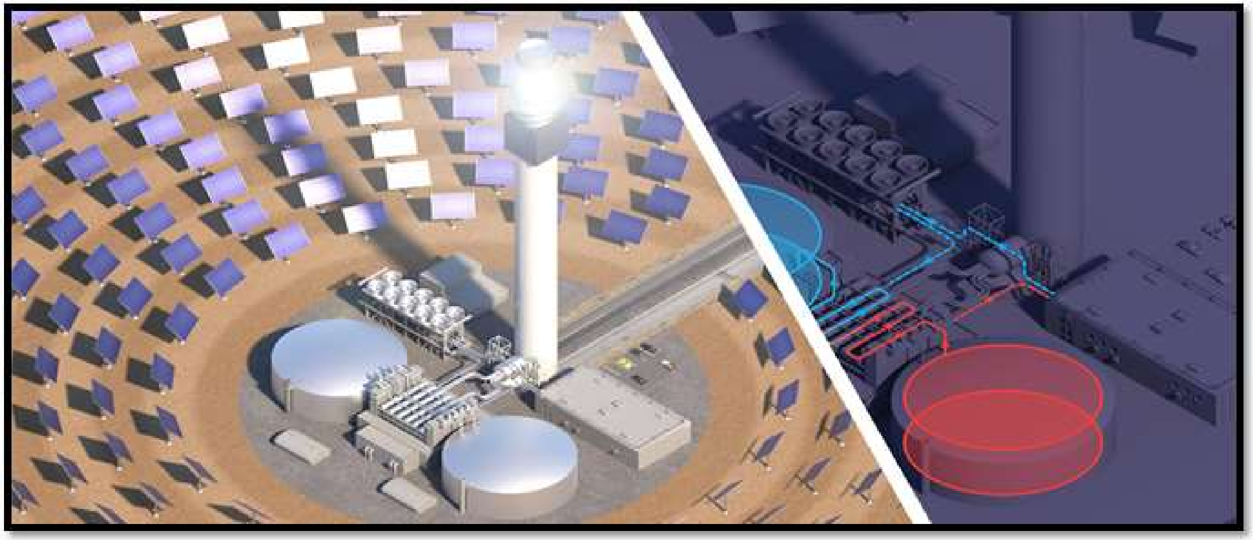
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Sodium receiver



Gen3 CSP Summit
August 25, 2021

Joe Coventry
Chief Investigator
Australian National University

Sandia National Laboratories

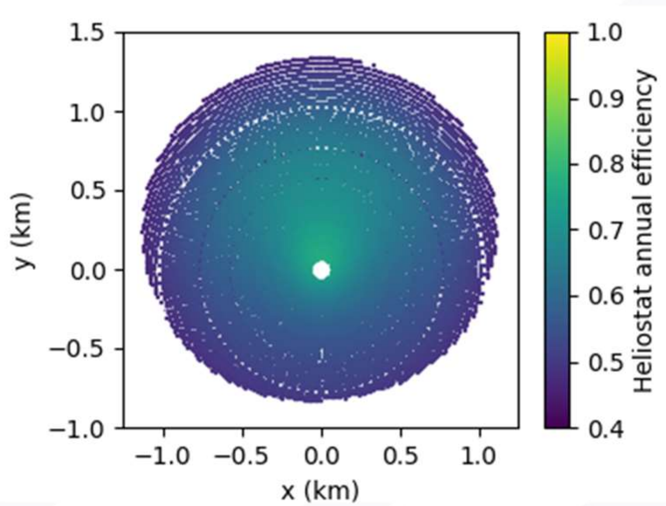
NREL NATIONAL RENEWABLE ENERGY LABORATORY

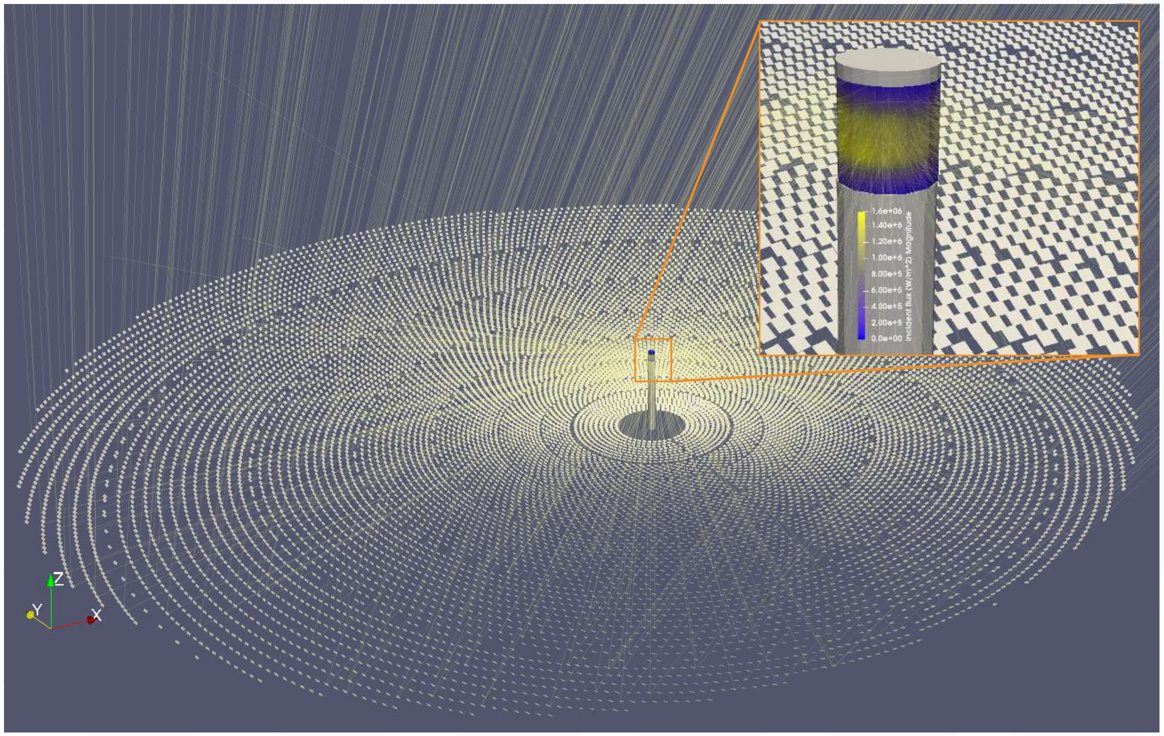
ARENA Australian Government Australian Renewable Energy Agency

