AVR Experiences
Overview

Lessons of 21 years of successful operation

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AVR GmbH

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AVR

Plant history

1956  Engagement of AVR in HTGR, from the very beginning
1961  Begin plant construction
1964  First core ordered (UCC)
1966  First core delivered, First criticality

Electricity production:  1670 GWh (~ 6 MWh/pebble)
### AVR Experimental Nuclear Power plant

#### Main Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power</td>
<td>46 MW</td>
</tr>
<tr>
<td>Electrical output</td>
<td>15 MW</td>
</tr>
<tr>
<td>Core: Diameter</td>
<td>3.0 m</td>
</tr>
<tr>
<td>Core: Height</td>
<td>2.8 m</td>
</tr>
<tr>
<td>Power density</td>
<td>2.6 MW/m³</td>
</tr>
<tr>
<td>Fuel: Composition</td>
<td>HEU/Thorium or LEU (10%: 17%)</td>
</tr>
<tr>
<td>Fuel: Arrangement</td>
<td>pebble bed</td>
</tr>
<tr>
<td>Fuel: 92,000 pebbles</td>
<td></td>
</tr>
<tr>
<td>Discharge burn-up</td>
<td>112 % fifa</td>
</tr>
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<td>18.2 % fima, 162 GWd/to</td>
</tr>
<tr>
<td>Max. temperature</td>
<td>&gt; 1350 °C</td>
</tr>
<tr>
<td>Coolant: Pressure</td>
<td>11 bar</td>
</tr>
<tr>
<td>Coolant: Inlet temperature</td>
<td>275 °C</td>
</tr>
<tr>
<td>Coolant: Outlet temperature</td>
<td>950 °C</td>
</tr>
</tbody>
</table>
AVR

Time Availabilities of AVR

Fig. 1
AVR Personnel Radiation Exposure Data for AVR Annual Collective Doses

Fig. 2
AVR
Release of Radioactive Noble Gases to Environment over the Years 1968-’88

Licenced: $37 \times 10^{11}$ Bq / yr

Activity of Released Noble Gases [Bq $\times 10^{11}$]

Year

1968–1988

Fig. 3
AVR Pebble fuel variety

AVR as mass test bed

Pebble structure

- Shell type 37,700
- Pressed type 253,000

Fuel design

HEU

- $(^{238}\text{U} / ^{232}\text{Th})\text{C}_2$ with 5 g Th 87,600
- $(^{238}\text{U} / ^{232}\text{Th})\text{O}_2$ with 5 or 10 g Th 129,400
- Feed / Breed, $\text{UO}_2$, $\text{UC}_2$, $\text{UCO}$, $\text{ThO}_2$ 20,300

LEU

- $\text{UO}_2$, different enrichments 53,400

Coating design

- BISO type 202,900
- TRISO type 74,300
- Feed / Breed (TRISO / BISO mixed) 13,500
Coolant fission gas activity

Coolant outlet temp.

Coolant activity

GLE 1

Year

1000
800
600
400
200
100
0

73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88

10^{12} \text{ Bq}
AVR Fuel Performance

At maximum fuel temperature $> 1350 \, ^\circ C$

And very low fission product release:

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<th>Burn-up</th>
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Irradiation achievements

Fast fluence
$10^{21}$ cm$^{-2}$

$(E > 0.1$ MeV$)$

Burnup / GWd t$^{-1}$
Pebble crushing strength and diameter in dependence of irradiation

Crushing strength

kN

Pebble diameter

mm

Fast fluence / $10^{21}$ cm$^{-2}$ ($>0.1$ MeV)
Arisings of pebble scrap in 21 years of operation

Integral number of broken fuel pebbles

(1) Sensitivity of pressed fuel elements to shocks and jolts

(2) Sphere jams at new dosing wheel

(3) Disturbances during input of new fuel elements

Cycled pebbles / millions
Arisings of pebble scrap 1969 to 1975 (first 22 scrap cans)

Integral number of broken fuel pebbles

Cycled pebbles / millions

Shell type

U

Pressed

GK+GO

Lessons from Mass Fuel Testing

Fig. 2
Post-irradiation standard oxidation test results

Oxidation rate
mg cm$^{-2}$ h$^{-1}$

- Temp. rise to 950 °C
- Steam generator leak

○ Carbidic fuel
+ Oxide fuel

Therm. power integral / 10$^4$ MWd

Year
Peeling effect

Cross section of peel, magnified
### Coolant data, stationary operation, 950 °C

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Activity concentration in Bq/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total fission gases</td>
<td>$4.6 \cdot 10^8$</td>
</tr>
<tr>
<td>Tritium</td>
<td>$3.7 \cdot 10^7$</td>
</tr>
<tr>
<td>C 14</td>
<td>$1.9 \cdot 10^7$</td>
</tr>
<tr>
<td>Co 60</td>
<td>$1.0 \cdot 10^1$</td>
</tr>
<tr>
<td>Sr 90</td>
<td>$2.0 \cdot 10^2$</td>
</tr>
<tr>
<td>Ag 110 m</td>
<td>$4.9 \cdot 10^1$</td>
</tr>
<tr>
<td>I 131</td>
<td>$5.2 \cdot 10^2$</td>
</tr>
<tr>
<td>Cs 137</td>
<td>$3.0 \cdot 10^2$</td>
</tr>
</tbody>
</table>

