

A Summary of Generation IV Non-Classical Nuclear Systems

Generation IV Roadmap TW-4, Non-Classical Concepts

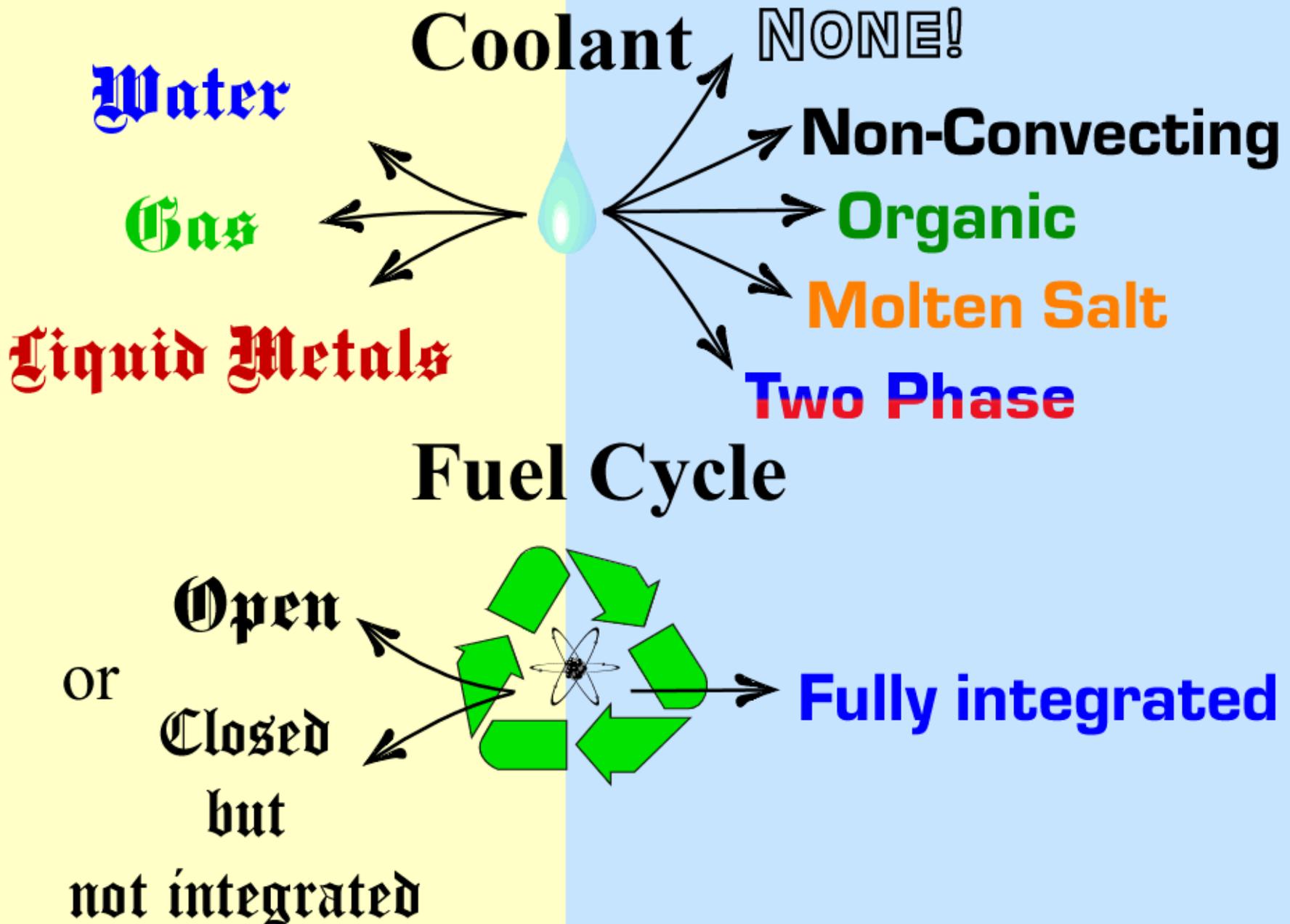
***Generation IV Roadmap Session II
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People Involved in this Work

- ***TWG-4 Non-Classical Reactor Concepts Members***

- ***Anghaie, Samim, Chair*** ***University of Florida, USA***
- ***Delpech, Marc,*** ***CEA, France***
- ***Forsberg, Charles,*** ***ORNL, USA***
- ***Garzenne, Claude,*** ***EDF, France***
- ***Herring, Steve,*** ***INEEL, USA***
- ***Klein, Andy,*** ***Oregon State University, USA***
- ***Lennox, Tom,*** ***NNC Limited, UK***
- ***Leroy, Maurice,*** ***EURATOM/JRC), Germany***
- ***Lewis, Dave, Technical Director*** ***ANL, USA***
- ***Park, Won Seok,*** ***KAERI, Korea***
- ***Peddicord, Lee,*** ***Texas A&M University, USA***
- ***Pickard, Paul,*** ***SNL, USA***
- ***Takano, Hideki,*** ***JAERI, Japan***
- ***Wilson, Paul,*** ***University of Wisconsin, USA***

