2004 Program Review

Development of Solar-Powered Thermochemical Production of Hydrogen from Water

Ken Schultz for the
Solar ThermoChemical Hydrogen (STCH) Team

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UNLV Research Foundation
Las Vegas, Nevada
STCH
SOLAR THERMOCHEMICAL HYDROGEN GENERATION PROJECT
Sponsored by U.S. Department of Energy

STCH Team and our Leaders

- UNLV Research Foundation: Bob Perret
- University of Nevada, Las Vegas: Bob Boehm
- Sandia National Laboratories: Rich Diver
- General Atomics: Gottfried Besenbruch
- National Renewable Energy Laboratory: Allan Lewandowski
- University of Colorado: Alan Weimer

Can solar-powered water-splitting generate hydrogen competitively?

- Emulate the successful DOE NERI search for thermochemical cycles well-suited to nuclear energy by replacing nuclear with solar power
- Use screening and evaluation criteria unique to solar energy
- Take benefit from solar's advantages of very high temperature and very clean energy
- Preliminary estimates are very encouraging -- if cycles well–matched to solar energy can be identified

Objective: Define economically feasible concepts for solar-powered production of hydrogen from water

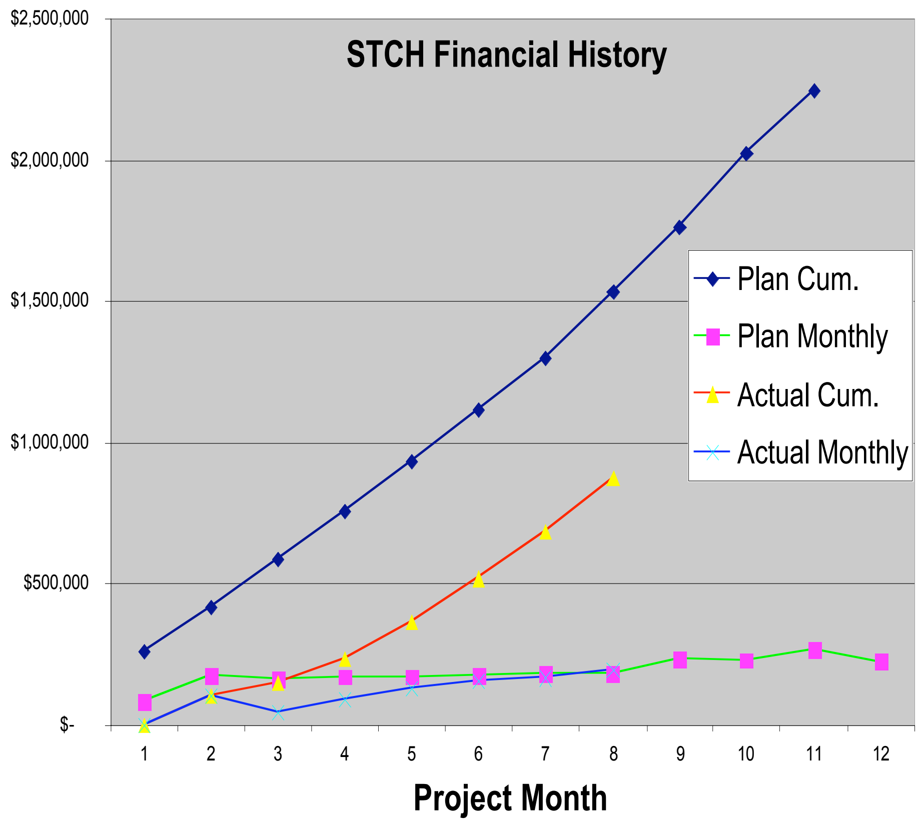
- **Task I: Screen and select cycles and systems**
  - Update thermochemical water-splitting cycle database
  - Establish objective Evaluation Criteria for solar thermochemical hydrogen production
  - Select and validate leading candidate cycles
  - Develop solar receiver/reactor design concepts for top cycles
    - Different receivers may favor different cycles
  - Develop system process flowsheets and receiver/reactor designs
  - Analyze and select best systems and estimate production cost
  - Develop recommendation for national review
    - Should solar thermochemical hydrogen development be continued?
    - What cycles and systems are recommended?
    - What are the needed next steps, including a pilot plant demonstration?

