Generation IV Nuclear Energy Systems

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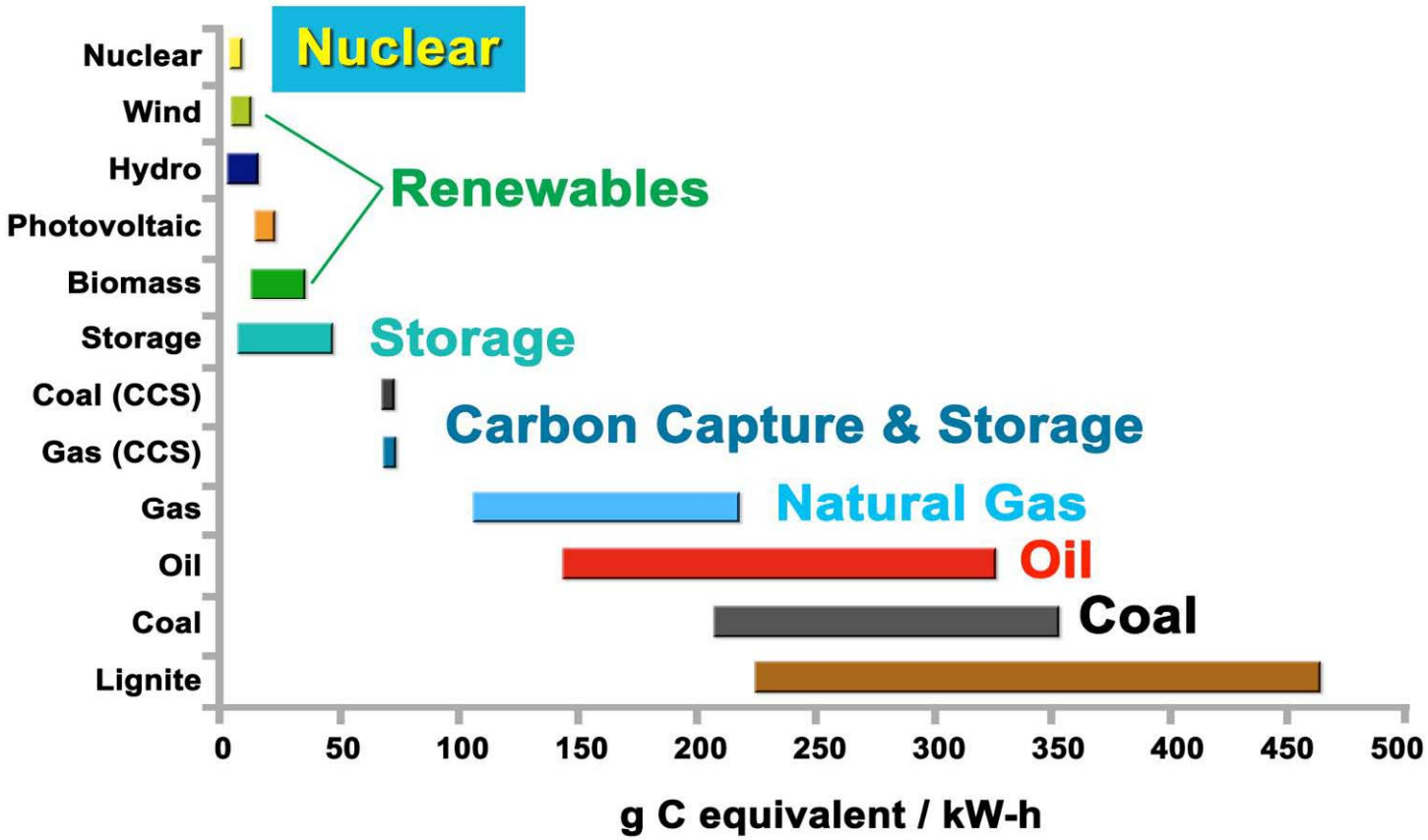
July 2010

Life Cycle Greenhouse Gas Emissions

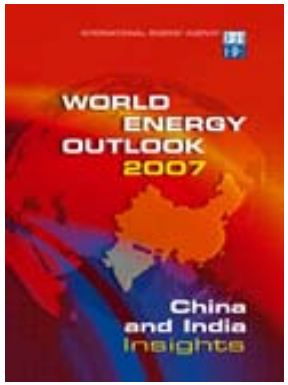


CO_2 emission rates for electricity generating alternatives (storage: batteries, pumped hydro, compressed air storage; CCS Carbon Capture and Storage) (Weisser 2007)

Source: IAEA 2006

Our Vision for Nuclear Energy:

- **Clean—*Delivering a major non-emitting source***
- **Affordable—*Keeping energy costs competitive***
- **Secure—*Providing diversification of supply***



The challenge for all countries is to put in motion a transition to a more secure, lower-carbon energy system, without undermining economic and social development."

World Energy Outlook 2007 (OECD/IEA)

Generations of Nuclear Energy

Generation I

Early Prototypes

- Shippingport
- Dresden
- Magnox

Generation II

Commercial Power

- PWRs
- BWRs
- CANDU

Generation III

Advanced LWRs

- CANDU 6
- System 80+
- AP600

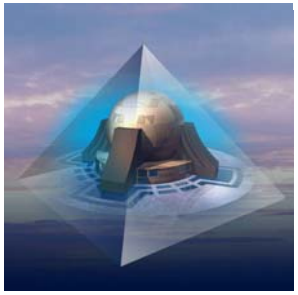
Generation III+

Evolutionary Designs

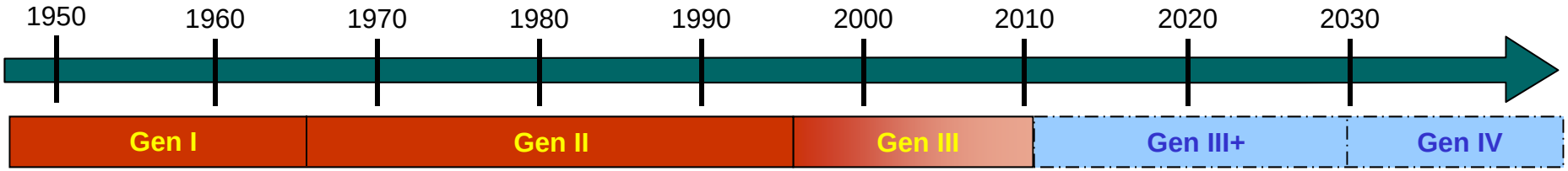
- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

