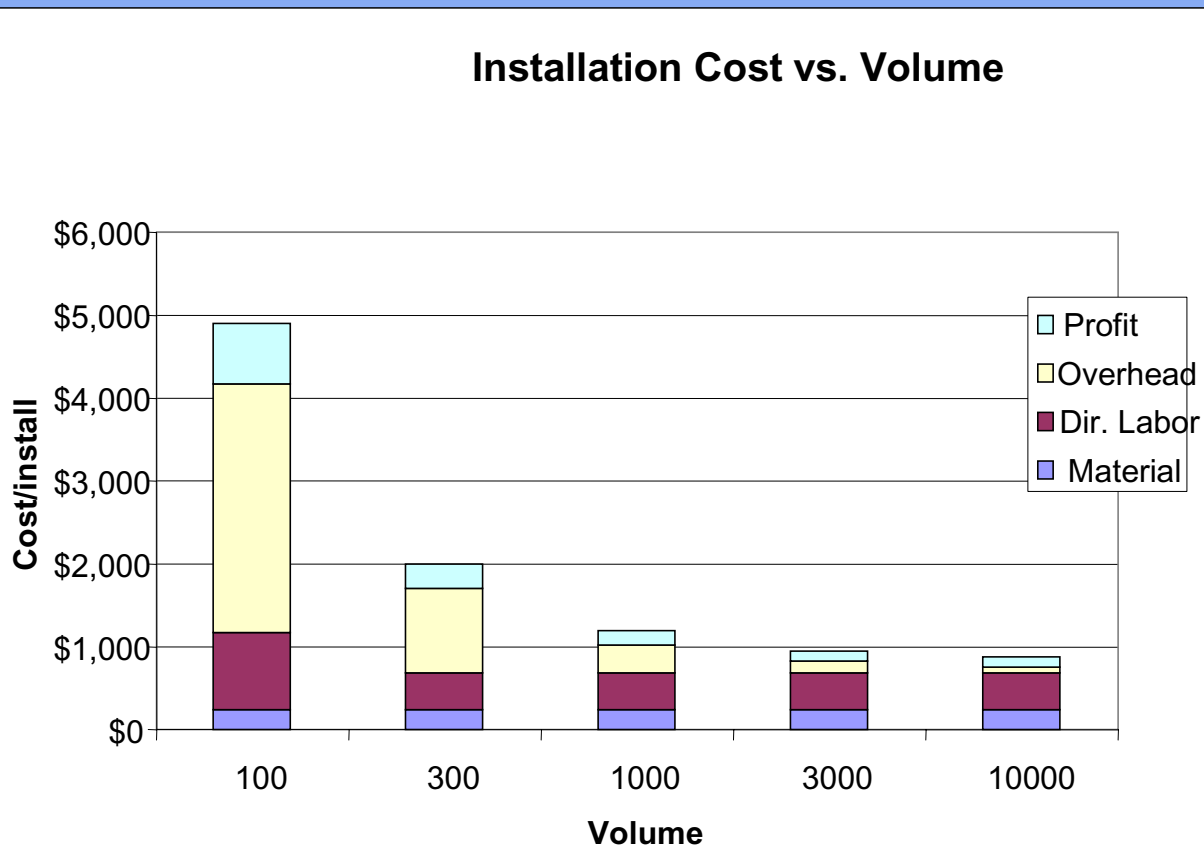
Collector Labor Costs

Operation	Labor Class	Labor rate ($/hr)	Hours per system	Cost/ System ($)	Comments/Source
1. Absorber Production	Foreman	25.00	0.4	10.00	Foreman's time pro-rated among sub-assembly operations
1.1 Tube and Header Fabrication, including connections.	pipe fitter	18.00	1.6	28.80	Header from subcontractor-furnished 8 foot tubes.
	laborer	9.00	0.8	7.20	
1.2 Apply selective coating					No direct labor. Subcontracted job. See Coll Matls sheet.
1.3 Leak Test Assembly	tester	12.00	0.6	7.20	
2. Enclosure Production	Foreman	25.00	0.3	7.50	
2.1 Cut and Miter Sides, Fasten to form frame	metal worker	12.00	0.4	4.80	
	helper	9.00	0.4	3.60	
2.2 Adhesively Bond Insulation Board to Back Sheet	laborer	9.00	0.2	1.80	
2.3 Insert Back Sheet with Insulation into Frame	laborer	9.00	0.2	1.80	
3. Assembly Completion	Foreman	25.00	0.1	2.50	
3.1 Install sealant and glazing	technician	12.00	0.3	3.60	
3.2 Install gasket and cap	technician	12.00	0.3	3.60	
4. Inspection	Foreman	25.00	0.1	2.50	
	Inspector	15.00	0.2	3.00	
5. Warehousing/Shipping	Foreman	25.00	0.1	2.50	
5.1 Place in Shipping Crate	laborer	9.00	0.2	1.80	
5.2 Move to Shipping Area	fork lift operator	15.00	0.3	4.50	
		average:			
	Totals:	14.88	6.50	$96.70	

Solar Water Heating System Cost Model



Solar Water Heating System Cost Model

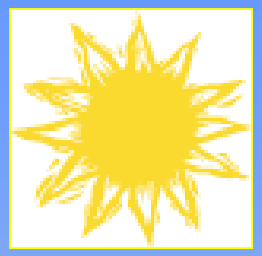


Solar Water Heating System Cost Model

First Cost				% 1st cost
Collector	10,000	per year	$899	32%
Materials		$488.05		
Labor (Direct + burdened @ 0.477)		$142.78		
Overhead	explicit method	$133.54		
Profit Before Tax (@15.0%; A.T.Profit =10.2%; Tax = 32.0%)		$134.89		
Cost/ft2 = $28	(O+P)/(M+L):	43%		
Installation	1,000	per year	$1,074	38%
Balance of System Materials + Coll. finance		$246.85		
Labor (Direct + burdened @ 0.497) + Rentals		$439.16		
Overhead	explicit method	$227.16		
Profit Before Tax (@15.0%; A.T.Profit =10.2%; Tax = 32.0%)		$161.15		
	(O+P)/(M+L):	57%		
Market			$849	30%
Sales (94 systems/person-year)		$696.74		
Advertising		$30.79		
Distribution (shipping + 10.0% mark-up)		$121.18		
Total first cost:			**$2,822**	
Cost/ft2 = $88				

Solar R&M/Life-cycle cost (20 yr. period, disc. rate=3.8%)			% LCC
First Cost		$2,822	84%
Repair and Maintenance (present value)		$536	16%
Total Real Cost		$3,359	

Economic Indicators for Phoenix**	(El =8.0 c/kWh; Gas = 6.0/.8 $/MM	No O&M	With O&M
Annual Savings ($/yr)*		$164	$125
Cost of saved energy (cents/kWh)		9.9	11.8
Return on Investment		1.5%	-1.1%
Monthly net cash flow (elec., 30 yr loan @ 8.0%, no tax)		-$7.23	-$10.46
Simple payback vs Electric (yr)		17.3	20.6
Simple payback vs Gas (yr)		53.8	64.0
Life cycle cost savings (Elec.)		-$554	-$1,090
Life cycle cost savings (Gas)		-$2,242	-$2,778



Material Durability Analysis

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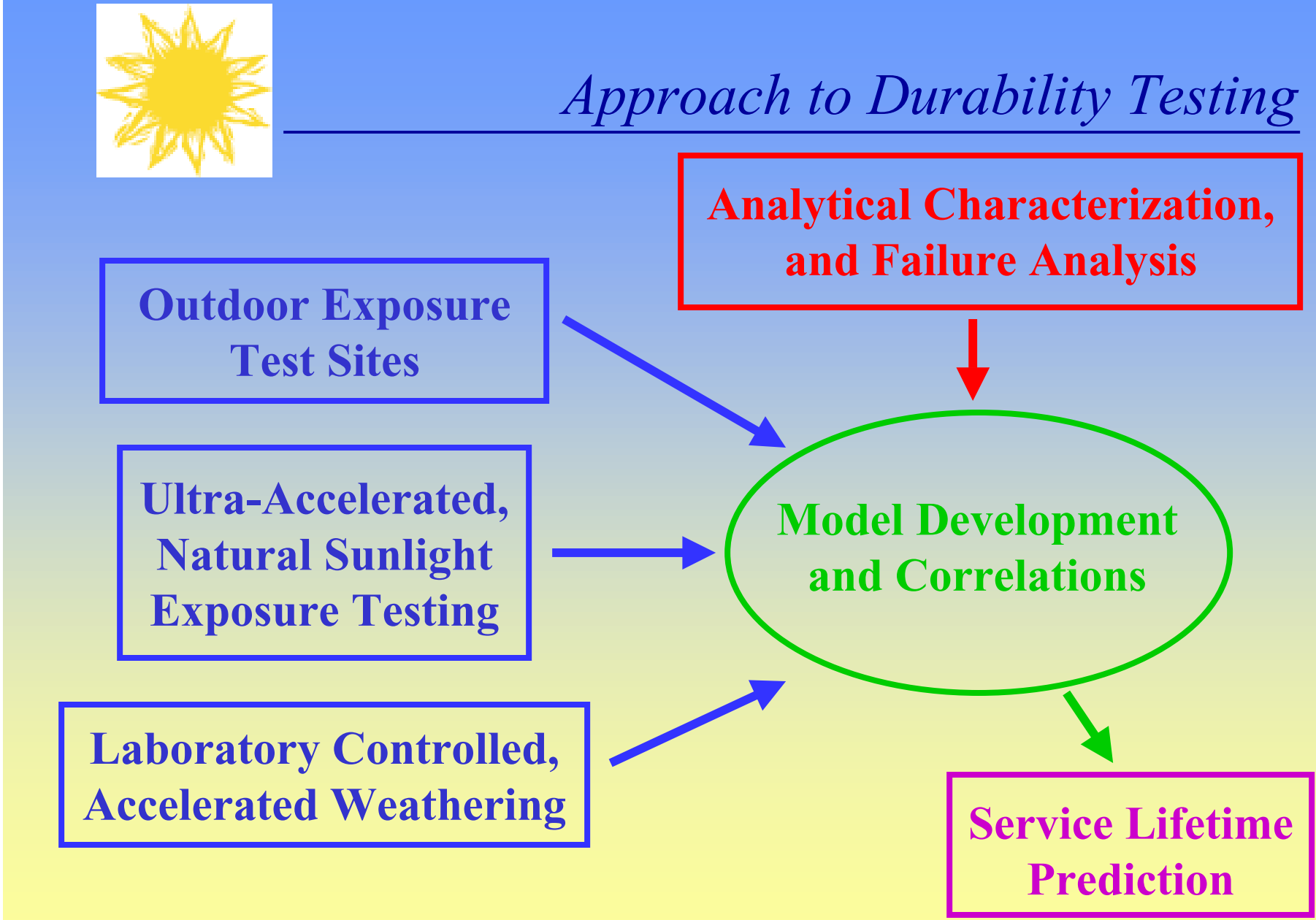
Approach to Durability Testing



