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HEMCP:Helmholtz Energy Materials Characterization Platform

Direct energy conversion of heat to electricity using AMTEC

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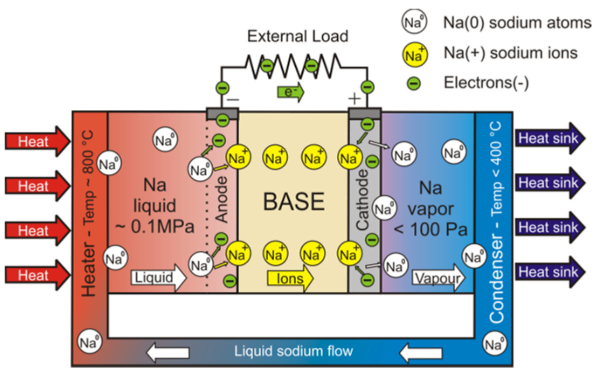
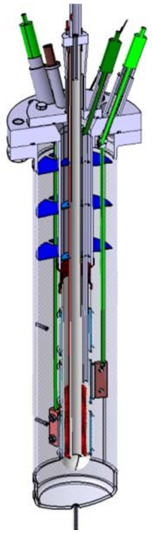
IYCE 2015, Pisa

Karlsruhe Institute of Technology (KIT) – Institute for Neutron Physics and Reactor Technology (INR)





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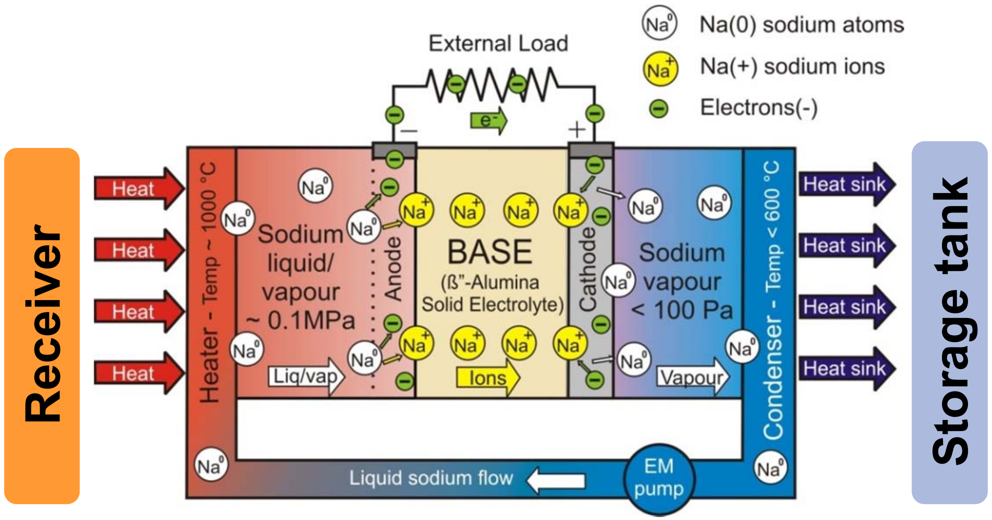
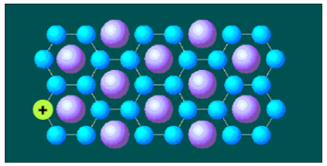
AMTEC – direct heat to electricity conversion

Alkali Metal Thermal to Electric Converter





- Key component:
  β''-Alumina Solid Electrolyte (BASE)
- Key process: Na-ionization
  ΔP across BASE → Δ(sodium activity)

$$Na \rightarrow Na^{+} + e^{-}$$

Main advantages

- High theoretical efficiency (40 %)
- Flexible regarding the heat source
- Suitable for modular design
- No moving components

Issues

- Real efficiency of 20 %
  - Heat losses (10 – 15 %)
  - Electrical losses (12 – 15 %)
- Power degradation over time
  - Degradation of BASE
  - Electrode sintering (grain growth)