Classical vs Non-Classical – Coolant & Fuel



Classical vs Non-Classical – Fuel Design

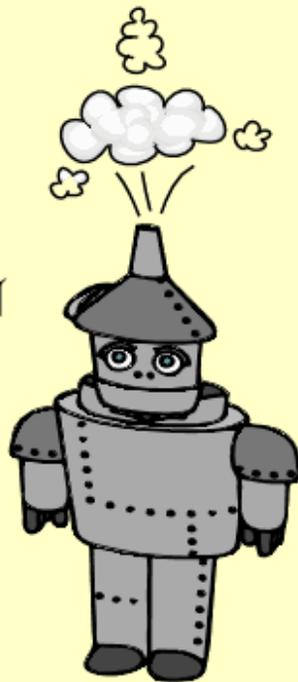
Classical

vs

Non-Classical

Fuel Design

Solid Clad



No Clad

Liquid

Gas or Vapor

Thin Film

Classical vs Non-Classical – Power

Carnot ΔT

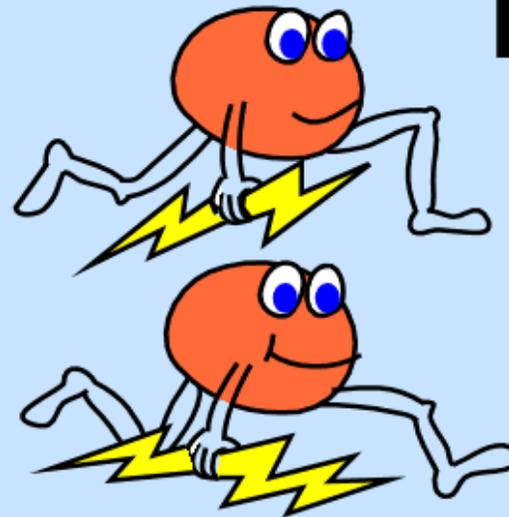
300-1000 K



300-3000 K

Power Cycle

**Steam
Rankine
or
Brayton**



Direct

MHD

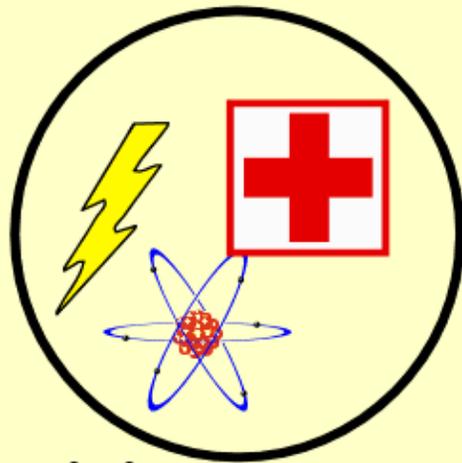
Thermionic

AMTEC

Combined

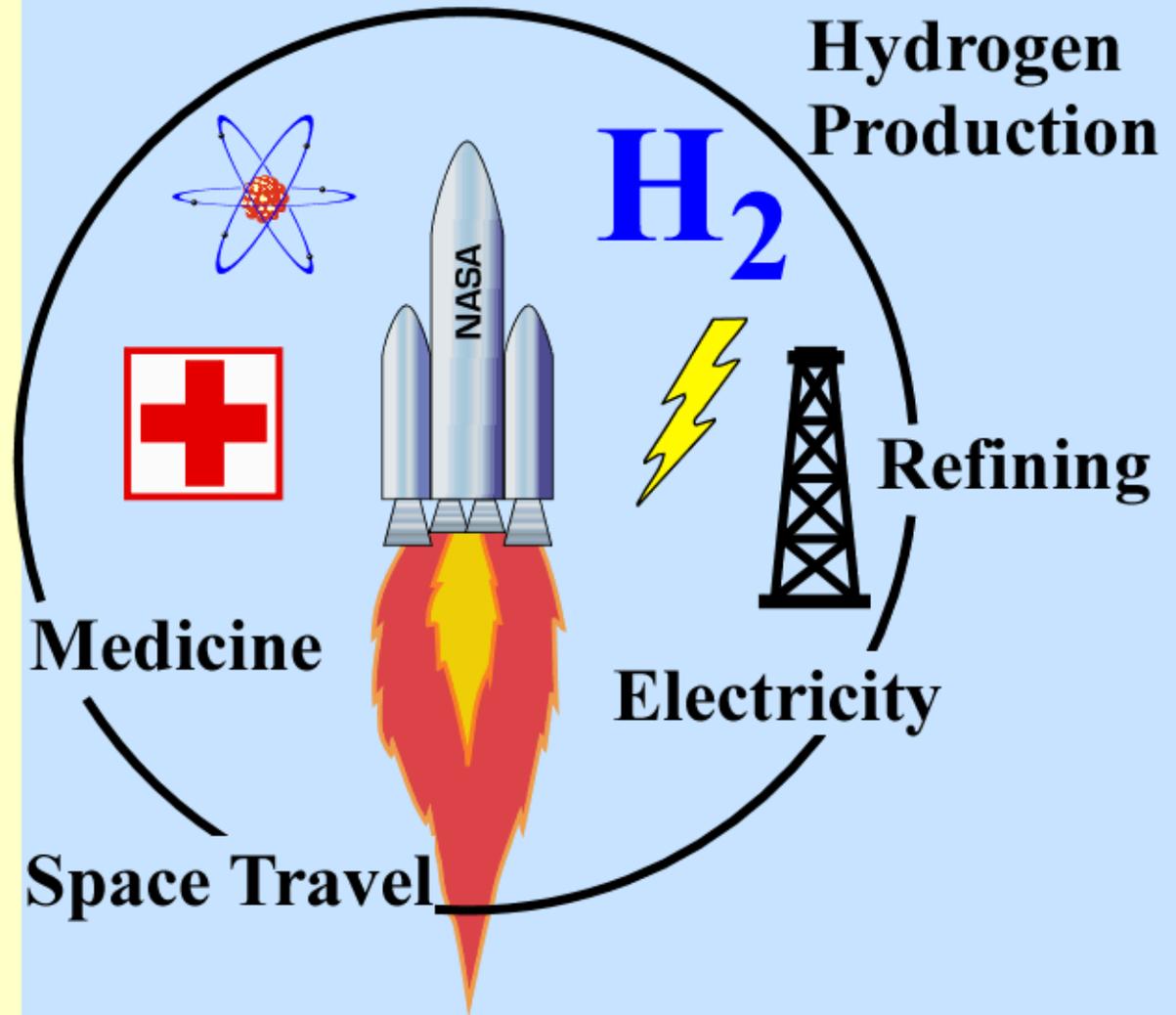
Classical vs Non-Classical – Applications

