Agenzia nazionale per le nuove tecnologie, l'energia
e lo sviluppo economico sostenibile

Ministero dello Sviluppo Economico

RICERCA DI SISTEMA ELETTRICO

Collaborazioni internazionali per studi su Small Modular Reactors (SMR)

M.E. Ricotti, S. Boarin

RdS/2012/162

COLLABORAZIONI INTERNAZIONALI PER STUDI SU SMALL MODULAR REACTORS (SMR)

M.E. Ricotti, S. Boarin CIRTEN

Settembre 2012

Report Ricerca di Sistema Elettrico
Accordo di Programma Ministero dello Sviluppo Economico - ENEA
Area: Governo, Gestione e Sviluppo**,** del Sistema Elettrico Nazionale
Progetto: Nuovo Nucleare da Fissione: Collaborazioni Internazionali e sviluppo Competenze in Materia Nucleare
Responsabile del Progetto: Massimo Sepielli,ENEA

CIRTEN

<u>**C**</u>onsorzio <u>**I**</u>nteruniversitario per la <u>**R**</u>icerca <u>**TE**</u>cnologica <u>**N**</u>ucleare

POLITECNICO DI MILANO

DIPARTIMENTO DI ENERGIA, Sezione INGEGNERIA NUCLEARE-CeSNEF

Collaborazioni internazionali per studi su Small Modular Reactors (SMR)

M.E. Ricotti, S. Boarin

CERSE-POLIMI RL-1481/2012

Milano, Agosto 2012

Lavoro svolto in esecuzione della linea progettuale LP1– punto B.3

AdP MSE-ENEA "Ricerca di Sistema Elettrico" - PAR2011

Progetto 1.3.1 – "Nuovo Nucleare da Fissione: collaborazioni internazionali e sviluppo competenze in materia nucleare".

INDEX

EXECUTIVE SUMMARY

The document reports the description of the main international meetings attended by POLIMI in the period 2011-2012, referred to international collaborations and corresponding contributions on the topic of Small Modular Reactors.
The four meetings/workshops are:

INTERNATIONAL ATOMIC ENERGY AGENCY
Technical Meeting on "Options to Enhance Energy Supply Security using NPPs based on SMRs"
IAEA Headquarters, Vienna, Austria, 3 – 6 October 2011, VIC, Building A: Room A0531
Scientific Secretaries: M. Hadid Subki (NENP/NPTDS), M. K. Laina (NENP/NPTDS)

INTERNATIONAL ATOMIC ENERGY AGENCY
Workshop on "Technology Assessment of Small and Medium-sized Reactors (SMRs) for Near Term Deployment"
IAEA Headquarters, Vienna, Austria, 5 - 9 December 2011, VIC, Building M, Room M6
Scientific Secretaries: M. Hadid Subki (NENP/NPTDS), M. K. Laina (Ms) (NENP/NPTDS)

INTERNATIONAL ATOMIC ENERGY AGENCY
Consultants' Meeting on "Incorporating Lessons Learned from the Fukushima Accident in SMR Technology Assessment for Design of Engineered Safety Systems"
IAEA Headquarters, Vienna, Austria, 30 May – 1 June 2012 VIC Building-A, Room A0541
Scientific Secretary: M. Hadid Subki (NENP/NPTDS)

OECD-NEA
Committee for Technical and Economic Studies on Nuclear Energy Development and The Fuel Cycle (NDC)
7th Meeting of the Working Party on Nuclear Energy Economics, 10 November 2011, OECD Headquarters, 2 Rue André Pascal, 75016 Paris, Conference Centre, Room E
Secretariat of the Meeting: Jan Horst Keppler, Marco Cometto

The last page of the report includes short info on the Collaboration Agreements between Politecnico di Milano and some Small Modular Reactors projects, namely NuScale, FlexBlue and Flibe Energy company.

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INTERNATIONAL ATOMIC ENERGY AGENCY

Technical Meeting on "Options to Enhance Energy Supply Security using NPPs based on SMRs"

IAEA Headquarters, Vienna, Austria, 3 – 6 October 2011

List of the presentations, contributions and discussions

<table>
<tr><td></td><td>Objectives of the Meeting and Update of IAEA Programme on Common Technology and Issues for SMRs</td><td>H. Subki NENP/NPTDS</td></tr>
<tr><td colspan="3">In the past three decades, Nuclear Power Technology Development Section at the IAEA has engaged with its Member States activities relating to cross-cutting technology and institutional issues for small and medium-sized power reactors. The IAEA ensures the overall coordination of Member State experts participating in SMR activities by facilitating the sharing of experience and transfer of knowledge in the field, coordinating efforts of Member States to facilitate the development of SMRs by taking a systematic approach to identify key enabling technologies to achieve competitiveness and reliable performance of SMRs, and by addressing common issues of deployment. The current focus has been on developing international recommendations and guidance on SMRs focusing on specific needs of newcomer countries.</td></tr>
<tr><td></td><td>Featured Presentation #1: Benefits from Integrating SMRs with Renewable Energy Resources in Electricity Generation</td><td>Mr. D. Shropshire EC – JRC, Petten, the Netherlands</td></tr>
<tr><td colspan="3">Nuclear power supports the goals of the European Union low-carbon society by being a dependable source of energy, while emitting no CO2. SMRs could supply balancing electricity to even out the supply from renewable resources. Current nuclear technology has the capability for a degree of load-following, and future reactors could extend this capability through increased flexibility over a wide power range. Strategies for integrating SMRs with wind energy to reduce the daily and seasonal power variation are presented. SMRs of various types, sizes, and operational conditions could lead to the largest reductions in power variability and highest utilization of transmission resources. Technology-SMRs coupled with off-shore wind could cut the power variability of the combined system in half.</td></tr>
<tr><td></td><td>Featured Presentation #2:The NEOP Approach - Ensuring Relevance of Nuclear Technology to the Emerging Users</td><td>Mr. R. Sollychin NEFW/RRS</td></tr>
<tr><td colspan="3">A study is required to investigate whether or not nuclear energy's contribution to world energy usage is really increasing. Centralized energy systems are being compared to the locally optimized energy systems. Nuclear energy of the populace system (NEOP) treats nuclear energy as part of the locally optimized energy system, in which the role of Thorium utilization is deemed essential. NEOP systems can be developed from existing or innovative technologies, requiring a shift in paradigm in design, licensing, economic assessment, and so forth.</td></tr>
<tr><td></td><td>Featured Presentation #3: Potential strategies for utilizing SMRs for Combined-Heat-and-Power Generation</td><td>Mr. D. Shropshire EC – JRC, Petten, the Netherlands</td></tr>
<tr><td colspan="3">A hybrid system of nuclear and renewables offer promising advantages. The current SMR technology can be utilized as "plug-in" power sources. The approach can facilitate high utilization and improve capacity factor in an energy system for electricity. Transmission infrastructure costs will be shared by both nuclear and renewable plants projects. From the operation point of view, the scheme would further reduce power variability from RES, provide energy sink for excess wind energy, and produce heat for various applications.</td></tr>
<tr><td></td><td>Role of Small and Medium Nuclear Reactors (SMRs) to Support Nuclear Power Program in Pakistan</td><td>Mr. W. M. Butt PAEC, Pakistan</td></tr>
<tr><td colspan="3">The first Nuclear Power Plant of the country started commercial operation in 1972 and this was a 137MWe PHWR. Due to non-availability of vendor support, the plant was operated indigenously. This involved all types of engineering support to ensure safe and continuing operation of plant. Necessary facilities were developed for supporting the O&M of first NPP and providing infrastructure for the future NPPs. At present, two more NPPs (325 MWe PWRs) are in operation, two under construction while more in planning phases. The operating experience resulted in developing the infrastructure for considering the effective use of SMRs for suiting with the energy requirements of</td></tr>
</table>