Generation IV

Revolutionary Designs



- Safe
- Sustainable
- Economical
- Proliferation Resistant and Physically Secure



Generation IV Goals

Sustainability

1. Generate energy sustainably, and promote long-term availability of nuclear fuel
2. Minimize nuclear waste and reduce the long term stewardship burden

Safety & Reliability

3. Excel in safety and reliability
4. Have a very low likelihood and degree of reactor core damage
5. Eliminate the need for offsite emergency response

Economics

6. Have a life cycle cost advantage over other energy sources
7. Have a level of financial risk comparable to other energy projects

Proliferation Resistance & Physical Protection

8. Be a very unattractive route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism

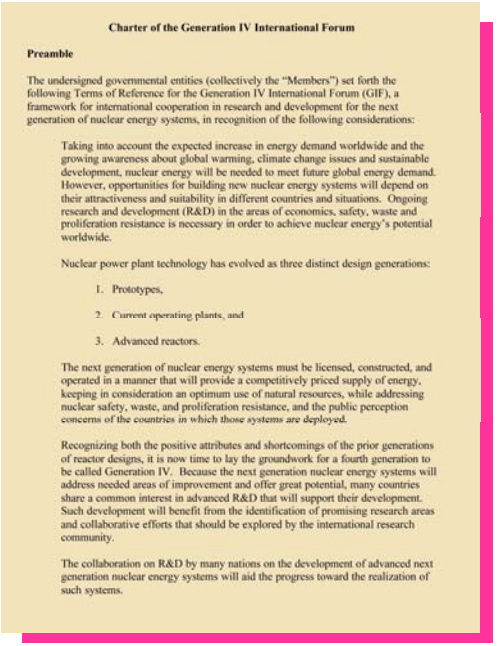
Creation of the International Forum

- **Started in Jan 2000 by nine countries and established Jul 2001**
- **Agreed that nuclear energy is needed to meet future needs**
- **Defined four goal areas to advance nuclear energy into its next, 'fourth' generation:**
  - **Sustainability**
  - **Safety & reliability**
  - **Economics**
  - **Proliferation resistance and physical protection**
- **Will collaborate to make 'Generation IV' systems deployable in large numbers by 2030, or earlier**

Generation IV International Forum

Chartered in July 2001

- **Set out Vision, Goals and Objectives**
- **Nine charter members**
- **Created a virtual organization**
  - **Government leaders in a Policy Group**
  - **Technical advisors in an Experts Group**
- **Makes decisions by consensus**
- **Members bear their own costs, and participate in the systems and R&D that they choose**
- **GIF works with other organizations, especially IAEA and OECD/NEA to draw expertise**
- **Shares information openly where possible**



Charter of the Generation IV International Forum

Preamble

The undersigned governmental entities (collectively the "Members") set forth the following Terms of Reference for the Generation IV International Forum (GIF), a framework for international cooperation in research and development for the next generation of nuclear energy systems, in recognition of the following considerations:

Taking into account the expected increase in energy demand worldwide and the growing awareness about global warming, climate change issues and sustainable development, nuclear energy will be needed to meet future global energy demand. However, opportunities for building new nuclear energy systems will depend on their attractiveness and suitability in different countries and situations. Ongoing research and development (R&D) in the areas of economics, safety, waste and proliferation resistance is necessary in order to achieve nuclear energy's potential worldwide.

Nuclear power plant technology has evolved as three distinct design generations:

1. Prototypes,
2. Current operating plants, and
3. Advanced reactors.

The next generation of nuclear energy systems must be licensed, constructed, and operated in a manner that will provide a competitively priced supply of energy, keeping in consideration an optimum use of natural resources, while addressing nuclear safety, waste, and proliferation resistance, and the public perception concerns of the countries in which those systems are deployed.

Recognizing both the positive attributes and shortcomings of the prior generations of reactor designs, it is now time to lay the groundwork for a fourth generation to be called Generation IV. Because the next generation nuclear energy systems will address needed areas of improvement and offer great potential, many countries share a common interest in advanced R&D that will support their development. Such development will benefit from the identification of promising research areas and collaborative efforts that should be explored by the international research community.

The collaboration on R&D by many nations on the development of advanced next generation nuclear energy systems will aid the progress toward the realization of such systems.

Founding Members now joined by:

- **Switzerland (2002), Euratom (2003), China and Russia (2006)**

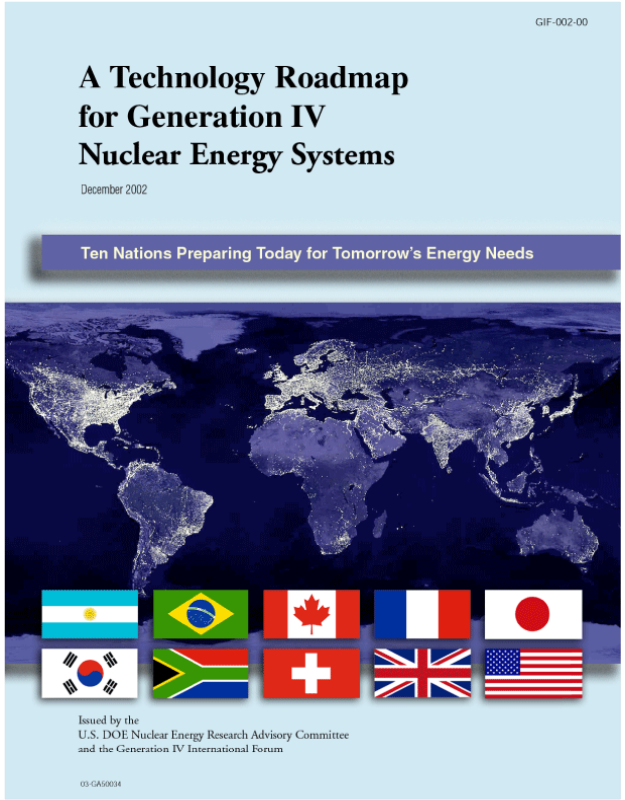
http://www.gen-4.org/PDFs/GIFcharter.pdf