Applications



Electricity

Medicine



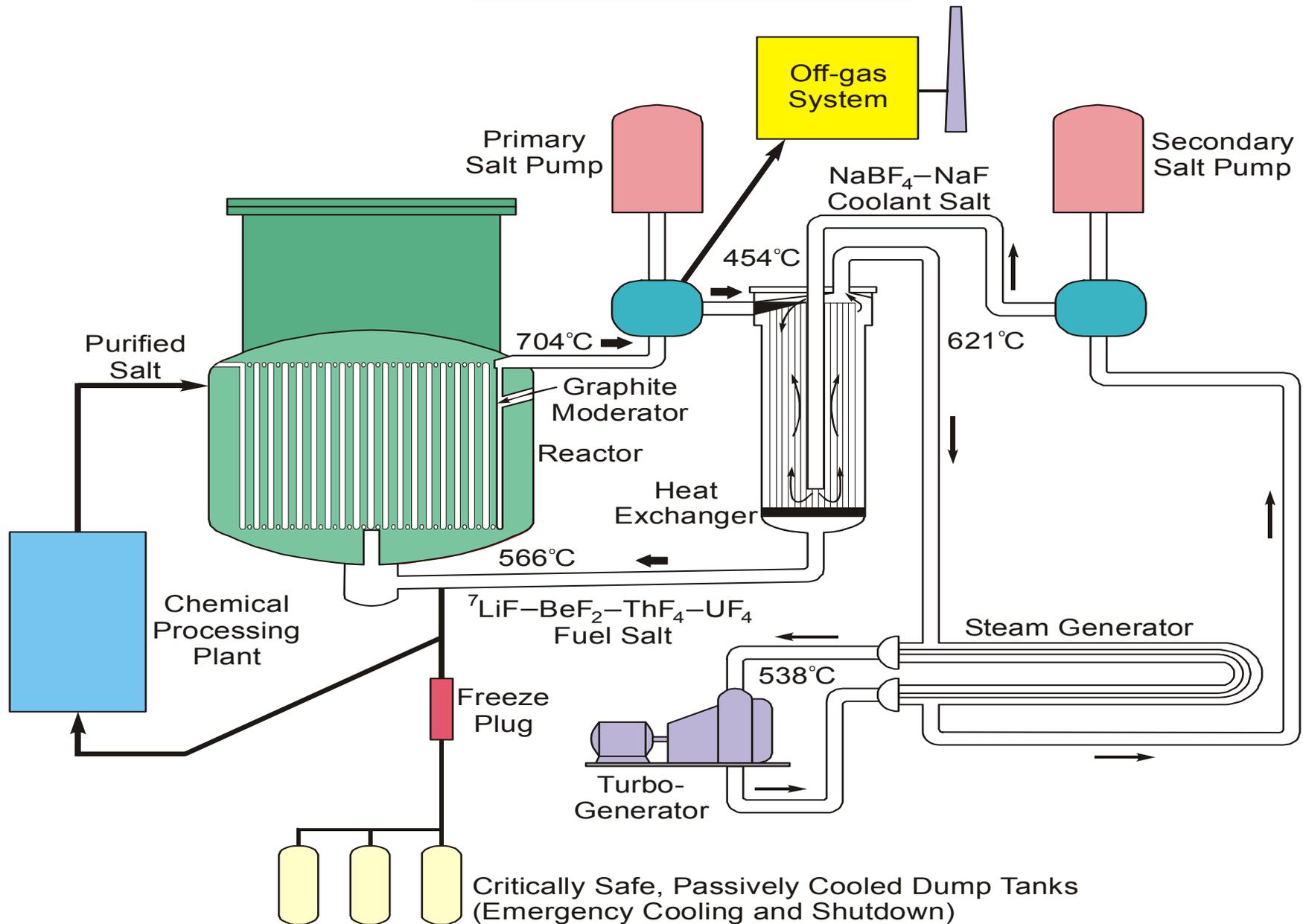
Non-Classical Reactor Concepts

- A total of 32 concepts gathered, among them 28 meet the Generation IV requirement of fission based self sustained criticality.
- Based on the primary design features , six “Concept Sets” are defined as:
 - 1. *Liquid Core Reactors*
 - 2. *Gas Core Reactors*
 - 3. *Non-Conventional Coolant Reactors*
 - 4. *Non-Convection Cooled Reactors*
 - 5. *Direct Energy Conversion Reactors*
 - 6. *Modular Deployable Reactors*
- Non-Classical reactor concepts feature higher potential to meet or exceed Gen IV performance goals at somewhat lower technology readiness level.

A Summary of Liquid Core Reactor Concepts

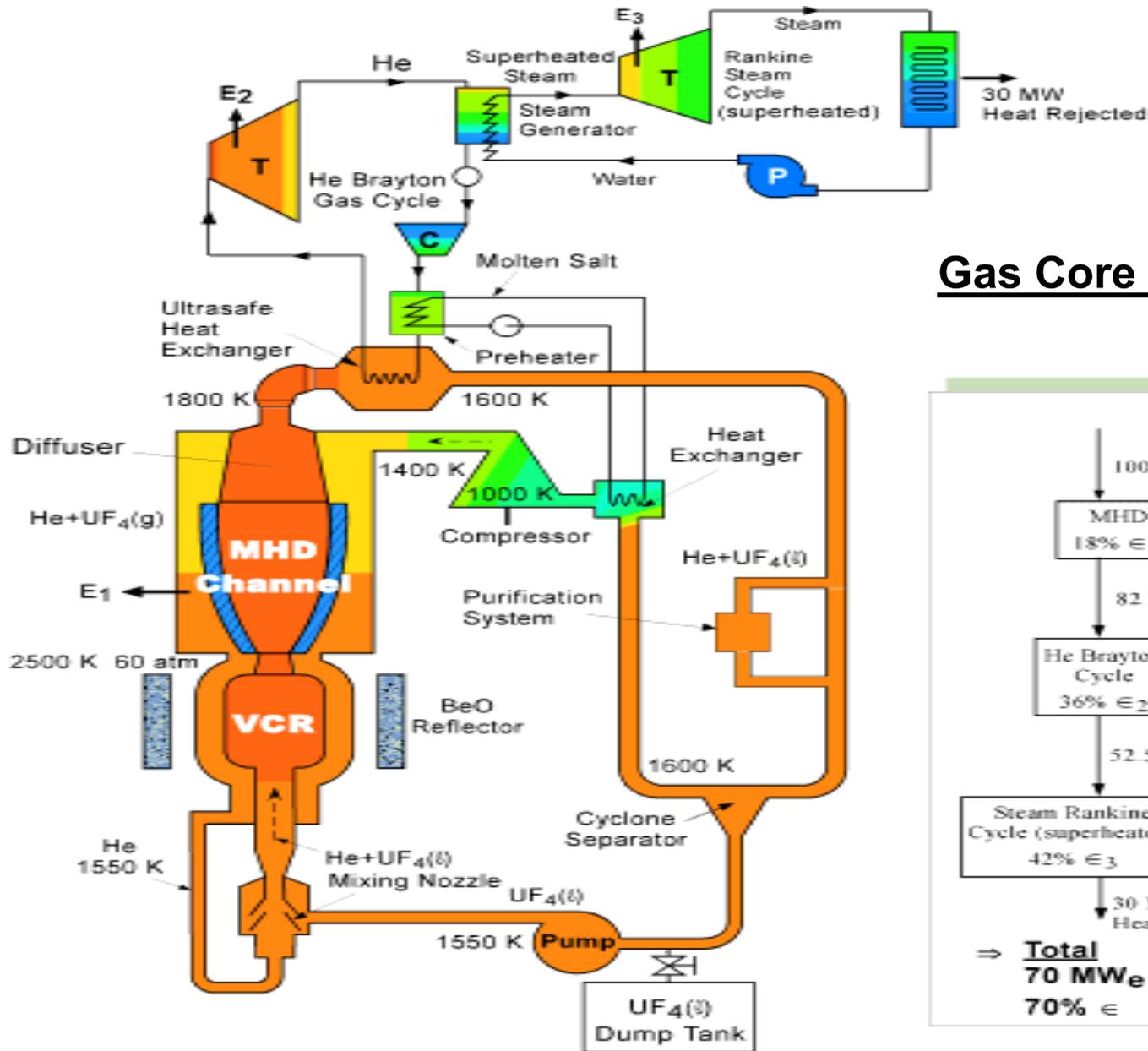
| Name | Organization | Country | Type (Category) | Fuel | Coolant | Moderator | Comments |
|-----------------------------|-------------------------------------|---------------|---|------------------------------------|-----------------------------|-----------------|---|
| HERACLITUS (MSR/MMR) | Argonne National Lab | USA | Molten Salt or Metal (Liquid Core) | Natural thorium fluid | Molten Salt or Metal | Graphite | Circulating fuel, natural thorium. |
| MSRE | Marshall Space Flight Center | USA | Molten Salt Core (Liquid Core) | U/Th Salt Fluid | Molten Salt | Graphite | Evolution of Organic Moderated Reactor Experiment. |
| MSBR | Oak Ridge National Lab. | USA | Molten Salt Core Pool (Liquid Core) | Liquid U & Th fluorides | Molten Salt | Graphite | Several options for molten salt reactor, including breeders. |
| LM-FR | – | USA | Equilibrium Fast Reactor (Liquid Core) | Mg-Pu eutectic | Sodium or NaK | None | Fuel is liquid in a pool with cooling pipes through pool. |
| MSR | Electricité de France | France | Molten Salt – AMSTER (Liquid Core) | Th, U, or TRU in salt | Molten Salt | Graphite | Graphite moderated molten salt reactor for multiple uses. |

