Stanje razvoja projekta IRIS reaktora i
komparativne prednosti modularnih reaktora

Bojan Petrovic
Nuclear & Radiological Engineering / Medical Physics
G.W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology, Atlanta, GA

FER – Zagreb, Hrvatska
20.03.2008.

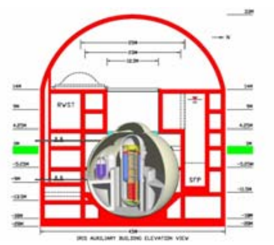
Outline

- Osnovni sadržaj predavanja je o trenutnom stanju razvoja IRIS reaktora, uz poseban osvrt na očekivanu ulogu reaktora manje i srednje snage u suvremenim energetskim sustavima. Također će biti prikazane komparativne prednosti modularnih reaktora manje snage pred jedinicama velike snage, kao i analiza njihove ekonomičnosti temeljene, ne na veličini nego, na standardiziranoj izgradnji odgovarajućeg broja manjih jedinica.
  Predavanje će završiti kratkim osvrtom na trenutno stanje nuklearne energetike u SAD.

IRIS Project Overview

IRIS – International Reactor Innovative and Secure

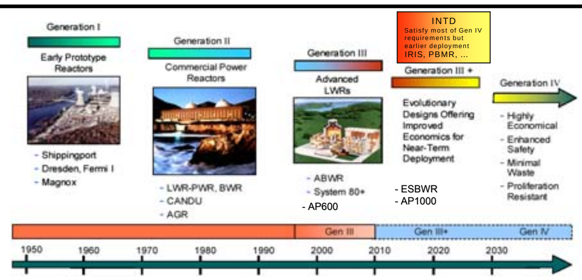
- Advanced integral light water reactor
- 335 MWe/module
- Innovative, simple design
- Enhanced Safety-by-Design™
- International team
- Recognized by Global Nuclear Energy Partnership (GNEP) as Grid Appropriate Reactor
- Anticipated competitive economics
- Cogeneration (desalination, district heating, bio-fuel)
- NRC pre-application underway
- Design Certification testing program underway
- Interest expressed by several countries
- Projected deployment target: 2015 to 2017



Background

- IRIS project started as a U.S. DOE – Nuclear Energy Research Initiative (NERI) program in 1999
- IRIS designed such to fulfill Gen IV objectives (safety, economics, proliferation resistance, waste management) using proven technology, with deployment ~ 2015-2017
- Nuclear renaissance and developing countries needs resulted in near term commercial interest in IRIS
- DOE launched GNEP (Global Nuclear Energy Partnership) including a "grid appropriate" small reactor program targeted for next decade. IRIS is the DOE chosen example.

How IRIS Fits in the Overall Picture?



- <u>To bridge the gap to Gen-IV:</u>
  An advanced design, essentially satisfying Gen-IV key requirements (safety, economics, sustainability, waste management), but available sooner (~2015) rather than after 2030 (Gen-IV reactors)
- <u>To address needs of smaller grids/markets:</u>
  For smaller grids of several GWe, it is technically not feasible to incorporate plants larger than several hundred MWe. Additionally, cannot support financing burden for large plants.

Project Achievements (Top Level)

- Established team, biannual meetings (19th in May 2008)
- NSSS preliminary design completed
- Pre-licensing / interaction with NRC since 2002
- “PSAR” reviewed by NRC
- Testing program reviewed by NRC
- Integral testing facility design completed
- Preliminary site layout (single/multiple units) prepared
- Top-down cost estimate performed
- Economics of SMRs examined to ensure competitiveness
- Preliminary market assessment performed
- Business case prepared
- Targeting deployment in 2015-2017 range

IRIS Development Schedule Targets

• Program started	1999
• Assessed key technical & economic feasibility	2000
• Performed conceptual design, preliminary cost estimate	2001
• Started pre-application licensing for Design Certification	2002
• Completed NSSS preliminary design	2005
• Initiated testing necessary for NRC Design Certification	2006
• Complete testing	2011
• Submit application for NRC Design Certification	2011-2012
• Obtain Final Design Approval from NRC	2014
• First module deployment	2015-2017