Durability Testing Methodology

- Perform accelerated tests using several levels of laboratory-controlled, constant stress values
- Develop material-specific model (damage function) that relates loss in performance (ΔP) to applied/experienced stresses
- Fit measured ΔP to model to obtain damage function coefficients
- Use model to predict in-service degradation

Model / Damage Function

1) For Constant Accelerated Stresses:

$$\Delta P_i = A\ I^n\ \Delta t_i\ \exp[-E/kT]$$

2) I and T are known/constant; measure ΔP_i ; obtain A, E, and n

3) For Variable Real-World Stresses:

$$\Delta P_i = \Sigma_j \{A\ I(t_j)^n\ \Delta t_j\ \exp[-E/kT(t_j)]\}_i$$

4) Monitor stresses; compare predicted degradation with measured outdoor results

Durability Testing

Outdoor

Accelerated Laboratory Chambers

Ultra-Accelerated, Natural Sunlight

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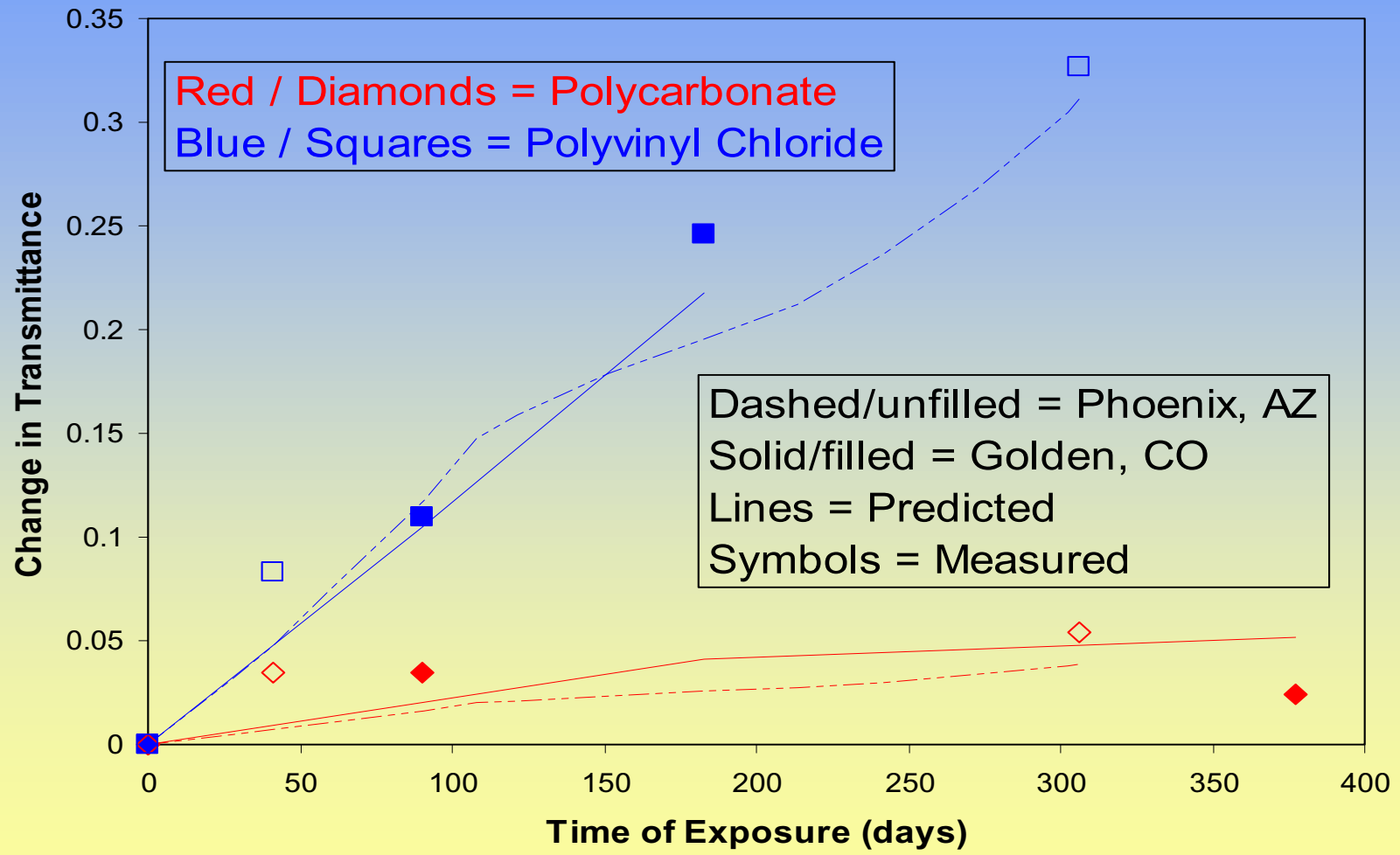
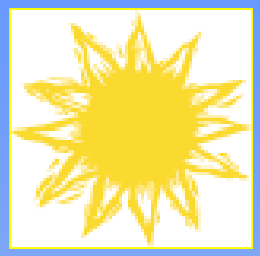
Measured vs. Predicted Δτ for 2 Glazings at 2 Sites





Market Analysis

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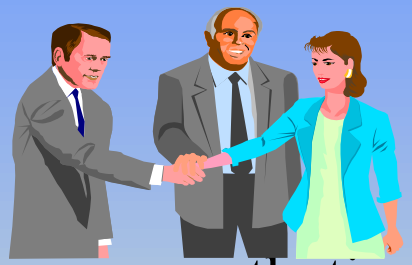
Solar Water Heating Market Research



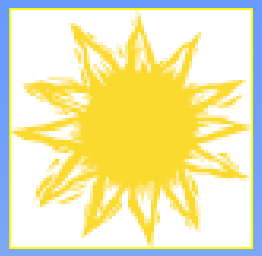
System Market Research:

"Understanding the Customers"

- **FY98 -** builders indicated their concerns over aesthetics, cost, reliability, & public awareness
- **FY98 -** survey of 300 recent home buyers indicated interest in, but widespread lack of awareness of solar water heating systems
- **FY99 -** development of a marketing plan for solar water heaters in new homes

Link to 9 solar water heating system market studies:

http://www.eren.doe.gov/solarbuildings/market.html



New Construction Market Studies

Desired solar water heating system features:

- **Consumers:**
  - Cost ~ $1,000-$1,500
  - Trouble-free
  - Warranty/Name Firm
- **Builders:**
  - Trouble-free
  - Easy to install
  - Unobtrusive
  - Cost < $1,500
- **Architects:**
  - Unobtrusive (skylight-like)
  - Small, inexpensive

Example of Systems Analysis Applied to Project Management

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Innovative, Low-Cost Solar Water Heaters

Project Goal:

Cut the delivered, life-cycle energy cost of solar water heating systems in half by the year 2005.

Source: Solar Buildings Strategic Plan - 1997

Innovative, Low-Cost Solar Water Heaters

- Hardware cost reduction
  - Polymer technology
  - Parts integration
- Installation cost reduction
  - Lighter collectors, flexible bundled piping
  - Integrated balance of system
- Marketing cost reduction
  - New construction: SWH as standard feature or standard option
  - Do-it-yourself/Home Depot

Polymer Solar Water Heaters

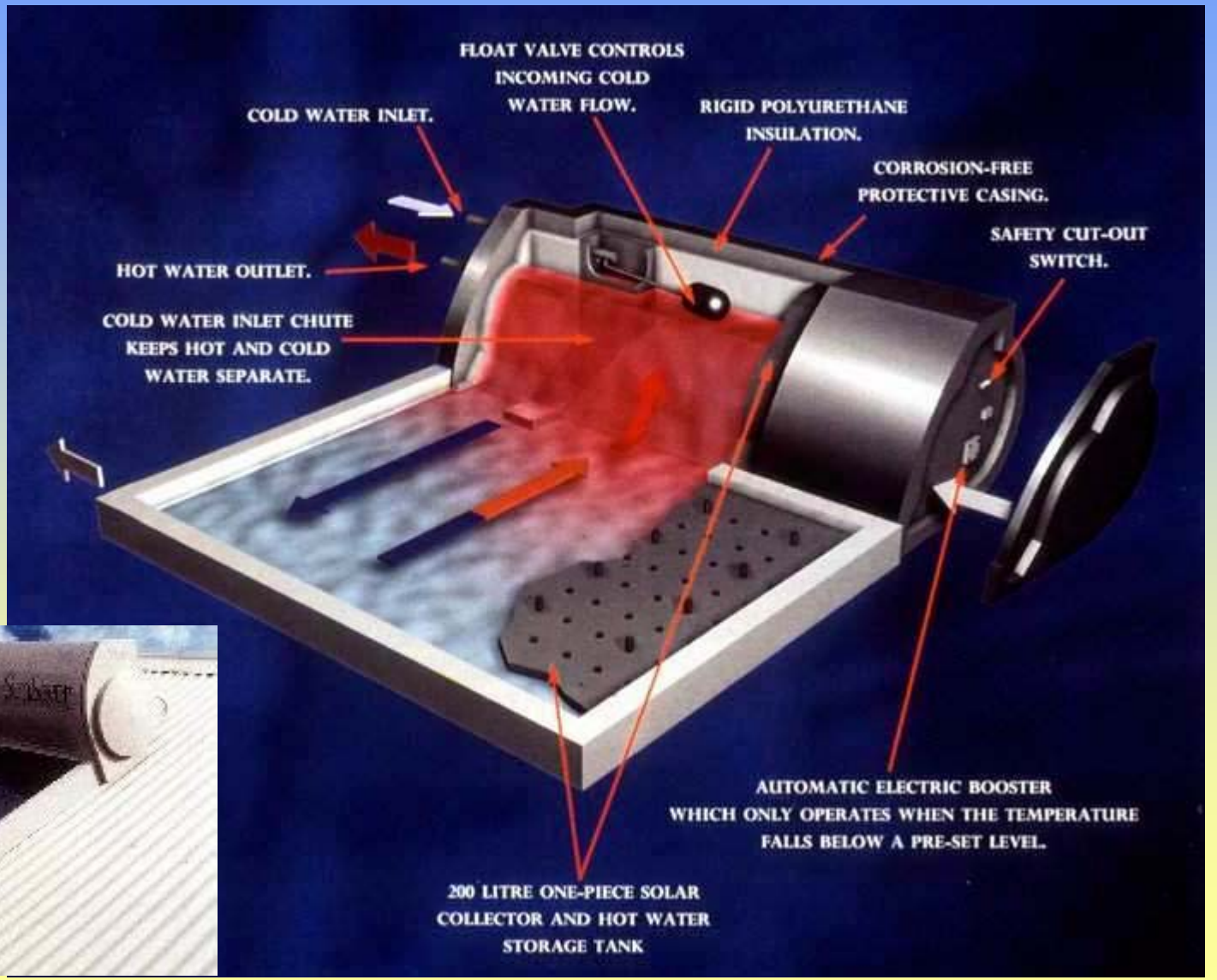
Technical basis for polymer-based systems:

- Low materials **cost**
- Parts integration ☑ lower manufacturing **cost**
- Light weight ☑ lower installation **cost**