NREL Award # 34209 (agreement number)

Commercial sodium receiver

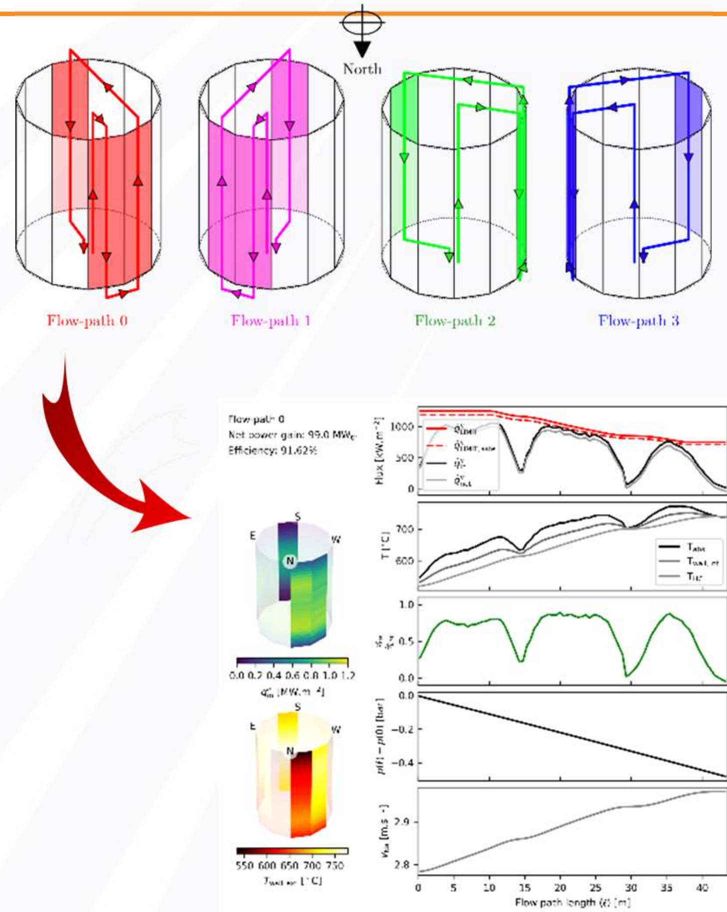
- **“Conventional” cylindrical sodium receiver concept, similar molten salt receivers**
  - System design output 50 MW_e
  - Solar multiple ~3.0
  - Temperature range: 520°C to 740°C.
  - Receiver 14.5 m high x 14 m diam.
  - Nominal receiver output: 350 MW_{th}





Performance Summary

- Receiver sizing based on annual performance simulation
- Flow-path adapted to liquid sodium properties
- Flux controlled to remain below limits determined by creep-fatigue behaviour of the tube material (1)
- Efficiency consistently high throughout the year



Design point

	Summer			Equinox				Winter		
	Noon	Noon +2h	Noon +6	Noon	Noon +2h	Noon +4h	Noon +5h	Noon	Noon +2h	Noon +4h
DNI (W/m2)	950	930	520	980	950	805	590	930	875	510
Field efficiency	0.647	0.632	0.416	0.639	0.618	0.539	0.420	0.590	0.562	0.369
Intercept efficiency	0.978	0.972	0.962	0.968	0.955	0.961	0.957	0.952	0.957	0.950
Solar absorption efficiency	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987
Thermal efficiency	**0.923**	**0.924**	**0.830**	**0.921**	**0.922**	**0.906**	**0.846**	**0.920**	**0.913**	**0.792**
Receiver efficiency	**0.912**	**0.912**	**0.819**	**0.909**	**0.910**	**0.895**	**0.835**	**0.908**	**0.901**	**0.782**
Receiver and intercept efficiency	**0.891**	**0.886**	**0.788**	**0.881**	**0.869**	**0.860**	**0.799**	**0.865**	**0.862**	**0.743**
Overall efficiency	**0.577**	**0.560**	**0.328**	**0.563**	**0.537**	**0.463**	**0.335**	**0.511**	**0.484**	**0.274**

(1) Wang, C-A. Asselineau, W.R. Logie, J. Pye, J. Coventry, Solar Energy, Vol 225, 2021

Sodium in industry

Sodium is a commodity

- Sodium production and consumption is well over 100,000 tonnes/year, mainly in China
- Chemical uses
  - A substantial amount is used in sodium alkyl sulfates as the principal ingredient in synthetic detergents
  - Manufacture of indigo dyes, for dyeing cotton along with manufacturing denim
  - Deoxidant and reducing agent for producing Ca, Zr, Ti and other transition metals
- Largest producers are Nippon Soda, Lantai, Wanji, Yinchuan, Tiantai, and MSSA

Sodium in nuclear

- Since the 1950s RD&D in power generation has been linked to funding for Fast Breeder Reactor (FBR) programs
- Today sodium-cooled FBRs operate in Russia, India and China
- Overall there are over 400 years cumulative operation of sodium-cooled FBRs in plants at scales of 10s to 100s of MWe
- Sodium is a safe heat transfer fluid to use when handled properly