Objective: Define economically feasible concepts for solar-powered production of hydrogen from water

- **Task II: Build on earlier CU/NREL work to study metal oxide reduction cycles**
  - Ultra-high temperature solar-thermal reactor design
    - Design an improved efficiency solar aerosol flow reactor with reduced re–radiation losses
    - Develop preliminary design and evaluate economics for an ultra-high temperature solar hydrogen plant
  - Fundamental studies using CU transport tube reactor and the NREL High-Flux Solar Furnace
    - Both have demonstrated capability for temperatures over 2000K
    - $ZnO \rightarrow Zn + {}^{1}/_{2}O_2$ thermochemical cycle kinetics, reaction rate expression
      - 1500 – 2200°C; 0.1 – 1 s residence time
    - Mn_3O_4/MnO cycle data measurements and feasibility experiments

Budget: This project is a team effort

FY'03 Budget ($K)*	Total	Match
• UNLV Res. Found.	116.2	–
• UNLV	506.6	109.2
• SNL	442.2	–
• GA	821.6	177.1
• NREL	198.3	–
• Univ.Col.	163.4	35.2
• Total	2248.3	321.6



*: Work being done in FY'04

Technical Targets and Barriers for solar thermochemical hydrogen are challenging

Targets

Table 3.1.9. High- and Ultra-High-Temperature Thermochemical Hydrogen Production					
Characteristics		Units	2003 Status	2005 Target	2010 Target
High-Temperature Production[1]	Cost at the plant gate	\$/kg	NA[2]	10	2
	Energy Efficiency	%	NA[2]	25	40
Ultra-High Temperature Solar Production[3]	Cost at the plant gate	\$/kg	12	8	4
	Solar concentrator cost	\$/m²	250	130	75
Process efficiency[4]		%	20	40	45

Barriers

- V. Thermochemical technologies must be demonstrated
- W. High temperature materials are needed
- Y. Lower cost solar collectors are needed

Source: Hydrogen, Fuel Cells & Infrastructure Technologies Program, Multi-Year Research, Development and Demonstration Plan, Planned program activities for 2003-2010, DRAFT (June 3, 2003)

The *STCH* project addresses these barriers

V. Thermochemical technologies

- Evaluate, select and demonstrate thermochemical cycles
- Measure selected cycle data
- Design, fabricate and test components

W. High temperature materials

- Evaluate, select and test materials for chosen TC cycles
  - Integrate results of Nuclear H_2 Initiative efforts on HTHX and Materials (UNLVRF, UNLV, SNL, GA, UCB, MIT)