Molten Salt Reactor



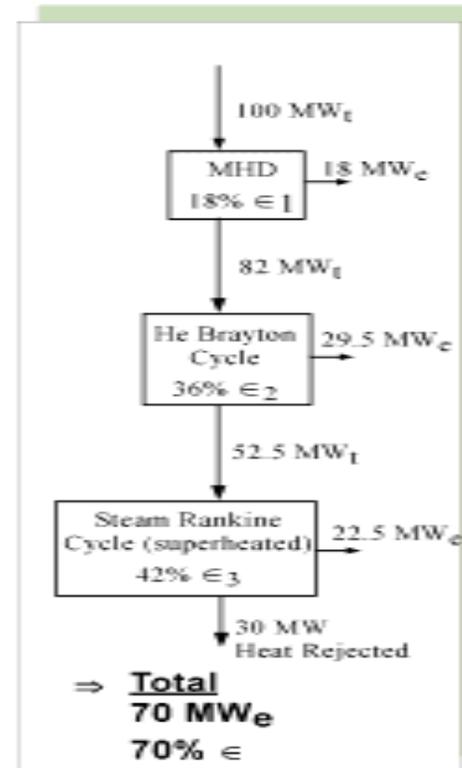
A Summary of Gas Core Nuclear Systems

| Name | Organization | Country | Type (Category) | Fuel | Coolant | Moderator | Comments |
|--------------------|-----------------------------------|------------------------|--|-----------------------------|-----------------------|-------------------------|--|
| GCR/VCR-MHD | Univ. of Florida | USA | Gas/Vapor Fuel Reactor (Gas Core) | UF₄ vapor | KF or He | To be determined | Fission enhanced ionization with direct MHD conversion. |
| GCR-U-C-F | Technische Univ. Eindhoven | The Netherlands | Gas Core-Graphite Wall (Gas Core) | UF_n vapor | CF₄ | Water | High T wall corrosion is neutralized. |
| GCR-UF6 | Los Alamos National Lab | USA | Vortex Flow (Gas Core) | UF₆ vapor | He | – | Low inventory, zero core meltdown chance. |
| Plasma Core | Los Alamos National Lab | USA | Plasma Vortex Flow (Gas Core) | U vapor, Argon | He | Beryllium | Diverse use, high efficiency. |



Vapor Core Reactor with Combined Direct/Indirect Energy Conversion (VCR-DEC)

Gas Core Reactor Power System



Thermodynamic Efficiencies and Power Outputs

Liquid and Gas/Vapor Core Reactors

1. Significant advances can be made in conversion efficiency, diversification of energy products, resource utilization and waste minimization.
2. Excellent non-proliferation characteristics due to one to two orders of magnitude lower fuel inventory and plutonium buildup.
3. Minimized source term due to online separation and removal of fission products and ultralow equilibrium concentration of minor actinides.
4. Gas/vapor core reactors could potentially eliminate the need for Offsite Emergency Planning, which is a key safety goal for the Gen IV reactors.
5. Many technology challenges; high temperature materials, energy conversion, dynamics and control, remote operation, fuel chemistry and fuel handling, fission product separation, and safety.