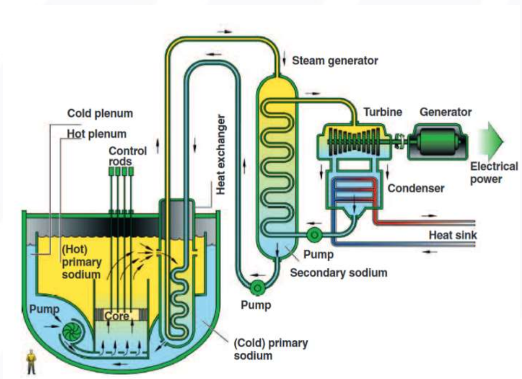
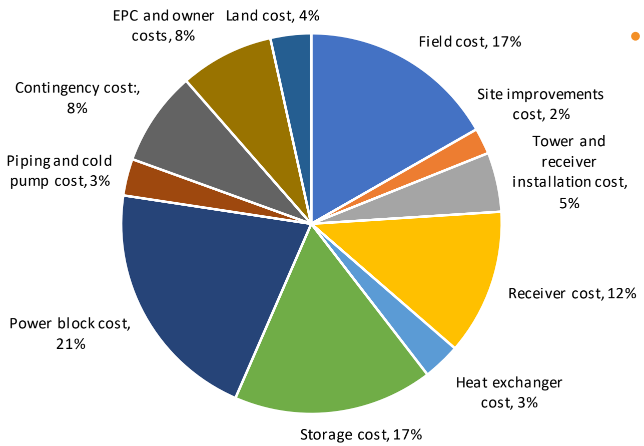


Image: CEA

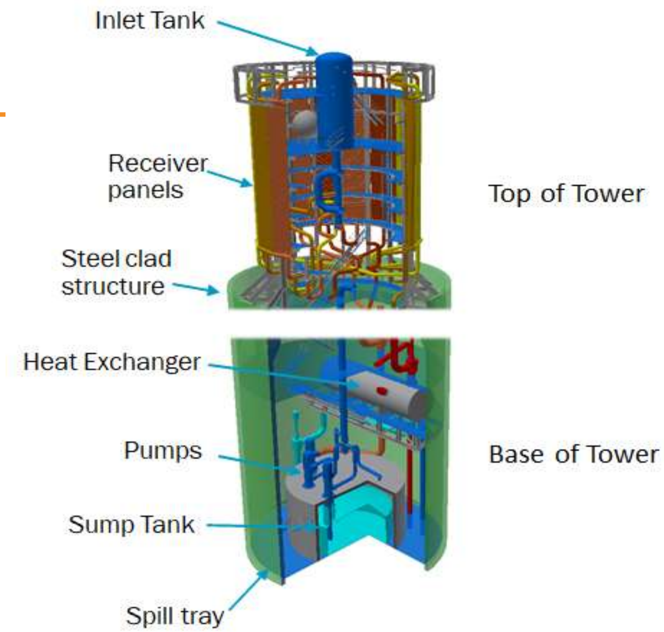
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

System components

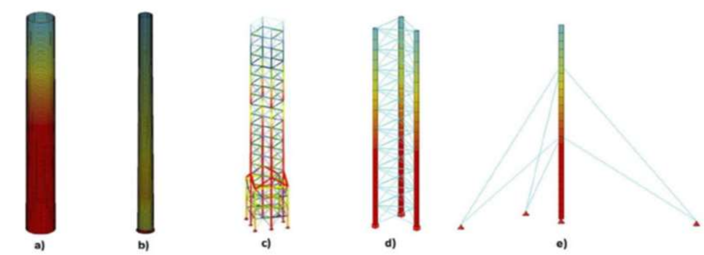
- Key sodium components are available commercially
  - Sump tank
  - Inlet vessel
  - Purification skid (cold trap)
  - Argon tank, cryogenic tank, atmospheric heater
  - 4 x 33% pump configuration, each 4-stages
- Shorter towers may provide cost reduction opportunities



- Details of the capital cost breakdown in the final report [NREL/TP-5700-79323]



Sodium loop components (source: John Cockerill)



spb compared several tower designs

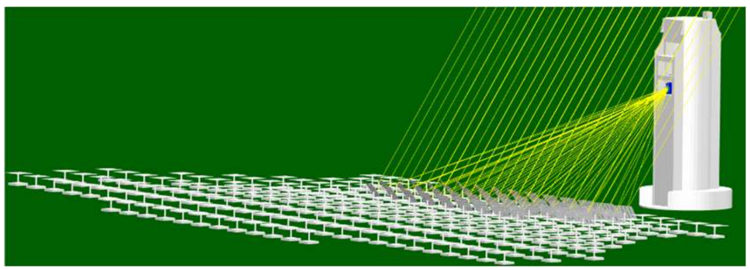
Do not distribute beyond project team.

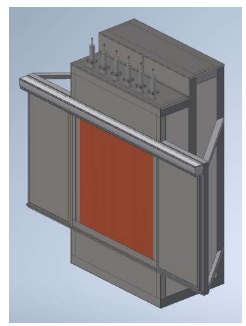
De-risking by testing

- Sodium receiver operation is not new *however* successful demonstration is required at the Gen3 CSP temperatures
- A 1 MWth "billboard" style receiver was designed for Phase 3
- The Australian Solar Thermal Research Institute (ASTRI) is planning to test a 740°C prototype sodium receiver in 2022

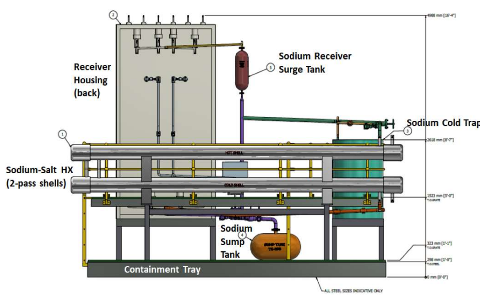

Vast Solar's pilot plant at Jemalong, NSW, Australia

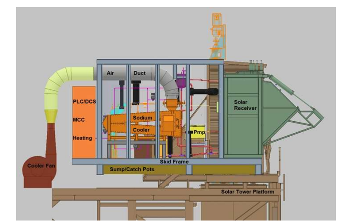
Source: ABC News





The 1 MWth receiver and sodium loop designed for Phase 3 prototype testing at Sandia National Laboratories





The 700 kWth 'Mark 1' receiver to be tested in 2022 by ASTRI at CSIRO Newcastle, will operate at a temperature range compatible with next-generation CSP (520-740°C)

Do not distribute beyond project team.