The IRIS Team

- 9 Countries
  - Brazil
  - Croatia
  - Italy
  - Japan
  - Lithuania
  - Mexico
  - Spain
  - United Kingdom
  - United States
- 18 Organizations
  - Industry
  - Power Producers
  - Laboratories
  - Universities

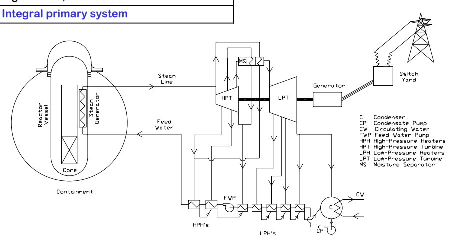
The IRIS Team (Cont’d)

INDUSTRY		
Westinghouse	USA	Overall coordination and commercialization; leading core design, safety analyses and licensing
Ansaldo Energia	Italy	Steam generators design
Ansaldo Camozzi	Italy	Steam generators fabrication
ENSA	Spain	Pressure vessel and internals
NUCLEP	Brazil	Containment
Rolls Royce (pending)	UK	Control rods drive mechanisms
LABORATORIES		
ORNL	USA	Instrumentation and Control, PRA, desalination, shielding, pressurizer
CNEN	Brazil	Transient and safety analyses, pressurizer, desalination
ININ	Mexico	PRA, neutronics support
LEI	Lithuania	PRA, district heating co-generation
ENEA	Italy	Testing, seismic, shielding
UNIVERSITIES		
Polytechnic of Milan (CIRTEN)	Italy	Safety analyses, shielding, thermal hydraulics, economics, bio-fuel generation
MIT	USA	Advanced cores, maintenance
Tokyo Institute of Technology	Japan	Advanced cores, PRA
University of Zagreb	Croatia	Neutronics, safety analyses
University of Pisa (CIRTEN)	Italy	Containment analyses, severe accident analyses, neutronics, thermalhydraulics
Polytechnic of Turin (CIRTEN)	Italy	Source term, thermalhydraulics
Georgia Institute of Technology (pending)	USA	SUNRISE, shielding
POWER PRODUCERS		
Eletronuclear	Brazil	Developing country utility perspective

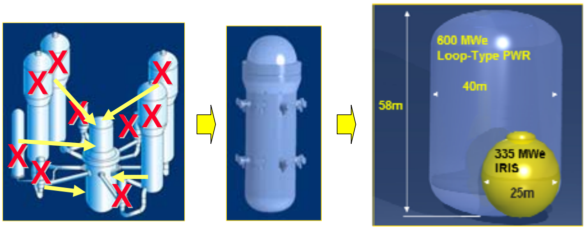
IRIS Design

IRIS-Based Power Plant Schematic

Plant Data (single unit)	
Core thermal power	**1000 MWt**
Power plant output, net	**335 MWe**
Mode of operation	**Base load operation standard Enhanced load follow mode with MSHIM**
Load factor Availability factor	**Target >96% over the plant lifetime Target >98%**
Plant design lifetime	**>60 years (reactor vessel and structures)**
Coolant and moderator	**Light water, subcooled**
Number of coolant loops	**Integral primary system**



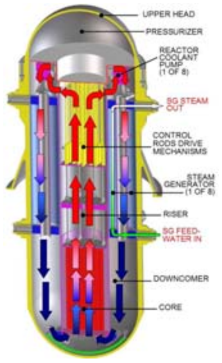
Integral Primary System Reactor



- Simplifies design by eliminating loop piping and external components.
- Enhances safety by eliminating major classes of accidents.
- Compact containment (small footprint) enhances economics and security.