A Summary of Non-Conventional Cooled Reactor Concepts

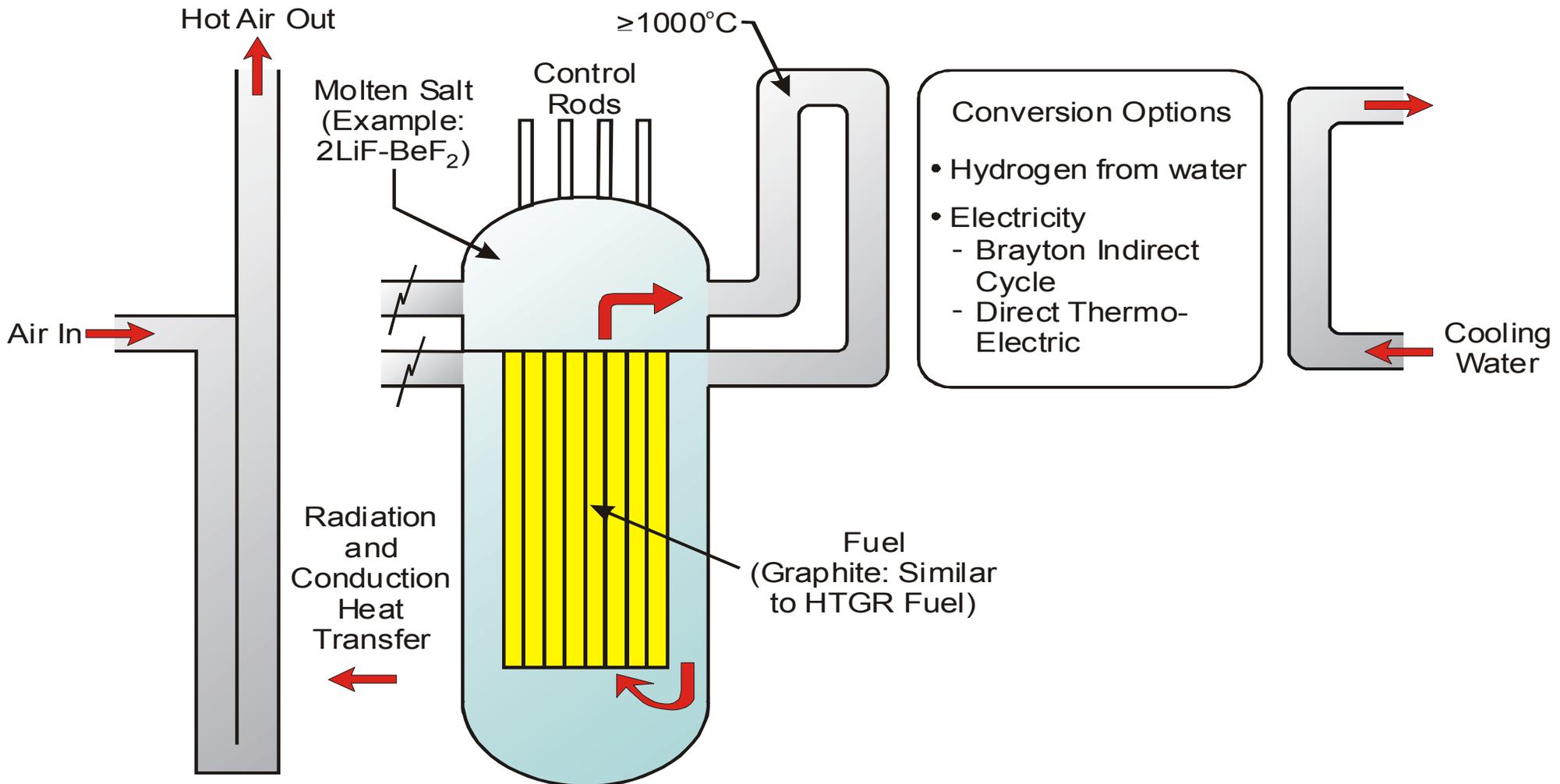
| Name | Organization | Country | Type (Category) | Fuel | Coolant | Moderator | Comments |
|--------------|--|-------------------------------|--|-----------------------------|------------------------------------|------------------------|--|
| AHTR | Oak Ridge NL Sandia NL | USA | High T Molten Salt (Non-Conventional Cooled) | Graphite matrix | Molten Salt | Graphite | High temp to produce hydrogen and electricity. |
| OCR | Univ. of Wisconsin | USA | Organic Cooled (Non-Conventional Cooled) | Uranium carbides | Organic compound | Heavy water | Reduced size/costs. |
| FSEGT | Obninsk Inst. of Phys. & Power Eng. | Russian Federation | Liquid Metal Cooled (Non-Conventional Cooled) | U or Pu | Sodium Evaporati on | Graphite | Unique gas turbine for use with sodium vapor. |
| FSGT | Obninsk Inst. of Phys. & Power Eng. | Russian Federation | Liquid Metal Cooled (Non-Conventional Cooled) | U or Pu | Sodium | Graphite | Unique gas turbine for use with sodium vapor. |
| FLGT | Obninsk Inst. of Phys. & Power Eng. | Russian Federation | Liquid Metal Cooled (Non-Conventional Cooled) | U or Pu | Lead | Graphite | Unique gas turbine for use with lead vapor. |

AHTR, Molten Salt Cooled Reactor

Passive Decay Heat Removal

Reactor

Energy Conversion Options



Non-Conventional Cooled Reactors

1. Molten Salt Cooled Reactors

Significant advances can be made in conversion efficiency, and diversification of energy products.

High temperature operation at low pressure, low power density, high heat capacity.

High temperature materials, fuel design, molten salt to water heat exchanger, mixed nuclear/hydrogen safety issues.

2. Organic Cooled Reactors

High conversion ratio, superior coolant properties, low pressure operation, lower cost coolant (compared to CANDU).

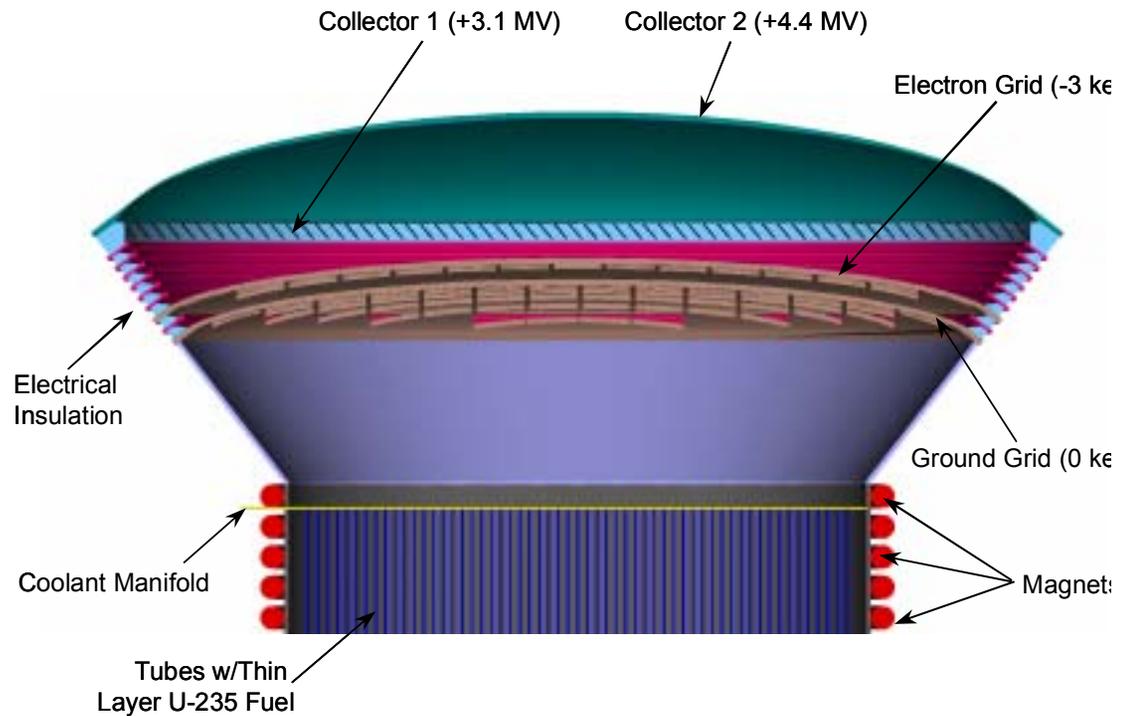
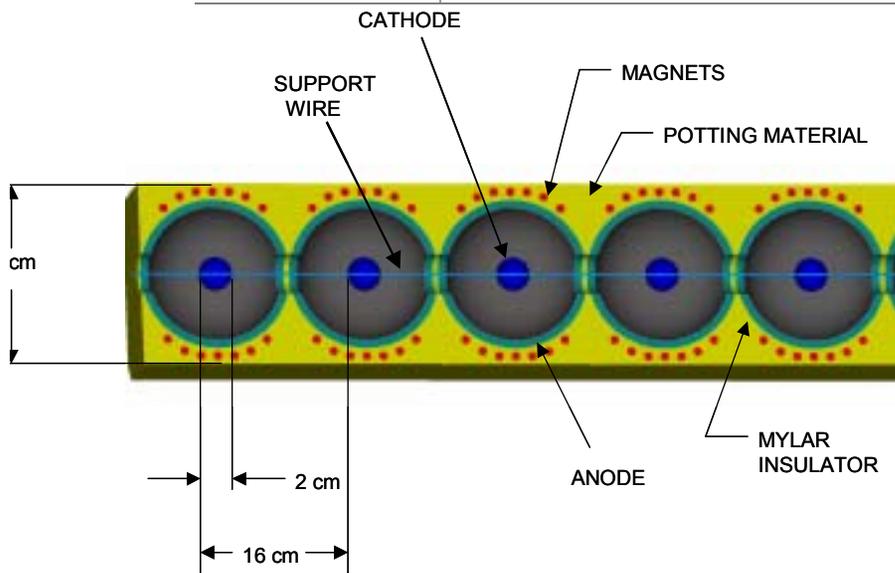
Fuel (UC) reaction with water and air, coolant flammability, coolant fouling, coolant radiolysis, reactivity coefficients.