X. Lower cost solar collectors

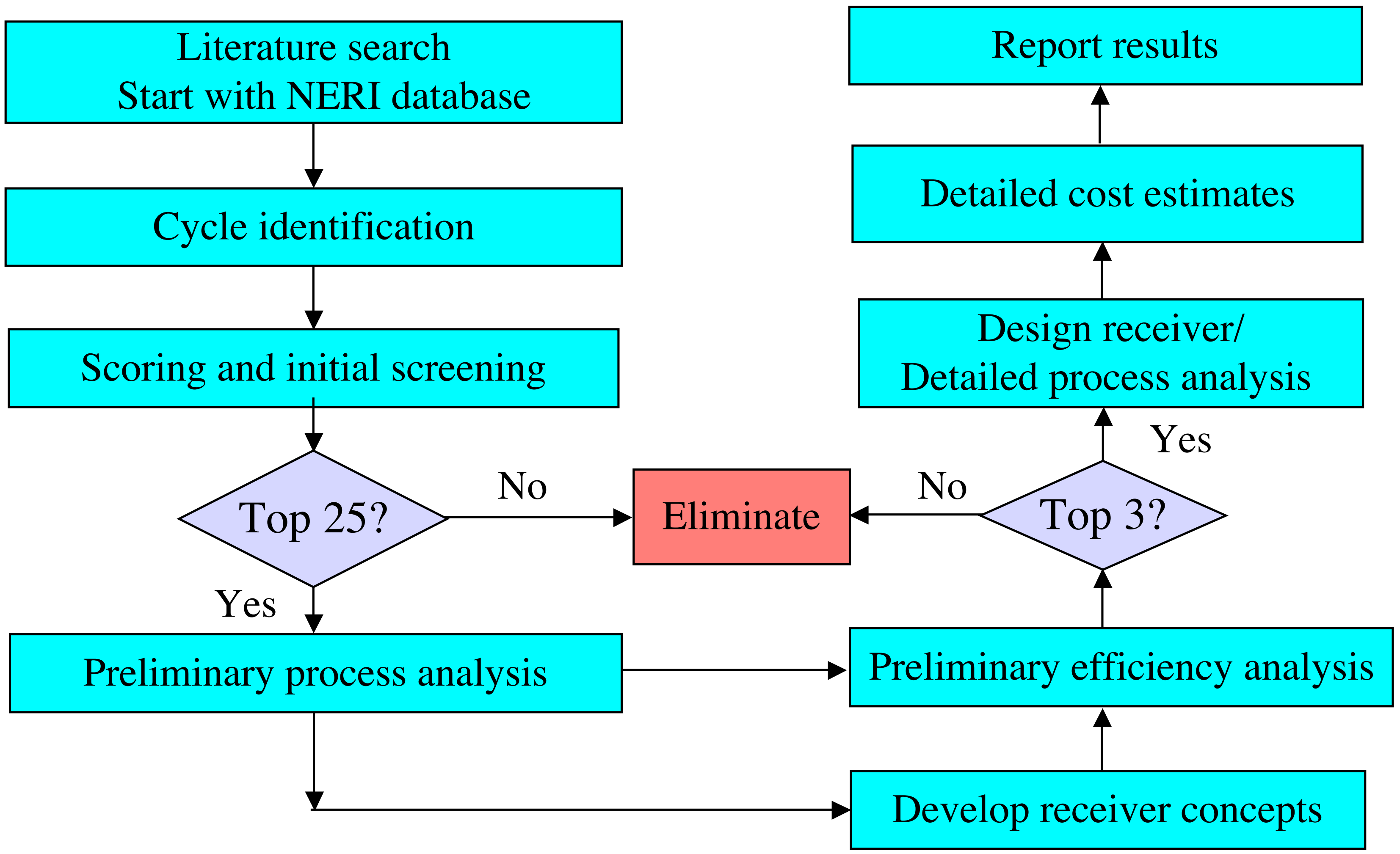
- Use Solar Technology Program expertise to select best collectors
- Match collectors and cycles for optimum synergy

Technical approach to solar thermochemical water-splitting:

Objective search and quantitative evaluation of options

- Develop and apply screening & evaluation criteria specific to solar-powered thermochemical hydrogen (TCH) cycles
- Screen and select limited number of attractive TCH cycles for detailed engineering evaluation and conceptual design
- Develop TCH system flowsheets, receiver designs and cost estimates for the best systems
- Evaluate these and develop at least one preliminary design for a Demonstration Project (Phase II)

Cycle screening methodology



Project timeline is aggressive

10/03 10/04 10/05

Phase 1: Cycle Screening and Selection	Phase 2: Solar Hydrogen System Selection
1 2 3,4	5,6,7 8

- Project start 10/1/03
- Project end 9/30/05
- Major milestones
  1. Develop screening criteria, update database, screen cycles – 1/12/04
  2. Design receivers, complete systems analysis, downselect – 8/23/04
  3. Complete improved aerosol flow reactor design – 9/1/04
  4. Measure ZnO reaction kinetics – 9/1/04
  5. Test ZnO decomposition in improved aerosol flow reactor at NREL HFSF – 9/1/05
  6. Demonstrate Mn_2O_3/MnO cycle – 9/1/05
  7. Complete design and evaluation of lead candidate systems – 9/1/05
  8. Prepare recommendation for National Review - 9/30/05
- Success criteria and expected date to meet them