<table>
<tr><td colspan="3">different regions of the country.</td></tr>
<tr><td></td><td>Application of Small Fast Reactor 4S for Energy Supply Security</td><td>Mr. K. Arie Toshiba Corp., Japan</td></tr>
<tr><td colspan="3">The small fast reactor, 4S (Super-Safe, Small and Simple) has distinguished features such as enhanced passive safety, long refuelling interval and low maintenance requirements as well as high temperature capability and enhanced security. Using these features, the 4S is suitable to supply electricity and/or heat for remote area communities, mining sites, oil sands recovery, seawater desalination and hydrogen production. In addition, the 4S-based Hybrid System along with its enhanced nuclear safety could be a key social infrastructure for energy supply security by combination with smart grid, energy storage system, and desalination plant.</td></tr>
<tr><td></td><td>Update on Slovenia Nuclear Energy Programme</td><td>Mr. G. Miroslav Ministry of the Environment and Spatial Planning, Slovenia</td></tr>
<tr><td colspan="3">Slovenia is operating one unit of 700 MWe class two-loop pressurized water reactor made by Westinghouse at the Krsko NPP site, which is jointly owned by Croatia. The PWR was the first western nuclear power plant in eastern Europe. The construction of the plant was started in 1975 and the plant was connected to the grid in 1981, followed by the commercial operation in 1983. Replacement of the two steam generators was done in 2001 and the plant was uprated 6% then 3% subsequently. The reactor has 40 years operational life, but a 20-year extension is being pursued.</td></tr>
<tr><td></td><td>INPRO Methodology for Nuclear Energy System Assessment and Activities on Technology Assessment for Future Nuclear Energy System</td><td>Mr. R. Beatty NENP/INPRO</td></tr>
<tr><td colspan="3">INPRO has developed a methodology to assess sustainable nuclear systems on national, regional and global levels, consistent with the goals set out in its basic principles. With the methodology, Member States understanding has improved that the implementation of nuclear energy requires a holistic approach and a long range review. INPRO supports countries developing new nuclear energy capacity to consider technology assessment activities as they develop their nuclear system deployment plans.</td></tr>
<tr><td></td><td>Integrated Nuclear Infrastructure Development Programme for Newcomer Countries</td><td>Mr. D. Kovacic NENP/INIG</td></tr>
<tr><td colspan="3">The Integrated Nuclear Infrastructure Development Programme adopts the Milestones approach, which identifies gaps and helps Member States develop the national infrastructure to implement their first NPP based on the existing nuclear reactor technology. It deals with key infrastructure issues for newcomer countries and provides guidance for understanding the nuclear power option and issues associated with its long-term national and international commitments.</td></tr>
<tr><td></td><td>IAEA's Approaches to Assess Environmental Impacts due to NPP operation</td><td>Ms. A. Miketa NENP/PESS</td></tr>
<tr><td colspan="3">Planning and Economic Studies Section at the IAEA assists Member States in capacity building, so the countries have inherent capability to perform analysis and develop alternative strategies to achieve sustainable energy supply, to evaluate the energy-economic-environmental implications, and to assess the potential contribution of nuclear energy in securing affordable and clean supplies of energy. To date, the IAEA has developed and made available to its Member States various Energy Analysis and Planning tools for the assessment of nuclear energy contribution in country's national energy mix, and to provide justification for introduction of nuclear power, and helped establish national position that covers social, economic, environmental aspects.</td></tr>
<tr><td></td><td>Potential Contributions of Modular HTGRs to Energy Supplies in China</td><td>Mr. Y. Sun INET – Tsinghua University, China</td></tr>
<tr><td colspan="3">Nuclear energy is a practical energy source which can help to ease the challenge of energy supply security and power generation. China has already been implementing a nuclear power program. A large number of nuclear power plants are being operated, constructed or under planning. The graphite moderated high temperature gas-cooled reactor (HTGR) has been under development in China for the past decades and the first demonstration plant is under construction. The modular HTGR technology has unique features such as high temperature and inherent safety characteristics that apart from power generation enable supplying process heat at various temperature levels.</td></tr>
<tr><td></td><td>The Development of Small and Medium Reactors (SMRs) in China</td><td>Mr. S. Cui Huaneng Nuclear Power Development, China</td></tr>
</table>

