



COOLING AND DRYING USING SOLAR ENERGY

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OUTLINE OF TODAY'S PRESENTATION

- *Solar Drying*
 - ü Applications
 - ü Options
 - ü Economics
 - ü Future Prospects
- *Solar Cooling*
 - ü Applications
 - ü Options
 - ü Economics
 - ü Future Prospects
- *Cooling and Drying using a Single Solar Co-Generating System*
- *Selection of Solar Collector for an Application*
- *Economics of a Co-Generating System*
- *Conclusions*



SOLAR DRYING

Major Applications

- ***Food and Agricultural Product Drying***
 - ü **Fruits** >> *bananas, mangoes, grapes, apples, pineapples, etc.*
 - ü **Vegetables** >> *onions, potatoes, coriander, methi, etc.*
 - ü **Grains** >> *paddy, wheat, maize, millet, etc.*
 - ü **Herbs and Spices** >> *tulsi, neem, ginger, garlic, chillies, etc.*
 - ü **Cash Crops** >> *coffee, tea, flowers, etc.*
 - ü **Fish and Meat**
- ***Low Temperature Industrial Drying***
 - ü **Chemicals**
 - ü **Pigments**
- ***High Temperature Industrial Drying***
 - ü **Paint Booth Drying**
 - ü **Asbestos Sheet Drying**
 - ü **Paper and Fabric Drying**



SOLAR DRYING

Types of Solar Dryers

- *Solar Energy Incident on the Product being Dried*
 - ü Traditional drying racks in the open air
 - ü Covered racks, protecting against dust and insects
 - ü Drying boxes with insulation, absorptive material and air vents

- *Indirect Heating of Product being Dried*
 - ü Heating the drying air using solar energy and then passing it over the product to be dried
 - ü Using a heating media to heat the product being dried and passing drying air over it

- *Solar Regenerated Desiccant Drying of Product*
 - ü Passing hot dehumidified air over the product to be dried and recirculating it after dehumidifying it using desiccant, the desiccant is regenerated using solar energy



FOOD AND AGRICULTURAL PRODUCT DRYING

Some Important Features

- ***Indirect Dryers***

- **ü Better product quality** >> *exposed to lower temperatures*

- **ü Chlorophyll levels are better retained** >> *not exposed to ultraviolet radiation*

- **ü Condensation of moisture in upper layers** >> *can be prevented by stacking the product to a lesser height, by stacking it less closely, using a larger collector, working with higher inlet air temperature, and increasing air circulation rate*

- **ü These dryers usually have higher cost and complexity**

- **ü Possibility of eliminating fan/blower** >> *using a heating media to heat the product being dried and passing drying air over it because moisture pickup per kg dry air is much higher*

- ***Solar Regenerated Desiccant Dryers***

- **ü Lower cost and faster drying at lower temperatures** >> *humidity in the air can be reduced, heat losses can be reduced*

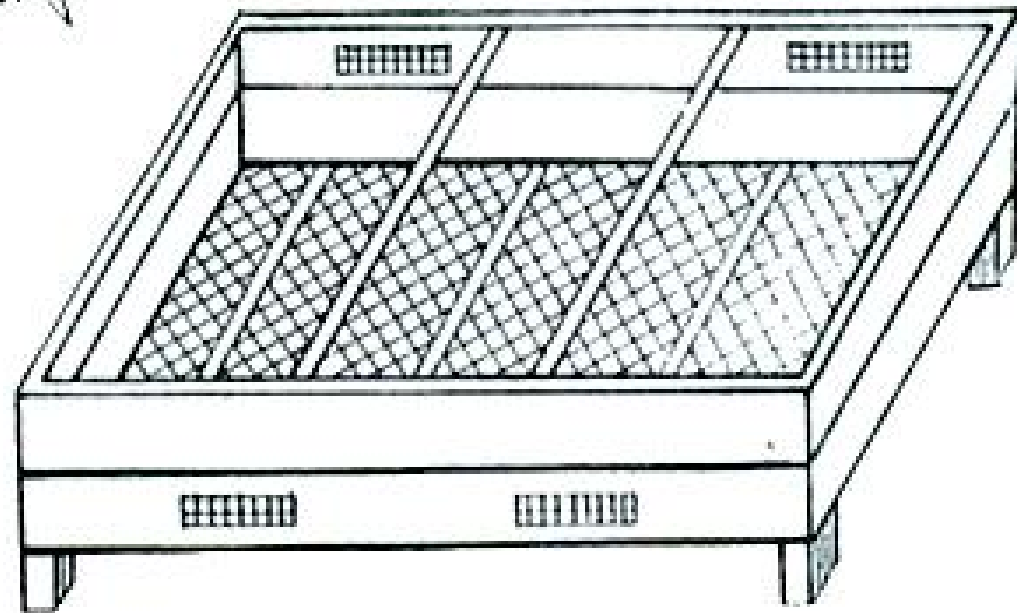
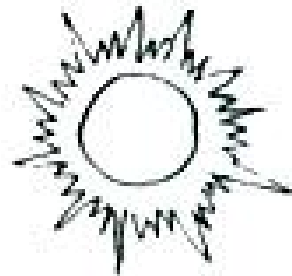


SOLAR DRYING

Flat Solar Dryers

Features

- ***Simple*** >> can be locally manufactured
- ***Passive*** >> no moving part, no auxiliary power required
- ***Moderate Cost***
- ***Low Efficiency*** >> air circulation limits drying rate
- ***Suitable for Small Capacities*** >> few kg of moisture removal per day



Flat Solar Dryer

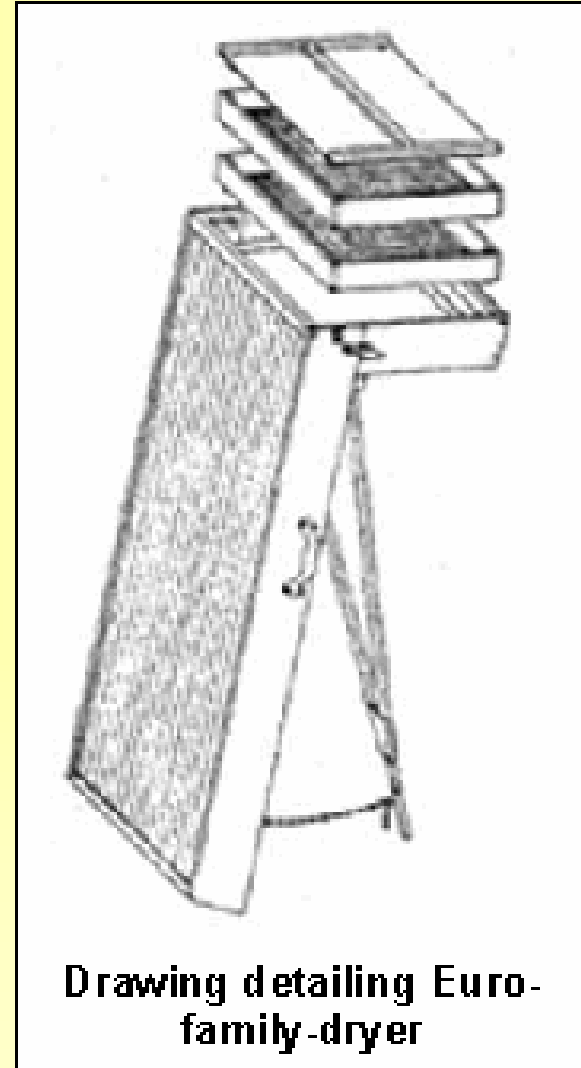


SOLAR DRYING

Euro-Family-Dryers

Features

- ***Simple*** >> can be folded and relocated easily
- ***Passive*** >> no moving part, no auxiliary power required
- ***Low Cost*** >> wooden construction
- ***Low Efficiency*** >> air circulation limits drying rate
- ***Suitable for Small Capacities*** >> few kg of moisture removal per day for household purpose