Rotomolded Polymer Solar Water Heater

Australia

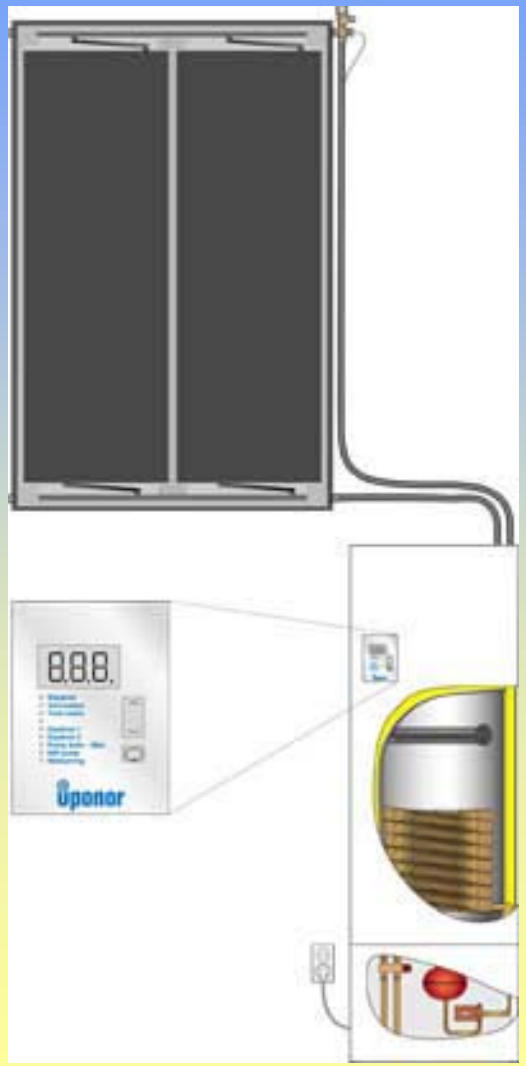
Solco Industries Pty Ltd
Western Australia

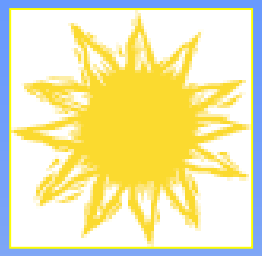


IEA Task 24 Competition in Sweden

Finland & Sweden

Uponor AB
Espoo, Finland





Innovative, Low-Cost Solar Water Heaters

Project Phases:

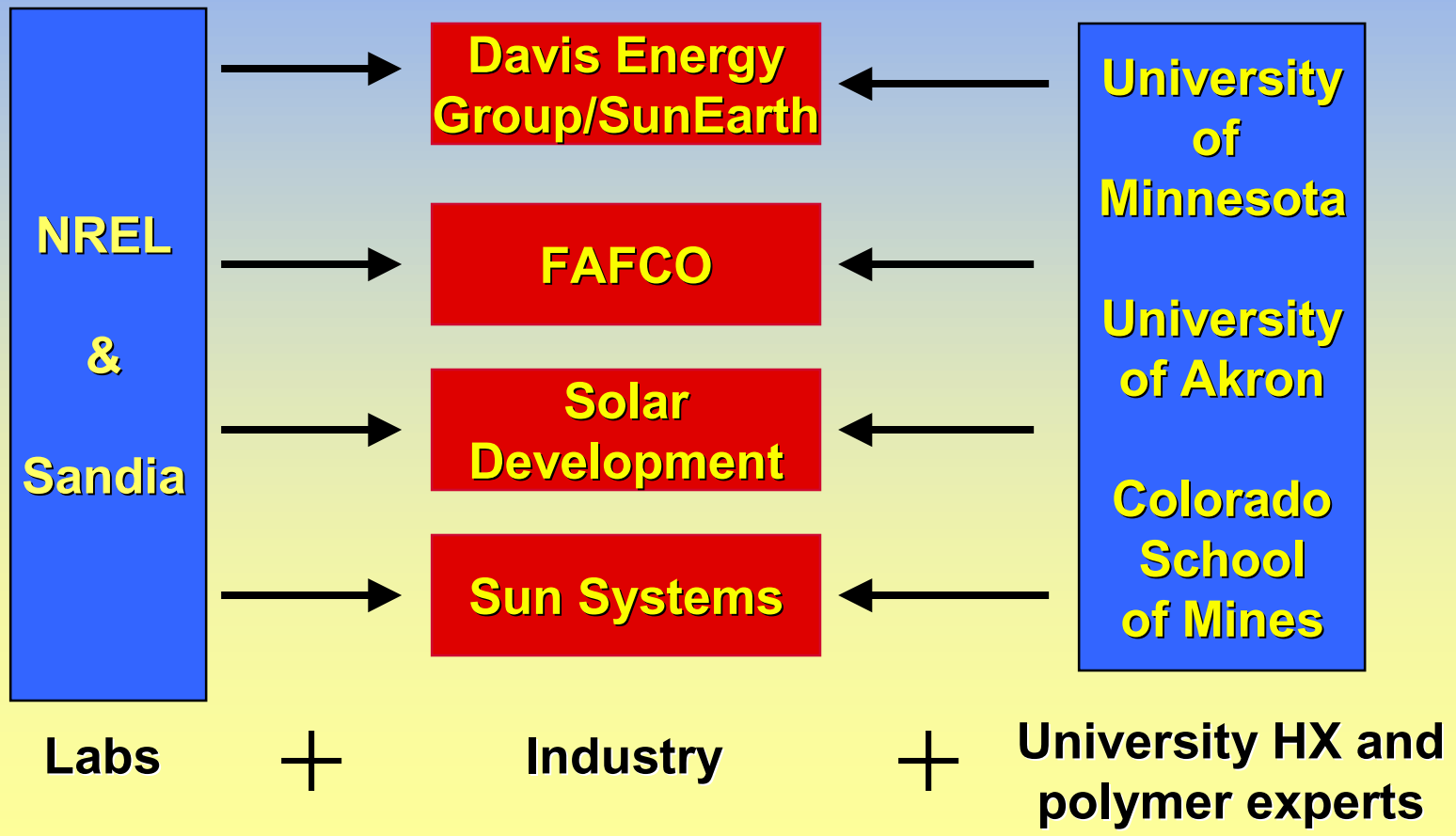
- **Concept Generation / Exploratory Research**
  - Identification of general system configurations which could conceivably reach the project's cost goal
- **Concept Development / Prototype Test**
  - Development of detailed designs for promising concepts and construction and evaluation of prototypes
- **Advanced Development / Field Test**
  - Development of second-generation prototypes and conducting limited field testing and evaluation
- **Engineering / Manufacturing Development**
  - Construction of manufacturing facilities and evaluation of "near-final" systems in "real-world" applications

Innovative, Low-Cost SWH Project History

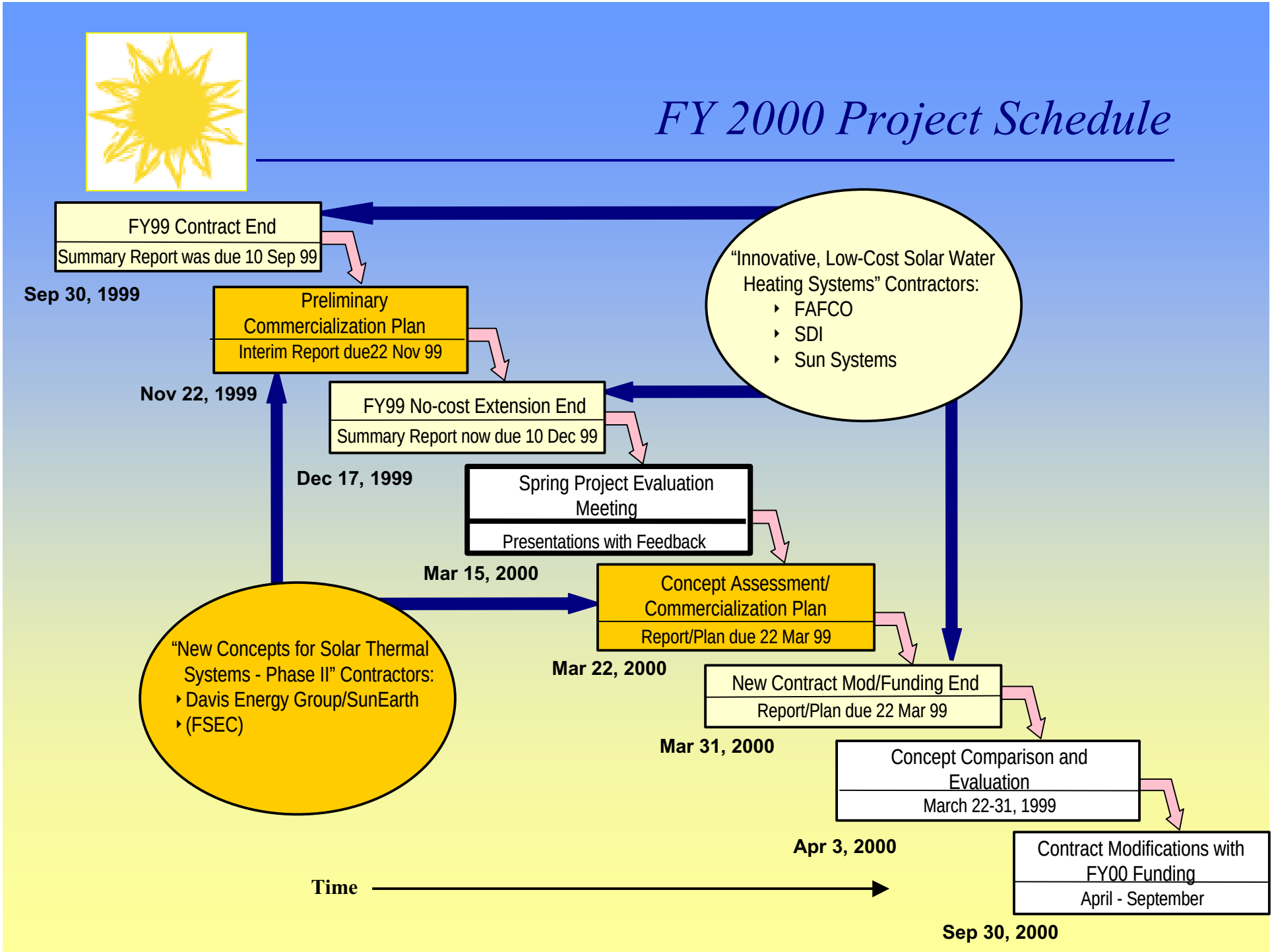
- **1997 -** Polymers for Solar Thermal Energy Workshop
- **1998** - New Concepts for Solar Systems RFP
- **1999** - Low-Cost Solar Systems RFP to industry; Phase 2 of New Concepts for Solar Systems RFP; solicitations to thermal and polymer consultants
- **2000** - Concept evaluation and cost analysis; "Best" concepts selected for focused R&D
- **2001 to 2003** - Develop and test prototypes; develop manufacturing process

Innovative, Low-Cost Solar Water Heaters

Industry partners developing innovative, low-cost solar water heaters:



FY 2000 Project Schedule

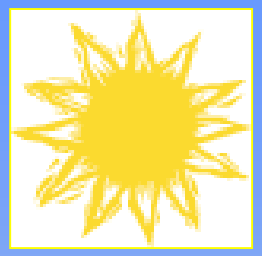


Phase One Evaluation:

Evaluation Criteria	Weight
• **Technical Criteria**	**33 1/3%**
• **Market Criteria**	**33 1/3%**
• **Probability of Success**	**33 1/3%**
• **Programmatic Criteria**	**N/A**
– (Applied After Evaluations Completed)	

Technical Criteria	Weight
• **Cost of Saved Energy**	**67%**
• **Life Cycle Savings**	**33%**

- Material properties were used as inputs to TRNSYS to determine energy performance, since prototypes had not yet been tested.
- Hardware and installation costs were determined by the detailed system cost model
- O&M costs were based on the repair histories of each component in the system
- Business/Marketing Costs were standardized for this evaluation



Innovative, Low-Cost Solar Water Heaters

Market Criteria	Weight
• **Market Size/Restrictions**	**40%**
– What is the geographic region for this technology?	
• **Code Requirements**	**40%**
– What installation skills are required? Does the unit address building code requirements?	
• **Aesthetics**	**20%**
– Installed profile, color(s), and appearance.	