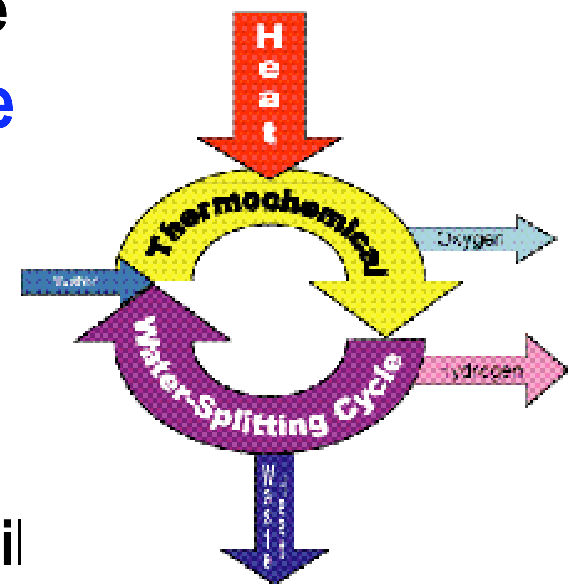
  Hydrogen cost projection < $8/kg (DOE solar H_2 2005 target) – 9/30/05

Technical accomplishments to date meet plans

- Updated thermochemical cycle database
- Developed screening and evaluation criteria
- Cycle scoring has begun
- Proof of Concept ZnO decomposition demonstrated
- Receiver/reactor concept evaluation has begun

Thermochemical cycle database was updated

- **Start with DOE NERI 1999 database**
  - MS Access files include references, thermodynamics, temperatures and pressures for each cycle
- **2004 literature review updated database**
  - 997 references, 181 unique cycles
- **Database now available on Internet**
  - Currently for STCH project use only
  - Will be available for public access
  - Evaluation scoring system will also be avail

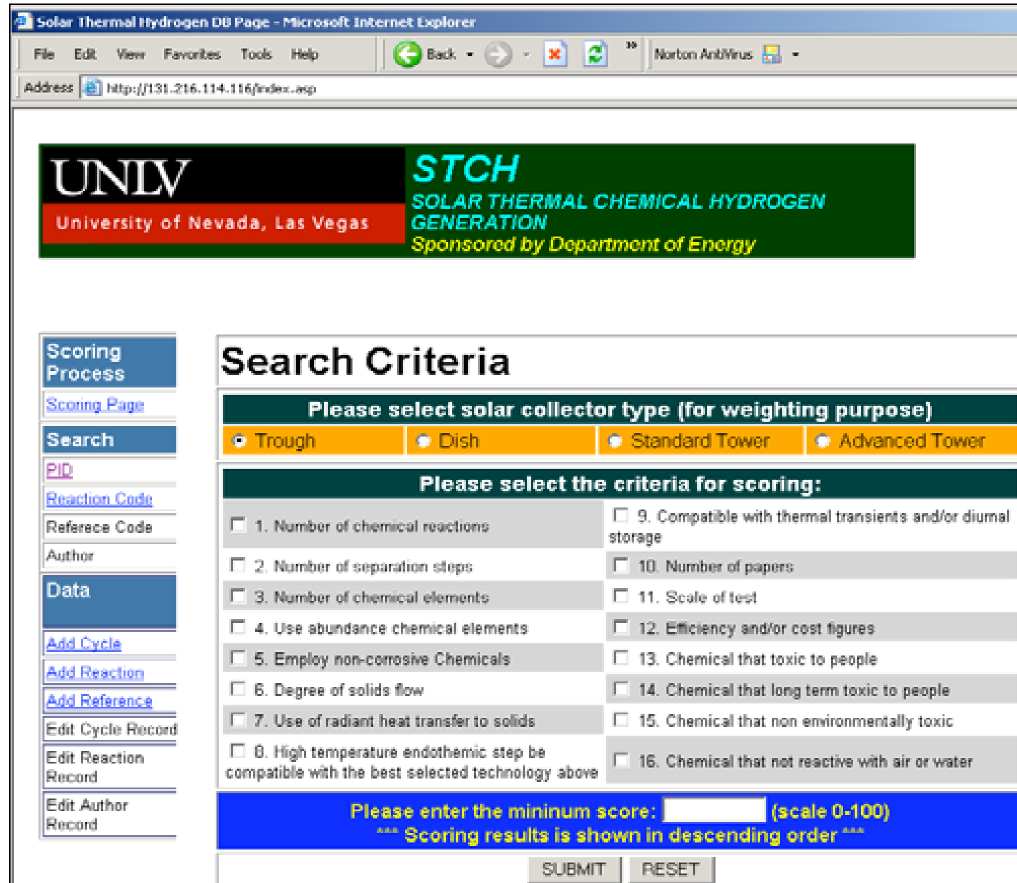


- **Hierarchical access control and configuration management implemented**

Database and evaluation scoring system will be available to the community on the Internet