The Technology Roadmap

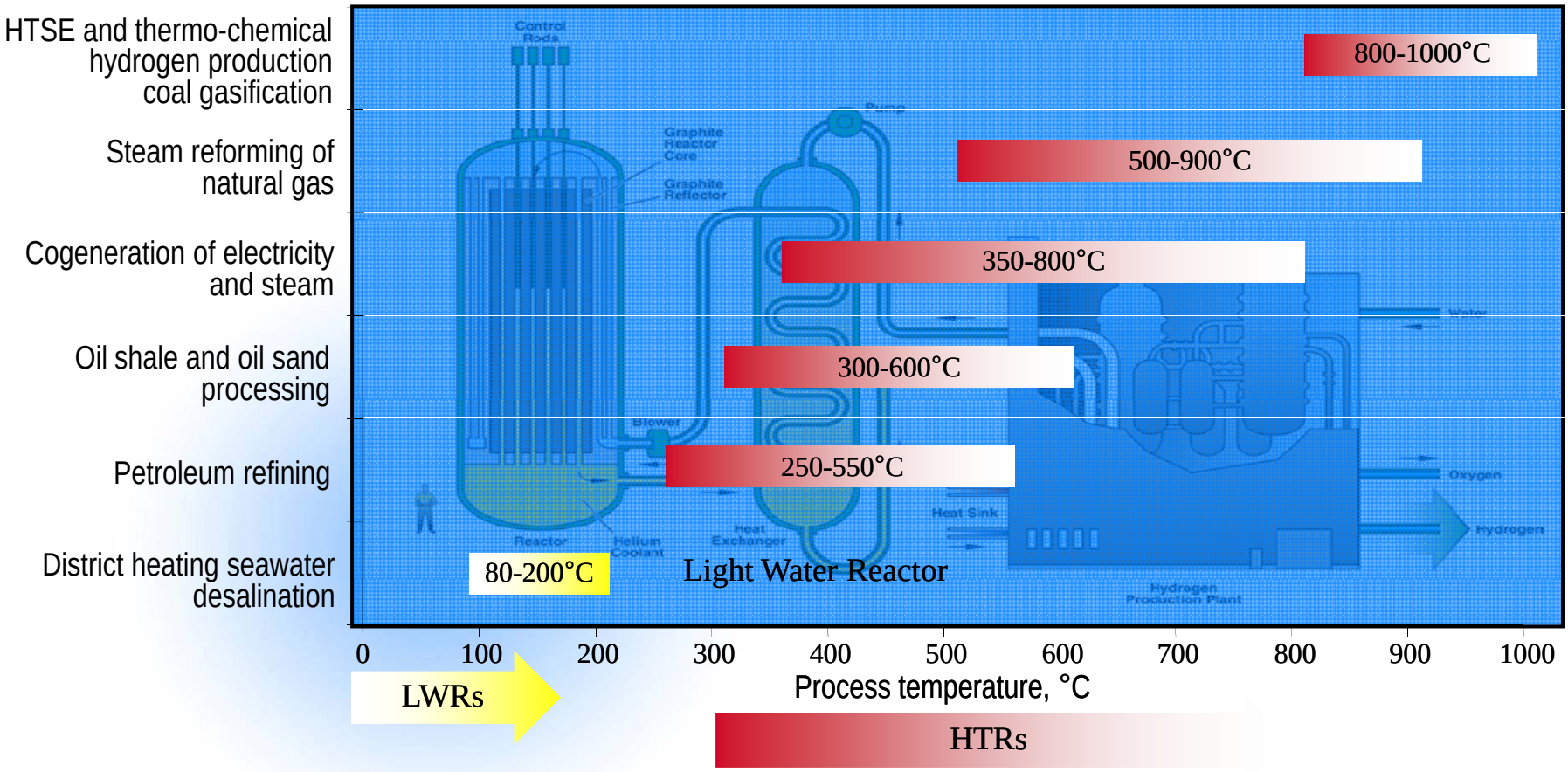
- **Two-year effort by 100 international experts finding the most promising nuclear systems**

- **Six *systems* were selected:**
  - **Sodium-Cooled Fast Reactor (SFR)**
  - **Very-High-Temperature Reactor (VHTR)**
  - **Gas-Cooled Fast Reactor (GFR)**
  - **Supercritical-Water Reactor (SCWR)**
  - **Lead-Cooled Fast Reactor (LFR)**
  - **Molten Salt Reactor (MSR)**

- **Timelines and research needs were developed for the needed technology**



Higher temperature expands the range of applications



Most Gen-IV concepts operate above 500°C

Overview of the Generation IV Systems

System	Neutron Spectrum	Fuel Cycle	Size (MWe)	Missions	R&D Needed
Sodium Cooled Fast Reactor (SFR)	Fast	Closed	300-1500	Electricity, Actinide Management	Advanced recycle options, Fuels
Very-High-Temperature Reactor (VHTR)	Thermal	Open	250	Electricity, Hydrogen, Process Heat	Fuels, Materials, H_2 production
Gas-Cooled Fast Reactor (GFR)	Fast	Closed	1200	Electricity, Hydrogen, Actinide Management	Fuels, Materials, Thermal-hydraulics
Supercritical-Water Reactor (SCWR)	Thermal, Fast	Open, Closed	1500	Electricity	Materials, Thermal-hydraulics
Lead-Cooled Fast Reactor (LFR)	Fast	Closed	50-150 300-600 1200	Electricity, Hydrogen Production	Fuels, Materials
Molten Salt Reactor (MSR)	Epithermal or Fast	Closed	1000	Electricity, Hydrogen Production, Actinide Management	Fuel treatment, Materials, Reliability