Overview of AMTEC systems

Year	Author	AMTEC cell characteristics	Comments / Electrical properties
1969	Kummer & Weber	single tube, liquid anode	Developed Sodium Heat Engine (SHE)
1986	Hunt	single tube, liquid anode	Pout = 8 W (0.4 – 0.5 W/cm²); T ~ 800 °C; η = 19 %; t_{op} = 1500 h
1989 - 1993	Heinzel et al. (KIT - INR)	single tube, liquid anode	Pout = 112 W (1.8 W/cm²); 910 °C; t_{op} = few hours
1992 - 1998	Air Force Philips Laboratory	multitube, vapor anode	Series connected AMTEC for advanced radioisotope power system to fulfill the mission of Pluto Express. Pout = 4.3 W (0.12 W/cm²); 750 °C; η ~ 12 %; t_{op} = 600 h
2006	Hunt & Rasmussen	Small scale, multitube, vapor anode	Pout = 0.5 W (0.7 – 0.8 W/cm²); 740 °C; η ~ 13 %; t_{op} = 5 years

Heinzel et al. 1992

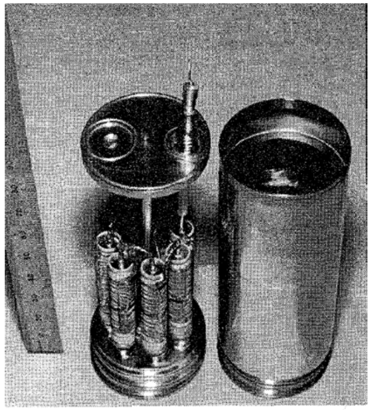


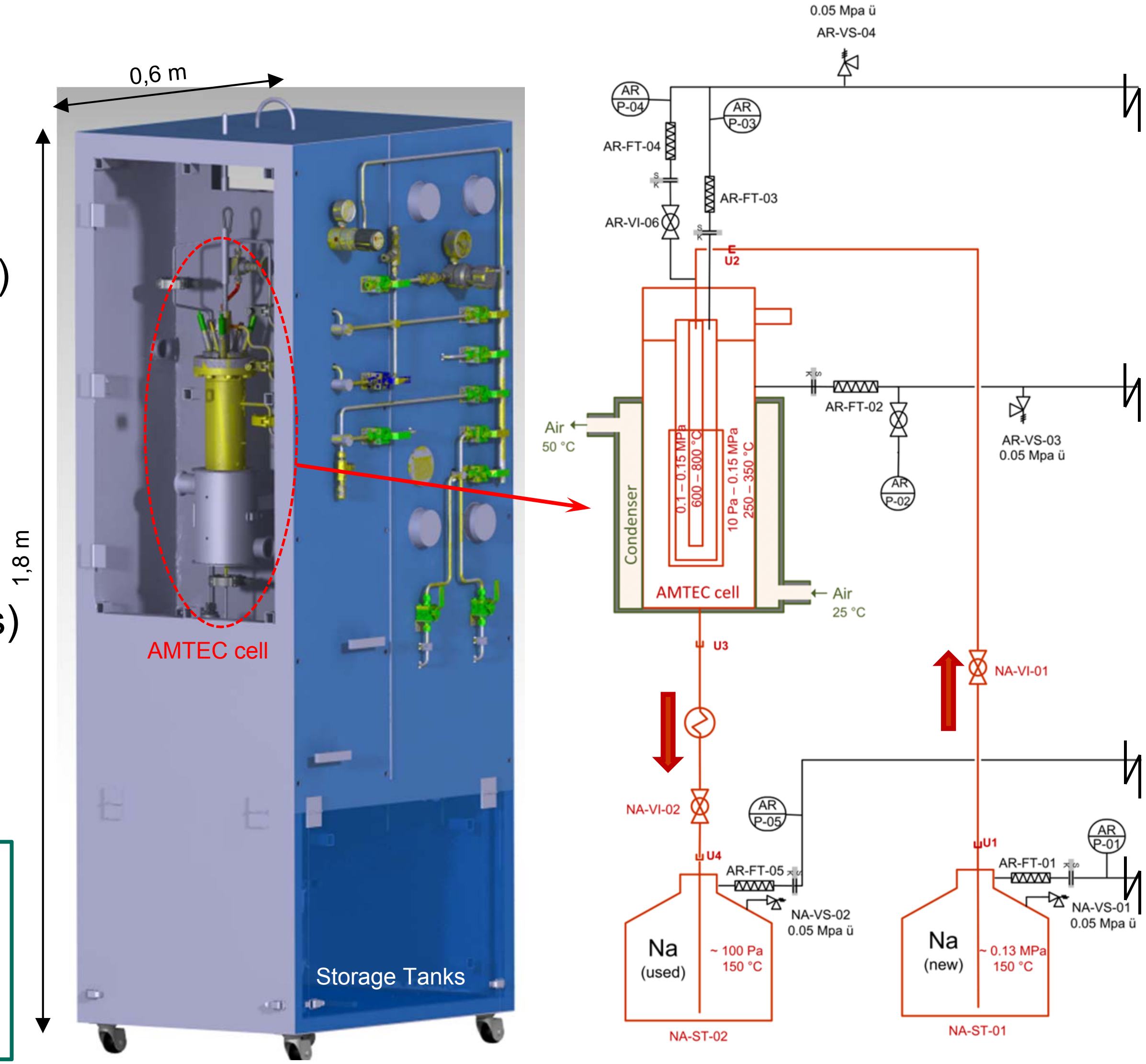
Figure 2 Series II, PX-2 AMTEC Cell