Drawing detailing Euro-family-dryer

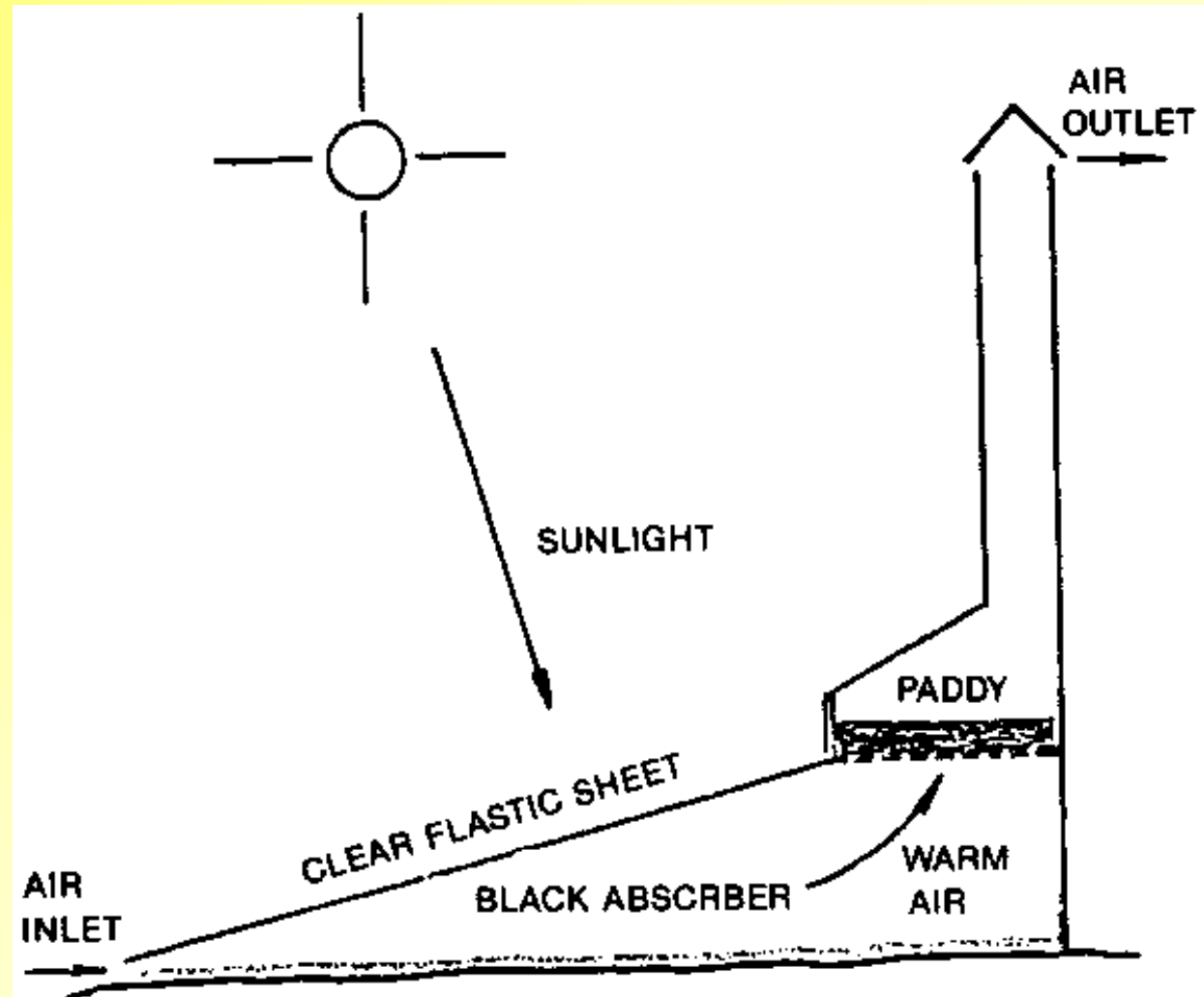


SOLAR DRYING

Chimney Assisted Air Circulation

Features

- ***Simple*** >> locally fabricated
- ***Passive*** >> no moving part
- ***Low Cost***
- ***Large Product Holding Area is Required*** >> to keep pressure drop across the bed small
- ***Capacities*** >> 10 to 100 kg of moisture removal per day



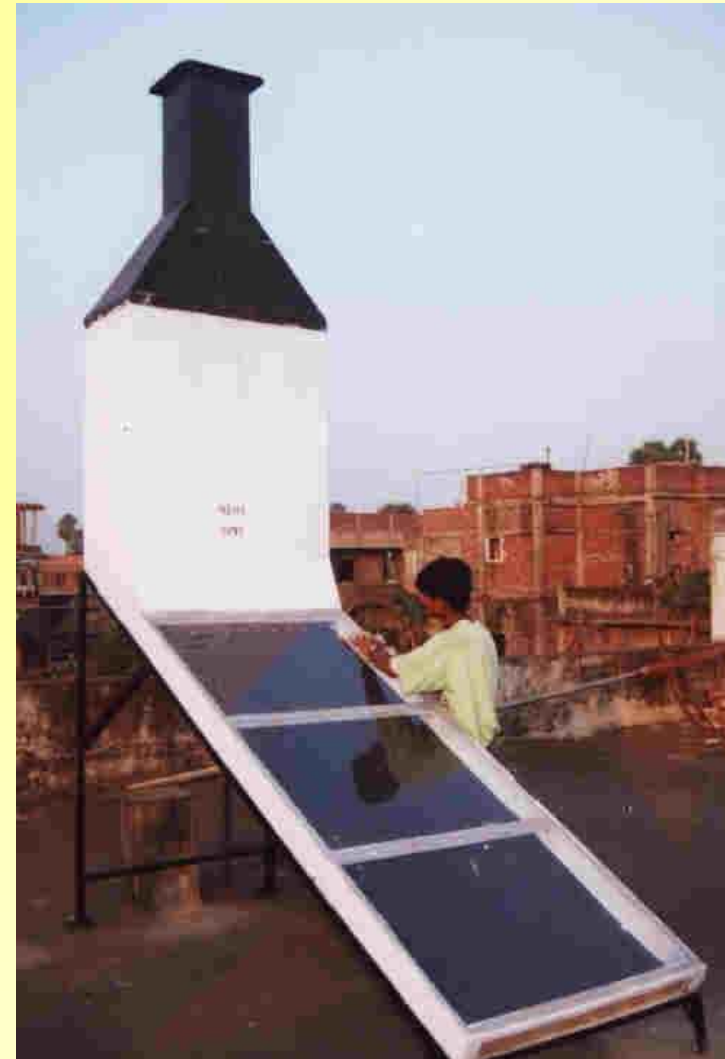


SOLAR DRYING

Chimney Assisted Air Circulation

Features

- *Passive* >> no moving part
- *Modest Efficiency* >> air circulation aided by draft due to the chimney
- *Suitable for Larger Product Loading* >> multiple trays to hold the material being dried
- *High Cost* >> FRP body