Innovative, Low-Cost Solar Water Heaters

Organizational Criteria	Weight
• **Probability of R&D success**	**40%**
• **Past performance**	**40%**
• **Team experience and skills**	**10%**
• **Team resources available**	**10%**
• **Management**	**0**
• **Production and distribution capability**	**0**

Programmatic Criteria

- **Funding Considerations**
  - Funds needed by the team
  - Available funding from the program
- **Time to Market**
  - Early introduction of the technology to the marketplace is critical to success of the program.
- **Geographic Diversity**
- **Technology Diversity**

Innovative, Low-Cost Solar Water Heaters

FAFCO:

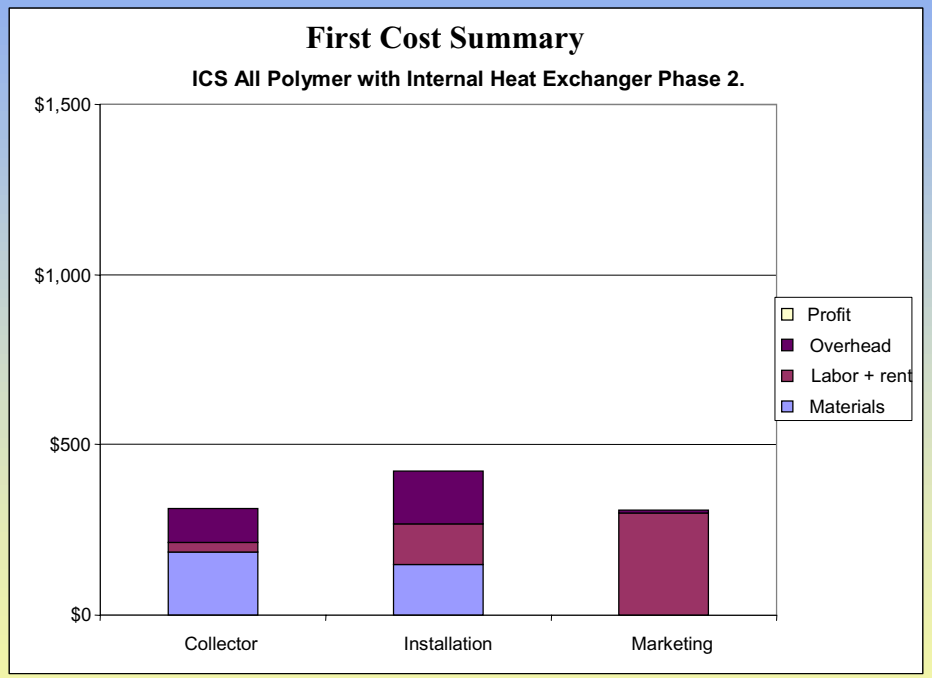
- thermoformed tank
- double glazed, back insulation
- boiling overheat protection ⇒ water makeup

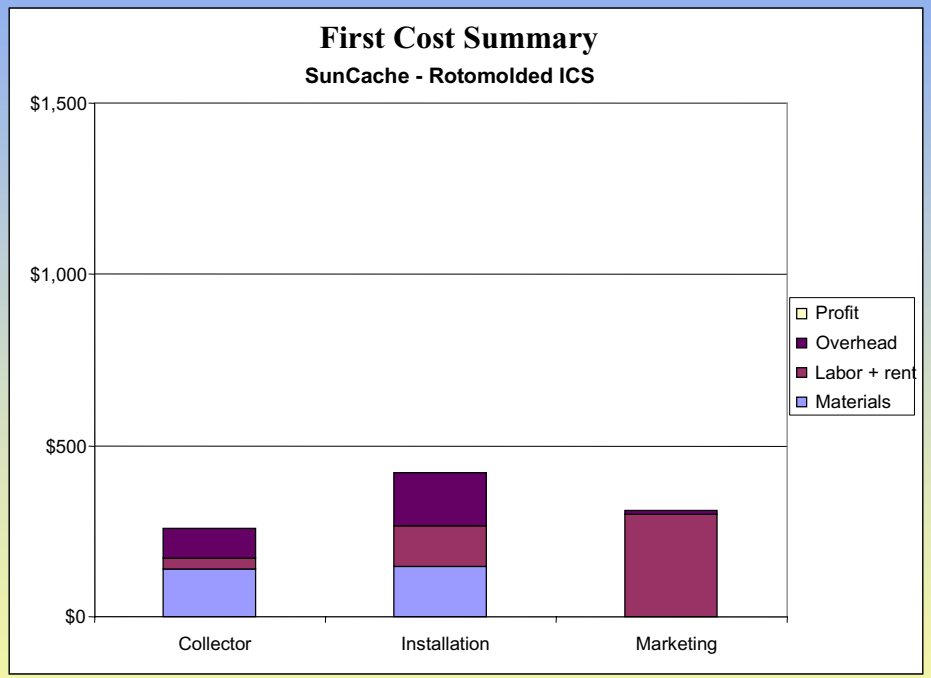
Davis Energy Group (DEG) / SunEarth:

- rotomolded tank
- single glazed, no back insulation
- no overheat protection with sealed tank

Innovative, Low-Cost Solar Water Heaters

Project Evaluation Results





FAFCO Unpressurized ICS

DEG Unpressurized ICS

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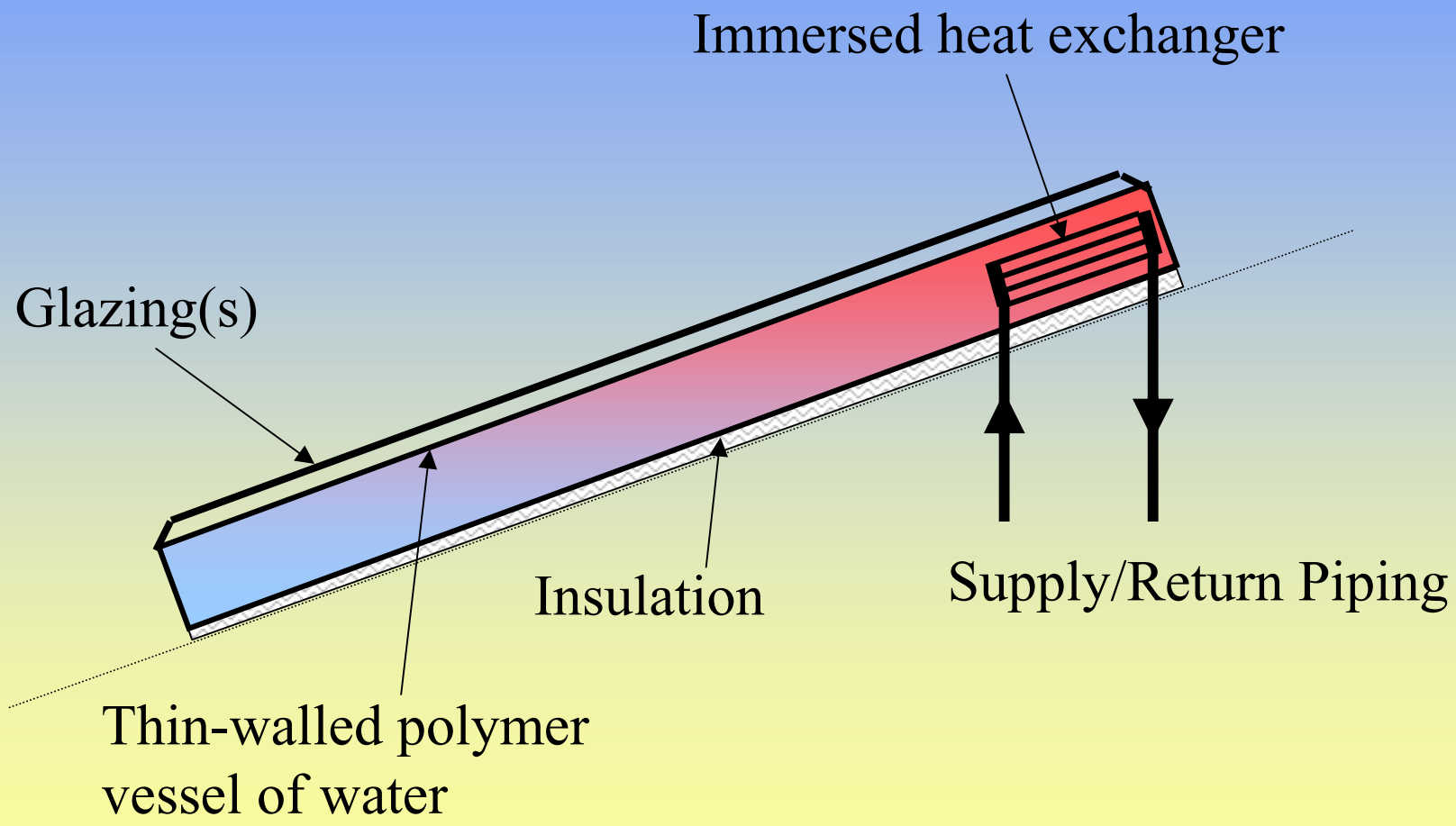
Unpressurized Integral Collector Storage