Sievers et al. 1997

AMTEC TEst FAcility (ATEFA)

- Research on AMTEC cell
- Test facility consists of Na-side + Ar-side.
- **Na-side** includes:
  - Two storage tanks (~ 4,5 l)
    T_{Na} ~ 150 °C
  - AMTEC test cell
    T_{Na} = 600 – 800 °C
  - Air-cooled condenser
    T_{Na} ~ 300 °C
  - Heating trace
  - Vol_{Na} ~ 0.3 l (without tanks)
- **Ar-side** controls Na-flow and pressure in cell and tank
  - Max. p = 1.5 bar

Safe design!
- ✓ In-housed in a metallic box
- ✓ Possibility to float with Ar
- ✓ Safety equipped lab.



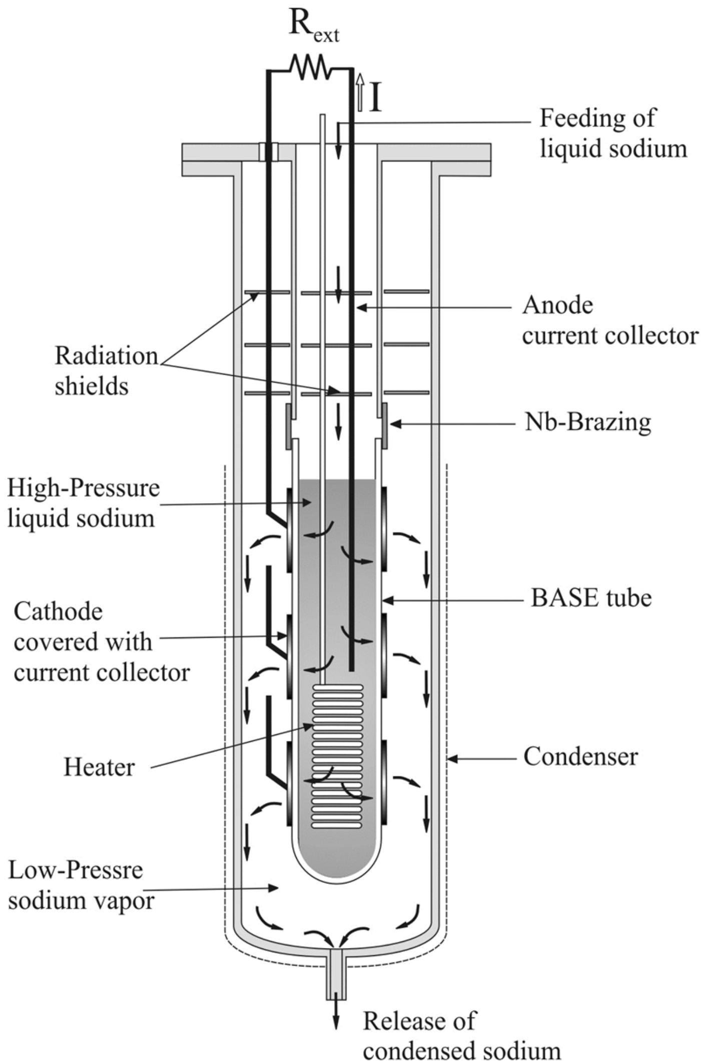
AMTEC test cell

- Single BASE tube
  (D=3cm, L=22cm, wall thickness 1mm)
- Na-liquid anode
- Sputtered cathodes (~ 5 µm thickness)
- BASE-Nb-Steel brazing
- 21 thermocouples → ΔT measurement in axial, radial, circumferential direction
- Pressure sensors in Argon atmosphere
- Electronic load → IV curve measurements