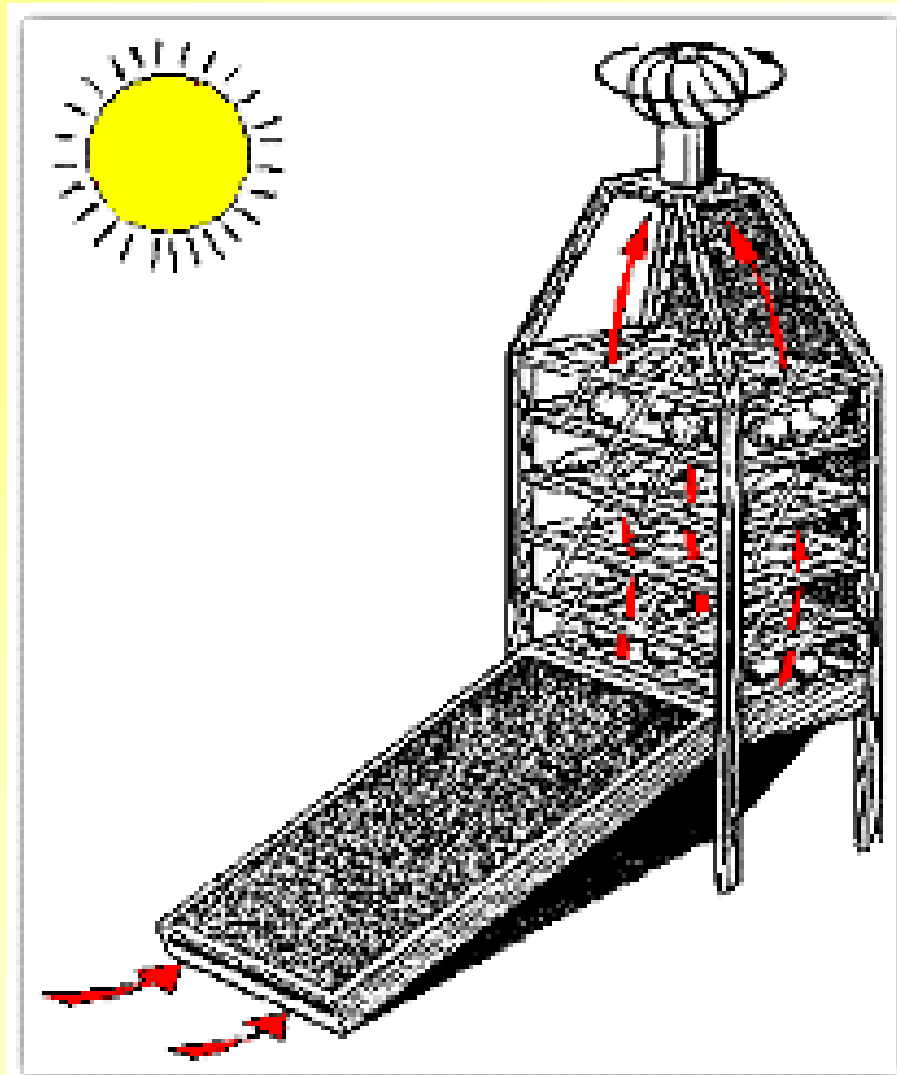


SOLAR DRYING

Chimney Assisted Air Circulation

Features

- *Wind Powered* >> air circulation
- *Moderate Cost*
- *Modest Efficiency* >> air circulation aided by draft due to the chimney
- *Suitable for Larger Product Loading* >> multiple trays to hold the material being dried
- *Performance will Deteriorate at Low Wind Velocities*