Although the Fukushima nuclear accident has not reversed China's decision to develop nuclear power for satisfying the growing demand for electricity, it made the Chinese government elevate the safety standard for nuclear power plants. Under these circumstances, SMRs featuring safety, flexibility and compatibility to the grid begin to draw wide attention. Currently, SMRs under development in China include PWR type CNP, CANDU reactor, HTR (including High Temperature Gas-Cooling Reactor, HTGR), Fast Neutron Reactor and Nuclear Heating Reactor. China has given importance to the development of HTR, and has launched a demonstration project of 200MW HTGR in Shidao Bay. The project is run by China Huaneng Group.		
	Technology Development, Design and Utilization Features of **SVBR-100** and its Deployment Scheme	**Mr. S. Borovitskiy** JSC AKME Engineering, Russian Federation
SVBR-100 is an integral, modular, small sized fast reactor with the net electrical power of 100 MW, designed both for newcomer as well as expanding nuclear countries. The reactor has been developed since 2009 by the JSC AKME Engineering, a joint venture of Rosatom and EuroSibEnergo in collaboration with other established institutions. The SVBR-100 design takes advantage of 80 reactor-year experience in the operation of small lead-bismuth cooled reactors for nuclear submarines. The small fast reactor adopts up to 9 years fuel cycle that allows a significant reduction of natural uranium consumption.		
	Technology Development, Design and Utilization Features of **IRIS** and its Deployment Scheme	**Mr. M. Ricotti** Politecnico di Milano, Italy
The first 10 years of the IRIS project will be presented, summarizing its technical achievements and influence on the resurgence of SMRs. IRIS is one of several small reactor concepts originated in late 1990s. The reactor design incorporates a number of novel technology advancements that it either introduced for the first time, or improved from its predecessors to bring them into a higher technical level.		
	Major findings of the **INPRO project** on **Legal and Institutional Issues for Transportable NPPs** and possible follow-up activity	**Mr. V. V. Kuznetsov** NENP/INPRO
A Transportable Nuclear Power Plant (TNPP) is a factory manufactured, transportable and relocatable NPP that when fuelled is capable to produce final energy products like electricity, process heat, and so forth. The deployment of TNPP could face new legal issues in the international context, related for instance to obligation and responsibility of the operators to comply with international legal instruments as well as with IAEA safety standards and security recommendations. The INPRO project on the subject has studied legal and institutationl issues for TNPP deployment and to propose solutions to address the identified challenges.		
	Malaysia Energy Policy: New Role to **Malaysia** Nuclear Agency	**Mr. M. Rawi** Malaysia Nuclear Agency, Malaysia
The previous and current status of the Malaysia Energy Policy will be discussed. The Malaysia Energy Policy in the tenth Malaysia Plan emphasizes on the nuclear power as an energy option for Malaysia and the new role for the Malaysian Nuclear Agency in supporting the National Nuclear Power Programme. The Malaysian Government has formulated the first National Energy Policy in 1979, with three objectives: (1) sustainable energy supply, (2) optimum utilisation and (3) environmental preservation. The environmental objective is about securing that factors pertaining to environmental protection are not neglected in pursuing the energy supply and utilisation objectives.		
	Prospects of SMRs in Indonesia's Energy System	**Ms. C. Johari, Mr. S. Soenarko** NENP/INPRO and INIG
Indonesia possesses unique features that present opportunities to incorporate SMRs in the national energy system for the introduction of electricity, and possibly co-generation, in small islands, given the fact that nuclear energy is already part of the national energy mix policy. Recent study indicates that SMRs are a viable option for a capital cost of less than US$3,500 /kWe. The deployment of SMRs in such locations, however, poses real challenges with regard to issues such as infrastructure development, electricity grid, availability of skilled personnel, emergency preparedness, and safety-security-safeguard aspects, and more importantly due to recent Fukushima accident, political commitment and public acceptance.		
	Small Sized Reactors: Case for the Asia-Pacific Region	**Mr. H. Peimani** Energy Studies Institute/NUS, Singapore
The countries of the Asian-Pacific region, suffering from land scarcity and some facing financial restrains and/or electricity demand from small scattered energy-consuming locations could benefit from SMRs. As determined by their specific geographical, geological and climatic circumstances, a combination of SMRs and renewables operating in a well-integrated power grid can address growing electricity requirements without contributing to global warming. This kind of systems could be a means to deal with the excessive demand and to replace some of		

their existing fossil fuelled-power generators; they can also be a measure for combating global warming through reducing their current CO2 emissions.		
	Prospects and Constraints of SMR Deployments in Thailand: A regulatory perspective	**Mr. P Boonsuwana** Bureau of Nuclear Safety Regulation, Thailand
In Thailand, the need for reliable energy sources in response to increased electricity demand makes nuclear power an alternative reliable energy option, regardless public opposition due to Fukushima. Large LWR-type-reactors are most likely to be approved primarily due to their proven technology and established licensing process. However, their construction cost, large footprint and the possibility to produce large-scale accidents make their construction less attractive. The SMRs start making economic sense, as they are smaller, cheaper, easier to deploy and probably safer than the typical LWRs due to their smaller size and passive safety features. Despite the benefits, concerns that SMR technologies are not "proven", the issues of nuclear proliferation, and the licensing process are perceived as challenges.		
	Technical Requirements of **Jamaica** for Nuclear Reactor Technology for Near Term Deployment	**Mr. Z. Mian** Office of Utilities Regulation, Jamaica
Jamaica is the largest English Speaking Island economy in the Caribbean with a total land area of about 11 thousand km2 and a population of 2.7 million. The per capita income is US$ 4,980 (2010). The country is determined to reduce its dependency on imported oil by optimizing the potentials of renewable energy. The government has created a roadmap towards achieving 20% fuel supply mix shift towards renewable sources. The Energy Policy places enhanced reliance on fuel diversification strategy that would rely on natural gas and other such fuel in the short- to medium-term. In view of development of SMRs and advancements in nuclear technology, in the longer-term Jamaica would have to evaluate the potential role of nuclear options in its overall energy supply mix.		
	Technical Requirements of **Mongolia** for Nuclear Reactor Technology for Near Term Deployment (tentative)	**Mr. G. Manlaijav,** Nuclear Technology Authority, Mongolia
	Development of New and Renewable Energy in Mongolia (tentative)	**Mr. T. Tseren** Ministry for Mineral Resources and Energy, Mongolia
	Guideline of Development of NE Series Report on the Subject	**Mr. H. Subki** – IAEA **Mr. D. Shropshire** – EC-JRC
	Working Session #1: Development of Outline for the publication on the subject	All – lead by Meeting Chairmen
	Working Session #2: Development of Terms of Reference, Introduction/Executive Summary for the publication	All – lead by Meeting Chairmen
	Wrap Up Session, Meeting Conclusion and Action Plan	**H. Subki** NENP/NPTDS

During the meeting, the presentation offered by prof. Ricotti is in the largest part similar to the presentation offered in the IAEA Workshop on "Technology Assessment of Small and Medium-sized Reactors (SMRs) for Near Term Deployment" (5 - 9 December 2011). The content of the speech is reported in the following section hence is not repeated here.