Tests*

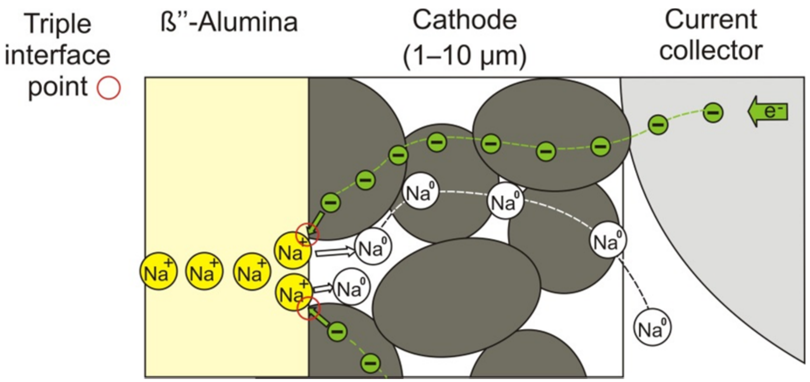
- BASE (thickness, chemical stability, homogeneity, ionic conductivity)
- Electrode composition (Mo, TiN, TiC)
- Electrode and current collector structure
- Ceramic-metal brazing

*together with other institutes in KIT

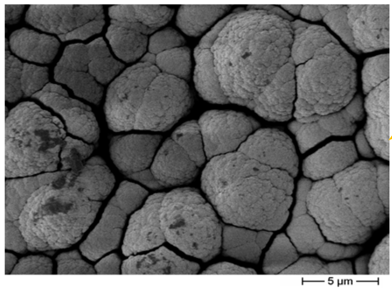


AMTEC test cell

- Electrode – current collector structure
  - Magnetron-Sputtered porous cathode (~ 5 µm grain size)
  - Transport in cathode
    - Recombination of Na ions at triple interface points
    - Porosity vs. current density
    - Tickness vs. electrical resistance
  - Current collector
    - Metallic grid, metallic foam, knitted wire…



Transport process in the cathode



Molybdenum cathode (h~ 5 µm)

BASE

- Sintering of electrode decreases cell performance with time
  → refractory materials or ceramics (Mo, TiN, TiC)

Nerea Díez de los Ríos et al.

Scoping tests of PEEK in liquid sodium

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- Polyether ether ketone (PEEK) is a polymer with excellent mechanical and chemical resistance properties at high temperatures.
- Liquid / vapor sodium is a challenge for sealing materials in valves and instrumentation
- Little information about chemical test of polymers – liquid sodium
- Seven PEEK samples of ~1cm² were introduced in a sodium bath at different temperatures inside a glove box with argon atmosphere
- Chemical and mechanical analysis of the samples foreseen

Temp.	Duration	Remark
100 °C	15 min.	No changes
120 °C	10 h	No changes
150 °C	10 h	Appearance of black spots
200 °C	1h	Sample completely darkened and apparent changes in mechanical properties

Oberview of the performed PEEK chemical test

0 sec. – 120 °C

10h – 120 °C

0 sec. – 150 °C

10h – 150 °C

5 min. – 200 °C

10h – 200 °C

VICTREX-PEEK-450G™ samples before / after chemical test in liquid sodium

Summary and outlook

- AMTEC test cell and test facilty have been designed and are under construction
- Tests in sputtering and brazing started
- Scoping test of PEEK in liquid sodium

- Experimental infrastructure (ATEFA facility, AMTEC prototype) to be set into operation by September 2015
- Experimental campaign focused on:
  - Open issues (BASE analysis, electrodes)
  - Performance evaluation
  - Technology improvement
- Further analysis of the PEEK samples

ATEFA facility

LIMTECH Alliance *and HEMCP:*
Helmholtz Energy Materials Characterization Platform