Systems Analysis Applied to Program Management

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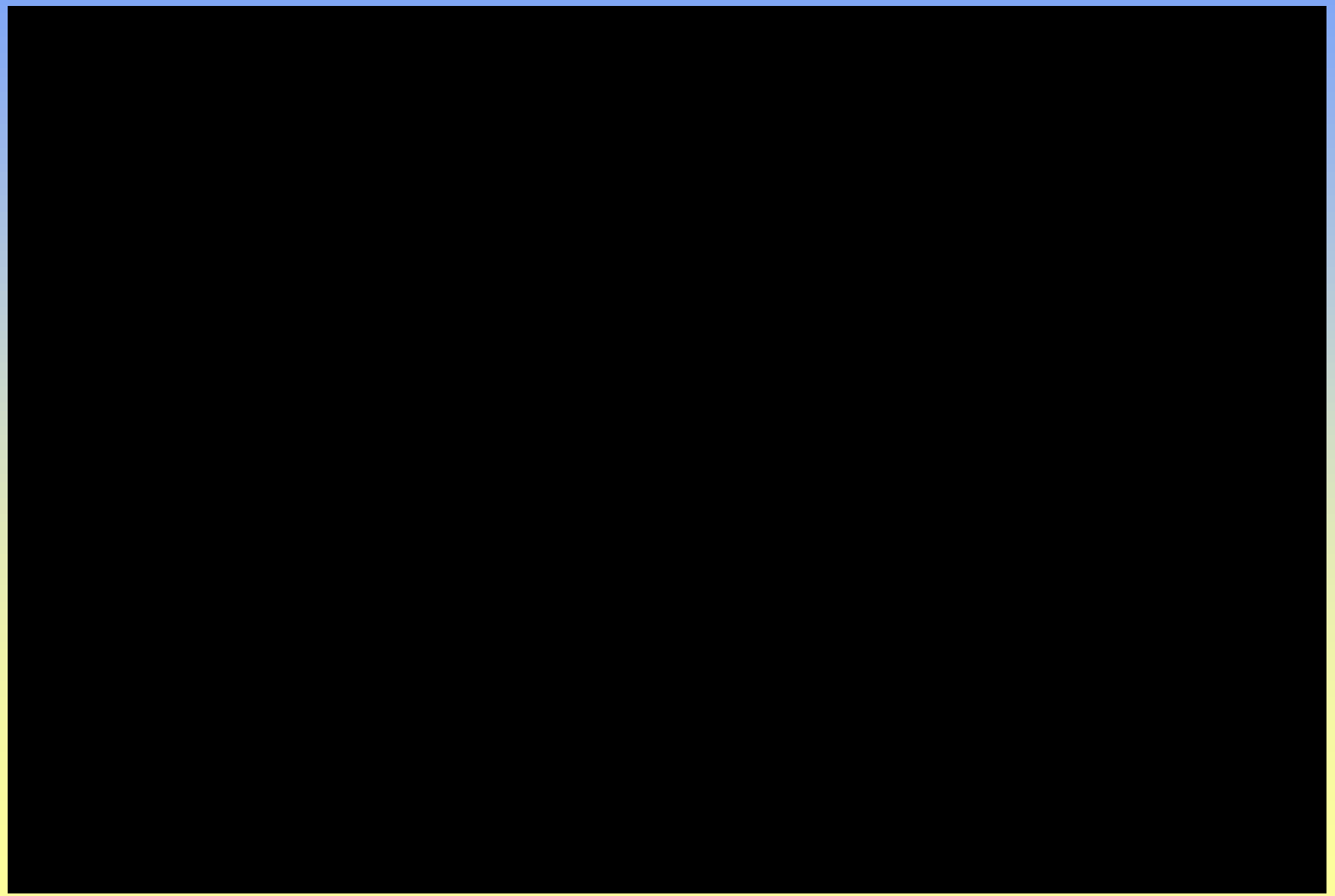
Solar Buildings Historical R&D Areas

- **Water heating**
  - Low-cost solar water heating systems
  - Solar system standards and certification
  - Solar collector manufacturing assistance
- **Space heating**
  - Packaged solar systems
- **Ventilation air heating**
  - Transpired solar collector (R&D 100 Award - 1994)
- **Space cooling**
  - Desiccant cooling
  - Absorption air conditioning

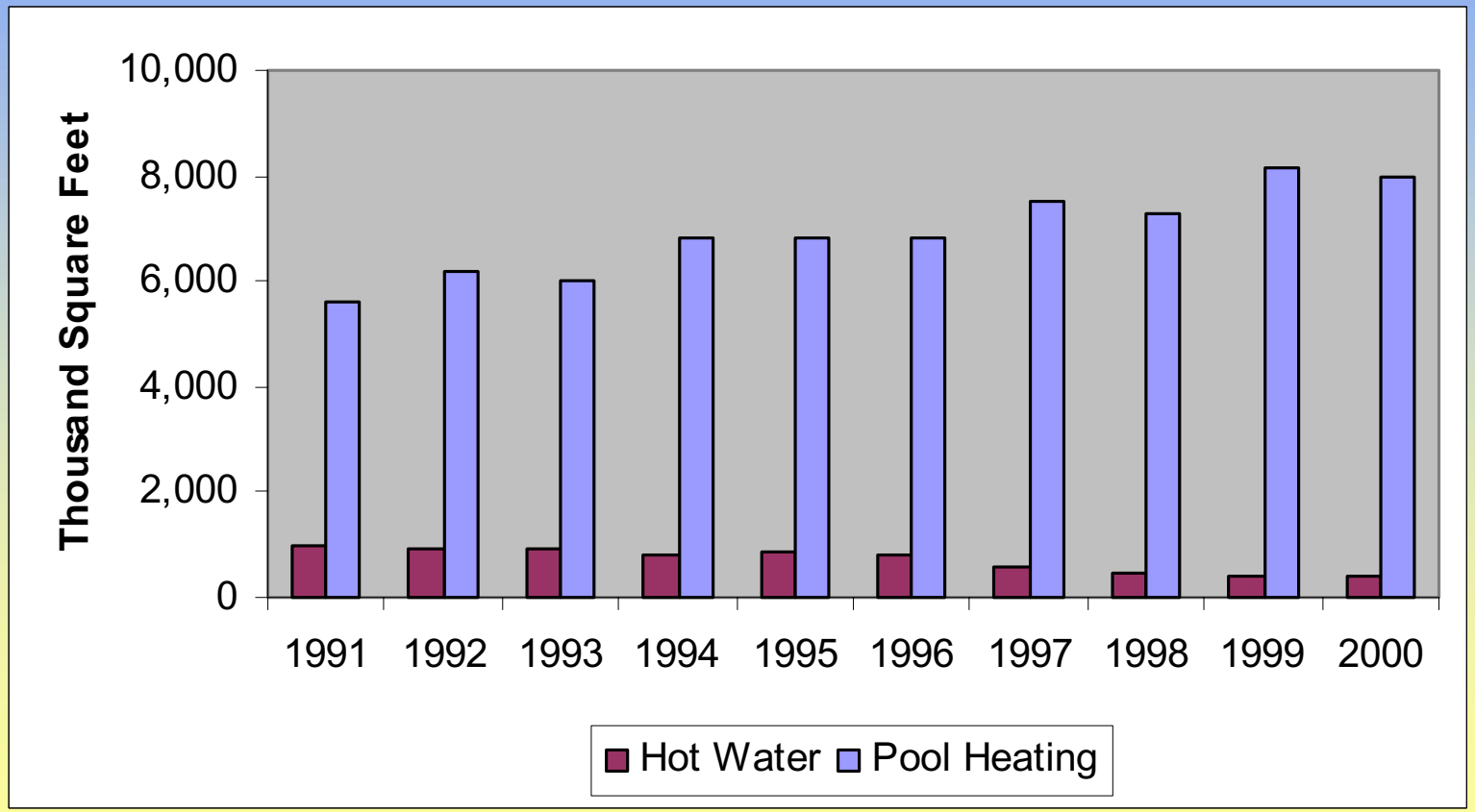
EERE Renewable Program Budgets



U.S. Solar Water Heating Industry

Solar Thermal Collector Shipments

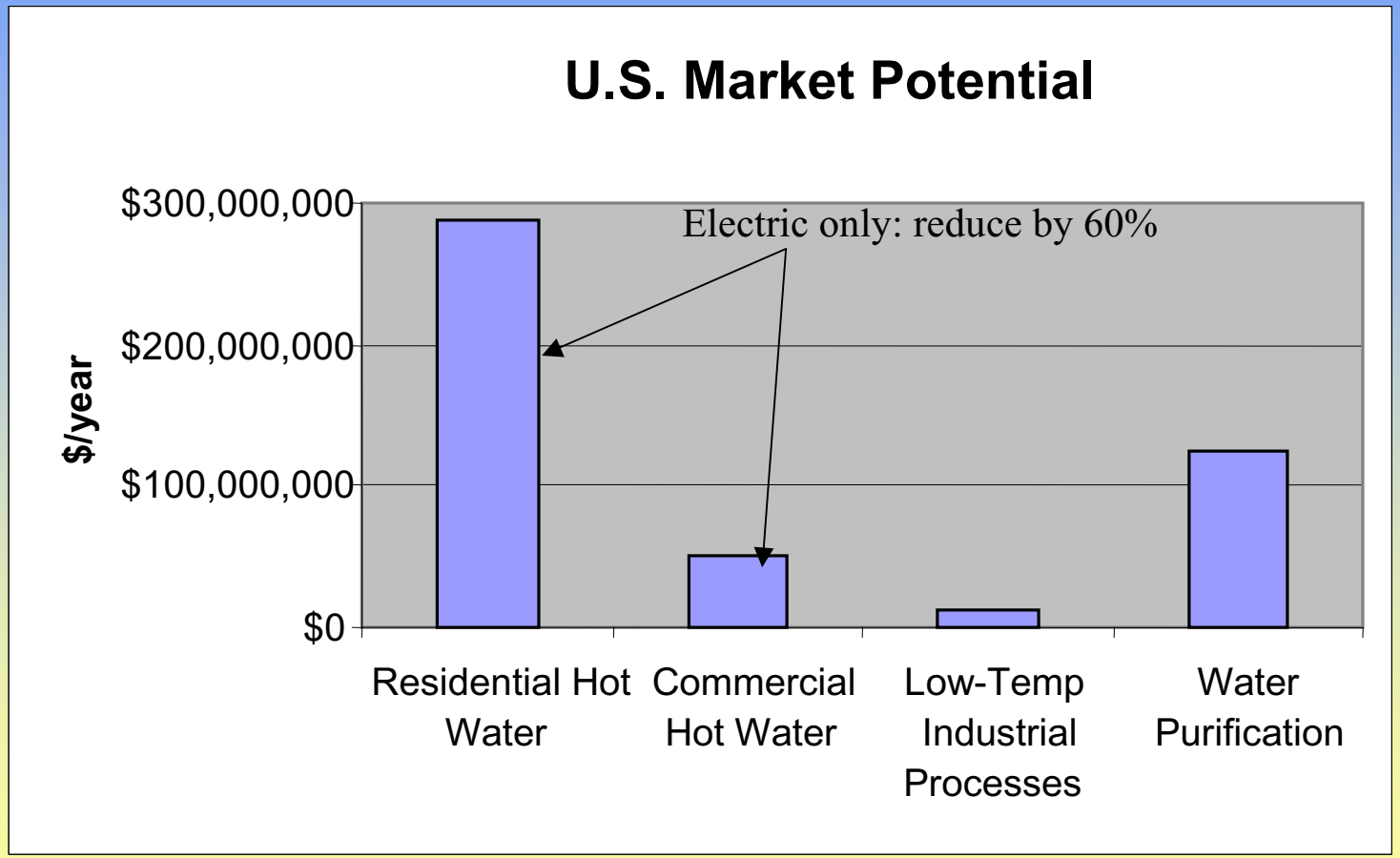
Source: EIA Renewable Energy Annual 2000