http://www.gen-4.org/Technology/systems/index.htm

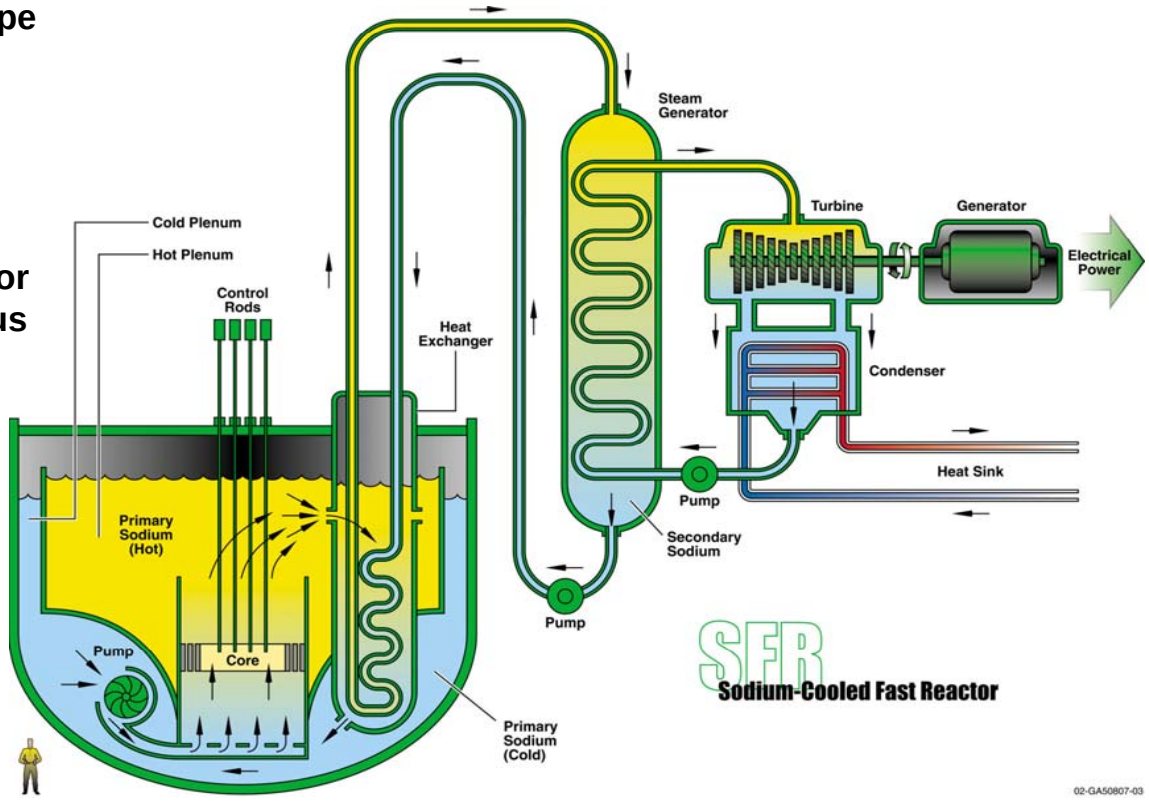
Sodium-Cooled Fast Reactor (SFR)

Characteristics

- **Sodium coolant, pool or loop type**
- **550C outlet temperature**
- **600-1500 MWe large size, or**
- **300-600 MWe intermediate size**
- **50 MWe small module option**
- **Metal fuel with pyroprocessing or MOX fuel with advanced aqueous separation**

Benefits

- **High thermal efficiency**
- **Consumption of LWR actinides**
- **Efficient fissile material generation**



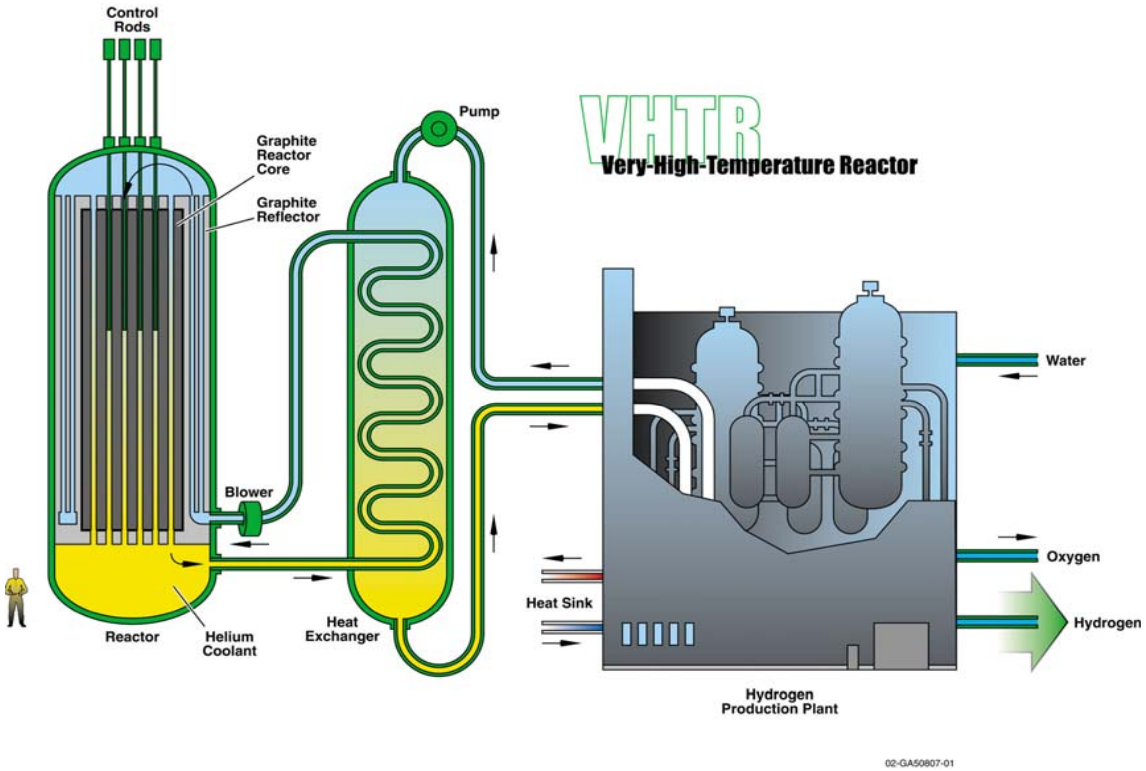
Very-High-Temperature Reactor (VHTR)

Characteristics

- **He coolant**
- **>900C outlet temperature**
- **250 MWe**
- **Coated particle fuel in either pebble bed or prismatic fuel**