Thank you for your attention

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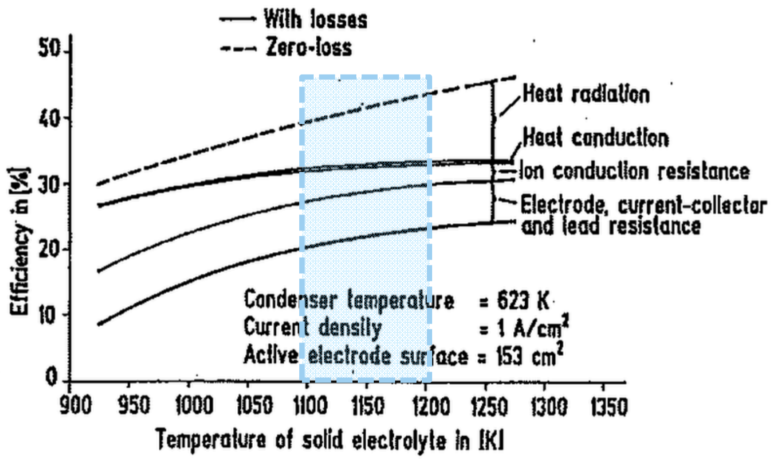
Funding:
LIMTECH (Liquid Metal Technology) Alliance → HGF Alliance
HEMCP (Helmholtz Energy Materials Characterization Platform)

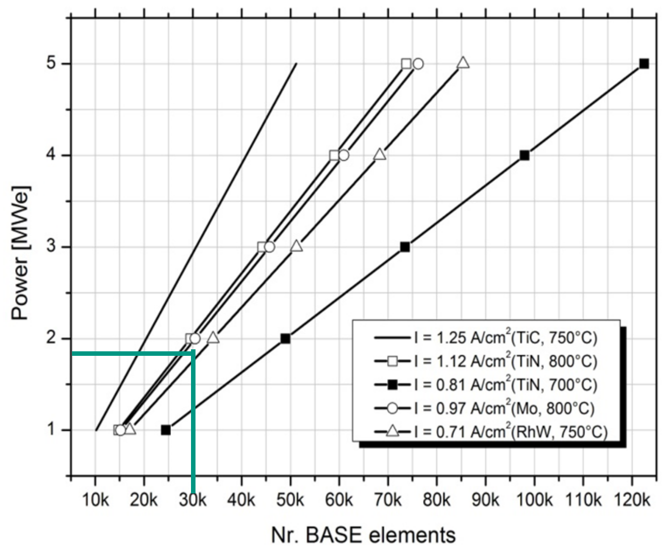
Challenges of AMTEC for CSP:

- Efficiency optimization
  - Heat losses (10 – 15 %)
  - Electrical losses (12 – 15 %)
- Constant performances for long time operation (~ 60000 h)
  - Degradation of BASE (formation of molten dendrites, internal crack formation, contamination through impurities, grain growth)
  - Electrode sintering (grain growth)
- Cyclic operation (fatigue)
- Costs: special materials for construction, safety design

- Present technology: ~2MWe with ~30k BASE elements at 750-800°C and 1 A/cm²



Heinzel et al.– KEM 59&60, 1991



Onea et al. – accepted for publication MHD, 2015

Liquid metals as HTF for CSP

Heat transfer fluid (HTF)	Therminol VP-1	Solar Salt (60% NaN03/ 40% KNO3)	Liquid metals (General)	Liquid Sodium	Steam@ 10bar
Stability	400 °C	~ 585 °C	800-2600 °C	873 °C	-
Therm. Cond. 400 / 600 °C	0.0956 W/mK	≥ 0.58 W/mK	> 15 W/mK	60 W/mK	0.09 W/mK
Melting Point	12 °C	228 °C	< 0-300 °C	97.7 °C	-
Density 400 / 600 °C	696 kg/m³	1867 kg/m³	500 kg/m³ - - 10000 kg/m³	810 kg/m³	2.5 kg/m³
Spec. heat 400 / 600 °C	~ 2,5 kJ/kgK	1,5 kJ/kgK	0,15 - 4,16 kJ/kgK	1,25 kJ/kgK	2.2 kJ/kgK

Advantages of Na:

- **Thermal stability 870 °C**
- **High thermal conductivity**
- Low melting point
- Low density

Disadvantages of Na

- Reactive with air and water

→ Safety oriented design and maintenance

- Comparison of HTFs *:
  Na identified as the best HTF for CSP-TS
  - $\frac{(E_{grid})^{Na}}{(E_{grid})^{Sol\,Salt}}$ ~1.06
  - $\frac{(E_{grid})^{Na}}{(E_{grid})^{Steam}}$ ~1.11