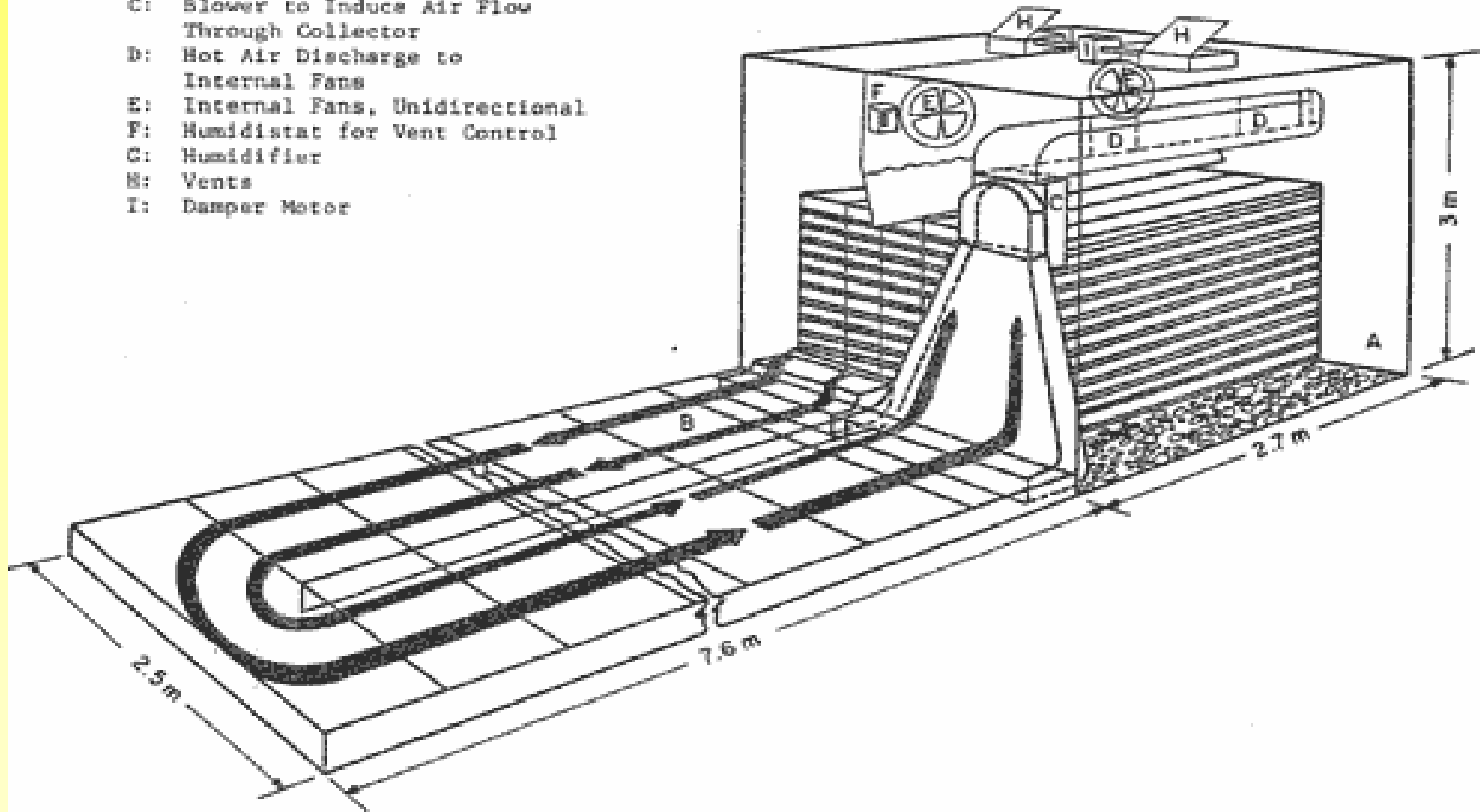




SOLAR DRYING

Electric Fan Assisted Air Circulation

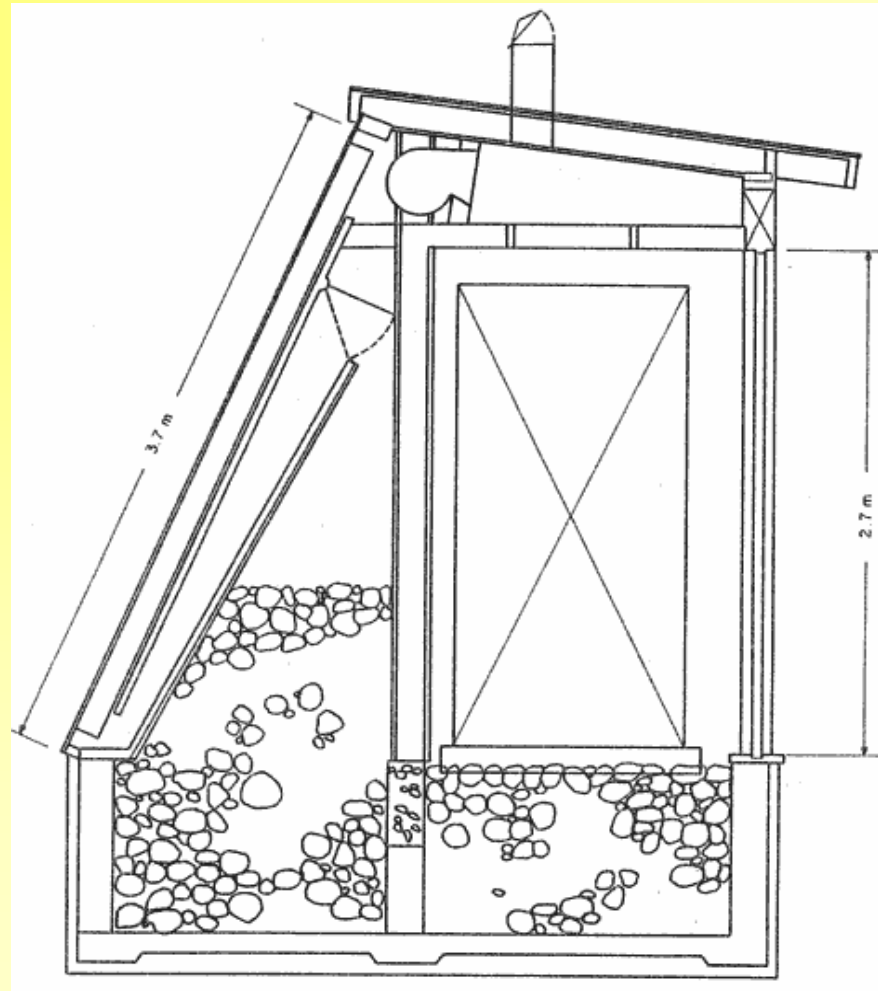
- A: Drying Chamber
- B: Solar Collector
- C: Blower to Induce Air Flow Through Collector
- D: Hot Air Discharge to Internal Fans
- E: Internal Fans, Unidirectional
- F: Humidistat for Vent Control
- G: Humidifier
- H: Vents
- I: Damper Motor





SOLAR DRYING

Electric Blower Assisted Air Circulation and Rock Bed Thermal Storage





SOLAR DRYING

Economic Viability and Future Prospects

- *How can the Economics be Improved?*
 - **Developing passive dryers to reduce initial and operating cost** >> *without fans/pumps and associated auxiliary power requirement*
 - **Reducing cost of collectors, to reduce the investment needed per unit heat collected** >> *to Rs 3,000 to 5,000/kW_h to get 900 solar hour payback @ 750 kW/m² solar insolation, fuel cost Rs 20/kg, CV 40 MJ/kg, efficiency fuel fired air heater 80%*
 - **Developing dryers with multi-use capabilities and backup firing** >> *to ensure year round utility which will lead to lower payback*
- *New Developments and Their Prospects*
 - **All plastic passive solar dryers** >> *without moving parts and the dryer cost about Rs 3000/m² solar aperture*
 - **Evacuated-tube collectors with collection efficiencies up to 0.5 at air delivery temperatures in the range of 150 to 200°C** >> *reduce the size and cost*



SOLAR COOLING

Applications

- *Vaccine Storage*

- **Ü storage capacity 15 to 240 litre; typical storage temperatures 2 to 8°C; refrigeration capacity 20 to 240 W; PV powered vapour compression system or concentrating collector heated ammonia/water systems**

- *Ice Making*

- **Ü production 5 to 75 kg/day ice; evaporator temperatures -10 to -15°C; collector area 1 to 30 m²; concentrating collector heated ammonia/water and AC/methanol intermittent systems; preservation of fish and meat; precooling of milk, fresh fruits and vegetables**

- *Cold Storage*

- **Ü storage capacity 1 to 20 Tonne; flat plate collectors with ammonia/water and LiBr/water systems; seasonal storage of potatoes, onions, etc.**



SOLAR COOLING

Types of Solar Refrigeration Systems

- *PV Powered Vapour Compression Refrigeration Systems*
 - ü **Cycle COP 0.8 to 1.0; typical PV conversion efficiency 0.1 to 0.15; solar COP 0.08 to 0.15; large collector area required; PV cells are costly**
- *Mechanical Power Generation and its use to Operate Vapour Compression Refrigeration Systems*
 - ü **Cycle COP 0.8 to 2.0; mechanical power generation efficiency 0.1 to 0.15; solar COP 0.08 to 0.3; large collector area needed; several moving parts**
- *Direct Thermal Energy Driven Sorption Refrigeration Systems*
 - ü **Cycle COP 0.2 to 0.6; collector efficiency 0.3 to 0.5; solar COP 0.06 to 0.3; simpler construction; less maintenance; still not economically viable**



SOLAR COOLING

Economic Viability and Future Prospects

- *How can the Economics be Improved?*
 - ü **Developing refrigeration cycles with high COP** >> *in the range of 1.5 to 4 for vapour compression and 0.5 to 1.0 for sorption*
 - ü **Developing collectors with high efficiency** >> *in the range of 0.15 to 0.25 for PV and 0.4 to 0.6 for high temperature thermal*
 - ü **Reducing cost of collectors to reduce the investment needed for unit heat collected** >> *about Rs 15,000 @ 120°C; Rs 30,000 /kW_h @ 150°C; Rs 40,000 /kW_h @ 180°C*