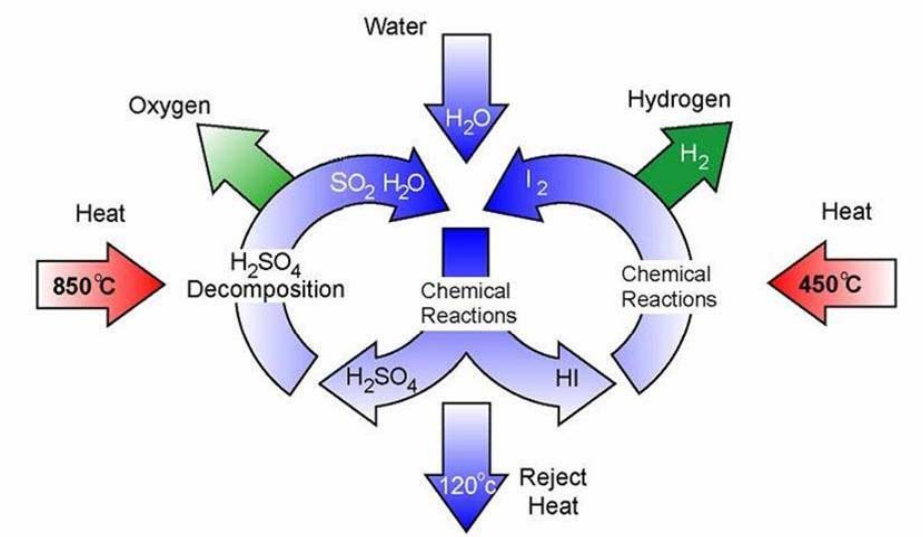
Benefits

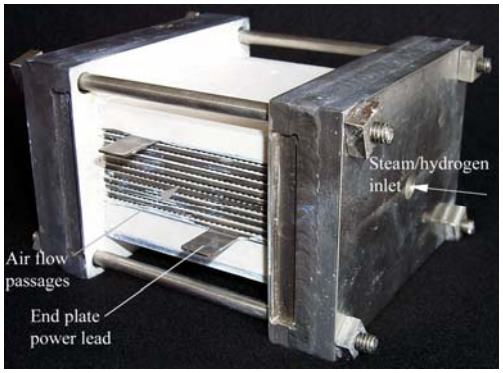
- **Hydrogen production**
- **Process heat applications**
- **High degree of passive safety**
- **High thermal efficiency option**



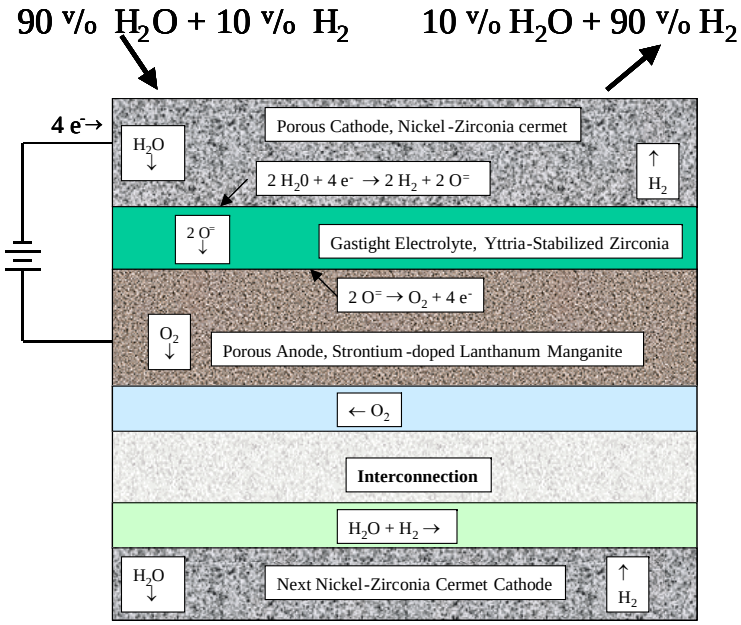
VHTR Hydrogen Options

Sulfur-iodine cycle





High temperature electrolysis



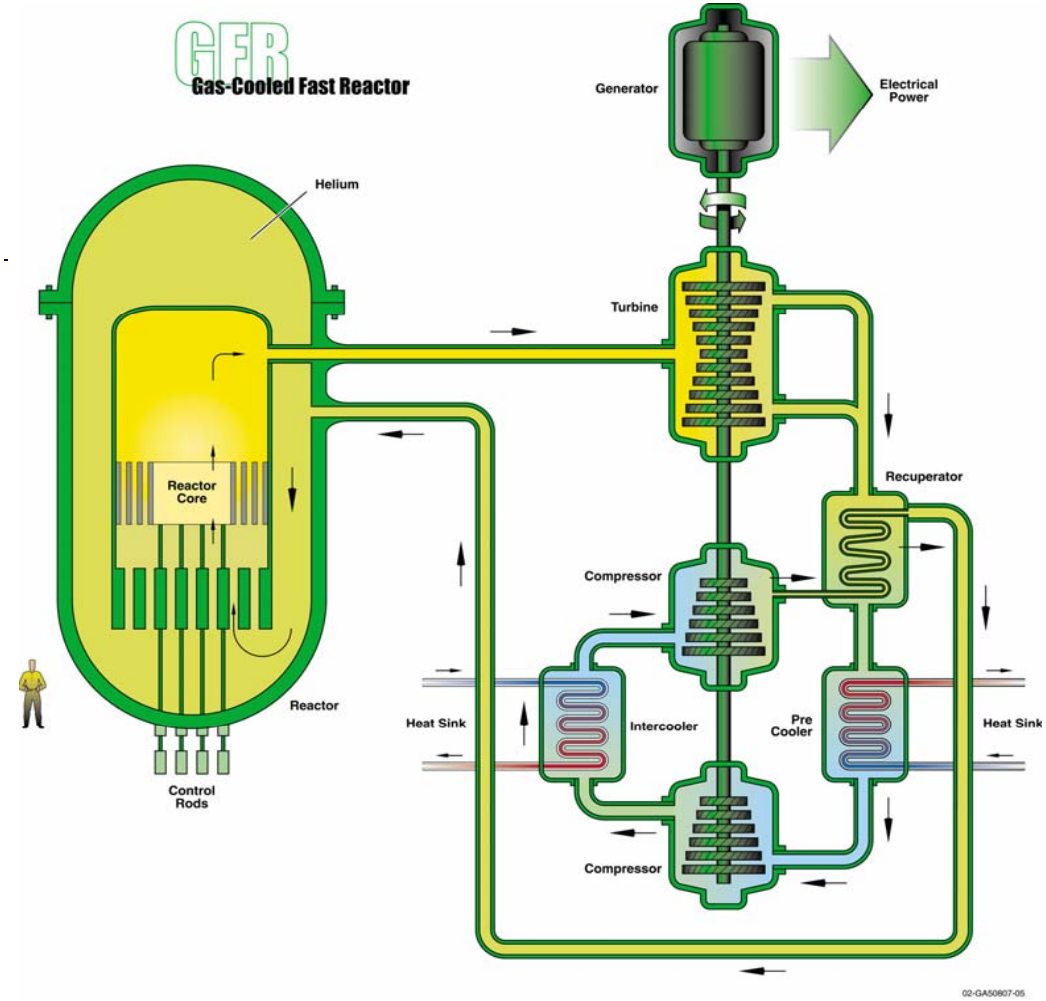
Gas-Cooled Fast Reactor (GFR)