Thank you!

Associate Professor Joe Coventry
Solar Thermal Group, School of Engineering
Australian National University
T +612 6125 2643
E joe.coventry@anu.edu.au

Acknowledgement

I would like to acknowledge the contributions of all the Australian (ASTRI) team who contributed to the Gen3 Liquids Pathway project, included John Pye, Charles-Alexis Asselineau, Felix Venn, William Logie, Armando Fontalvo, Shuang Wang, Robbie McNaughton, Daniel Potter, Theodore Steinberg and Geoffrey Will.

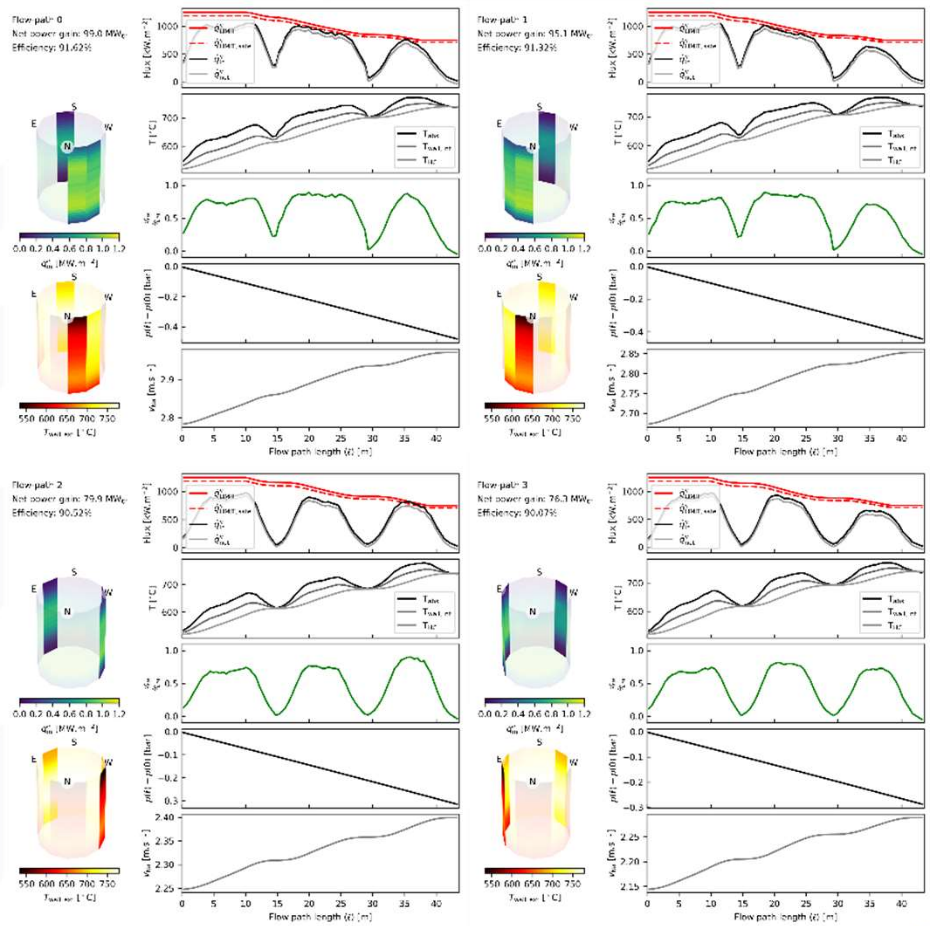
ANU's sodium research is supported by the Australian Solar Thermal Research Institute (ASTRI), a program supported by the Australian Government through the Australian Renewable Energy Agency (ARENA)

SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

Backup slides

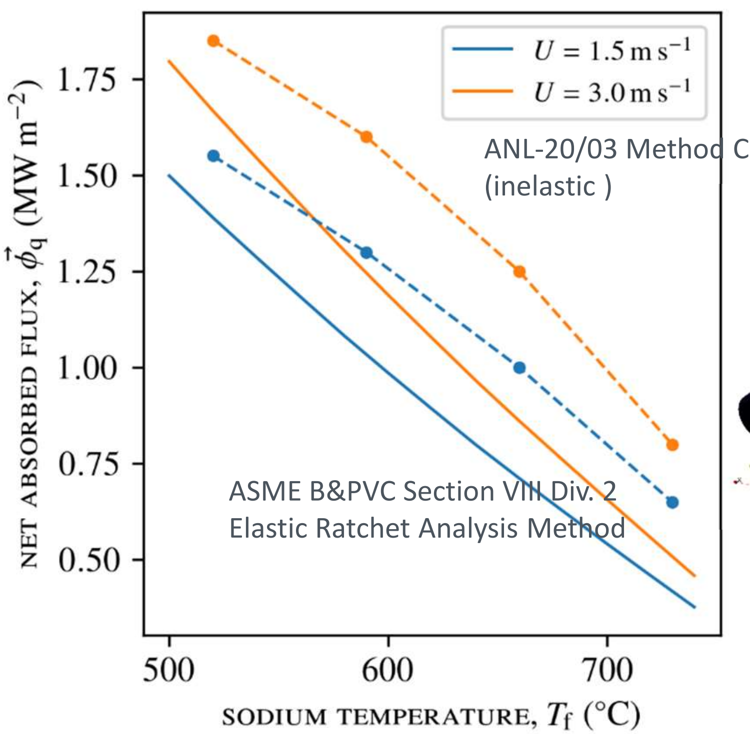
Commercial-Scale Sodium Receiver Performance Summary