### Table 1

<table>
<thead>
<tr>
<th>Component</th>
<th>Impurity concentrations in ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>&lt; 0.05 ... 0.3</td>
</tr>
<tr>
<td>CO</td>
<td>30 ... 100</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.3 ... 1</td>
</tr>
<tr>
<td>N₂</td>
<td>3 ... 7</td>
</tr>
<tr>
<td>CH₄</td>
<td>&lt; 0.1 ... 1</td>
</tr>
<tr>
<td>H₂</td>
<td>10 ... 30</td>
</tr>
</tbody>
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### Table 2
1 THERMAL POWER  
2 SPEED OF BLOWERS  
3 AVERAGE POSITION OF SHUT-DOWN RODS  
4 REFLECTOR NOSE TOP  
5 REFLECTOR NOSE MIDDLE  
6 SIDE REFLECTOR INSIDE  
7 REFLECTOR BOTTOM

$P_{TH} = 44000 \text{ kW}$

SECONDARY CIRCUIT OUT OF ACTION

$P_{MAX} = 1800 \text{ kW}$

$P_{AVG} \text{ CA.} 300 \text{ kW}$

SIMULATED FAILURE OF SHUT DOWN EQUIPMENT AND INTERRUPTED DECAY HEAT REMOVAL FOR THAT TIME

Fig. 5
AVR
Stop-of- Forced-Cooling and Re-Criticality Experiment

\[ \frac{n}{\text{min}^{-1}} \]
\[ \frac{z}{\text{SKT}} \]
\[ \frac{P_{\text{th}}}{\text{kw}} \]

\( t/\text{h} \) 0 2 4 6 8 10 12 14 16 18 20 22 23.5 24 25 26

- \( P_{\text{th}} \) thermal power
- \( n \) blower speed
- \( z \) shut-down rod position

Reactor recritical

Shut-down rod nose, core midheight
Side reflector, core midheight, inner surface
Bottom reflector
Rod nose above pebble bed
Temperature Shift in a LOCA (Calculated)
Until $t=0$: $P=6\text{ MW}$

Total power (fission power stepwise)

Real decay heat still present from former power operation including heat-up phase (4 MW)

Test duration/h
Accident simulation initiated by shut-down of blowers

Fig. 6

Measured Temperature Curves during LOCA Simulation of October 14, 1988

AVR GmbH
Uniqueness of AVR

- Mass test with all development steps of pebble fuel elements
- Highest coolant temperature of 950 °C (nominal, inlet steam gen.) and > 1280 °C (max., exit pebble bed)
- Release of Sr 90 from carbide fuel (BISO) at high burn-up at 950 °C operation
- Excellent mass behaviour of BISO and TRISO oxide fuel at high burn-up and fuel temperatures of > 1350 °C
- First HTGR loaded with LEU (up to 50 %) as normal fuel
- Water ingress event with little consequences
- LOCA simulation experiment
AVR: Our HTGR Manifesto (Summary)

- Global challenge: nuclear fission energy as the major replacement for fossil fuel
- Reactor choice: pebble-bed HTGR, simple, continuous fuelling, highest burn-up of all thermal reactors
- Keep it simple: cylindrical core, economy of smaller units by large-serious production
- Overall efficiency: maximize useful energy extraction from the given unit of natural fuel!
- Peu-a-peu: Yes when spent fuel pebbles further used in multi-pass pebble bed
- Accuracy of pebble measurement important, via Cs-137 standard, but new method for very short cooling times
- Weapon-grade Pu: in pebble bed consumed to almost 100%
- AVR as base for fuel licensing: high burn-ups and fuel temperatures >1350 °C
- Licensing: cold-shutdown requirement with rods obsolete!
- No regular air ingress by fresh pebble loading: preliminarily fill the graphite pores with He!
- Simple disposal of major HTGR waste: spent fuel and graphite embedded in concrete blocks, abundant storage space in all given-up underground mines
At maximum fuel temperature $> 1350 \, ^\circ\text{C}$

And very low fission product release:

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