- *New Developments and Their Prospects*
 - ü **Sorption systems with high cooling COP** >> *in the range of 0.9 to 1.2 reduces the solar collector area*
 - ü **Evacuated-tube heat-pipe collectors with collection efficiencies up to 0.5 at collection temperatures in the range of 150 to 200°C** >> *reduce the size and cost*

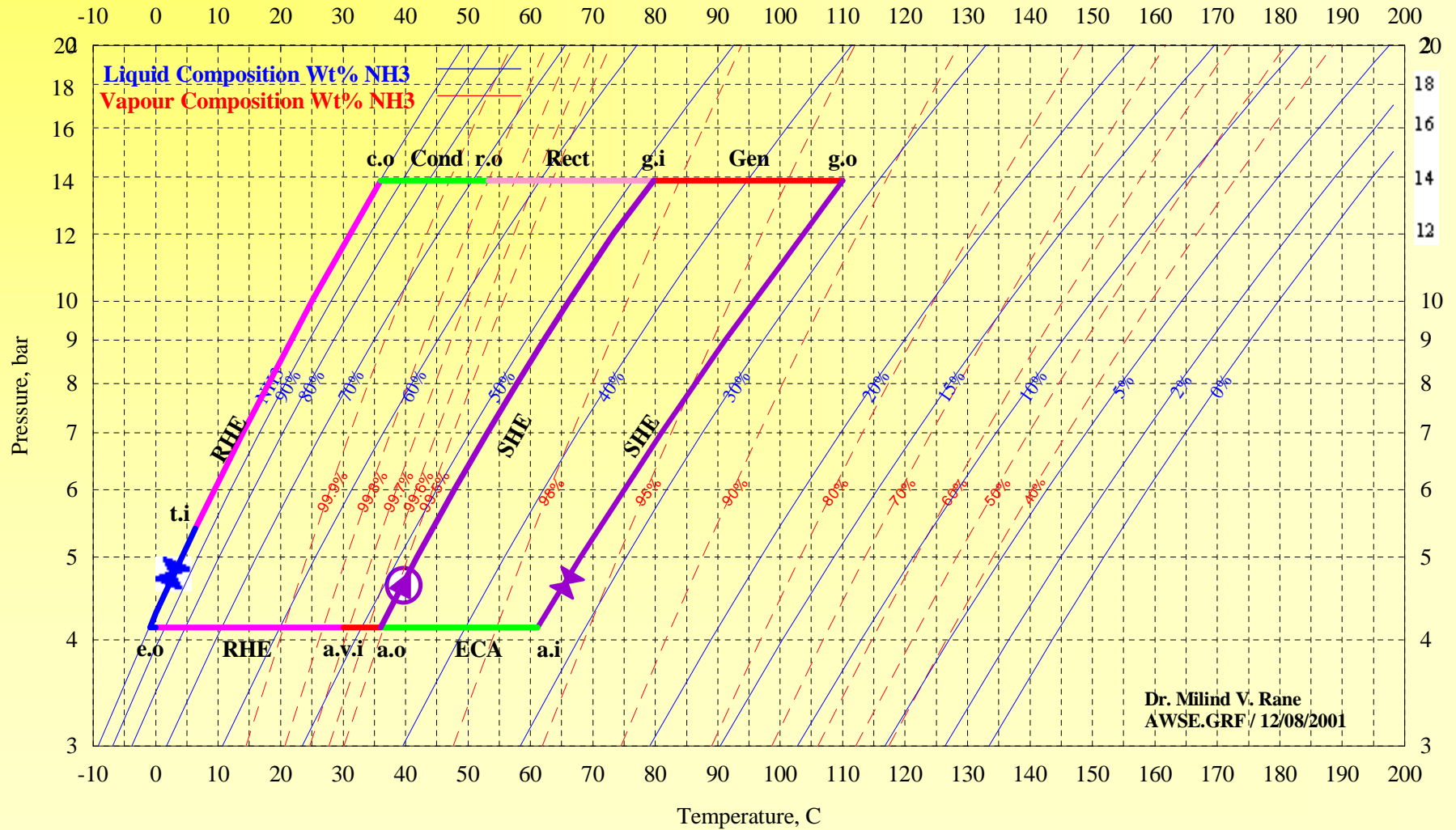


VAPOUR ABSORPTION CYCLES

- *Single Effect Vapour Absorption Cycle (SE Cycle)*
 - ü COP 0.63
 - ü Construction is simple
 - ü Fabricated for many applications
- *Single Effect with Absorber & Generator Heat Exchanger Cycle (SEA&GHX Cycle)*
 - ü COP 0.7
 - ü Additional cost of heat exchanger is less than reduction in cost of solar collector
- *Generator Absorber Heat Exchange Cycle (GAX Cycle)*
 - ü COP 1.1
 - ü Reduction in absorbent solution circulation losses >> *by incorporating a generator-absorber heat exchanger*