STCH Data Management System

- Facilitates Project work on cycle evaluation
  - On-line real time analysis
  - Automated scoring
    - — Elements, resources, hazards fully automated
    - — Engineering judgement factors may be entered
- Will be useful tool for the hydrogen community
  - Updateable database
  - User can vary evaluation criteria
  - Flexible search capability



Cycle screening criteria were developed and adopted

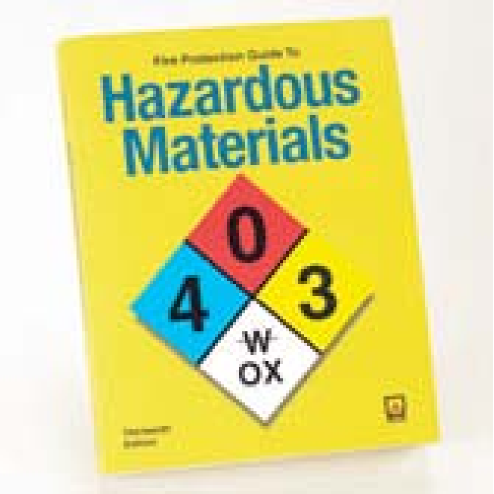
- 16 quantifiable criteria adopted
  - Scores ranges from 0 (poor) to 10 (excellent)
- Different weighting factors used for different technologies:
  - Trough, tower, dish, advanced tower (ultra-high temperature)
  - Each criterion weighted 0 to 10
  - "Six Sigma" approach used to determine weighting factors
    - "Quality Function Deployment" technique used to weight the importance of criteria to the achievement of a low cost of hydrogen
      - Ranking Factors: Capital cost, O&M, Development Risk, Diurnal cycle, Environmental risk
- Provides a numerical score for each cycle applied to each solar technology

Evaluation Criteria - weighted for importance, weighted for each collector technology

	Importance	Few Chemical Reactions	Few Separation Steps	Few Elements	Abundant Elements	Minimize Corrosive Chemicals	Minimize Flow of Solids	Use Radiant Heat Xfer to Solids	Temp Compatible with Solar Source	Oxygen Release from High T Step	Many Papers Published	Extensive Testing Done	Basis for Economic Justification	Safety: NIOSH Immed. Danger to Life	Safety: NIOSH Rec. Exposure Limit	EPA Release/Reportability Limit	Not Flammable/Water Reactive
Capital Cost	5	9	9	3	9	9	3	0	9	9	0	0	0	9	3	3	3
O&M Cost	4	3	3	1	1	3	9	0	0	3	0	1	0	9	3	3	1
Development Risk	2	3	3	3	0	9	3	0	3	1	9	9	9	9	3	3	1
Diurnal Cycle	5	0	0	0	0	0	0	9	0	9	0	0	0	0	0	0	0
Environmental Risk	2	0	0	0	0	3	0	0	0	1	1	0	0	0	0	9	1
		63	63	25	49	81	57	45	51	#	20	22	18	99	33	51	23
Trough		6	4	2	3	7	10	0	10	0	2	2	2	3	2	3	2
Standard tower		6	4	2	3	7	7	0	10	0	2	2	2	3	2	3	2
Advanced Tower		6	4	2	3	7	7	8	10	5	2	2	2	3	2	3	2
Dish		10	8	2	3	7	10	4	10	5	2	2	2	3	2	3	2

Safety is a key consideration in our analysis

- Four of our 16 evaluation criteria are safety-related, based on chemical reactivity and toxicity
  - Public safety, worker safety and environmental safety are each part of evaluation process
- National Fire Protection Association chemical reactivity, NIOSH, OSHA, EPA ratings being used
- Safety will be a major criterion of future lab work and demonstrations