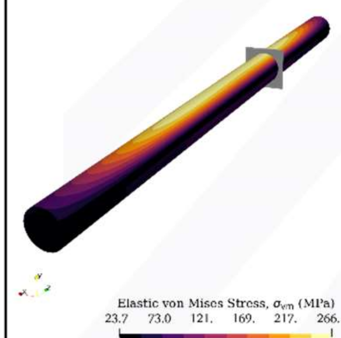
	Summer			Equinox				Winter		
	Noon	Noon +2h	Noon +6	Noon	Noon +2h	Noon +4h	Noon +5h	Noon	Noon +2h	Noon +4h
DNI (W/m2)	950	930	520	980	950	805	590	930	875	510
Field utilization	0.882	0.926	1.000	0.877	0.937	1.000	1.000	1.000	1.000	1.000
Field efficiency	0.647	0.632	0.416	0.639	0.618	0.539	0.420	0.590	0.562	0.369
Intercept efficiency	0.978	0.972	0.962	0.968	0.955	0.961	0.957	0.952	0.957	0.950
Solar absorption efficiency	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987
Thermal efficiency	**0.923**	**0.924**	**0.830**	**0.921**	**0.922**	**0.906**	**0.846**	**0.920**	**0.913**	**0.792**
Receiver efficiency	**0.912**	**0.912**	**0.819**	**0.909**	**0.910**	**0.895**	**0.835**	**0.908**	**0.901**	**0.782**
Receiver and intercept efficiency	**0.891**	**0.886**	**0.788**	**0.881**	**0.869**	**0.860**	**0.799**	**0.865**	**0.862**	**0.743**
Overall efficiency	**0.577**	**0.560**	**0.328**	**0.563**	**0.537**	**0.463**	**0.335**	**0.511**	**0.484**	**0.274**
Spillage loss (MW_{th})	8.78	10.93	6.17	12.58	17.96	12.48	7.97	19.26	15.70	7.09
Solar power through aperture (MW_{th})	384.0	384.1	154.2	385.1	383.8	307.8	176.2	383.0	346.6	133.7
Solar reflection loss (MW_{th})	4.92	4.93	1.98	4.94	4.92	3.95	2.26	4.91	4.44	1.71
Emission loss (MW_{th})	25.4	25.4	22.5	26.3	26.1	25.0	23.5	26.5	26.1	24.0
Convection loss (MW_{th})	3.57	3.56	3.34	3.64	3.62	3.53	3.41	3.66	3.62	3.46
Net thermal power to the HTF (MW_{th})	350.0	350.2	126.3	350.2	349.2	275.4	147.1	347.9	312.4	104.5
Peak absorbed flux (kW)	1062	1087	583	1040	1067	1013	670	1047	1019	514
Peak tube wall temperature (K)	1052	1052	1035	1053	1051	1053	1039	1049	1055	10328
Peak fraction of allowable flux	0.94	0.95	0.51	0.91	0.90	0.90	0.62	0.94	0.93	0.48
Max HTF velocity (m/s)	2.75	2.96	1.14	2.97	2.91	2.44	1.35	2.90	2.67	0.93
Receiver pressure drop (MPa)	0.041	0.048	0.007	0.048	0.046	0.032	0.010	0.046	0.039	0.005

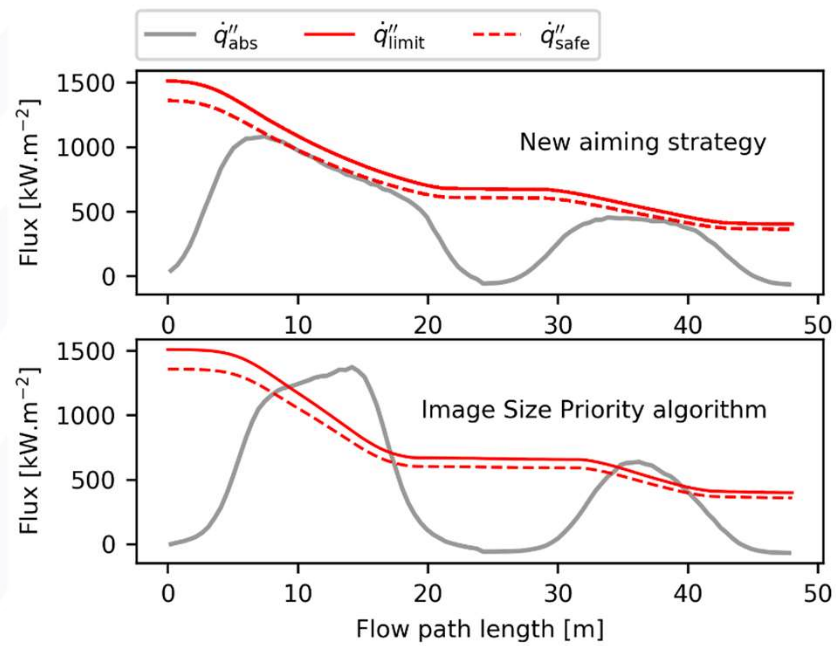


Sodium Receiver Mechanical Analysis

- Implementation of the new "Design Guidance for High Temperature Concentrating Solar Power Components" (ANL-20/03)
- Significantly higher flux limits possible