INTERNATIONAL ATOMIC ENERGY AGENCY

Workshop on "Technology Assessment of Small and Medium-sized Reactors (SMRs) for Near Term Deployment"

IAEA Headquarters, Vienna, Austria, 5 - 9 December 2011

List of the presentations, contributions and discussions

• **Workshop Outline** and Update of IAEA Programme on **Common Technology and Issues for SMRs**	**M.H. Subki** NENP/NPTDS
• IAEA Programme on **Advanced Nuclear Power Technology Development**	**T. Koshy** SH - NENP/NPTDS
• IAEA Programme on **Reactor Technology Assessment and Selection**: Process and Approach	**S. P. Schultz** **NENP/NPTDS**
• Technology Development, Design and Safety Features of **CAREM-25** and its Deployment Scheme	**P. Zanocco** CNEA, Argentina
• Technology Development, Design and Safety Features of **KLT-40s** and its Deployment Scheme	**Y. Fadeev** OKBM Afrikantov, Russian Federation
• Technical Requirements of **Malaysia** for Nuclear Reactor Technology for Near Term Deployment	**M. Maskin (Ms)** MOSTI, Malaysia
• Technology Development, Design and Safety Features of **CNP-300** and new Small Reactors in China	**Q. Lin** SNERDI, China
• Pakistan's Experience in Operating **CNP-300s** and Near Term Deployment Scheme	**M. K. Chughtai** PAEC, Pakistan
• Overview of Nuclear Power **Infrastructure Preparedness** in Newcomer Countries	**D. Kovacic,** NENP/INIG
• **INPRO Methodology** for Nuclear Energy System Assessment and Activities on Technology Assessment for Future **Nuclear Energy System**	**R. Beatty** NENP/INPRO
• **IAEA Safety Assessment Requirements**	**H. Khartabil** NSNI/NSNS
• Technology Development, Design and Safety Features of **SMART** and its Deployment Scheme	**H.K. Joo** KAERI, Republic of Korea
• Technology Development, Design and Safety Features of **mPower** and its Deployment Scheme	**D.E. Lee** Babcock & Wilcox, USA
• Technology Development, Design and Safety Features of **NuScale** and its Deployment Scheme	**J. N. Reyes** NuScale Power, USA
• Technology Development, Design and Safety Features of **Westinghouse SMR** and its Deployment Scheme	**M. Anness** Westinghouse Electric, USA
• Technology Development, Design and Safety Features of **IRIS** and its Deployment Scheme	**M.E. Ricotti** Politecnico di Milano, Italy
• A Proposal to Prepare for Introduction of SMR Using Feasibility Studies Based on the **SUSTINE-NEOP Approach**	**R. Sollychin** NEFW/RRS
• Breakout Session #1: Member States Exercise on Technology Assessment for Light Water Reactor - SMRs	Lead by T. Koshy NENP/NPTDS

• Technology Development, Design and Safety Features of the **Enhanced CANDU6 (EC-6)** and its Deployment Scheme	**J. Hopwood** CANDU Energy, Inc. Canada
• Technology Development, Design and Safety Features of **PHWR 220, PHWR 540,** and **PHWR 700** and their Operating Performance	**U. Muktibodh** NPCIL, India
• Technology Development, Design and Safety Features of **AHWR300-LEU** and its Deployment Scheme	**A. K. Nayak** BARC, India
• Breakout Session #2: Member States Exercise on Technology Assessment for Heavy Water Reactor - SMRs	Lead by J.H. Choi NENP/NPTDS
• Technical Requirements of **Uruguay** for Nuclear Reactor Technology for Near Term Deployment	**P. De Lucia Terni (Ms)** ANCAP, Uruguay
• Possible **Financing Schemes** for Current and Near Term Nuclear Power Projects	**N. Barkatullah (Ms)** NE/PESS
• Technical Requirements of **Ghana** for Nuclear Reactor Technology for Near Term Deployment	**I. Aboh** GAEC, Ghana
• IAEA Programme on **Non-Electric Applications** coupled with Small and Medium-sized Reactors	**I. Khamis** NENP/NPTDS
• Member States Exercise on Technology Assessment for Non-Electric Applications	Lead by I. Khamis NENP/NPTDS
• IAEA Programme on **Gas Cooled Reactors** Technology	**B.M. Tyobeka** NENP/NPTDS
• Technology Development, Design and Safety Features of **HTR-PM** and its Deployment Scheme	**Y. Sun** INET, China
• Technology Development, Design and Safety Features of **EM2/GT-MHR** and its Deployment Scheme	**R. W. Schleicher** General Atomic, USA
• Member States Exercise on Technology Assessment for Gas Cooled Reactor - SMRs	Lead by B.M. Tyobeka NENP/NPTDS
• Technical Requirements of Indonesia for Nuclear Reactor Technology for Near Term Deployment	M. D. Purwadi BATAN, Indonesia
• IAEA Programme on Fast Reactors Technology	S. Monti NENP/NPTDS
• Technology Development, Design and Safety Features of PRISM and its Deployment Scheme	E. Loewen GE Hitachi, USA
• Member States Exercise on Technology Assessment for Fast Reactor / Liquid Metal Reactor - SMRs	Lead by S. Monti
• **Newcomer Countries' Exercise and Feedback Presentations:** o LWR - SMRs o HWR - SMRs o GCR - SMRs o FR/LMR-SMRs o Non-Electric Applications	Member States and NPTDS Technical Leads
• **Closing Remarks**	**T. Koshy, S/H-NPTDS**

Breakout Session #1: Member States Exercise on Technology Assessment for LWR - SMRs

Group **Room**	**A** **M6**	**B** **M 0E 67**	**C** **M 0E 68**
Technology Developers	Korea – SMART Italy – IRIS USA – mPower	Russian Federation – KLT-40s China – CNP300 Pakistan – CNP300	Argentina – CAREM-25 USA – NuScale USA – Westinghouse SMR
Scope of Discussion	Standardization & Simplification Safety	Plant performance and operability Proven Technology	Economics Constructability
Facilitators:	T. Koshy S.P. Schultz	A.S. Rao K. Yamada	J. Cleveland D. Ingersoll
Newcomer Countries:	Albania Algeria Indonesia Vietnam	Croatia Ghana Malaysia Sudan Singapore	Bangladesh Kenya Nigeria Thailand Uruguay