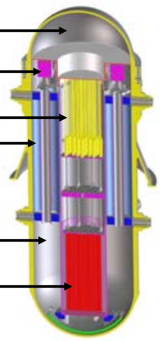
IRIS Design Features
Integral Vessel

- 335 MWe PWR
- Long Life core: up to 4 years without refueling
- 8 helical-coil steam generators
- 8 axial flow fully immersed primary coolant pumps
- Internal control rod drive mechanisms
- Integral pressurizer with large volume-to-power ratio

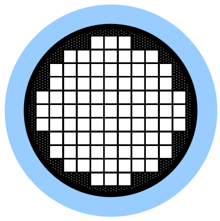


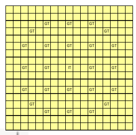
Integral Components Offer Simpler Design and Improved Performance

Pressurizer	Much larger volume/power ratio gives much better pressure transients control. No sprays.
Primary coolant pumps	Axial, fully immersed. No seal leaks. No shaft breaks. No maintenance.
Internal CRDMs	No RV head penetrations, no seal failures.
Steam generators	Tubes in compression. Tensile stress corrosion cracking eliminated (responsible for over 70% reported failures).
1.7m thick downcomer	Vessel fast flux 10^5 times lower. Cold vessel. Almost no outside dose. Minimal embrittlement, no surveillance. Simpler decommissioning.
Fuel Assembly	Almost the same standard W PWR, but can have extended cycle up to 48 months.



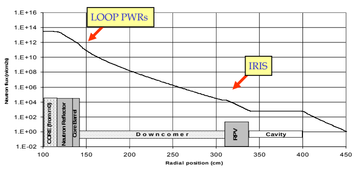
Core and Fuel Assembly





- 89 assemblies, 1,000 MWt
- 17x17 fuel assembly
- UO_2 fuel
- Standard fuel rod size/OD
- Incorporates standard W design features
- Enhanced moderation option
- Enrichment <5%
  Burnup <62 GWd/tU
- Long plenum eliminates potential rod internal pressure issues, enables future core upgrades and increased discharge burnup

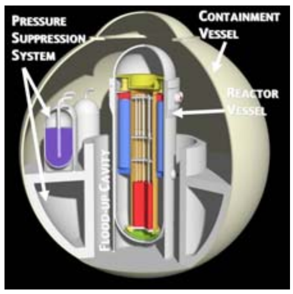
IRIS Integral Layout Minimizes Pressure Vessel Embrittlement



- Fast neutron fluence to RV drastically reduced
- Practically no embrittlement
- RV surveillance program not needed (O&M cost reduction)
- Strongly reduced activation
- "Cold" outer RV surface
- Reduced dose in maintenance
- Reduced dose/simpler ultimate decommissioning
- Vessel could act as sarcophagus for ultimate disposal

Innovative Containment Design
Coupled to Integral Vessel Design

- Spherical steel 25 meter diameter
- Design pressure 220 psig
- Small elevated suppression pool limits peak pressure to 130 psig and is available to provide gravity driven core makeup during LOCA as necessary
- Self limiting LOCA by equalization of pressure across the break
- External cooling of steel shell rejects heat to atmosphere (redundant to the Emergency Heat Removal System)



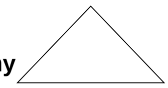
Reduced O&M Cost in IRIS

- Less refueling outages (up to 4 years without refueling)
- Less maintenance outages (up to 4 years without outage)
- Higher capacity factors
- Less personnel
- “Cold” vessel
- No vessel upper head problems (no CRDM penetrations)
- No vessel lower head problems (no instrumentation penetrations)

Safety

IRIS Approach

Simplicity

Economy  **Safety**

- Simplicity enables safety and economy
- IRIS uses proven light water technology
- Implements engineering innovations, new solutions, but does not require new technology development

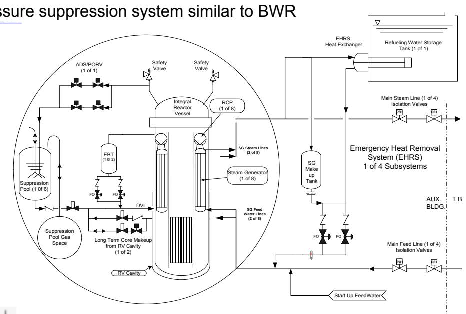
IRIS Enhanced (Three-Tier) Safety

1. **Safety-by-Design™**
   Aims at eliminating by design possibility for accidents to occur. Eliminates systems/components that were needed to deal with those accidents.
2. **Passive Safety Systems**
   Protect against still remaining accidents and mitigate their consequences. Fewer and simpler than in passive LWRs.
3. **Active Systems**
   No active safety-grade systems are required. But, active non-safety-grade systems contribute to reducing CDF (core damage frequency).