→ Sodium good candidate as a HTF in CSP systems

* Liu et al. SE 101, 220-231, 2014

Long time perspective

Hybrid system **CSP + Na + AMTEC**

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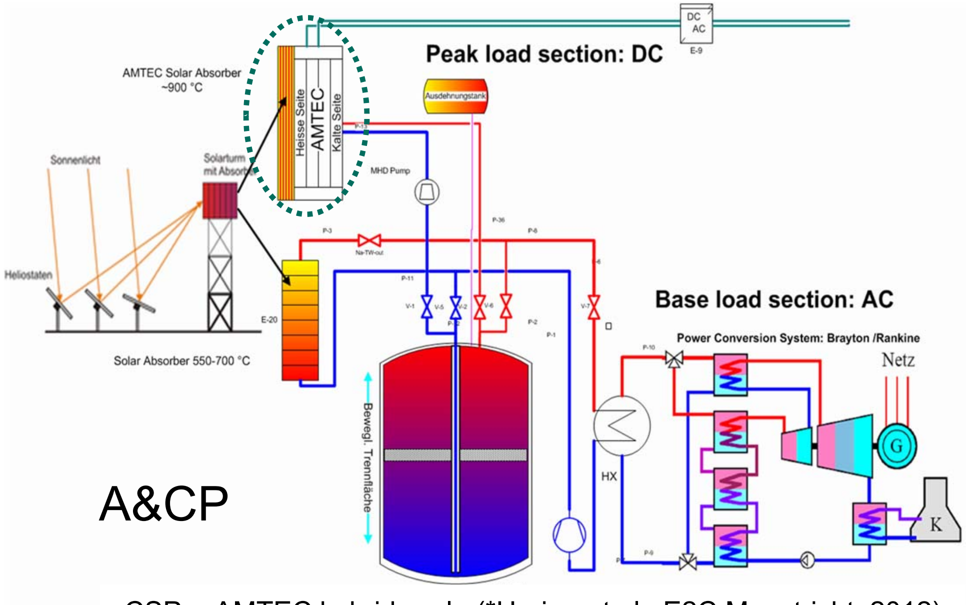
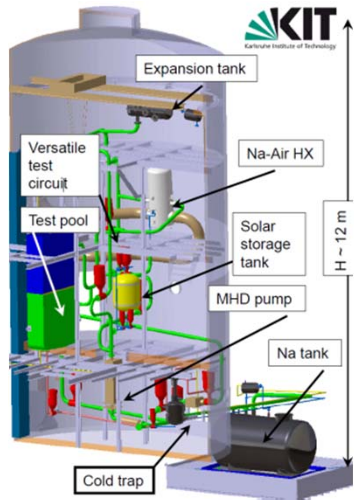


CSP - AMTEC hybrid cycle (*Hering et al., E2C Maastricht, 2012)

- HTF + storage fluid: Na
- $T_{receiver}$ ~ 550 – 700 °C
- AMTEC as topping system
- Plant size: ~ 100 MWth
- Compensation of fluctuations in source
- AMTEC excess energy reused in TS
- Longer and more flexible operation
- Increase PCS lifetime
- Increase system efficiency* (η ~ 25 %)

Research in projects LIMTECH, HEMCP

- AMTEC prototype
- Material characterization in Na
  → SOdium Loop for Test Materials and Corrosion (SOLTEC)
- High temperature thermal storage device
- A&CP → integration of small prototype in Karlsruhe Sodium Laboratory (KASOLA)



Different direct energy conversion systems

Energy Conversion System	T_{min} / T_{max} [°C]	η [%]	Comments
Thermoelectric converter (Seebeck effect)	100 / 900	< 20	Availability of good semiconductors that sustain high temperatures
Thermionic converter	T_{max} > 1500	< 20	High operating temperatures
Solar cell	30 / 60	15 - 30	High costs, "environmentally" expensive, contain toxic elements
Fuel cell	200 / 1000	35 – 60	Fuel storage, fuel generation and lifetime research needed. High costs.
AMTEC	200 / 1000	~ 20 (40)	Lifetime and efficiency under research

- All ECS are under development for being competent in the industry
- Issues like lifetime, efficiency, output power and costs need still to be treated

AMTEC - Advantages

- **High theoretical efficiency (40%)**
- **Flexible regarding the heat source**
- Suitable for modular design
- No moving parts
- Silent operation
- **Flexible connection (to other heat-to-electric systems)**

→ **Application for solar energy conversion**