The invited Group Leads (Rapporteurs) for the LWR – SMRs breakout sessions:

Group A Lead: Mr. Zaki Su'ud – Indonesia

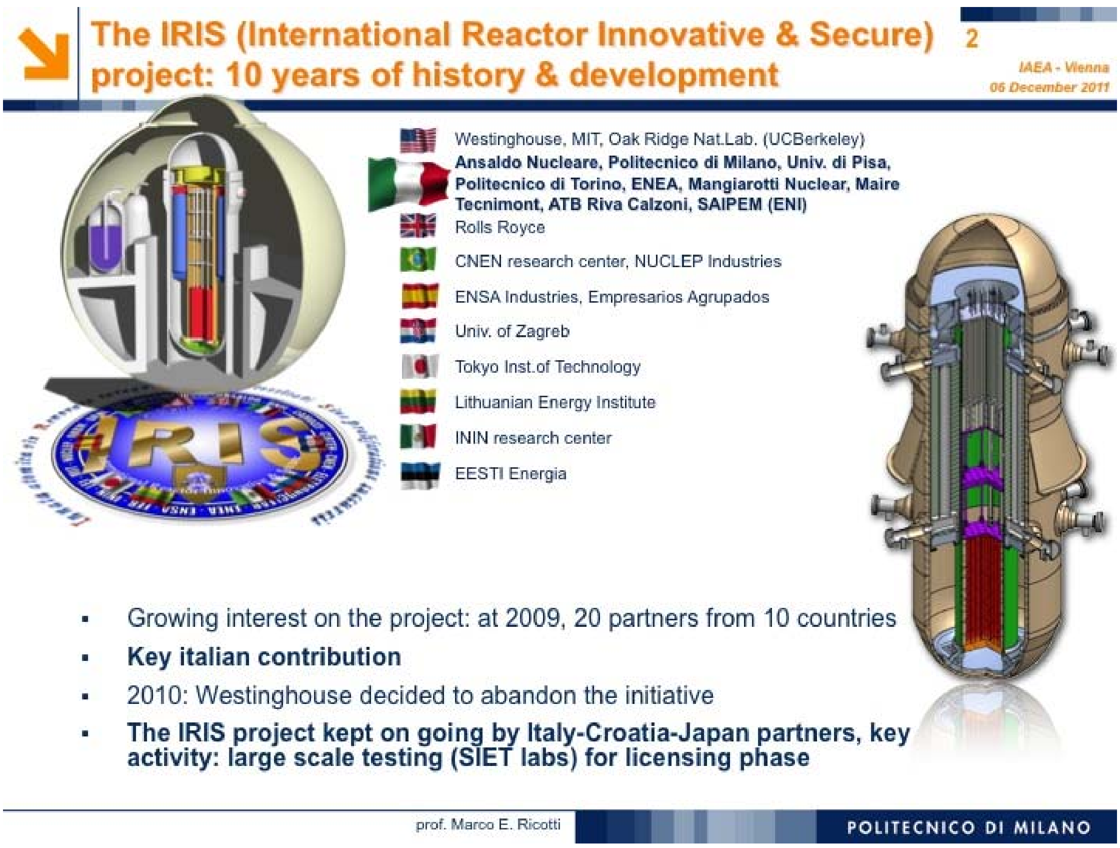
Group B Lead: Mr. Zeljko Tomsic – Croatia

Group C Lead: Mr. Francis Ibitoye – Nigeria

The presentation offered by prof. Ricotti during the workshop is reported in the next section.

The subsequent section ("Newcomer Countries' Exercise and Feedback Presentation – Group C for LWR - SMRs") shows the results of the Breakout Session #1 and the related discussion and Q&A process, including the contribution given by POLIMI on the IRIS SMR concept.


Technical Meeting/Workshop on
Technology Assessment of SMRs for
Near Term Deployment
IAEA, Vienna, 5 – 9 December 2011
POLITECNICO DI MILANO
Technology Development, Design and Safety
Features of IRIS and its Deployment Scheme
prof. Marco E. Ricotti
Politecnico di Milano, Department of Energy, CeSNEF-Nuclear Engineering Division
Vienna, 06 december 2011


The IRIS (International Reactor Innovative & Secure)
project: 10 years of history & development
2
IAEA - Vienna
06 December 2011
Westinghouse, MIT, Oak Ridge Nat.Lab. (UCBerkeley)
Ansaldo Nucleare, Politecnico di Milano, Univ. di Pisa, Politecnico di Torino, ENEA, Mangiarotti Nuclear, Maire Tecnimont, ATB Riva Calzoni, SAIPEM (ENI)
Rolls Royce
CNEN research center, NUCLEP Industries
ENSA Industries, Empresarios Agrupados
Univ. of Zagreb
Tokyo Inst.of Technology
Lithuanian Energy Institute
ININ research center
EESTI Energia
Growing interest on the project: at 2009, 20 partners from 10 countries
Key italian contribution
2010: Westinghouse decided to abandon the initiative
The IRIS project kept on going by Italy-Croatia-Japan partners, key activity: large scale testing (SIET labs) for licensing phase
prof. Marco E. Ricotti
POLITECNICO DI MILANO

HISTORY OF IRIS

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IAEA - Vienna
06 December 2011

09/09/1999, kick-off meeting at MIT:
Westinghouse, MIT, UCBerkeley, POLIMI

prof. Marco E. Ricotti — POLITECNICO DI MILANO

Original Team and assignments (yellow: Italian partners)

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IAEA - Vienna
06 December 2011