IMPROVED SAFETY WITH SIMPLIFIED DESIGN

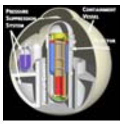
Passive Safety Systems (Second Tier)

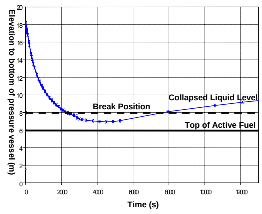
- IRIS safety systems are similar to AP600/AP1000, but simplified and fewer in number
- Pressure suppression system similar to BWR



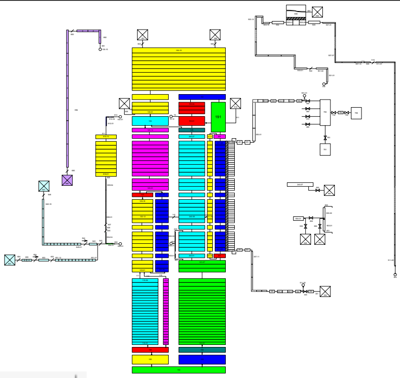
IRIS Response to Small Break LOCA

- No large break LOCA.
- Reactor vessel and containment become thermodynamically coupled in small break LOCA.
- Reactor vessel depressurized by heat removal.
- Pressure allowed to rise in high design pressure containment.
- Pressure differential across the break equalizes quickly.
- Long term response depends on containment heat removal.
- Core remains covered by water without external injection.





IRIS RELAP SB-LOCA Model



RELAP nodalization/model (FER, University of Zagreb)

•Performed IRIS SB LOCA analyses

IRIS – Implementation of Safety-by-Design™

IRIS Design Characteristic	Safety Implication	Accidents Affected	Condition IV Design Basis Events	Effect on Condition IV Event by IRIS Safety-by-Design
Integral layout	• No large primary piping	• Large break LOCAs	Large break LOCA	Eliminated
Large, tall vessel	• Increased water inventory • Increased natural circulation	• Other LOCAs • Decrease in heat removal various events		
	• Accommodates internal Control Rod Drive Mechanisms	• Control Rod ejection • Head penetrations failure	Spectrum of Control Rod ejection accidents	Eliminated
Heat removal from inside the vessel	• Depressurizes primary system by condensation and not by loss of mass	• Other LOCAs		
	• Effective heat removal by Steam Generator and Emergency Heat Removal system	• Other LOCAs • All events requiring effective cooldown • Anticipated Transient Without Scram (ATWS)		
Reduced size, higher design pressure containment	• Reduced driving force through primary opening	• Other LOCAs		
Multiple, integral, shaftless coolant pumps	• No shaft	• Shaft seizure/break	Reactor coolant pump shaft break	Eliminated
	• Decreased importance of single pump failure	• Locked rotor	Reactor coolant pump seizure	Downgraded
High design-pressure steam generator system	• No Steam Generator safety valves • Primary system cannot over-pressure secondary system • Feed/Steam System Piping designed for full Reactor Coolant System pressure reduces piping failure probability	• Steam generator tube rupture	Steam generator tube rupture	Downgraded
		• Steam line break • Feed line break	Steam system piping failure	Downgraded
Once through steam generators	• Limited water inventory	• Feed line break • Steam line break	Feedwater system pipe break	Downgraded
Integral pressurizer	• Large pressurizer volume/reactor power	• Overheating events, including feed line break • ATWS		
			Fuel handling accidents	Unaffected

Safety-by-Design™– The Bottom Line

Criterion	Typical Advanced LWRs	IRIS
Defense-in-Depth (DID)	Redundant and/or diverse active systems; Passive Systems	No active safety-grade systems Safety-by-Design™ with fewer passive safety systems
Class IV Design Basis Events	8 typically considered	Only 1 remains Class IV (fuel handling accident)
Core Damage Frequency (CDF)	$\sim 10^{-5}$—10^{-7} events per year	$\sim 10^{-8}$ events per year
Large Early Release Frequency (LERF)	$\sim 10^{-6}$—10^{-8} events per year	$\sim 10^{-9}$ events per year

Provides basis for enhanced licensing, such as reducing (or eliminating) the emergency response requirements.