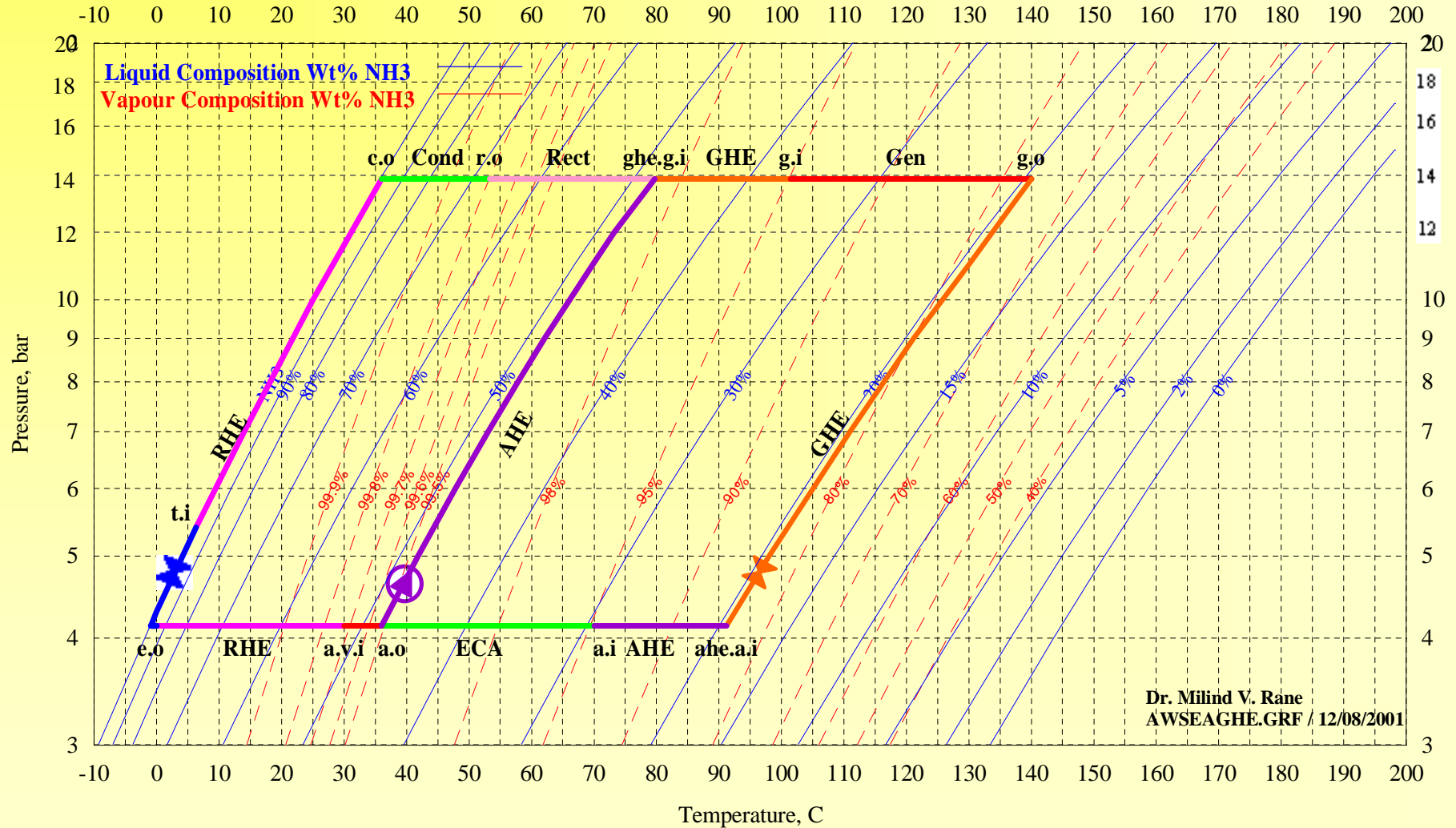


SINGLE EFFECT CYCLE ON PTX DIAGRAM



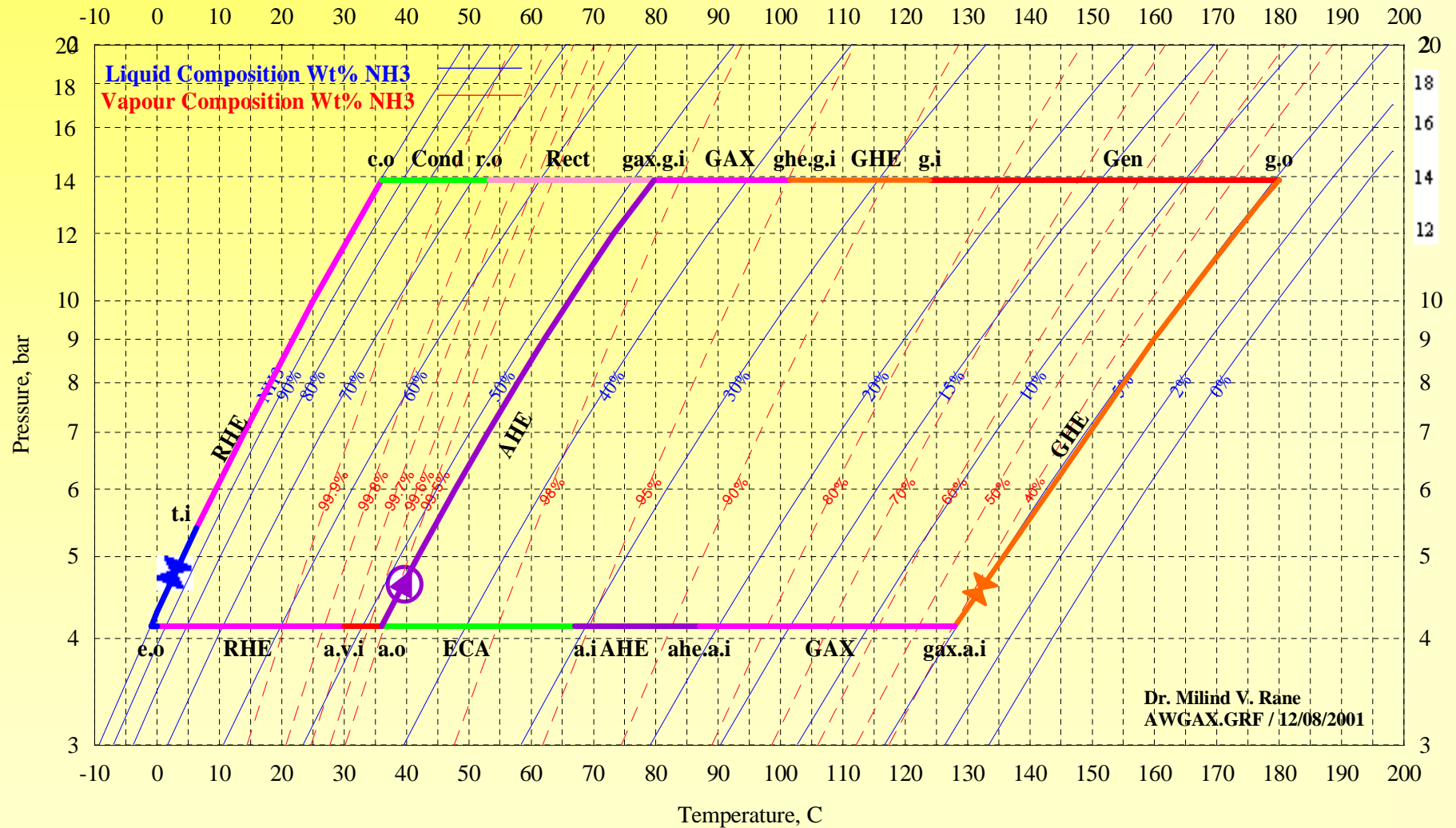


SINGLE EFFECT CYCLE WITH A&GHE ON PTX DIAGRAM



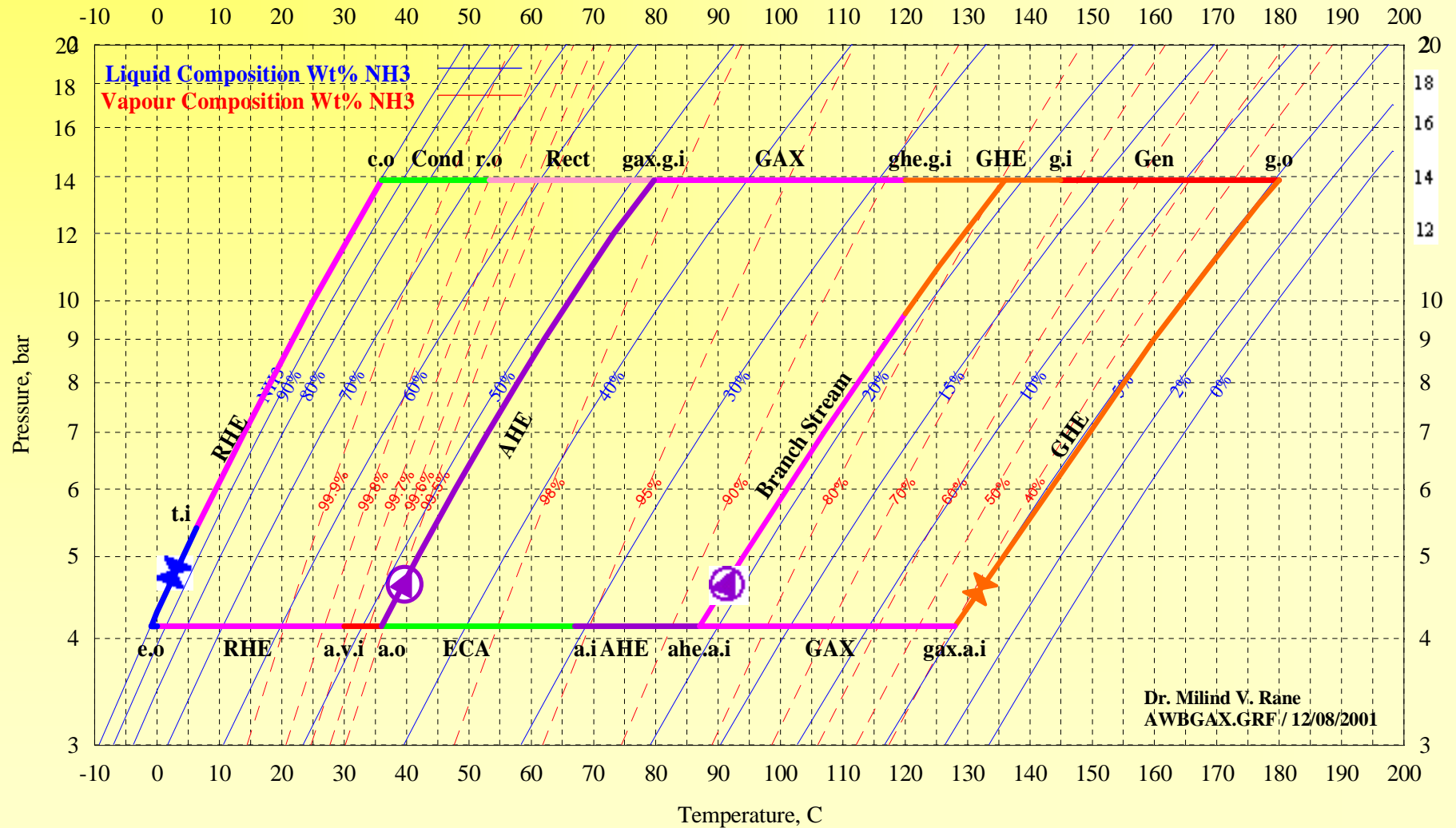


GAX CYCLE ON PTX DIAGRAM





BRANCHED GAX CYCLE ON PTX DIAGRAM





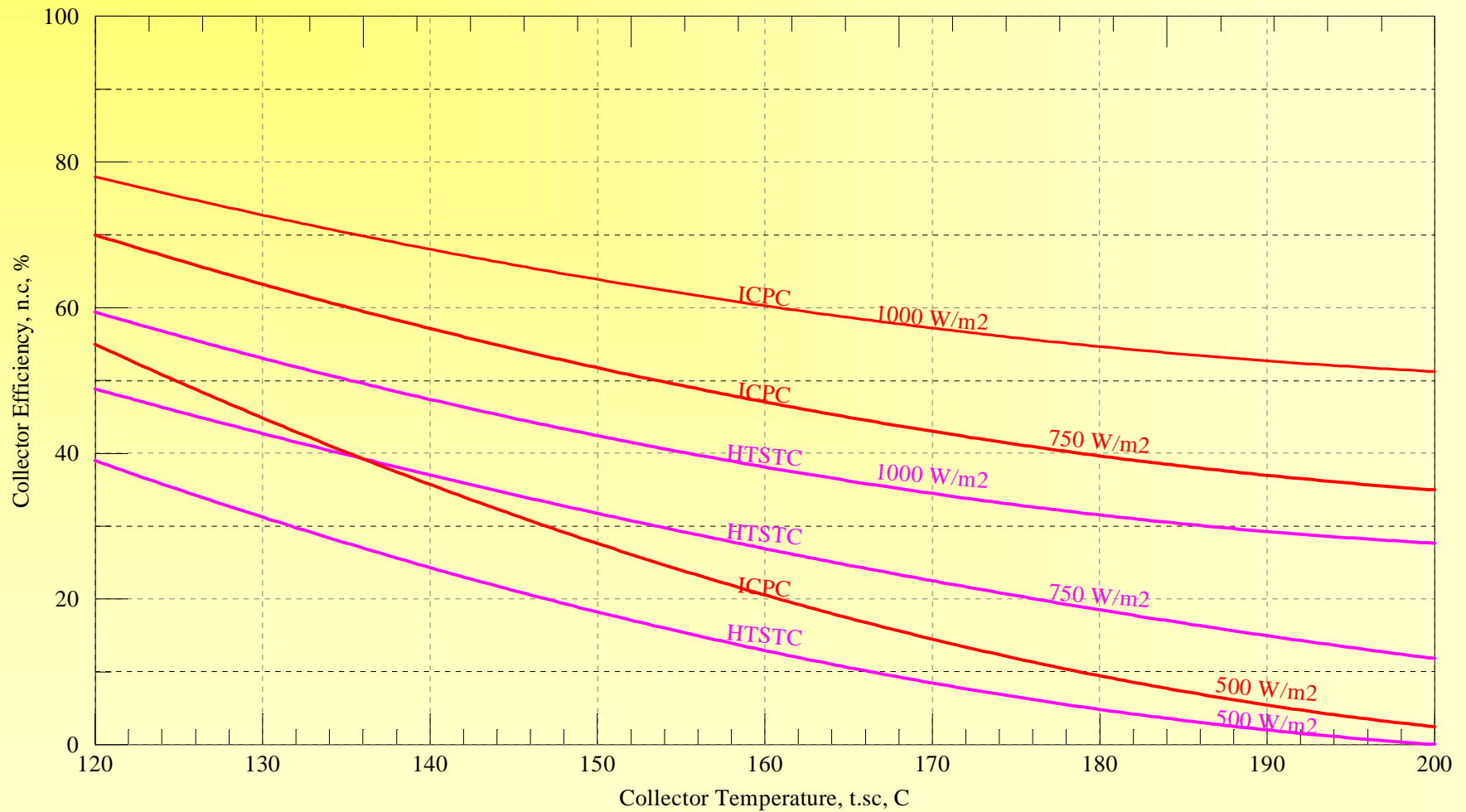
VAPOUR ABSORPTION CYCLES

(Continued)

- ***Branched GAX Cycle (BGAX Cycle)***
 - ü **COP 1.2**
 - ü **Solution flow rate through the temperature overlap section of the absorber is increased >> in order to increase the heat release**
 - ü **Additional components are required to divert the solution >> like the pump, branched solution preheater and control mechanism**
 - ü **Added cost and complexity**
- ***Vapour Exchange GAX Cycle (VX GAX cycle)***
 - ü **COP 1.55**
 - ü **Designed to tap in to otherwise lost availability of absorber and rectifier**
 - ü **Achieved by incorporating a desorber and absorber at intermediate pressure level**
 - ü **It has not been commercialised due to multi stream heat exchangers and control requirement to implement the cycle**



VARIATION IN SOLAR COLLECTOR EFFICIENCY with Collector Temperature for HTSTC and ICPC