INDUSTRY		
Westinghouse	USA	Overall coordination, core design, safety analyses, licensing, commercialization
BNFL*	UK	Fuel and fuel cycle
Ansaldo Energia / Ansaldo	Italy	Steam generators design
Ansaldo Nucleare / Camozzi / Mangiarotti	Italy	Steam generators fabrication
ENSA – (ATB Riva Calzoni)	Spain – (Italy)	Pressure vessel and internals
NUCLEP – (ATB Riva Calzoni)	Brazil – (Italy)	Containment, pressurizer
(Rolls Royce)	UK	Control rod drive mechanisms
LABORATORIES		
ORNL	USA	I&C, PRA, desalination, shielding, pressurizer
CNEN	Brazil	Pressurizer design, transient analyses, desalination
ININ	Mexico	PRA, neutronics support
LEI	Lithuania	PRA, district heating co-generation
ENEA - SIET	Italy	Testing, integral facility, seismic, shielding
UNIVERSITIES		
Polytechnic of Milan	Italy	Safety analyses, shielding, thermal hydraulics, steam generators design, internal CRDMs, economics, bio-fuel co-generation
MIT	USA	Advanced cores, maintenance
Tokyo Inst. of Technology	Japan	Advanced cores, PRA, seismic
University of Zagreb	Croatia	Neutronics, safety analyses
University of Pisa	Italy	Containment analyses, severe accident analyses, neutronics, CFD, seismic
Polytechnic of Turin	Italy	Source term, thermal hydraulics
(Georgia Institute of Technology)	USA	Advanced core designs; shielding; dose reduction
POWER PRODUCERS AND ARCHITECT ENGINEER COMPANIES		
(Bechtel)* - SAIPEM, Maire Tecnimont	(USA) - Italy	BOP, AE
(TVA)*	USA	Maintenance, utility perspective
Eletronuclear	Brazil	Developing country utility perspective
(Empresarios Agrupados)	Spain	AE
(Esti Energia)	Estonia	Smaller country/grid utility perspective

prof. Marco E. Ricotti — POLITECNICO DI MILANO

UP TO 2009-2010, IRIS: REFERENCE SMR DESIGN FOR US DoE

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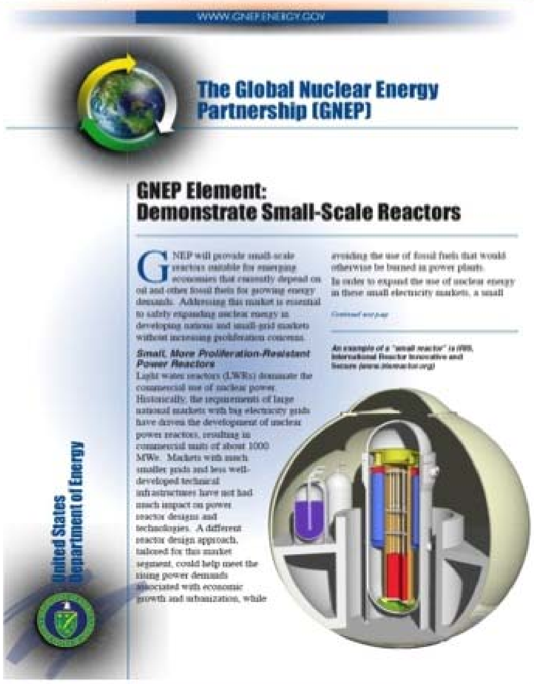
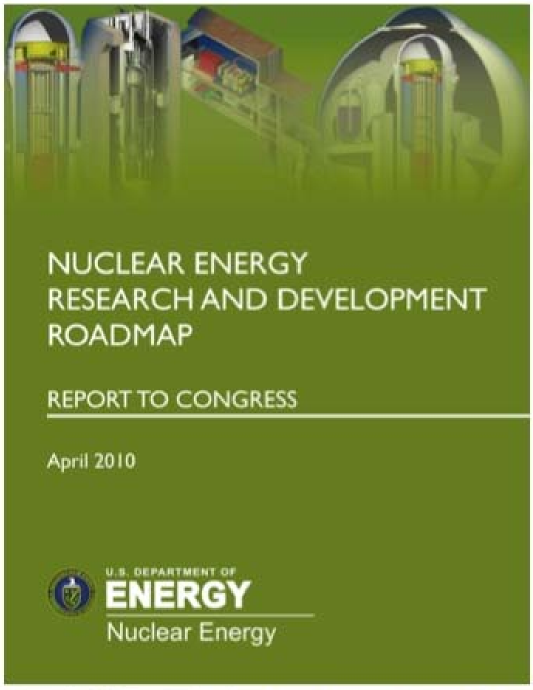
IAEA - Vienna
06 December 2011





prof. Marco E. Ricotti — POLITECNICO DI MILANO

The IRIS approach

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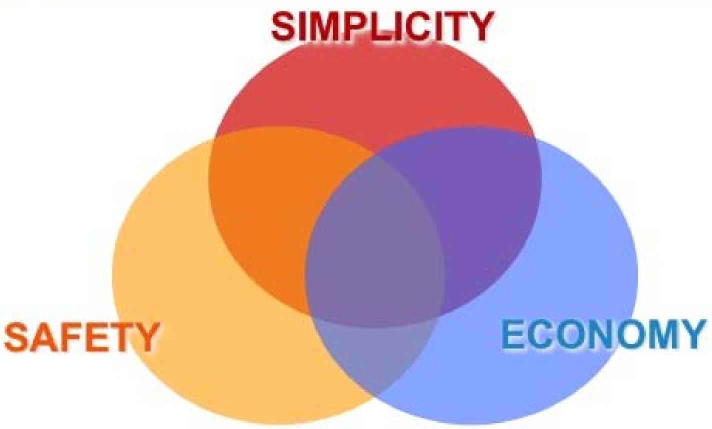

- Driven by simplicity to ensure safety and economy
- Uses proven light water technology (PWR)
- Implements engineering innovations, new solutions, but does not require new/breakthrough technology development

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IRIS Three-Tier Safety

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Safety-by-Design™

-aims at eliminating by design possibility for accidents to occur,
-at reducing probability of occurrence for remaining accidents,
-at reducing consequences,
-eliminates systems/components that were needed to deal with those accidents.

Passive Safety Systems

-protect against still remaining accidents and mitigate their consequences,
-fewer and simpler than in passive LWRs.

Active Safety Systems

-no active safety systems are required,
-but, active non-safety systems may contribute to reducing the probability of CDF (Core Damage Frequency).