Increased Reliability and Economics

- IRIS eliminates most of the accidents which are very improbable and their related safety systems

  Thus:
  - Increased reliability
  - Enhanced safety
  - Reduced cost

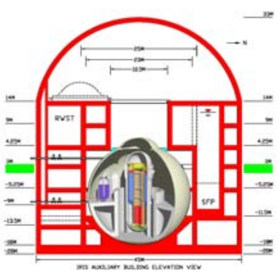
- Reliability-by-Design follows from Safety-by-Design™

Security-By-Design follows Safety-By-Design

- Aircraft crash (as in 9/11)
  - Circular nuclear island building
  - Low profile
  - Most containment below grade
  - Spent fuel pit underground
- Inside sabotage
  - Very few and passive safety systems
  - Key safety system (EHRS) has redundancy in numbers and locations
- 45m footprint

  allows economic use of isolators,

  eliminating seismic impact



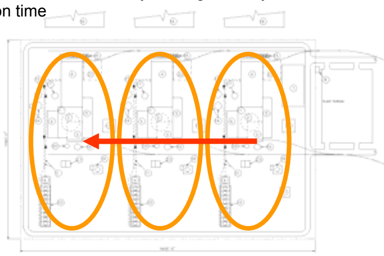
Site Layout

IRIS Plant Layout

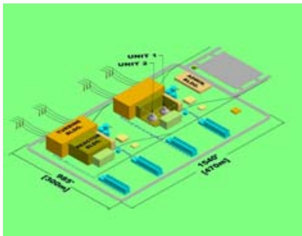
- Developed in response to US utilities as part of the Early Site Permit Program
- Basic configurations:
  - Single module (335 MWe)
  - Twin units (670 MWe)
  - Offered individually or in multiples
- For utilities requiring at least 1000 MWe, IRIS offers three single modules or two twin units
- For better growth match (and spin reserve), smaller power increments from multiple units will be more practical

IRIS - Multiple Single Unit Site Plot Plan

- Shared structures and systems are minimized
- Units constructed in “slide-along” manner with first unit(s) put into operation while subsequent unit(s) under construction
- Compact footprint (330m-by-480m site for 3 modules, 1005 MWe)
- Minimizes construction time and provides generating capability ASAP
- Maximizes workforce efficiency and significantly shortens 2nd and 3rd unit construction time



IRIS – Site Plot Arrangement Example



Multiple twin-units
(2 twin-units, 1340 MWe)

Economics of smaller modular reactors

Market Needs in Nuclear Renaissance

- Growing market; different market segments have different needs
- Market segments include large developed markets as well as smaller/emerging economies
- Large and small electrical grids
- “Traditional” and novel applications (e.g., high temperature, co-gen)
- Deployment considered now and in the next decade
- **Market is interested in larger and smaller units**
- **“One size/type-reactor fits all” approach – cannot satisfy market needs**
- **PWR and BWR, large and smaller reactors, are needed to adequately address diverse needs**

Why Small/Medium Reactors (SMRs)?