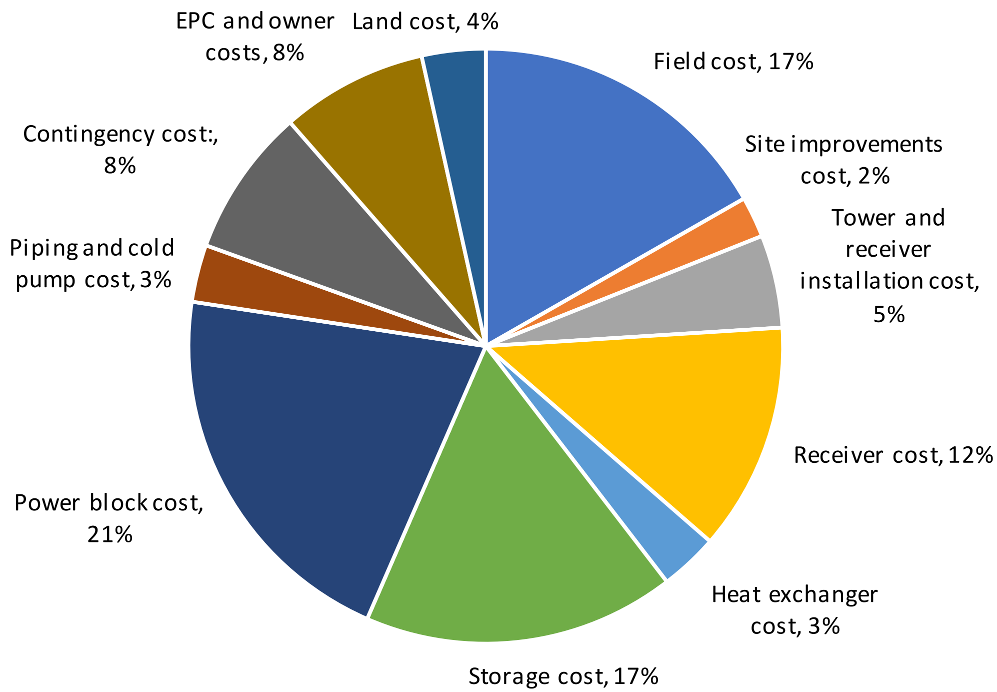






SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Capital Cost Breakdown at Commercial Scale



- Financial assumptions from DOE recommended values
- Further details in the final report [NREL/TP-5700-79323]

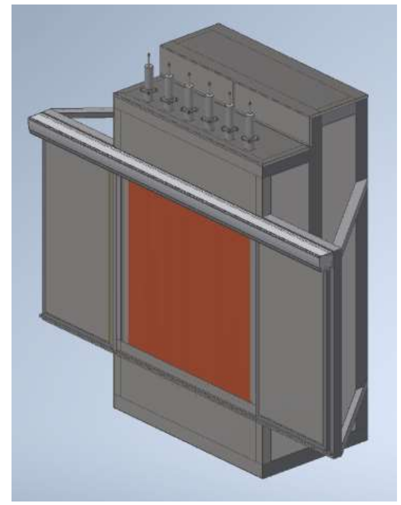
Item		$1{\times}50\ MW_e$ module	$100\ MW_e$ system ($2{\times}50\ MW_e$)
Heliostat field			
	Heliostats	$ 54,212,373	$ 108,424,746
	Site improvements	$ 7,228,316	$ 14,456,633
Sodium receiver		$ 26,260,650	$ 52,521,300
Tower		$ 16,339,938	$ 32,679,876
Sodium loop			
	Sodium valves	$ 907,980	$ 1,815,960
	Sump tank	$ 1,252,129	$ 2,504,259
	Inlet vessel	$ 218,298	$ 436,597
	Purification skid	$ 298,479	$ 596,959
	Sodium pumps	$ 3,800,633	$ 7,601,267
	Argon system	$ 94,999	$ 189,999
	Instrumentation and control	$ 328,314	$ 656,628
	Additional sodium piping	$ 1,207,663	$ 2,415,326
Sodium and salt piping			
	Riser†	$ 1,426,598	$ 2,853,197
	Downcomer†	$ 4,533,284	$ 9,066,568
	Salt piping	$ 697,596	$ 1,395,192
Salt storage			
	Tank and salt costs	$ 54,968,250	$ 109,936,501
	Cold salt pump	$ 2,772,615	$ 5,545,230
	Hot salt pump	$ 2,079,462	$ 4,158,924
	Salt valves	$ 2,106,720	$ 4,213,440
	N_2 ullage gas system	$ 2,860,000	$ 5,720,000
Power block and HXs			
	Sodium-to-salt HX	$ 10,290,385	$ 20,580,770
	Salt-to-CO_2 PHX	$ 26,576,576	$ 53,153,151
	s-CO_2 power block	$ 41,025,831	$ 82,051,663
Direct capital cost subtotal		$ 261,487,093	$ 522,974,186
Contingency (10%)		$ 26,148,709	$ 52,297,419
Total direct capital cost		$ 287,635,802	$ 575,271,604
EPC and owner costs (9%)		$ 25,887,222	$ 51,774,444
Land cost		$ 11,260,647	$ 22,521,293
Total capital (installed cost)		$ 324,783,671	$ 649,567,342

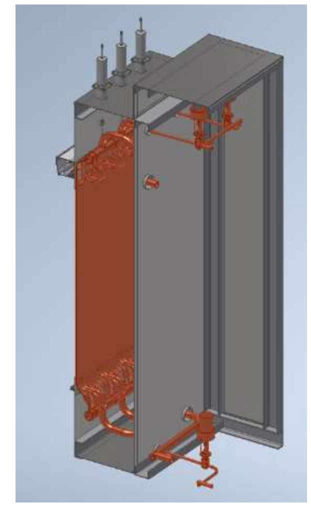
Do not distribute beyond project team.

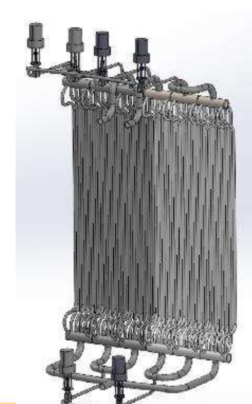
Pilot-scale Sodium Receiver Design

- Flat “billboard” style design
- Key design criteria:
  - Safety, reliability and structural integrity
  - Similarity with the proposed commercial receiver design
  - Performance
  - Cost

Parameter	Value
Design thermal capacity	1 MW_{th}
Design sodium inlet temperature	520°C
Design sodium outlet temperature	740°C
Design total sodium mass flow rate	3.7 kg/s
Flow paths	2
Flow path inlet location	Top of inner-most panel
Flow path outlet location	Bottom of outer-most panel
Panels per flow path	3
Tubes per panel	11
Irradiated length per tube (height of billboard)	1.77 m
Tube wall-to-wall spacing (within panels)	1.2 mm
Tube wall-to-wall spacing (between adjacent panels)	4.0 mm
Tube OD	25.4 mm
Tube thickness	1.65 mm
Tube material	Alloy 740H (seamless)
Tube coating	High performance solar-selective coating
Overall irradiated width of billboard	1.77 m



