Abstract. The general scheme of power installations based on nuclear reactions of fission and synthesis activated by external sources is analyzed. The external activation makes possible to support nuclear reactions at temperatures and pressures lower than needed for chain reactions, so simplifies considerably practical realization of power installations. The possibility of operation on undercritical masses allows making installations compact and safe at emergency situations. Installations are suitable for transmutation of radioactive nuclides, what solves the problem of utilization of nuclear waste products. It is proposed and considered schemes of power installations based on nuclear reactions of fission and fusion, activated by external sources, different from ADS systems. Variants of activation of nuclear reactions of fission (U-235, 238, Pu-239) and fusion (D, T, Li-6,7, B-10,11) are considered, designs of installations are proposed.
Problems of Nuclear Power Engineering

Atomic Power Stations

• Safety
  Nuclear accidents: Chernobyl, Fukushima...
  Nuclear terrorism
• Ecology
  Radioactive fuel mining, enrichment...
  Hundreds of tons of radioactive wastes
• Economy
  High cost of nuclear power fuel and plants
  Limited amount of fuel

Fast Neutron Reactors

• Safety
• Ecology
  Radioactive fuel mining, enrichment
  ~ Radioactive wastes
• Economy

Accelerator-Driven Systems

• Processing and Operating Complexity
  High-energy & intensity accelerator
• Ecology
  Radioactive fuel mining, enrichment
• Economy
  Low efficiency

Thermonuclear Reactors

• Not realized
• Processing and Operating Complexity
  Extra-high temperatures, pressures
• Economy
  High cost of power plants

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**ADS Reactors**

**Proton accelerator** → **Target (heavy metal)** → **Reactor** with fissile materials → **Generator**

- **Proton**: 0.5-1.5 GeV

**Charged Particle Activation**
- Low $\sigma$ of nuclear interactions
- Short length of neutron range (0.6 mm for Al)

**Neutron Activation**
- High $\sigma$ of nuclear interactions
- Acceleration?
Efficiency of NRA Installations

\[ \eta = \frac{P_u}{P} \approx 1 - \frac{I_{th}}{I_A} \]

\[ I_{th} = \frac{\Delta P_{Loss}(\eta = 0)}{\varepsilon_A k_L + \varepsilon_N k_N} \]

\[ k_N = \frac{n_N}{n} \int_{0}^{E_A} \frac{\sigma_N(E)}{\sigma_{tot}(E)} dE \]

**ADS Reactors**
- **proton:** 0.5-1.5 GeV
- **Accelerator:** \(~1.5\text{MW}\)
- **Reactor:** 10 MW

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ADS Reactors

**CLEAR-I** (China)

**MYRRHA** (Belgium)

**Need for Activation:** $n^0 \leq 1$ MeV!

**ADS Reactors**
- Proton: 0.5-1.5 GeV
- Accelerator: ~1.5 MW
- Reactor: 10 MW

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Neutron Activation

\[
\begin{align*}
n + ^{6}_3\text{Li} &\rightarrow T + \alpha + 4.78 \text{ MeV}; \\
n + ^{10}_5\text{B} &\rightarrow ^{7}_3\text{Li} + \alpha + 2.79 \text{ MeV}.
\end{align*}
\]

**Lithium-6**: \(\frac{4.78}{6}=0.80\text{ MeV/nucleon}\)

**Boron-10**: \(\frac{2.79}{10}=0.28\text{ MeV/nucleon}\)

**Uranium-235**: \(\frac{180}{235}=0.78\text{ MeV/nucleon}\)

**Lithium-6**: \(180/4.78=38\) neutrons

**Boron-10**: \(2.79/10=65\) neutrons

**Uranium-235**: \(180/180=1\) neutron
Basic chain reactions

\[ n + \frac{6}{3}Li \rightarrow T + \alpha + 4.78 \text{ MeV}; \]
\[ n + \frac{10}{5}B \rightarrow \frac{7}{3}Li + \alpha + 2.79 \text{ MeV}. \]
\[ \alpha + \frac{9}{4}Be \rightarrow n + \frac{12}{6}C + 4.44 \text{ MeV} \]