Potential Solar Thermal Collector Markets

- **Residential**
  - Domestic hot water; space heating and cooling; swimming pool heating
- **Commercial**
  - Service hot water in hotel/motels, hospitals, prisons; institutional swimming pool heating
- **Industrial**
  - Low temperature processes: food processing, chemicals,...
- **Water Purification**
  - Desalination; pasteurization

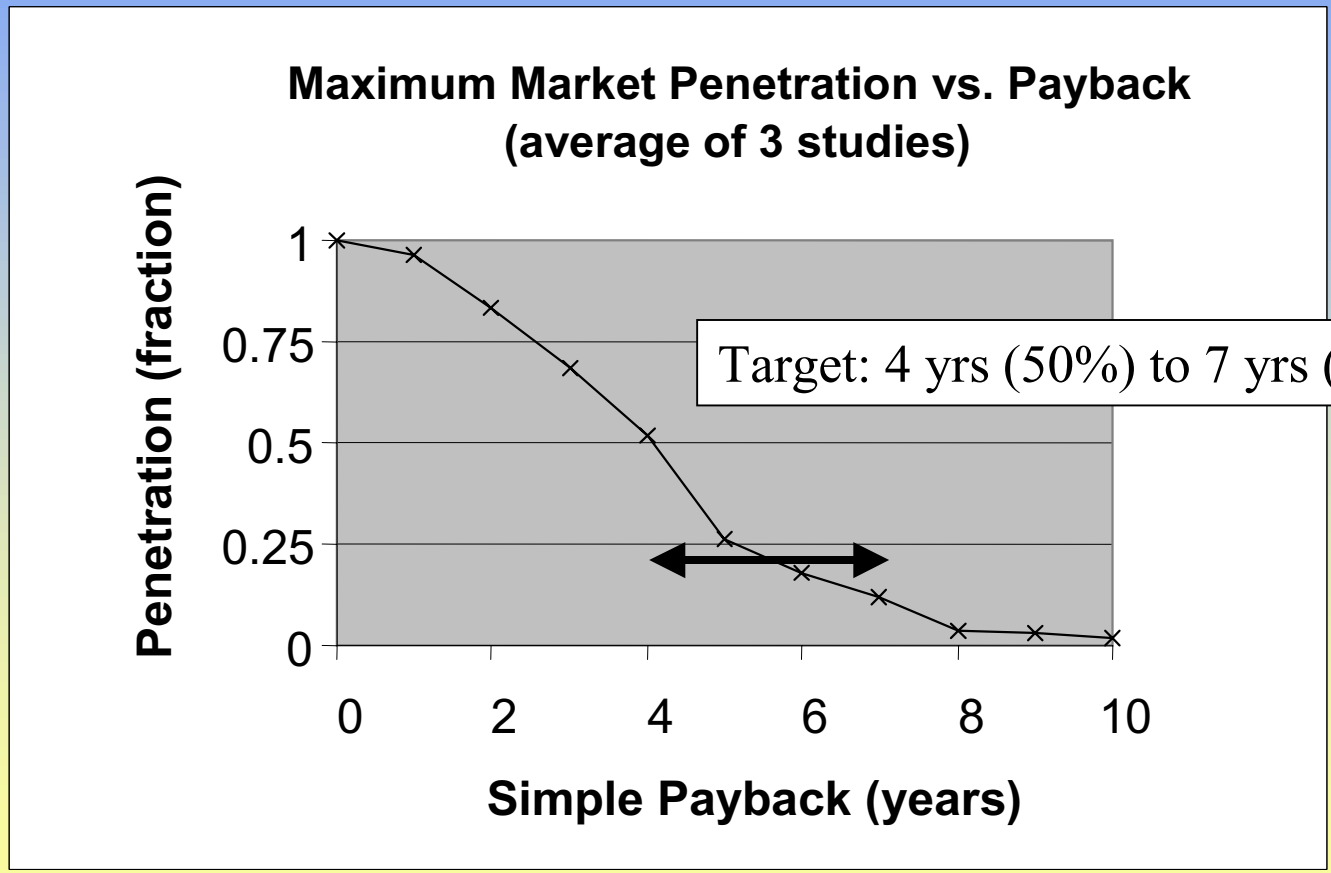
U.S. Solar Water Heating Market Size



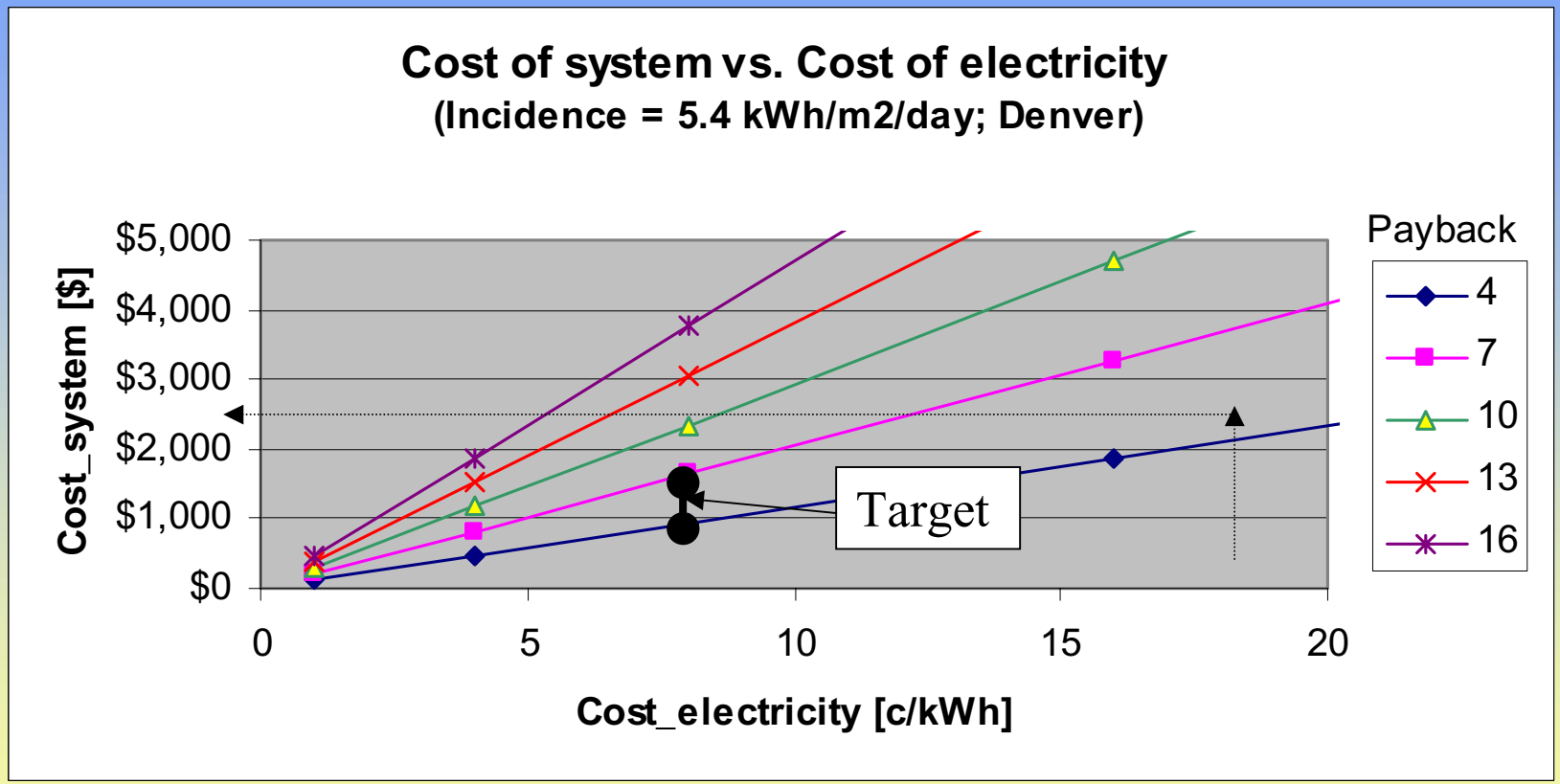
U.S. potential: >$450 Million/year

World potential: ~ 10x U.S. potential

Market Penetration Curve



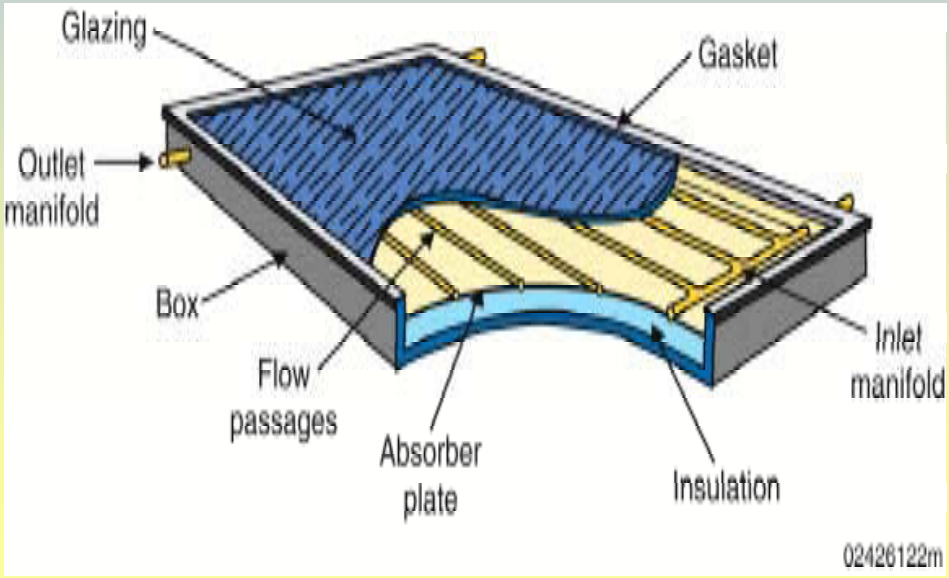