Characteristics

- **He coolant**
- **850C outlet temperature**
- **Direct gas-turbine cycle or supercritical CO2 cycle with optional combined cycles**
- **2400 MWth / 1100 MWe**
- **Several fuel options**
  - **Carbide in plates or pins**
  - **Nitride**
  - **Oxide**

Benefits

- **High efficiency**
- **Waste minimization and efficient use of uranium resources**



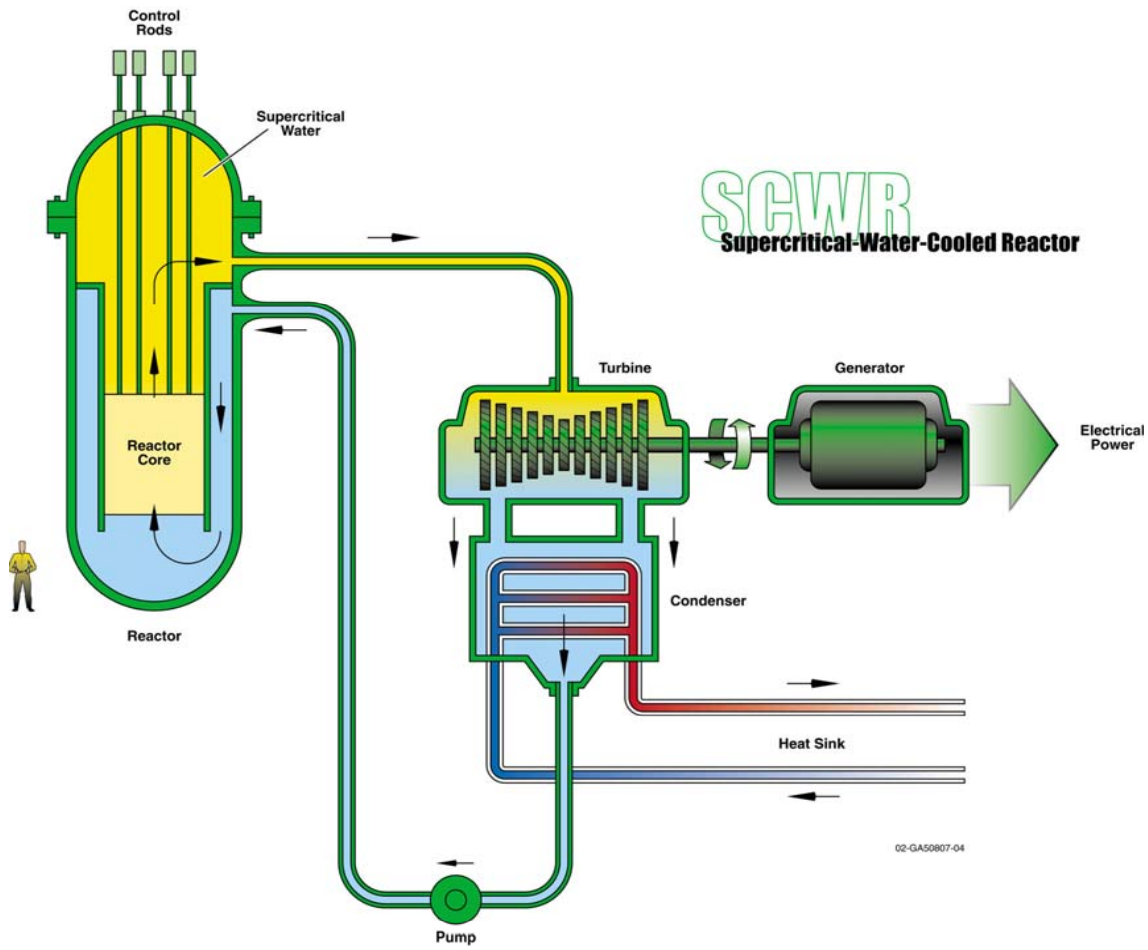
Supercritical-Water-Cooled Reactor (SCWR)

Characteristics

- **Water coolant above supercritical conditions (374C, 22.1 MPa)**
- **510-625C outlet temperature**
- **1500 MWe**
- **Pressure tube or pressure vessel options**
- **Simplified balance of plant**

Benefits

- **Efficiency near 45% with excellent economics**
- **Leverages the current experience in operating fossil-fueled supercritical steam plants**
- **Configurable as a fast- or thermal-spectrum core**