A Summary of Non-Convection Cooled & Direct Energy Conversion Reactor Concepts

| Name | Organization | Country | Type (Category) | Fuel | Coolant | Moderator | Comments |
|--------------------|--------------------------------|------------|---|---------------------------------|-----------------------------|-------------------------|---|
| Solid State | Oregon State University | USA | Heat Pipe, Solid State (Non-Convection Cooled) | Not specified | Heat Pipe, no fluid. | Not specified | Small reactors cooled by conduction & radiation. |
| QSMC | Sandia National Lab | USA | Fission Fragment Mag. Cell (Direct Conversion) | Fissionable Material | Radiation Cooling | To be determined | Direct conversion of fission fragments to electricity. |
| FFMC | Sandia National Lab | USA | Fission Fragment (Direct Conversion) | Thin film UO₂ | Heavy Water | Heavy Water | Direct conversion of fission fragments to electricity. |

Direct Energy Conversion Concepts

| Number | Concept Name | Sponsorship |
|--------|---|-------------|
| N9 | QFMC —Quasi-Spherical Fission Magnetic Cell Array | SNL |
| N12 | FFMC—Fission Fragment Magnetic Collimator | SNL |



Non-Convection Cooled and Direct Energy Conversion Concepts

1. Non-Convection Cooled Reactors

Low fuel inventory, static energy conversion, small scale power applications, remote site applications.

High temperature fuels and materials, lifetime of energy conversion unit, dynamics and control, fuel cycle.

2. Direct Energy Conversion Concepts

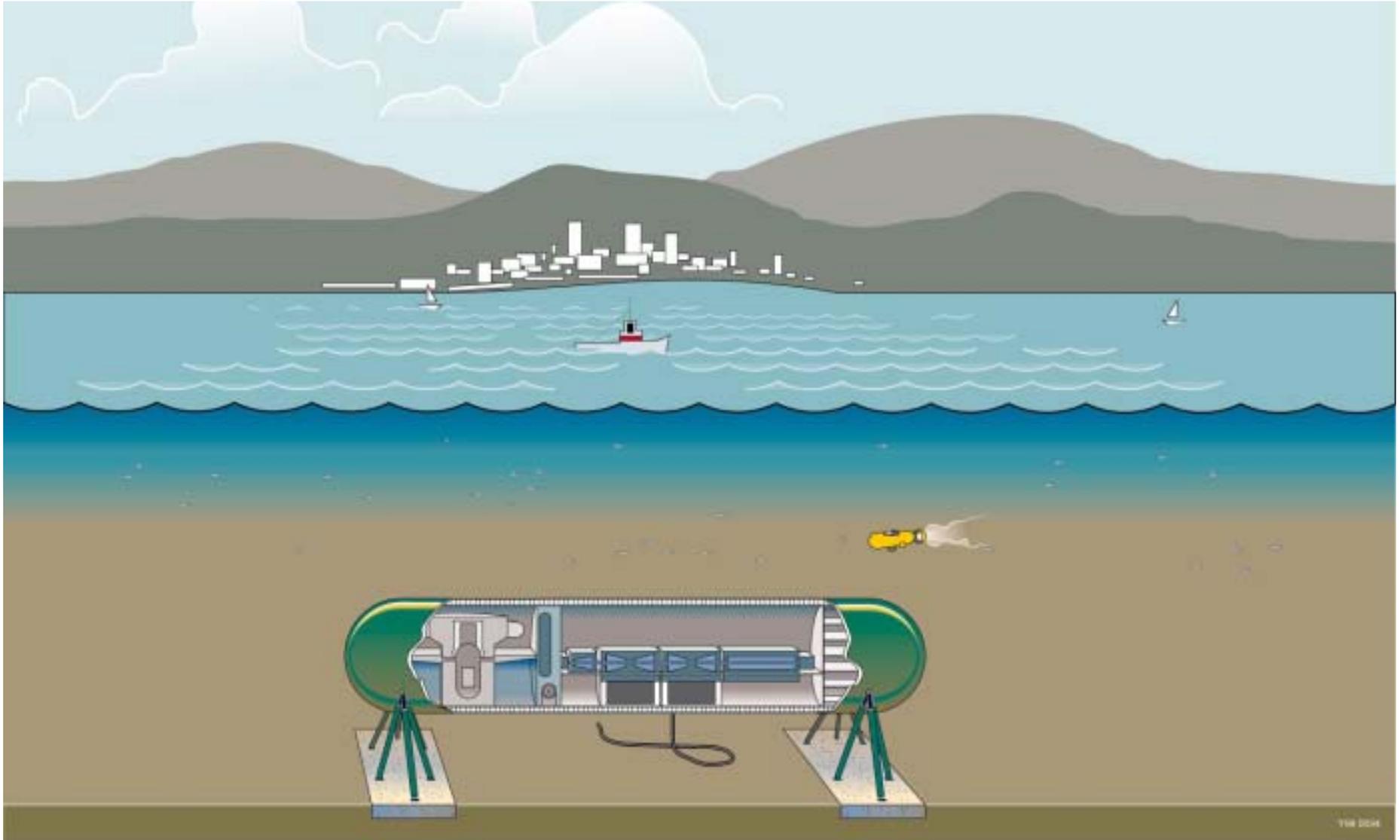
Low fissile inventory, proliferation resistant, no moving parts, no coolant, no flow, barely critical.