Example Solar Water Heating System Cost

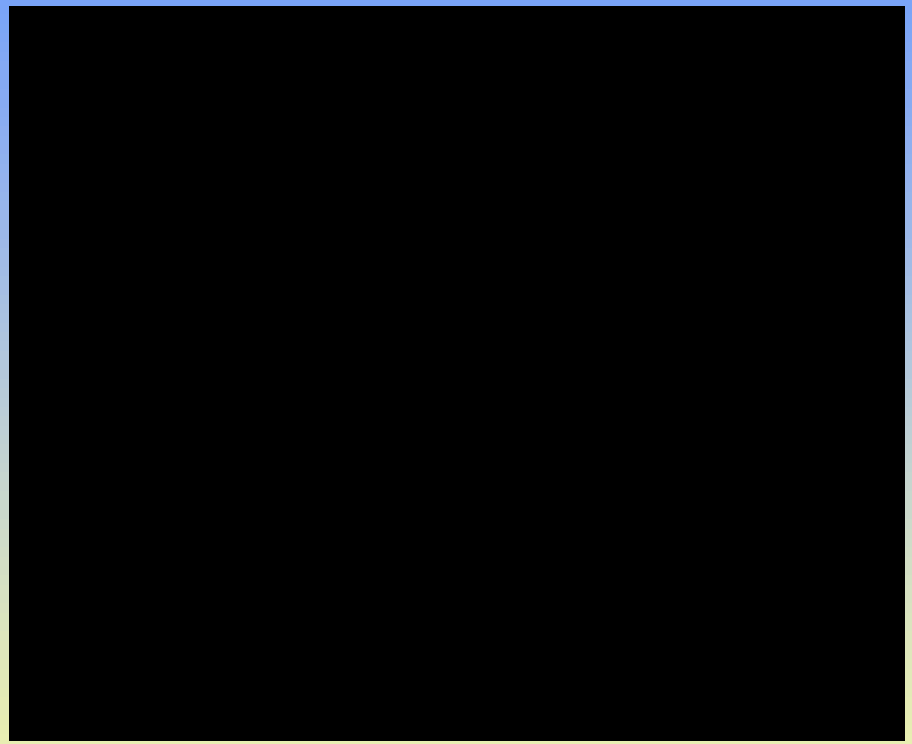


1. Choose market penetration % ==> payback (previous slide)
2. For site cost of fuel, find system cost @ payback line

Active Solar Water Heating

Flat Plate Collector





Indirect Circulation Solar System

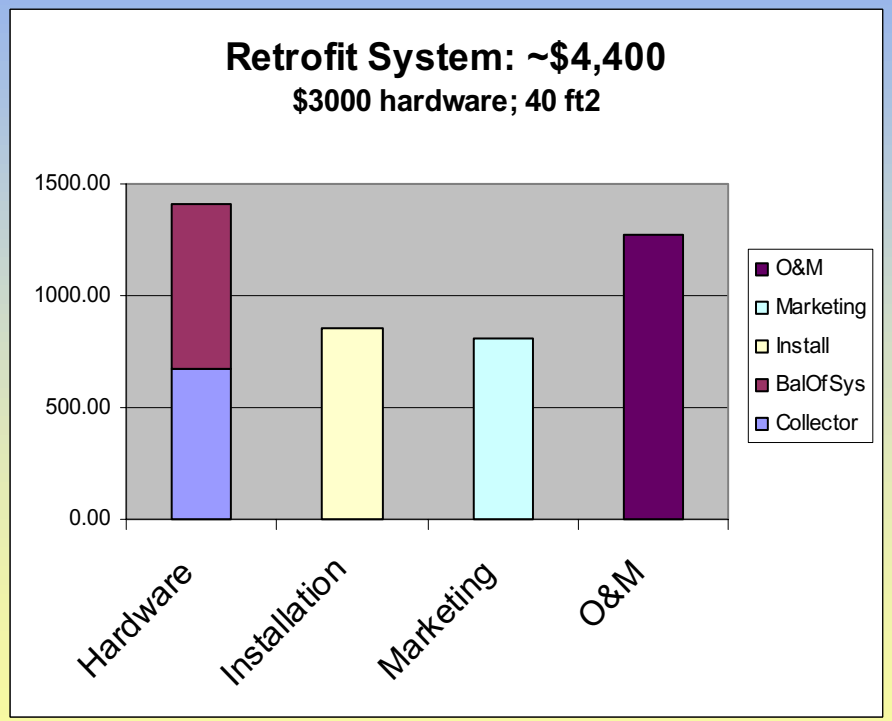
Active Solar System Cost Reduction

For active systems, large cost reductions are needed:

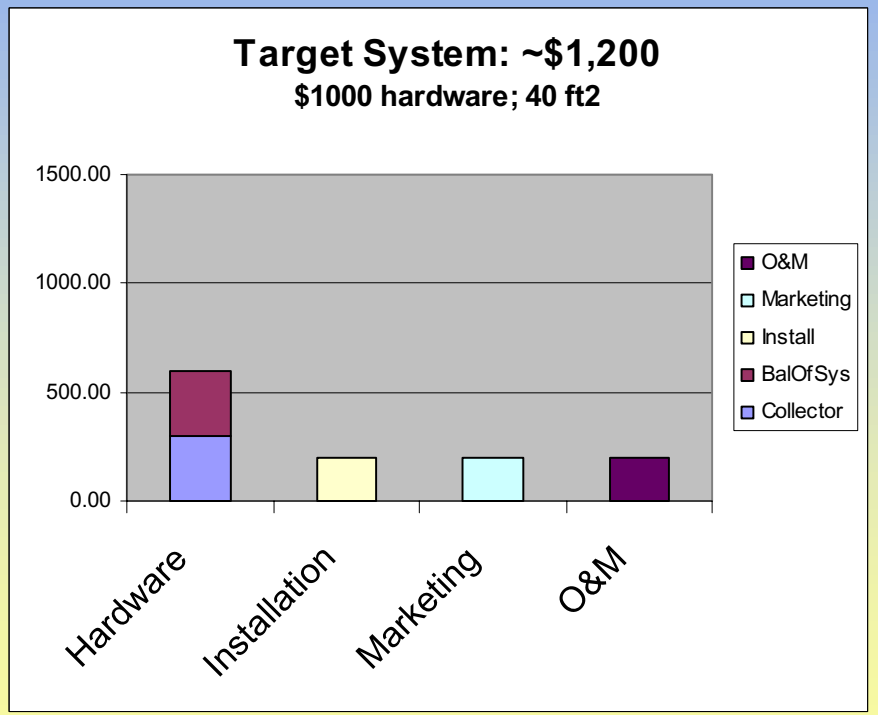
	Today	Goal
Hardware	$1,400	$600
Installation	$900	$200
Marketing	$800	$200
O&M	$1,300	$200
Total	$4,400	$1,200
Hardware cost reduction		**2.3**
System cost reduction		**3.7**