- Technical limitation – Grid size
  Rule of thumb:
  The largest power plant shouldn’t be larger than ~10% of the grid capacity Many developing countries have grids not larger than several thousands MWe, thus requiring smaller reactors of several hundreds MWe.
- Financial limitation – Investment capital needed and at risk
  Several billions dollar may be needed for a large plant
  Compared to hundreds of millions for a smaller plant
  The absolute number frequently of primary concern
- Large power plants may not be a viable solution for countries/markets with limited grid or financial resources

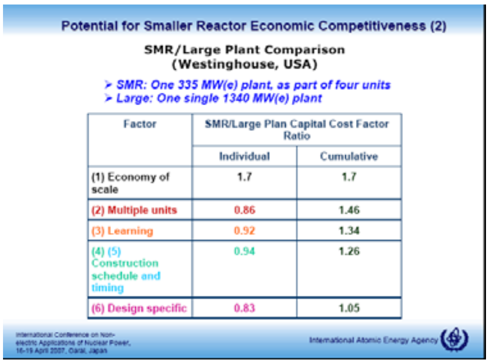
Economics of IRIS and Modular Design

- Conclusions derived from traditional economy of scale axiom favoring large units no longer apply to diverse design, modular plants like IRIS
- IRIS is cost competitive with much larger units because of:
  1. More efficient, simpler, safer design
     » Power per volume comparable or better than large reactors
     – Eliminated: large loop piping and supports; dedicated pressurizer; separate vessels for steam generators and pumps; all active safety systems; high pressure injection emergency core cooling system; pressurizer sprays
     – Significantly reduced: number of passive safety systems (also simplified); number of valves; size of containment/ reactor building

Economics of IRIS and Modular Design (cont.)

2. More Multiple modules deployment
   » Multiple units savings
   » Serial components fabrication
   » Accelerated learning
   » Shorter construction schedule
   » Modules deployment tailored to demand (does not depress the market price with over capacity)
   » Reduced cash outflow

SMR Potential for Competitiveness (source: IAEA)



Potential for Smaller Reactor Economic Competitiveness (2)

SMR/Large Plant Comparison (Westinghouse, USA)

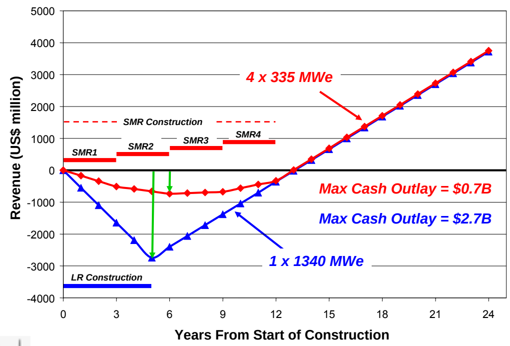
- *SMR: One 335 MW(e) plant, as part of four units*
- *Large: One single 1340 MW(e) plant*

Factor	SMR/Large Plan Capital Cost Factor Ratio	
	Individual	Cumulative
(1) Economy of scale	1.7	1.7
(2) Multiple units	0.86	1.46
(3) Learning	0.92	1.34
(4) (5) Construction schedule and timing	0.94	1.26
(6) Design specific	0.83	1.05

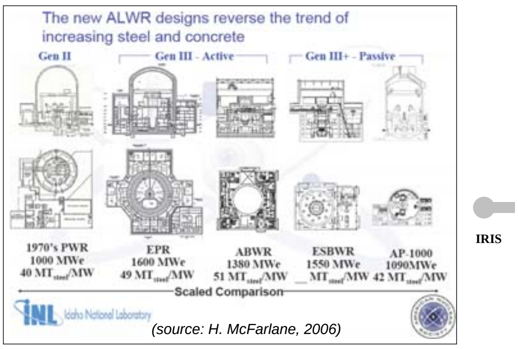
International Conference on Non-electric Applications of Nuclear Power, 16-19 April 2007, Oarai, Japan

International Atomic Energy Agency

Staggered Build Reduces Maximum Cash Outflow and Capital at Risk (Illustrative Example)



Design trends



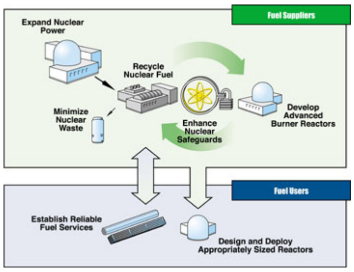
(source: H. McFarlane, 2006)