Hard to make critical, large systems, very low burnup, magnet design, direct energy conversion.

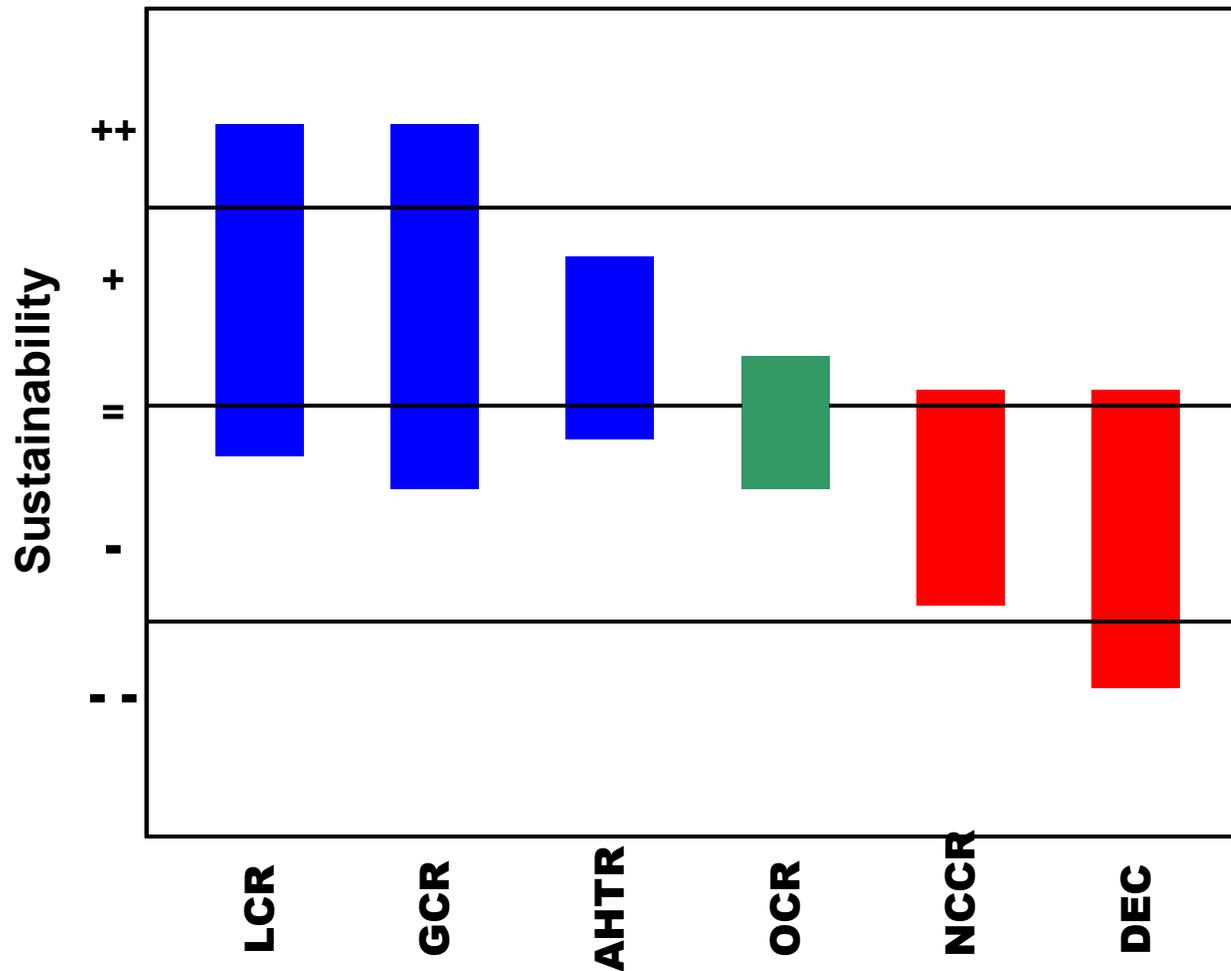
A Summary of Modular Deployable Reactor Concepts

| Name | Organization | Country | Type (Category) | Fuel | Coolant | Moderator | Comments |
|-------------|--|---------------------------|---|----------------|---------------|-----------------|---|
| MMDR | Sandia National Laboratory | USA | Not specified (Modular Deployable) | NA | Helium | NA | Transportable, factory built, easy assembly. |
| SPS | Idaho National Laboratory | USA | Not specified (Modular Deployable) | NA | NA | NA | Transportable, modular. |
| DORC | Obninsk Inst. of Phys. & Power Eng. | Russian Federation | Liquid Metal Cooled (Modular Deployable) | U or Pu | NA | Graphite | Remote operated. |