Cycle screening has begun. Example: Screening diagram for Ispra Mark 7A

Phase 1 screening:

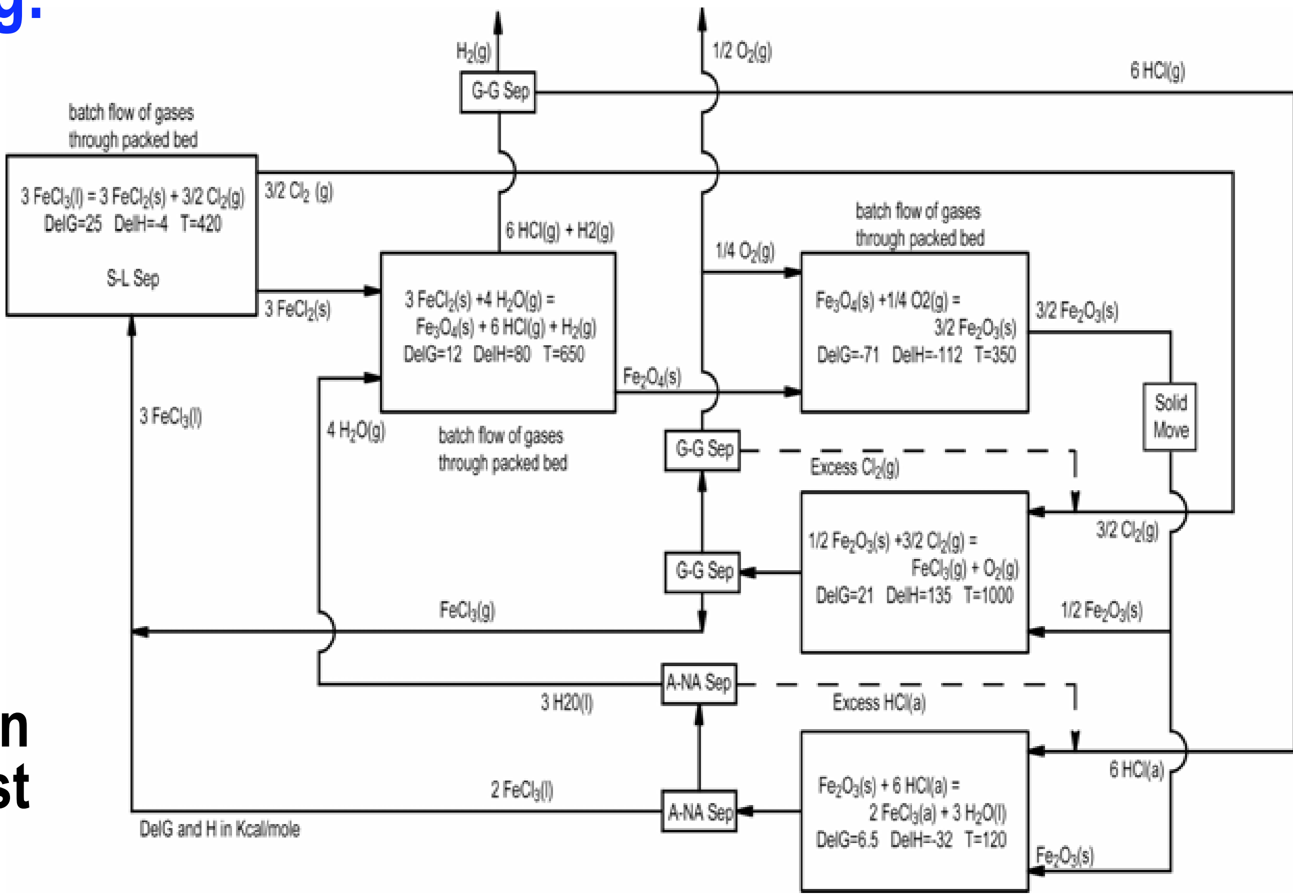
Block flow diagrams for all cycles

Temperatures, pressures, physical states

Engineering requirements

– Separations, solids

Sufficient information for evaluation against criteria

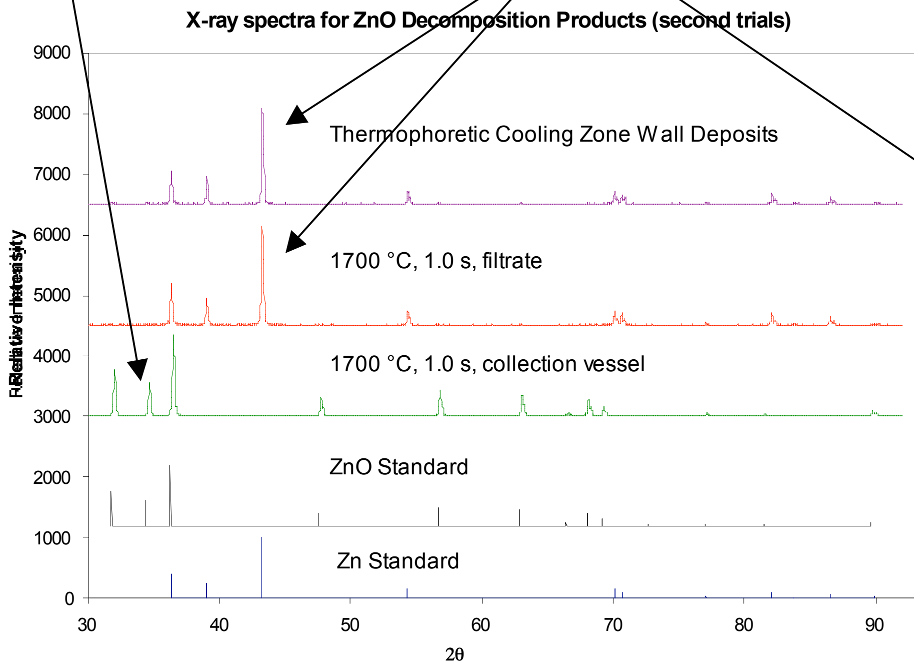


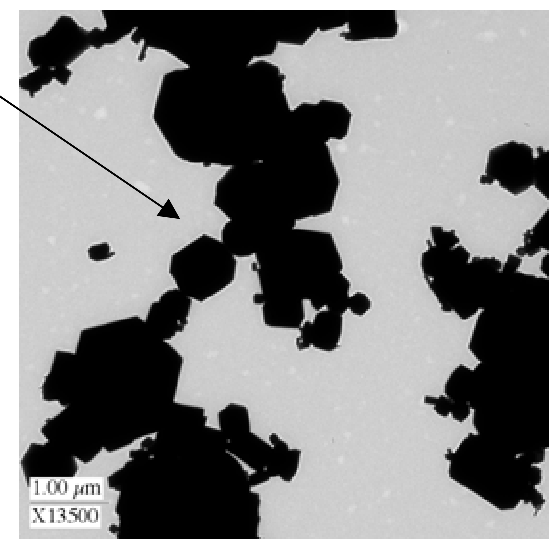
ZnO ➔ Zn + $^1/_2$ O_2 demonstrated

- **Initial experimental results from CU**
- **Sub μm Zn powder (1700°C; 0.5 s)**
  - **Should be highly reactive with water (hydrogen production step)**
- **50% Decomposition**
  - **Clear indication of potential to overcome recombination problem**

Zinc Oxide

Zinc





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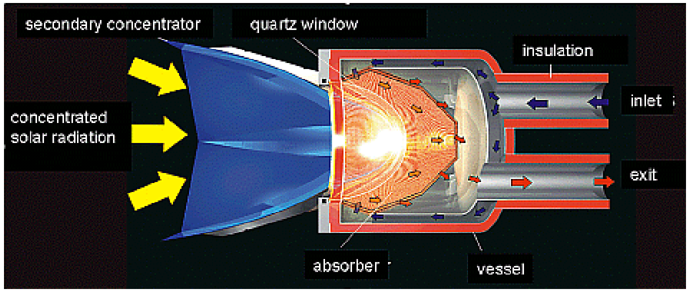
Receiver/reactor concepts evaluation begun