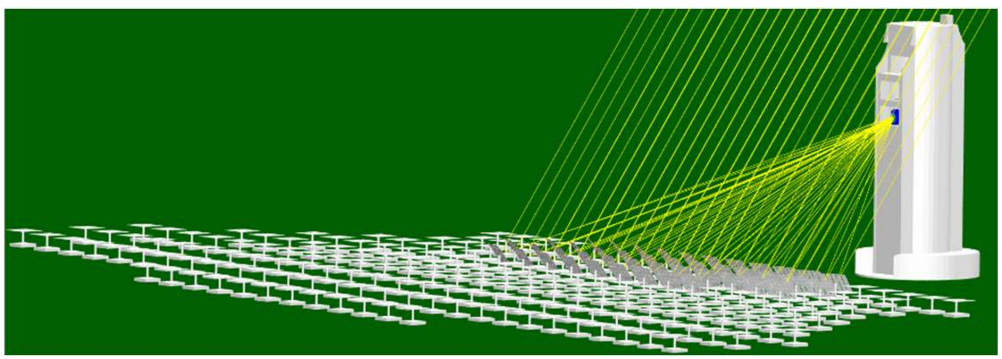


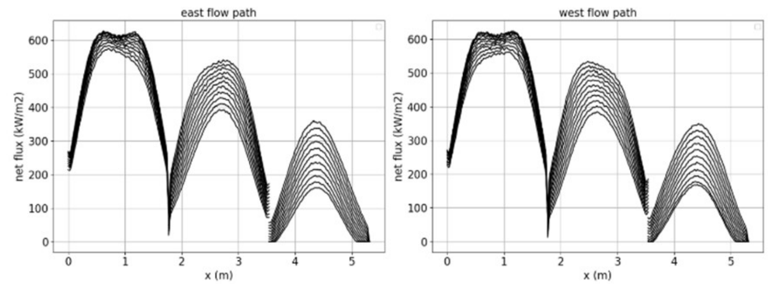


Pilot-scale Sodium Receiver Performance Modelling

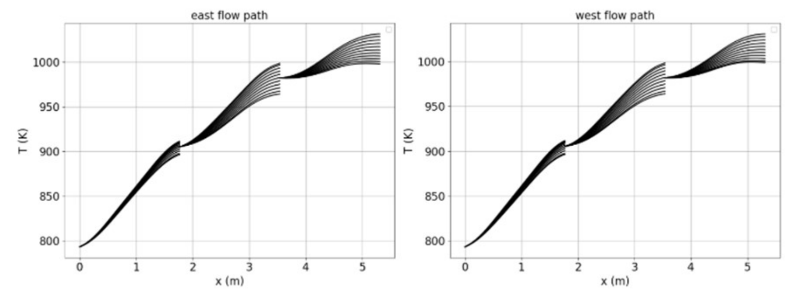
- Performance modelling in Heliosim
- Conservative allowable flux limits
- Maximum tube wall temperature disparities <30 K
- Pilot-scale efficiencies will be lower than commercial-scale

Date	Spring equinox		Summer solstice		Winter solstice	
Hours relative to solar noon	0	+3	0	+3	0	+3
DNI (W/m2)	1055	1000	1020	980	960	800
HTF thermal output (kw)	1018	1002	1012	1031	1003	1000
Aperture interception efficiency (%)	85.3	81.3	84.8	78.8	82.7	79.3
Receiver efficiency (%)	83.6	83.4	83.9	83.9	83.5	83.5
Combined interception and receiver efficiency (%)	71.3	67.9	71.1	66.1	69.1	66.2