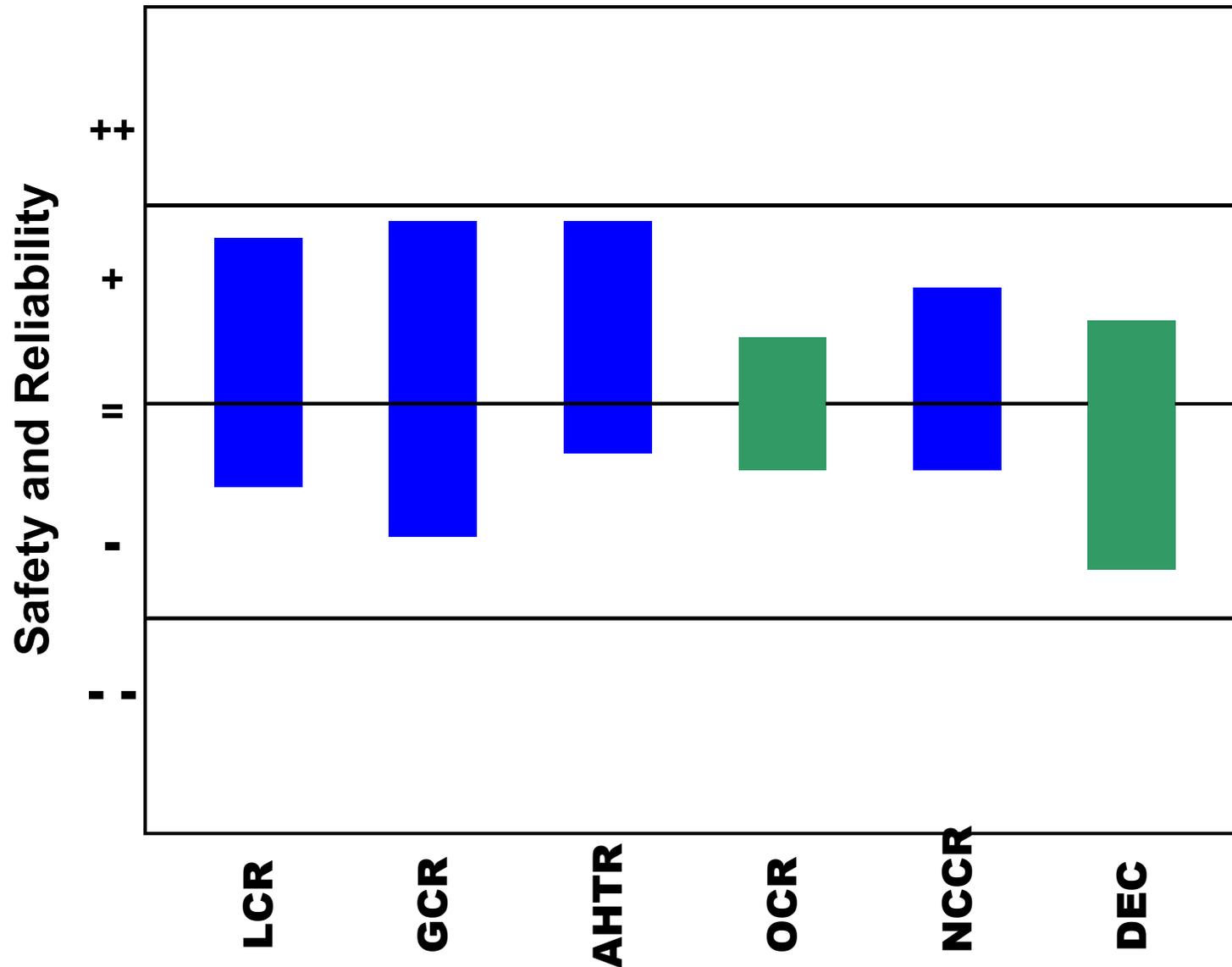
Modular Deployable Nuclear Systems



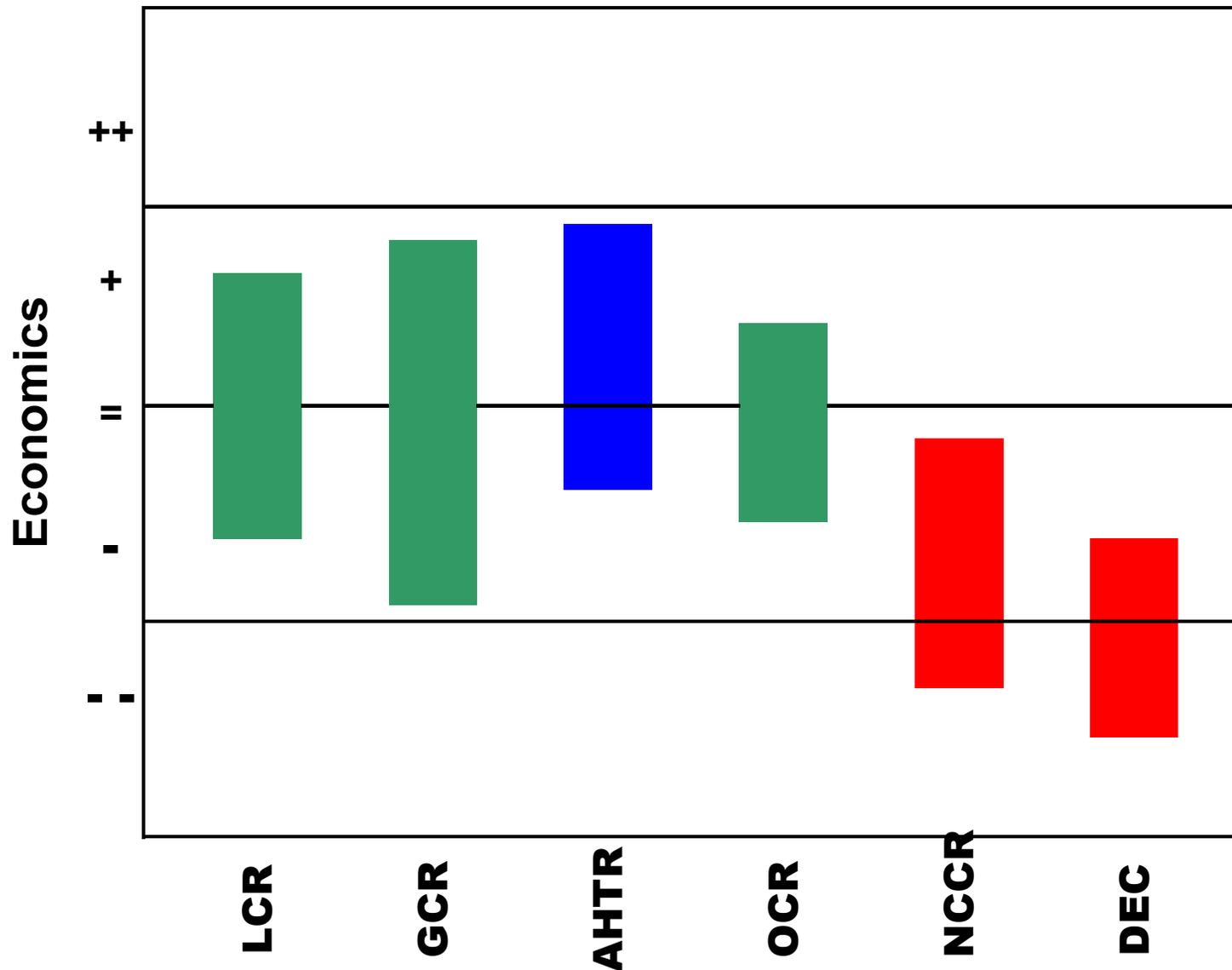
Non-Classical Reactor Systems Performance vs GenIV Sustainability Goals



Non-Classical Reactor Systems Performance vs GenIV Safety and Reliability Goals



Non-Classical Reactor Systems Performance vs GenIV Economic Goals



Summary

1. Despite of many technology gaps and data uncertainties, there is no lack of innovation and revolutionary ideas in Non-Classical reactor concepts.
2. Several concepts such as gas/vapor core reactors meet or exceed Gen IV goals for sustainability, safety, and economy, and have potential for making significant inroads toward achieving the optimum utilization of nuclear energy.
3. Gas/vapor core reactors set the upper performance potential in sustainability and safety with no insurmountable technology challenge.
4. Evaluation of modular deployable concepts are underway.
5. Direct energy conversion and non-convective cooled nuclear reactor systems are eliminated from further evaluation process.