VARIOUS SOLAR COLLECTORS

Features

- *Flat Plate Solar Collector with Heat Pipe (FPSC)*
 - Simple construction but can't be used above 120°C
 - Efficiency 25% at 100 to 120°C
 - Less due to high top loss coefficient
 - Cost: 9000 Rs/m² of collector area
- *Integrated Compound Parabolic Concentrator (ICPC)*
 - Low concentration version of CPC
 - It is difficult to maintain vacuum throughout the life of collector
 - Cost: 18,000 Rs/m² of collector area
- *High Temperature Solar Tubular Collector (HTSTC)*
 - Non evacuated, non tracking type
 - Cost: 10,000 Rs/m² of collector area



COLLECTOR CYCLE PAIRING

- *SE Cycle (COP_c = 0.63, t_{g0} = 110°C)*

<i>Collector Type</i>	<i>FPSC</i>	<i>HTSTC</i>	<i>ICPC</i>
Efficiency of Collector (%)	25	48	70
Collector Cost per kW _h @ 120°C (Rs)	48,000	27,800	34,300
Solar COP	0.158	0.302	0.441
Cost of Collector for 10 TR (Lakh Rs)	26.8	15.5	19.2

- *SEA&GHX Cycle (COP_c = 0.7, t_{g0} = 140°C)*

<i>Collector Type</i>	<i>FPSC</i>	<i>HTSTC</i>	<i>ICPC</i>
Efficiency of Collector (%)		33	52
Collector Cost per kW _h @ 150°C (Rs)		40,400	46,200
Solar COP		0.175	0.364
Cost of Collector for 10 TR (Lakh Rs)		20.3	23.2



COLLECTOR CYCLE PAIRING

- *GAX Cycle (COP_c = 1.1, t_{g0} = 180°C)*

<i>Collector Type</i>	<i>FPSC</i>	<i>HTSTC</i>	<i>ICPC</i>
Efficiency of Collector (%)		15	37
Collector Cost per kW _h @ 190°C (Rs)		88,900	64,900
Solar COP		0.165	0.407
Cost of Collector for 10 TR (Lakh Rs)		28.4	20.8

- *BGAX Cycle (COP_c = 1.2, t_{g0} = 180°C)*

<i>Collector Type</i>	<i>FPSC</i>	<i>HTSTC</i>	<i>ICPC</i>
Efficiency of Collector (%)		15	37
Collector Cost per kW _h @ 190°C (Rs)		88,900	64,900
Solar COP		0.18	0.444
Cost of Collector for 10 TR (Lakh Rs)		26.1	19.0



SAVING USING SOLAR COLD STORE

Fuel Saving During Day Time Operation

- *Cold Store Cooling Load* *35.2 kWe (10 TR)*
- *Generator Duty @ COP = 0.63* *55.9 kW*
(289,000 kcal/h)
- *Assumptions:*
 - **6 h/day solar operation for 300 day/year in Ahmedabad**
 - **84% thermal efficiency of HSD fired water heater**
 - **HSD price of Rs 18/kg**
 - **Calorific value of HSD 40,337 kJ/kg (9650 kcal/kg)**
- *Fuel Savings* $(55.9 \times 3600 \times 6000 / (9650 \times 4.18 \times 0.84))$ *10,690 kg HSD/yr*
- *Fuel Cost Savings* $(10,690 \times 18)$ *Rs 1.92 Lakh/yr*



PAYBACK PERIOD FOR SOLAR COLD STORE

With and Without Accounting for 100% Depreciation in the First Year

- *Cold Store Cooling Load* *35.2 kW_c (10 TR)*
- *Additional Cost of Solar Collectors* *Rs 15.5 Lakh*

- *Assumptions:*

- **ü Solar Ammonia Absorption Refrigeration (AAR) System is compared with**

- **a HSD Fired AAR**

- **ü Additional cost of the Solar AAR System, the solar collector cost**

- **ü HSD firing can serve as backup to the solar heat input**

- *Fuel Cost Savings (10,690 x 18)* *Rs 1.92 Lakh/yr*
- *Simple Payback* (compared to HSD Fired AAR System) *8 years*
- *Simple Payback with 100% Depreciation* *5.4 years*



SAVING USING ABSORBER HEAT RECOVERY

Additional Fuel Saving due to Water Heating

- *Cold Store Cooling Load* *35.2 kW_c (10 TR)*
- *Recoverable Absorber Heat* *55.9 kW*
(289,000 kcal/h)
- *Assumptions:*
 - ü **6 h/day solar operation for 300 day/year in Ahmedabad**
 - ü **84% thermal efficiency of HSD fired water heater**
 - ü **HSD price of Rs 18/kg**
 - ü **Calorific value of HSD 40,337 kJ/kg (9650 kcal/kg)**
- *Fuel Savings* (55.9 x 3600 x 6000 / (9650 x 4.18 x 0.84)) *10,690 kg HSD/yr*
- *Fuel Cost Savings* while Generating Hot Water (10,690 x 18) *Rs 1.92 Lakh/yr*
- *Total Fuel Cost Savings* *Rs 3.84 Lakh/yr*



PAYBACK PERIOD FOR SOLAR CO-GENERATOR

Operating Cold Store and Dryer using an Absorption Heat Pump

- *Cold Store Cooling Load* *35.2 kW_c (10 TR)*
- *Additional Cost of Solar Collectors* *Rs 15.5 Lakh*

- *Assumptions:*

- **ü Solar Ammonia Absorption Refrigeration (AAR) System is compared with a HSD Fired AAR**
- **ü Additional cost of the Solar AAR System is essentially the solar collector cost**
- **ü HSD firing can serve as backup to the solar heat input**

- *Total Fuel Cost Savings* *Rs 3.84 Lakh/yr*
- *Simple Payback* (compared to HSD Fired AAR System) *4 years*
- *Simple Payback with 100% Depreciation* *2.7 years*



CONCLUSIONS

- *Low Temperature Dryers can be made Economically Viable by Using Suitable Plastics as MOC and Eliminating Moving Parts*
- *Indirectly Heating the Product Using a Heat Transfer Media and Passing the Air Over it May Lead to Simpler Design*
- *Dryers with Multi-Use Capabilities and Backup Firing would Ensure Year Round Utility and Hence Lead to Lower Payback Periods*
- *All Plastic Passive Solar Dryers is Developed at Heat Pump Laboratory, IIT Bombay which Has 100 to 150 Solar Day Payback*
- *Evacuated-Tube Collectors with Collection Efficiencies Upto 50% at Air Delivery Temperatures in the Range of 150 to 200°C can Reduce Size and Cost of the High Temperature Industrial Air Heating Applications*



CONCLUSIONS

- *Economically Viable Solar Cold Stores Need to be Developed to Prevent Huge Amount of Loss Due to Storage at Room Temperature.*
- *HTSTC Offers Lowest Initial Cost of Solar Collector per Unit Heat Collected >> for temperature of 120 to 150°C Rs 27,800 to 40,400 /kW_h*
- *ICPC Offers Lowest Initial Cost of Solar Collector per Unit Heat Collected >> Rs 64,900 /kW_h for temperature of 180°C*
- *Combination of SE Cycle and HTSTC is the Best Option >> for an Evaporation Temperature of -5°C at Solar Insolation of 750 W/m²*
- *Total Collector Cost for 10 TR Cold Store >> about Rs 15.5 Lakh*
- *Simple Payback of a Solar Cold Store cum Dryer using an Absorption Heat Pump >> about 2.7 years*