Rival reactions:
\[ ^{6}\text{Li}(\alpha,n)^{9}\text{B} \quad ^{10}\text{B}(\alpha,n)^{13}\text{N} \]

Lithium-6: 9.29 MeV
Boron-10: 7.23 MeV

\[ K_n \approx 1 \]
Proton – Lithium-6 Activation

\[ p + ^\text{6}_\text{3}Li \rightarrow ^\text{3}_\text{2}He + \alpha + 4.0 \text{ MeV}; \]
\[ ^\text{3}_\text{2}He + ^\text{6}_\text{3}Li \rightarrow 2\alpha + p + 16.9 \text{ MeV}. \]

Basic reactions:

- \( p \rightarrow 6\text{Li} \rightarrow 3\text{He} \rightarrow 6\text{Li} \rightarrow \alpha \rightarrow \alpha \rightarrow p \)

Rival reactions:

- \( ^9\text{Be}(p,2\alpha)D \rightarrow +0.56 \text{ MeV} \)
- \( ^9\text{Be}(p,\alpha)^6\text{Li} \rightarrow +2.1 \text{ MeV} \)
Charged Particle Activation

Lithium-6,7; Berillium-9:

\[
D + ^6\text{Li} \rightarrow 2\alpha + 22.4\ \text{MeV}; \\
D + ^7\text{Li} \rightarrow 2\alpha + n + 15.0\ \text{MeV}.
\]

Rival reactions:

\[^6\text{Li}(D,n)^7\text{Be}\]

\[^6\text{Li}(D,p)^7\text{Li}\]

Boron-10,11; Berillium-9:

\[p + ^{11}\text{B} \rightarrow 3\alpha + 8.7\ \text{MeV}\]

Rival reactions:

\[^{10}\text{B}(p,\alpha)^7\text{Be}\]
1 - activation pins with uranium or plutonium,
2 - basic pins with lithium-6 or boron-10 with beryllium-9 or without it,
3 – neutron moderators, 4 – the coolant, 5 – the neutron reflector,
6 – the reactor vessel, 7 – control rods,
8, 9 – coolant inlet and outlet.
Autonomous Energy Sources

Activating Neutron isotope sources

**Spontaneous fission**

\(^{251}\text{Cf} (T_{1/2}=900 \text{ years}), \quad ^{249}\text{Cf} (T_{1/2}=351 \text{ years}),\)

\(^{250}\text{Cf} (T_{1/2}=13,08 \text{ years}), \quad ^{252}\text{Cf} (T_{1/2}=2,645 \text{ years}).\)

1 g of \(^{252}\text{Cf}\) emits \(3 \cdot 10^{12}\) neutrons per second

**Alpha-induced (\(\alpha, n\))**

\(^{210}\text{Po}, \quad ^{226}\text{Ra}, \quad ^{239}\text{Pu}, \quad ^{241}\text{Am} \quad (+ \quad ^{9}\text{Be})\)

Usual neutron flux \(10^7-10^9\) neutrons per second

1 - lithium-6 or boron-10 with beryllium-9,
2 - neutron moderator,
3 - activating neutron isotope sources,
4,5 - neutron reflector and absorber,
6 - core vessel.
Conclusion

The proposed power installations with activation of nuclear reactions are the nuclear-thermonuclear reactors and sources, in which fusion reactions are activated by fission ones. NTR installations do not need extra-high temperatures and pressures required for reactors on chain thermonuclear reactions and use much smaller amount of radioactive fuel than existing atomic power stations. It decreases considerably the amount of radioactive wastes in NTR and, for the most part, solves the ecological problems inherent to atomic power engineering. Decreasing an amount of radioactive materials with high neutron multiplication coefficient decreases the possibility of uncontrolled chain reactions, so it increases the operational safety of NTR power stations.

Nuclear-thermonuclear reactors can solve many serious problems of the nuclear and thermonuclear power engineering, but for practical realization of proposed installations a whole complex of researches, including theoretical and experimental investigations; detailed calculations; development of construction, etc., needs to be carried out.

Thank You for Attention

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