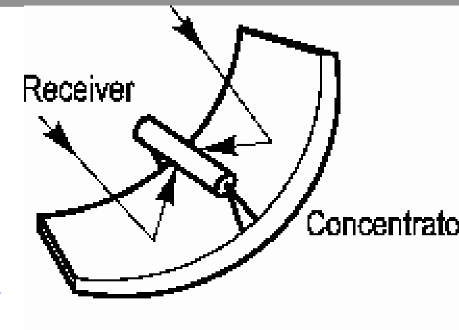
- Literature review conducted, heat transfer fluids evaluated and three basic receiver/reactor concepts identified

1. Directly illuminated tubular receiver/reactors
   – Conventional tubular geometries
   – Directly illuminated with solar flux
2. Indirect receiver/reactors
   – Utilize intermediate heat transfer fluid
   – Decouples receiver and reactor requirements
3. Direct absorption receiver/reactors
   – A “solar unique” option
   – Utilize a transparent window

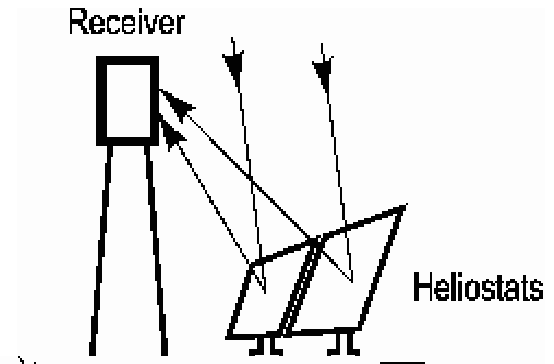


Four basic solar architectures being evaluated

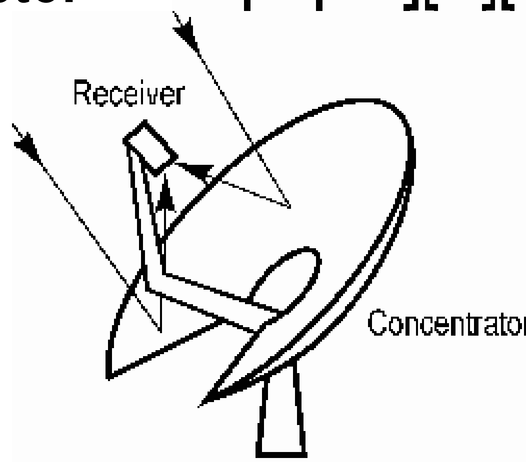
- **Parabolic Troughs**
  - Relatively low temperature (~400°C)
  - 354 MW currently operating in California



- **Conventional Molten-Salt Power Tower**
  - Established technology with molten nitrate salt intermediate fluid
  - Salt stability limits temperature to <650°C



- **Advanced power tower**
  - Includes non-nitrate salt receiver/reactor options and direct absorption
  - Ultra-high temperatures possible
- **Dish**
  - Ultra-high temperatures possible
  - Distributed generation



We benefit from strong interactions and collaborations

- UNLV, CU and GA are providing financial support
- GE and Arizona Public Service are providing support
  - Electrochemical materials and processes, ZnO/Zn process
  - Assistance with "Six Sigma" process for weighting factors
  - Dan Derr – GE, Ray Hobbs – APS
- Interaction with other national hydrogen activities
  - National H_2 Initiative HTHX and Materials effort, NERI NH_2 activities at SNL, GA, ANL, ORNL, etc.
  - CEA Saclay (I-NERI) contributed to TC cycle database.
- Significant benefit from investment at NREL, SNL and UNLV
  - >$1B Solar Technologies investment, ~$200M facilities available
  - CU lab test equipment and NREL High-Flux Solar Furnace

Future work will continue original plan

- **FY'04:**
  - Complete process screening; select leading candidates for each solar technology
  - Develop and analyze system flowsheets for selected candidates
  - Evaluate solar-thermal ZnO decomposition in aerosol flow reactor at NREL HFSF
  - Develop conceptual designs for surviving candidate systems
- **FY'05:**
  - Evaluate engineering, safety and economic features
  - Construct high efficiency solar-thermal aerosol flow tube reactor for ZnO decomposition and test at the HFSF
  - Experimentally evaluate Mn_2O_3/MnO 3-step cycle process feasibility
  - Complete design and evaluation of candidate systems and prepare recommendation for national review, including concept for pilot plant