Attractive Economics/Features of Modular SMRs

- Competitive cost of electricity ($/MWh)
- Reduced cash outflow
- Reduced capital at risk
- Matches energy growth needs
- Enhances energy supply security

GNEP

U.S. DOE Global Nuclear Energy Partnership (GNEP)

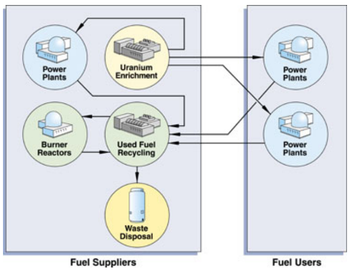


- **Global Nuclear Energy Partnership (GNEP)** seeks to develop worldwide consensus on enabling expanded use of economical, carbon-free nuclear energy to meet growing electricity demand. This will use a nuclear fuel cycle that enhances energy security, while promoting non-proliferation. It would achieve its goal by having nations with secure, advanced nuclear capabilities provide fuel services — fresh fuel and recovery of used fuel — to other nations who agree to employ nuclear energy for power generation purposes only. The closed fuel cycle model envisioned by this partnership requires development and deployment of technologies that enable recycling and consumption of long-lived radioactive waste.
- The Partnership would demonstrate the critical technologies needed to change the way used nuclear fuel is managed – to build recycling technologies that enhance energy security in a safe and environmentally responsible manner, while simultaneously promoting non-proliferation.

- Objective to limit spread of reprocessing/enrichment technology
- "Fuel suppliers" and "Fuel users"
- Fuel take back?
- Major change in U.S. policy

(http://www.nuclear.gov)

U.S. DOE Global Nuclear Energy Partnership (GNEP)



- **Reliable Fuel Services**
- Under the Global Nuclear Energy Partnership (GNEP), a consortium of nations with advanced nuclear technologies would provide fuel and reactors sized to meet the grid and industry needs of other countries. By participating in GNEP, growing economies can enjoy the benefits of clean, safe nuclear power while minimizing proliferation concerns and eliminating the need to invest in the complete fuel cycle (e.g., reprocessing and enrichment). In cooperation with the International Atomic Energy Agency, participating nations would develop international agreements to ensure reliable access to nuclear fuel.

(http://www.nuclear.gov)

IRIS in U.S. DOE GNEP

GNEP – Global Nuclear Energy partnership

Key implementing elements:

- Nuclear Power Expansion
- Reliable Fuel Services
- **Grid-Appropriate Reactors** (formerly "smaller reactors")
- Nuclear Safeguards

(From D. T. Ingersoll and W. P. Poore III), "Reactor Technology Options Study for Near Term Deployment of GNEP Grid-Appropriate Reactors", ORNL/TM-2007/157, Sept. 26, 2007

Table 2 – Maturity Indicators for Primary Reactor Types

Maturity Parameter	Coolant				
	Water	Gas	Sodium	Lead	Salt
Operational Experience (reactor - years)	23,000	1,600	300	80	4
Time for Final Design Approval (years)	3	5	5	>5	>5
Existing Vendors	9	4	3	1	0
Pre-Commercial Demonstration	No	Yes	Yes	Yes	Yes

This table summarizes the bases for DOE decision:

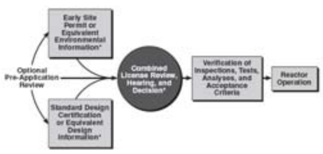
Near Term Advanced LWR

Long Term ?

New NPPs in US?

Streamlined Licensing (source: NRC)

Figure 1 - Relationships Between Combined Licenses, Early Site Permits, and Standard Design Certifications



*A combined license application can reference an early site permit, a standard design certification, both, or neither. If an application does not reference an early site permit and/or a standard design certification, the applicant must provide an equivalent level of information in the combined license application.