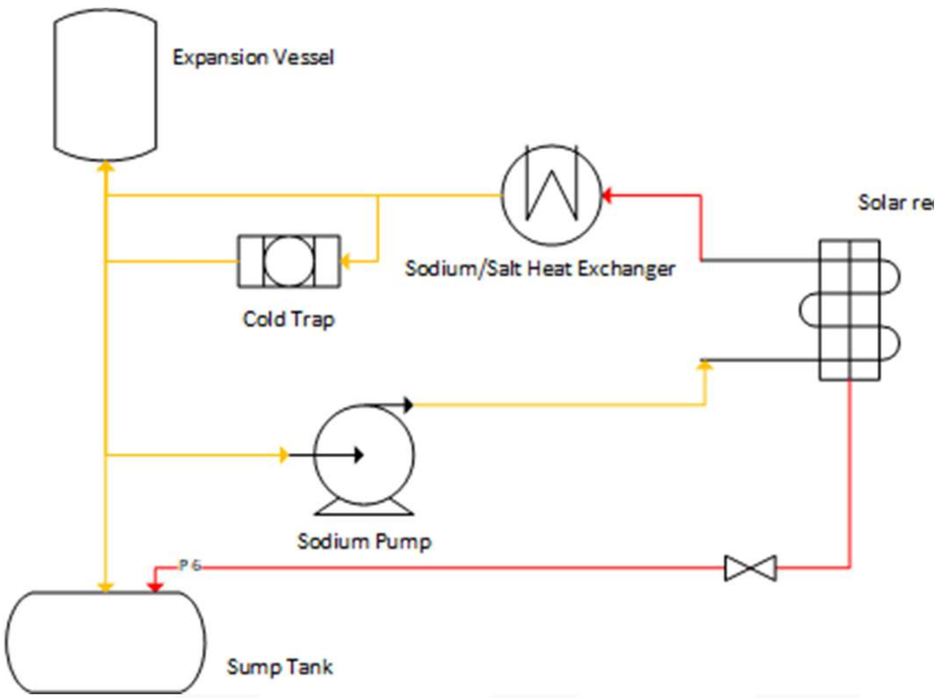


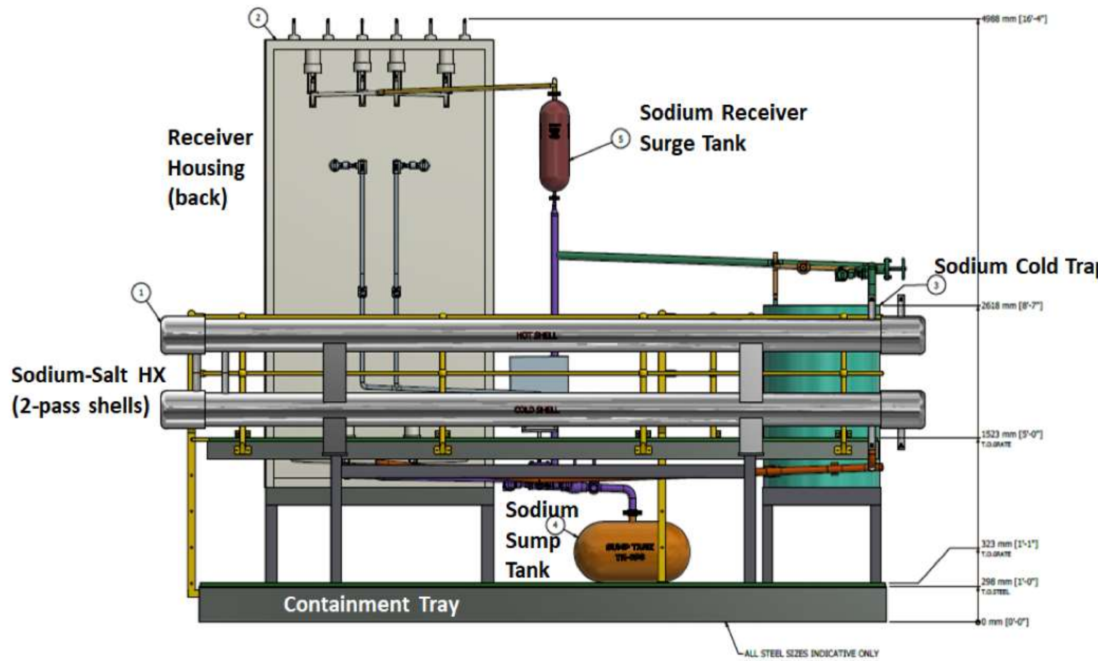
Net flux through the tube crown



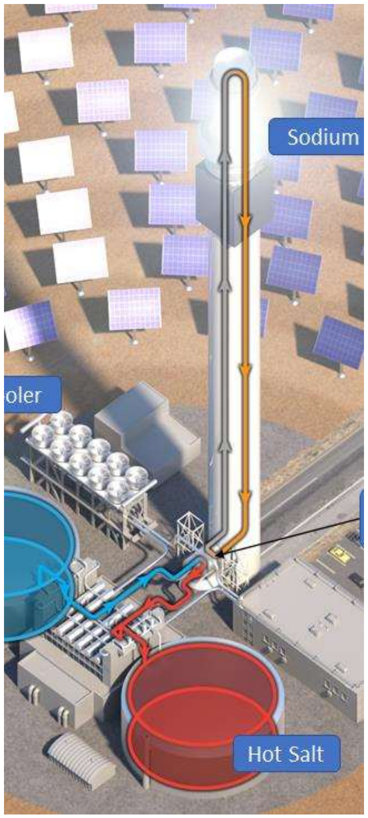
Bulk sodium temperature

Sodium Balance of Plant – Overall Layout





Sodium Safety and Acceptance



- Safety is core to the success of the sodium pathway and is <u>the</u> highest priority
- System design to minimise risk
  - Sodium contained in or near the tower within an isolation zone
  - Rapid drain back of all sodium to a sump tank if there is an incident
  - Secondary containment in a spill tray
  - The best action plan for fire fighters is likely No Action – let any fire burn out naturally

Design safety

- Good system design
- Minimized sodium inventory
- Adherence to high quality and performance standards
- Suitable material selections
- Fire safety engineering

Safety requirements

- Ensure containment, i.e. high integrity against rupture, leakage or corrosion
- Maintain high sodium purity
- Use steel liners & trays over concrete
- Ensure rapid draining
- Early leak detection systems
- Avoid proximity to water
- Separation of sodium and people
- Appropriate PPE

Sodium Safety and Acceptance

- Learning from the past
  - Review of literature (e.g. Sodium-NaK Engineering Handbook)
  - Understanding of risks (sodium chemistry to human factors)
  - Lessons learnt in design (mainly from nuclear facilities)
  - Review of sodium incidents, what happened, why, lessons learnt
- Learning from experts
  - Sodium suppliers (MSSA)
  - Researchers (Sandia, U. Wisconsin, ANL)
  - Operating labs (KIT, ANL, KAERI)
  - Operating plants (Vast Solar)
  - Use of expert consultants (Creative Engineering, Claude Reed, David Wait)
  - HAZMAT experts (NSW Fire Brigade)
- Study visit to Karlsruhe Institute of Technology, Germany, Aug 2017
- Sodium Safety & Handling workshop, Argonne National Lab, Mar 2019
- Technical meeting on Sodium Technologies, KAERI, Daejeon, Korea, Sep 2019
- Sodium Bankability Workshop, Seattle, Feb 2020

ANU visit to KIT sodium loop, Karlsruhe, Germany, Aug 2017

Sodium Safety & Handling workshop, ANL, Mar 2019

Do not distribute beyond project team.

Sodium Safety and Acceptance

- Learning by doing
  - Development of the high-temperature sodium laboratory at ANU
  - Development of the CSIRO and Sandia test loops (in progress)
  - HAZIDs, HAZOPs, FMEA (ANU, CSIRO, Sandia and other partners)
  - Handling sodium (cutting, transport, clean-up)
  - Controlled burning and explosive reactions with water
  - Fire fighting methods and fire extinguishing
  - Experience with different PPE
  - Chemical compatibility testing (e.g. Na, CO_2, PCMs)
  - Stakeholder engagement (ARENA, EPA, fire services, etc)
  - Training courses

Sodium Fire Training and Demonstration day, Canberra 2016

Sodium burn tests at SNL, Jun 2020