IMPROVES SAFETY WHILE SIMPLIFYING DESIGN

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IRIS: integral solution for primary system

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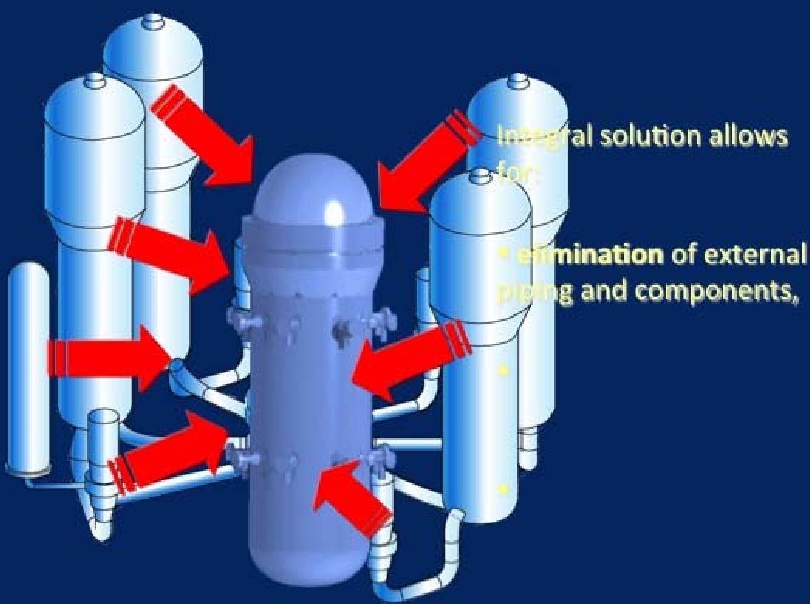

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IRIS: integral solution and reduced size containment

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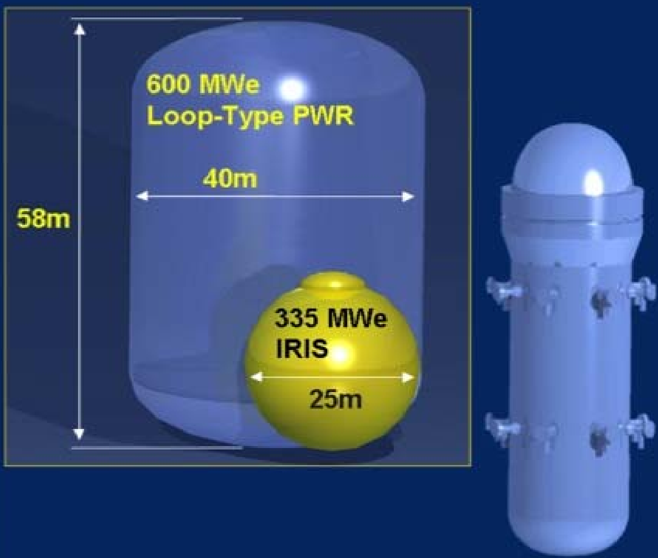

Integral solution allows for:

- **elimination** of external piping and components,
- adoption of a **compact** containment
- **reduce** NPP dimensions

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IRIS Design Features

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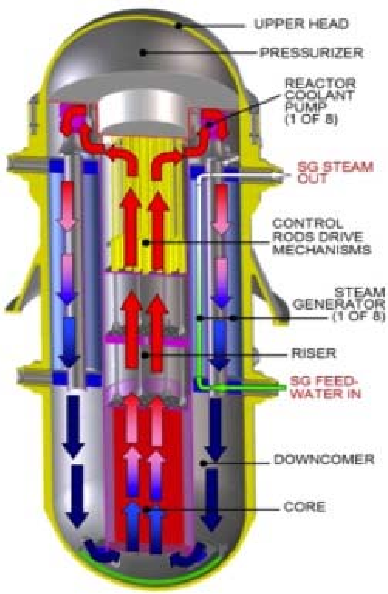
- **Integral PWR module 335 MWe, Safety-by-Design™ approach**
- **Long Life Core** (~4 years, no maintenance outage within it)
- **8 helical-coil steam generators** (compressed tubes, no crud: no Stress Corrosion Cracking)
- **8 axial flow fully immersed primary coolant pumps** (low ΔP, no leakages, no maintenance, self-cooled, already used at 500°C in chemical industry)
- **Internal Control Rod Drive Mechanisms** (no penetrations/leakages, no Rod Ejection Accident)
- **Integral Pressurizer** (high prz volume / reactor power ratio, no sprays)
- **CDF 10^{-8} event/r y** (internal+seismic)