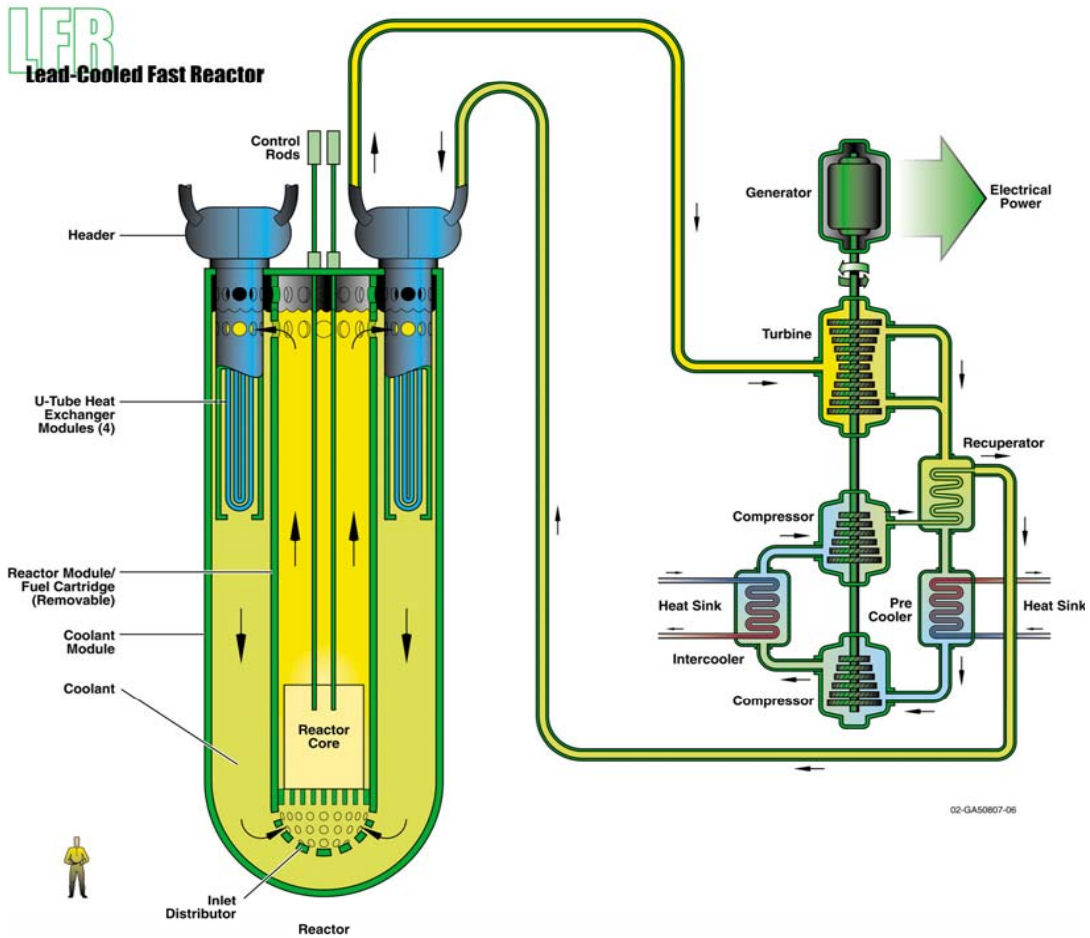
Lead-Cooled Fast Reactor (LFR)

Characteristics

- **Pb or Pb/Bi coolant**
- **550C to 800C outlet temperature**
- **Small transportable system 50-150 MWe, and**
- **Larger station 300-1200 MWe**
- **15–30 year core life option**

Benefits

- **Distributed electricity generation**
- **Hydrogen and potable water**
- **Replaceable core for regional fuel processing**
- **High degree of passive safety**
- **Proliferation resistance through long-life core**



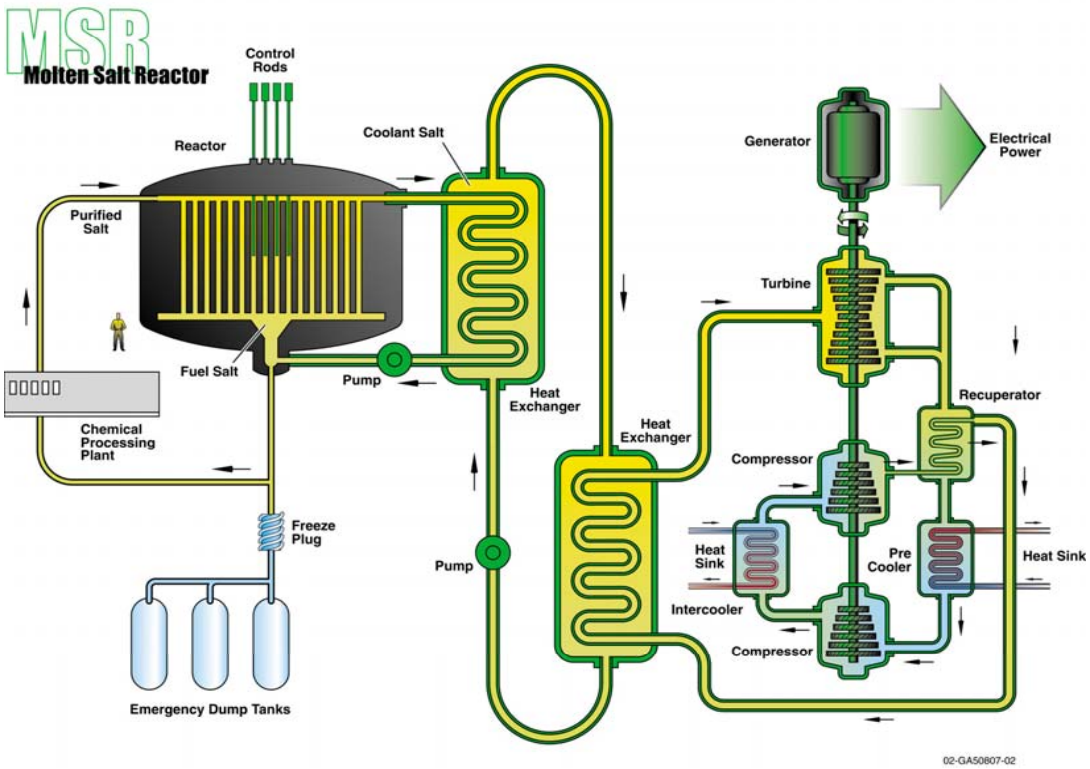
Molten Salt Reactor (MSR)

Characteristics

- **Fuel is liquid fluorides of U or Th with Li, Be, Na and other fluorides**
- **700–800C outlet temperature**
- **1000 MWe**
- **Low pressure (<0.5 MPa)**

Benefits

- **Waste minimization**
- **Avoids fuel development**
- **Proliferation resistance through low fissile material inventory**



Formal Agreements for R&D

GIF Framework Agreement Signing (Feb 2005)

- **GIF Framework Agreement: An agreement among the governments**
  - **For research and development collaborations**
  - **Assigns responsible ministries, departments and agencies**
  - **Affords protection of intellectual property and sharing of rights**
  - **Specifies '*steering committees*' for systems to manage the work, and '*projects*' under the steering committee to do the work**
  - **Supports the creation of 'multilateral R&D contracts' that can attract industry, universities and other countries into the collaborations**

http://www.gen-4.org/GIF/Governance/framework.htm

Participating Nations for Generation IV System Developments

Generation IV Systems	Argentina	Brazil	Canada	France	Japan	Korea	South Africa	Switzerland	U.K.	U.S.A.	EU	China	Russia
Sodium-cooled Fast Reactor (SFR)				○	◎	○				○	○	○	(○)
Very-high Temperature Gas-cooled Reactor (VHTR)			○	○	○	○	(○)	○		○	◎	○	
Gas-cooled Fast Reactor (GFR)				◎	○			○			○		
Supercritical-water cooled Reactor (SCWR)			○		○						◎		
Lead-cooled Fast Reactor (LFR)					○					○	○		
Molten Salt Reactor (MSR)				○						○	○		