(http://www.nrc.gov)

Expected new NPP Applications (source: NRC)

- 22 applications
- 33 units

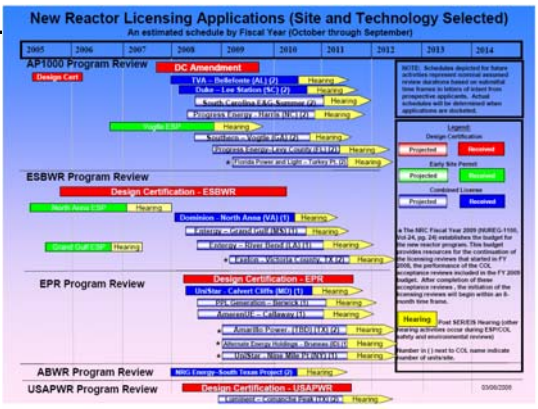
(http://www.nrc.gov)

Expected New Nuclear Power Plant Applications
Updated March 19, 2008

Company *	Design	Date Accepted	Site Under Consideration	State	Existing Op. Plant
Calendar Year (CY) 2007 Applications					
Duke (52-018/019)	AP1000	[illegible]	William Lee Nuclear Station (2 units)	SC	N
NuStart Energy (52-014/015)	AP1000	[illegible]	Bellefonte (2 units)	AL	N
Dominion (52-017)	ESBWR	[illegible]	North Anna (1 unit)	VA	Y
NRG Energy (52-012/013)	ABWR	[illegible]	South Texas Project (2 units)	TX	Y
2007 TOTAL NUMBER OF APPLICATIONS = 4; TOTAL NUMBER OF UNITS = 7					
Calendar Year (CY) 2008 Applications					
Progress Energy ([illegible])	AP1000		Harris (2 units)	NC	Y
Progress Energy ([illegible])	AP1000		Levy County (2 units)	FL	N
South Carolina Electric & Gas ([illegible])	AP1000		Summer (2 units)	SC	Y
Southern Nuclear Operating Co. ([illegible])	AP1000		Vogtle (2 units)	GA	Y
Entergy ([illegible])	ESBWR		River Bend (1 unit)	LA	Y
NuStart Energy ([illegible])	ESBWR		Grand Gulf (1 unit)	MS	Y
Exelon ([illegible])	ESBWR		Victoria County (2 units)	TX	N
UNISTAR (52-016)	EPR	[illegible]	Calvert Cliffs (1 unit)	MD	Y
PPL Generation ([illegible])	EPR		Berwick (1 unit)	PA	Y
AmerenUE ([illegible])	EPR		Callaway (1 unit)	MO	Y
UNISTAR ([illegible])	EPR		Nine Mile Point (1 unit)	NY	Y
Luminant Power ([illegible])	USAPWR		Comanche Peak (2 units)	TX	Y
Detroit Edison ([illegible])	TBD		Fermi (1 unit)	MI	Y
Amarillo Power ([illegible])	EPR		Vicinity of Amarillo (2 units)	TX	UNK
Alternate Energy Holdings ([illegible])	EPR		Bruneau (1 unit)	ID	N
2008 TOTAL NUMBER OF APPLICATIONS = 15; TOTAL NUMBER OF UNITS = 22					
Calendar Year (CY) 2009 Applications					
Florida Power and Light ([illegible])	AP1000		Turkey Point (2 units)	FL	Y
2009 TOTAL NUMBER OF APPLICATIONS = 1; TOTAL NUMBER OF UNITS = [illegible]					
Calendar Year (CY) 2010 Applications					
Transition Power	TBD		Utah	UT	N
Unannounced	TBD		TBD	TBD	[illegible]
2010 TOTAL NUMBER OF APPLICATIONS = 2; TOTAL NUMBER OF UNITS = 2					
2007 – 2010 Total Number of Applications = 22; Total Number of Units = 33					

*Project Numbers/Docket Numbers
Yellow = Acceptance Review Ongoing   Blue = Accepted/Docketed

New Reactor Applications by Technology (source: NRC)



(http://www.nrc.gov)

Conclusions

Summary and Conclusions

IRIS
- Advanced integral LWR
- Innovative solutions with proven technology
- Attractive design characteristics
- Competitive economics
- FER is IRIS team member

Smaller modular reactors
- May be economically competitive
- Offer a number of attractive features

USA Update
- GNEP
- New NPP applications