Active Solar Water Heating System Costs

Today

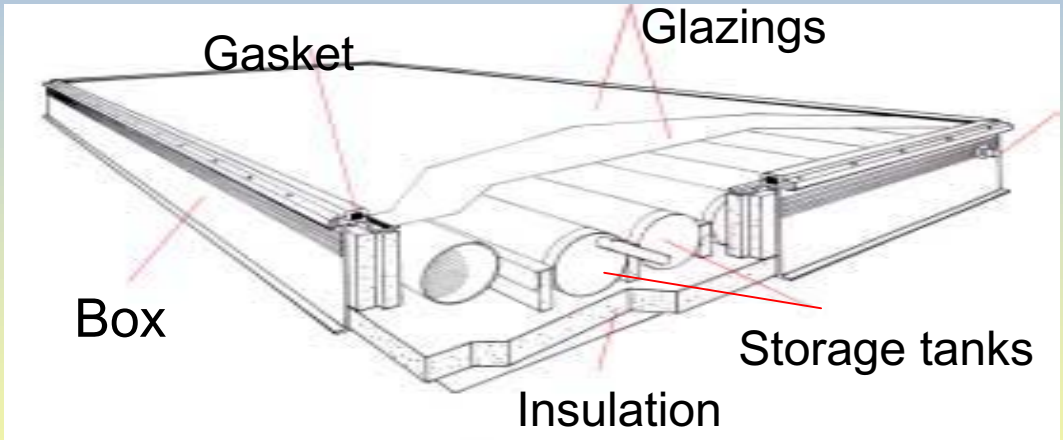


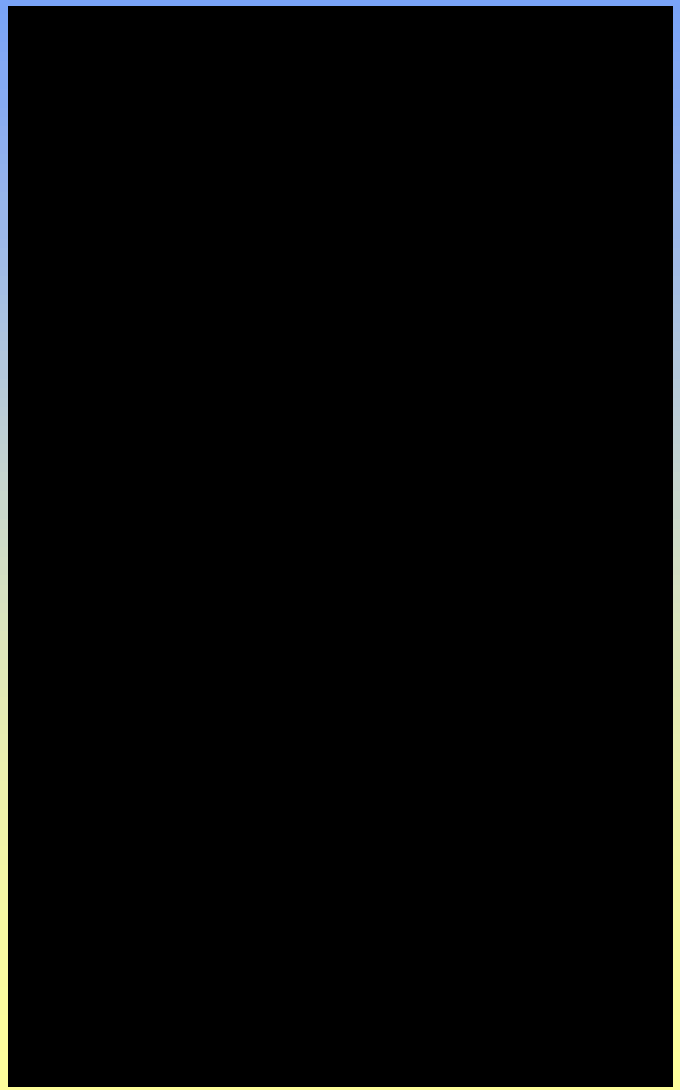
Goal



Passive Solar Water Heating

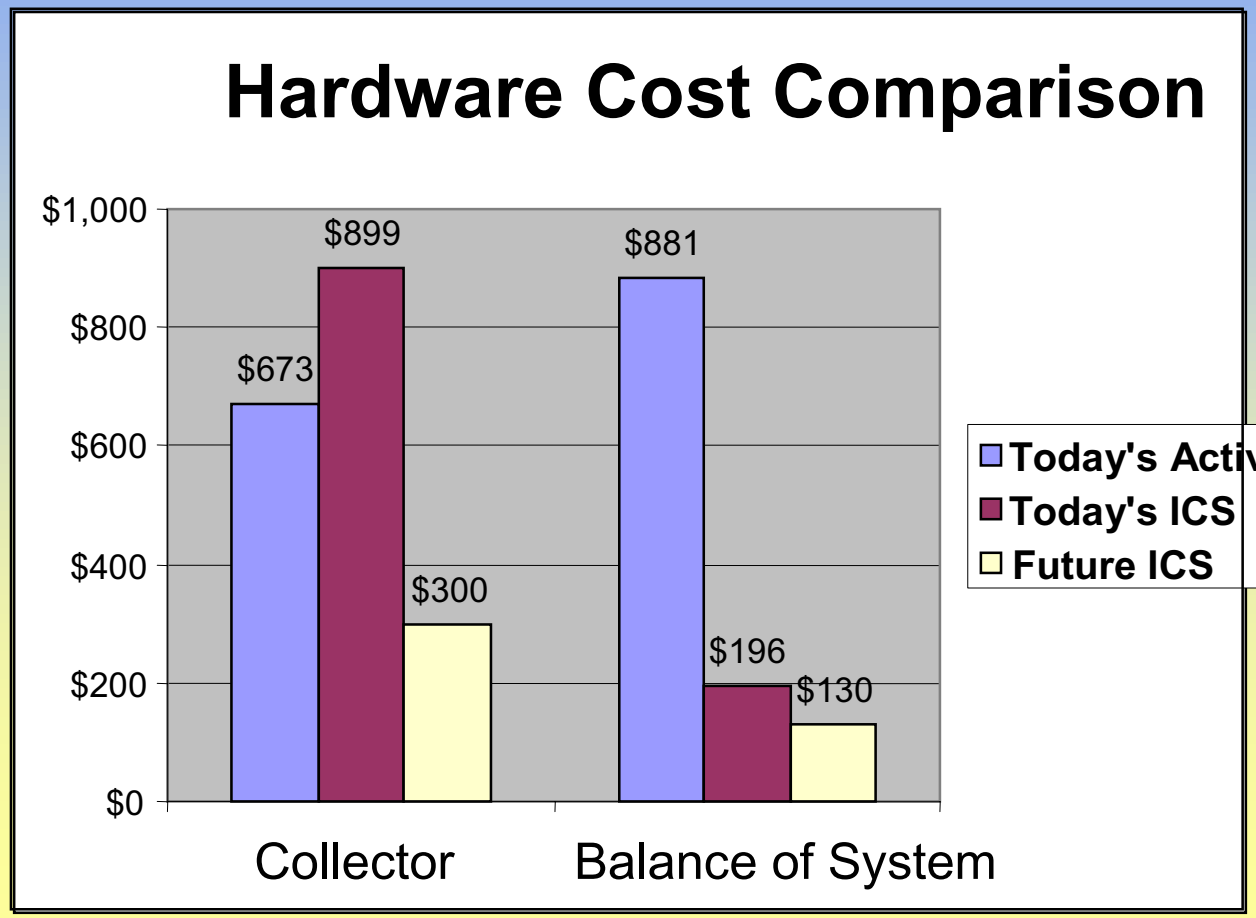
Integral Collector-Storage
(ICS) System



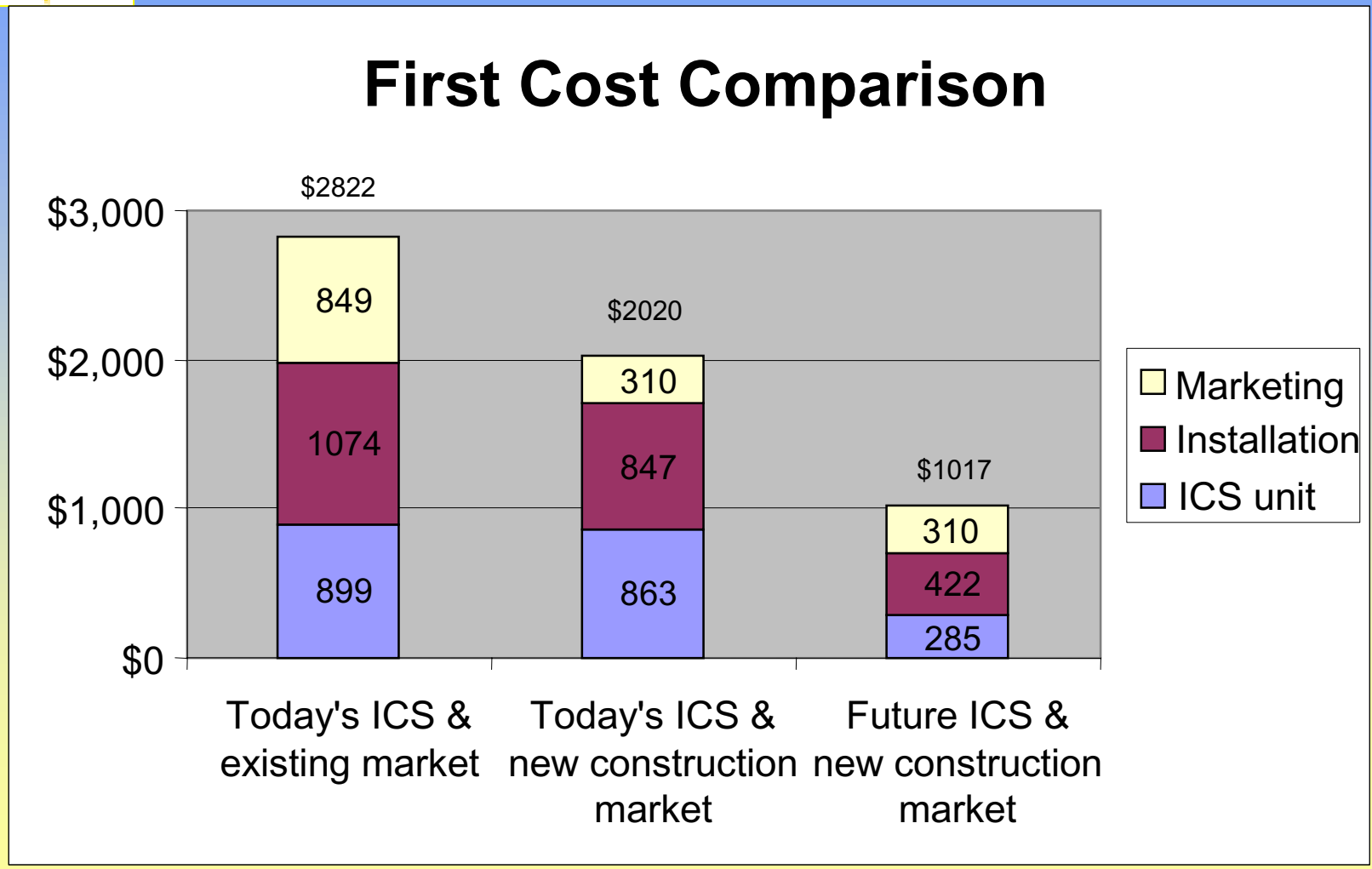


Solar Water Heating Hardware Costs

Balance of System costs makes ICS systems inherently less expensive than active



Passive Solar Water Heating System Costs



Phoenix; Discount Rate = 3.8%; Cost of Electricity = 8 c/kWh

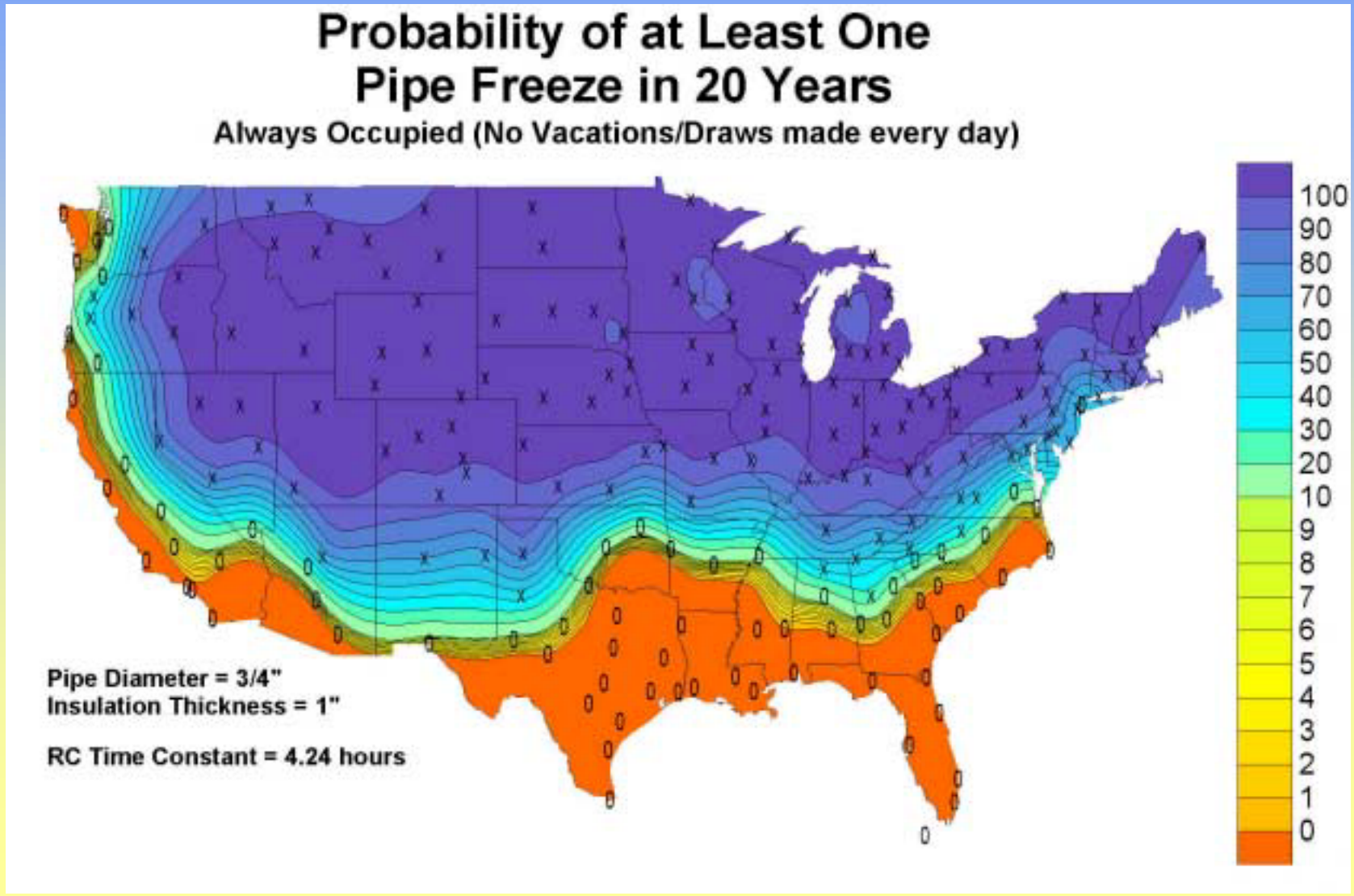
Innovative, Low-Cost Solar Water Heaters

Project Goal:

Cut the delivered, life-cycle energy cost of solar water heating systems in half by the year 2005.

Source: Solar Buildings Strategic Plan - 1997

Geographical Limitations of ICS Systems



Solar Thermal Systems R&D Goals

Near-Term (2005):

• Mild-climate solar water heating systems that deliver energy at $.04/kWh

Mid-Term (2008-2010):

• Cold-climate solar water heating systems that deliver energy at $.04-$.05/kWh

Long-Term (2015-2020):

• Solar space heating and cooling systems that deliver energy at $.04-$.05/kWh