Note ○ : Participating Nations, ◎ : Co-chair country, ( ) : Observer

Senior Industry Advisory Panel

- **Senior industry representatives from GIF Member countries**
- **Meets at least annually with Policy Group**
- **Subject areas include but not limited to:**
  - **R&D strategy & priorities**
  - **System technology needs**
  - **System deployment**
  - **Economics**
  - **International regulatory issues**
  - **Industrial infrastructure**
- **Provides interface to industrial organizations interested in R&D**

Research Plans and Activities

- System Steering Committees each create a System Research Plan
- Four systems have finalized plans
  - SFR, SCWR, VHTR and GFR
- LFR is under development
- MSR is planned in the future
- Each creates several projects
  - Project participants make binding commitments for the scope, schedule and resources for their contribution
  - Universities, industry and even countries outside the GIF may participate, with the approval of the Steering Committee

Economics MWG

- **Methodology Working Group (MWG)**
- **Created evaluation methods for the Roadmap**
- **Develops methods for system assessment**
- **Specific Accomplishments:**
  - **Cost Estimating Guidelines (Rev 4.2, Sep 2007)**
    - » **Levelized unit energy cost**
    - » **Capital-at-risk**
  - **G4ECONS Software (v2.0, EXCEL-based tool)**
  - **Simple, Universal and Transparent Cost Modules**
    - » **Reactor Cost**
    - » **Nuclear Heat Applications**
    - » **Fuel Cycle Facilities**

- **Representatives: economic specialists that are nominated by Member countries for indefinite terms**

PRPP MWG

- **Proliferation Resistance and Physical Protection (PRPP) MWG**
- **Created evaluation Measures for the Roadmap**
- **Develops assessment methods for systems/subsystems**
  - **Threats → System Response → Outcomes**
  - **System Response**
    - » **Pathways analysis**
    - » **Segmentation, decomposition and re-aggregation**
- **Specific Accomplishments:**
  - **PRPP Evaluation Methodology Report**
  - **Example SFR (ESFR) Assessment Report (in process)**

- **Representatives: nonproliferation and security specialists that are nominated by Member countries for indefinite terms**

Risk and Safety MWG

- **The youngest MWG; created after the Roadmap**
- **Develops assessment methods for systems**
  - **Phenomena identification and Ranking (PIRT)**
  - **Objective provision tree (OPT)**
  - **Probabilistic safety assessment (PRA)**
  - **Deterministic analysis**
- **Specific Accomplishments:**
  - **Basis for the Safety Approach for Design and Assessment of Generation IV Nuclear Systems**
  - **Active in NUREG-1860 and IAEA TECDOC-1570**

- **Representatives: nuclear plant risk and safety specialists that are nominated by Member countries for indefinite terms**

RSWG Workscope - Highlights

- **Promote a homogeneous approach to safety in design**
- **Define the framework for safety evaluation methodology**
- **Identify and encourage advanced safety assessment methodologies**
- **Consider defense in depth and safety standards to be adopted for all Generation IV systems**
- **Cooperate and coordinate with IAEA work on safety standards and associated safety initiatives**
- **Interact with PRPP Working Group to assure mutual understanding of safety priorities and their implementation in PRPP and RSWG evaluation methodologies**

May 2008 Report - Major Recommendations

- **Current nuclear systems are already very safe. Opportunities exist to achieve an even greater level of safety. "Safety is built-in, not added-on."**
- **Potential safety improvements must be simultaneously based on several considerations. Among these are:**
  - **The notion of "optimal risk reduction"**
  - **The adoption of ambitious safety objectives**
  - **Development and integration of innovative technologies to achieve improved system reliability and safety**
  - **Emphasis on prevention, backed up by mitigation**
  - **Demonstrated "robustness" relative to a broad range of challenges**

Recommendations - continued

- **An updated safety approach is needed for Generation IV systems**
  - **Consistent with current and future regulation**
  - **Demonstrate full implementation of defense in depth**
  - **Based on a technology-neutral framework**
  - **Combine deterministic and probabilistic perspectives**
  - **Address uncertainties, in part, through demonstration**
- **The principle of defense in depth is a keystone of nuclear safety and should be fully implemented in Generation IV systems.**

Recommendations – Continued

- **Generation IV system designs should be "driven by a risk-informed approach"**
- **While demonstration and prototyping are an important part of establishing Generation IV safety bases, modeling and simulation should play a large role in design and evaluation**
- **Generation IV design bases must address a full range of safety significant conditions**
  - **"Spectrum of design basis accidents"**
  - **Demonstration of "practical elimination" and low "residual risk"**

Achieving Extremely High System Reliability

- **Explicit consideration of all aspects of defense in depth**
- **Advanced instrumentation and control for improved process control, on-line condition monitoring, system prognostics, and better informed test and maintenance**
- **Increased use of passive systems, as appropriate, and other "naturally safe" design provisions such as improved materials, gravity, convection, conduction, negative reactivity feedback, thermal inertia, and similar features**
- **Reduced reliance on human interventions, and increased tolerance for human errors**
- **Reducing uncertainties through both analytical and empirical demonstration, and provision of safety margins where uncertainties remain**

Generation IV Annual Report

- **Captures key information and accomplishments from System Steering Committee annual reports into one widely distributed report**

- **Captures brief summaries of working groups' accomplishments, and background on the Forum**

- **Audience includes:**
  - **World-wide Research and Development Community**
  - **Governments sponsoring Generation IV R&D**
  - **GIF committees, boards and working groups**

- **The 2009 Report should be available any day**

Working Toward the Future

The GIF joined together to help assure a sustainable energy future

- **Underscored by the advance of global climate change**
- **Based on advanced nuclear energy systems that are sustainable, safe, economical, proliferation resistant and physically secure**
- **Accelerated by the collaboration of the GIF members, industry, academia and non-member nations and institutions**

GEN IV International Forum