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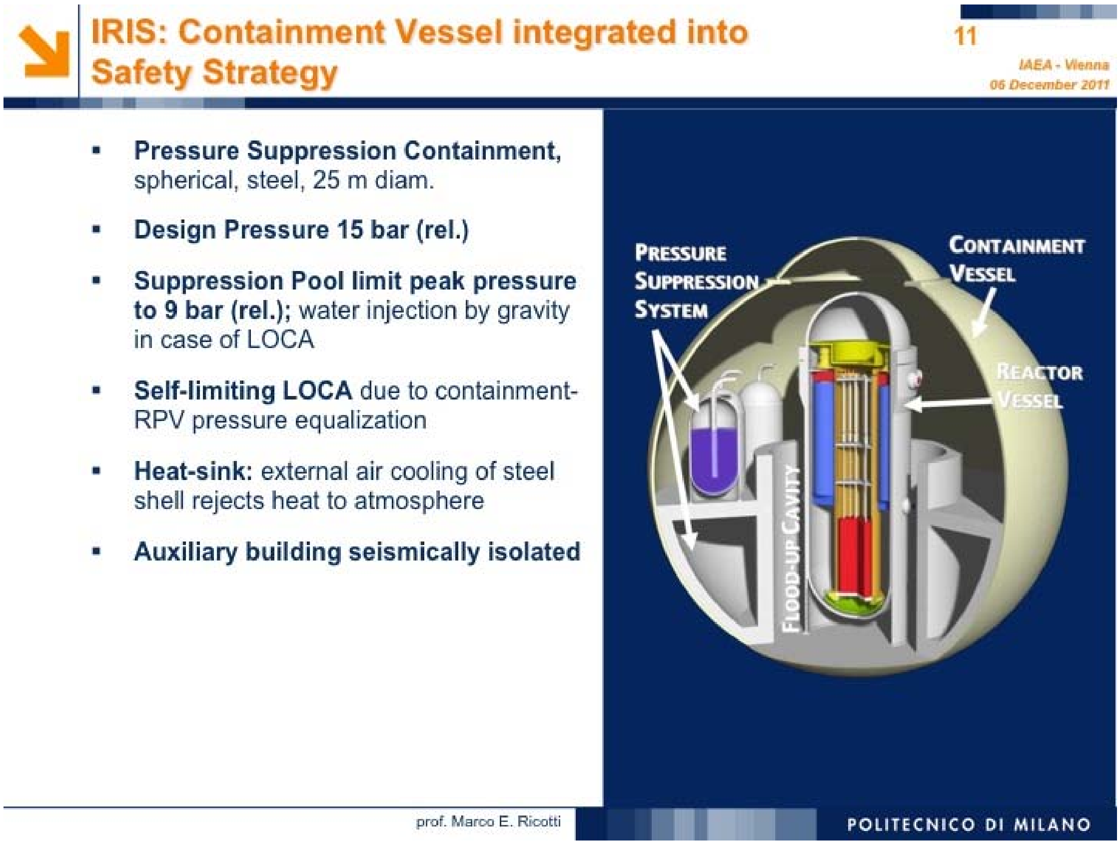
IRIS: Containment Vessel integrated into Safety Strategy
11
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▪ Pressure Suppression Containment, spherical, steel, 25 m diam.
▪ Design Pressure 15 bar (rel.)
▪ Suppression Pool limit peak pressure to 9 bar (rel.); water injection by gravity in case of LOCA
▪ Self-limiting LOCA due to containment-RPV pressure equalization
▪ Heat-sink: external air cooling of steel shell rejects heat to atmosphere
▪ Auxiliary building seismically isolated
PRESSURE SUPPRESSION SYSTEM
CONTAINMENT VESSEL
REACTOR VESSEL
FLOOD-UP CAVITY
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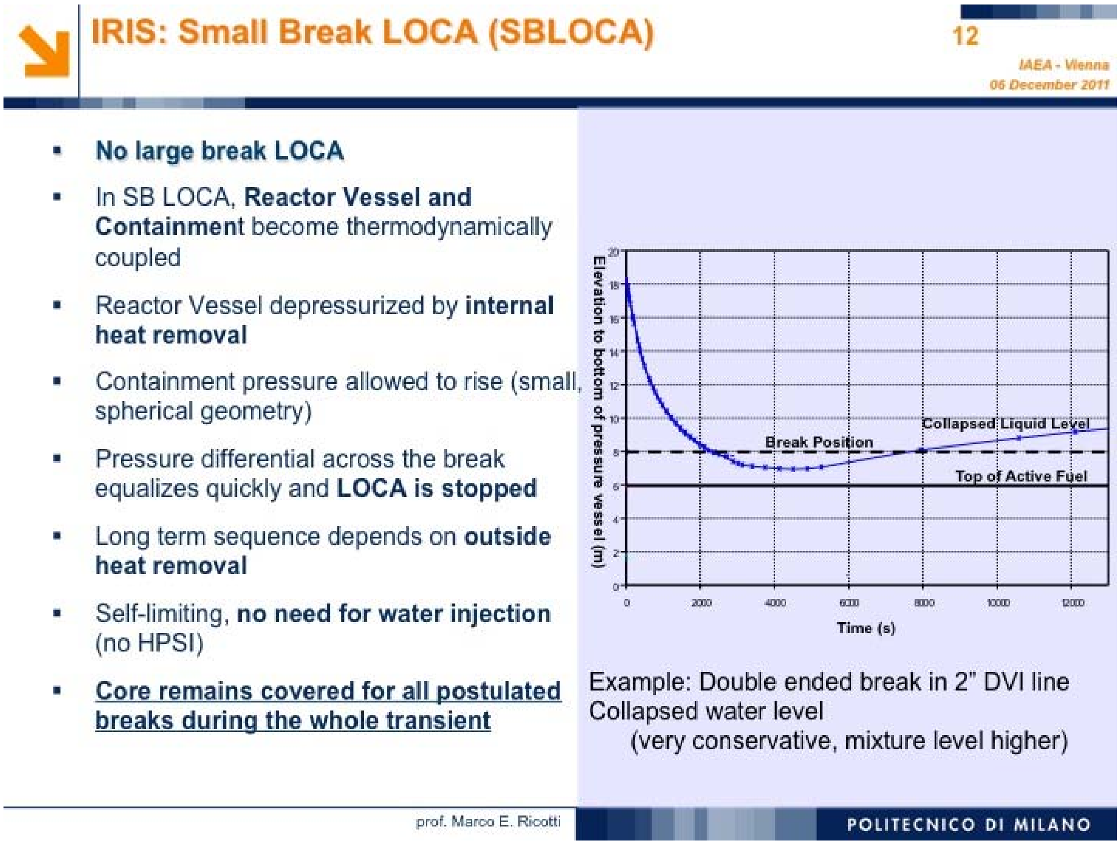
IRIS: Small Break LOCA (SBLOCA)
12
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▪ No large break LOCA
▪ In SB LOCA, Reactor Vessel and Containment become thermodynamically coupled
▪ Reactor Vessel depressurized by internal heat removal
▪ Containment pressure allowed to rise (small, spherical geometry)
▪ Pressure differential across the break equalizes quickly and LOCA is stopped
▪ Long term sequence depends on outside heat removal
▪ Self-limiting, no need for water injection (no HPSI)
▪ Core remains covered for all postulated breaks during the whole transient
Elevation to bottom of pressure vessel (m)
Time (s)
Collapsed Liquid Level
Break Position
Top of Active Fuel
Example: Double ended break in 2" DVI line
Collapsed water level
(very conservative, mixture level higher)
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IRIS: Safety-by-Design™ implementation

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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 Loss of Coolant Accidents (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 (CRDMs)	• 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	• LOCAs		
	Effective heat removal by Steam Generators (SG)/Emergency High Removal System (EHRS)	• LOCAs • All events for which effective cooldown is required • Anticipated Transients Without Screen (ATWS)		
Reduced size, higher design pressure containment	Reduced driving force through primary opening	• LOCAs		
Multiple, integral, shaftless coolant pumps	Decreased importance of single pump failure	• Locked rotor, shaft seizure/ break	Reactor coolant pump shaft break	Eliminated
	No shaft	• Loss of Flow Accidents (LOFAs)	Reactor coolant pump seizure	Downgraded
High design pressure steam generator system	No SG safety valves Primary system cannot over-pressure secondary system	• Steam generator tube rupture	Steam generator tube rupture	Downgraded
	Feed/Steam System Piping designed for full Reactor Coolant System (RCS) pressure reduces piping failure probability	• 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

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Passive emergency heat removal system (EHRS)

IRIS: Safety systems

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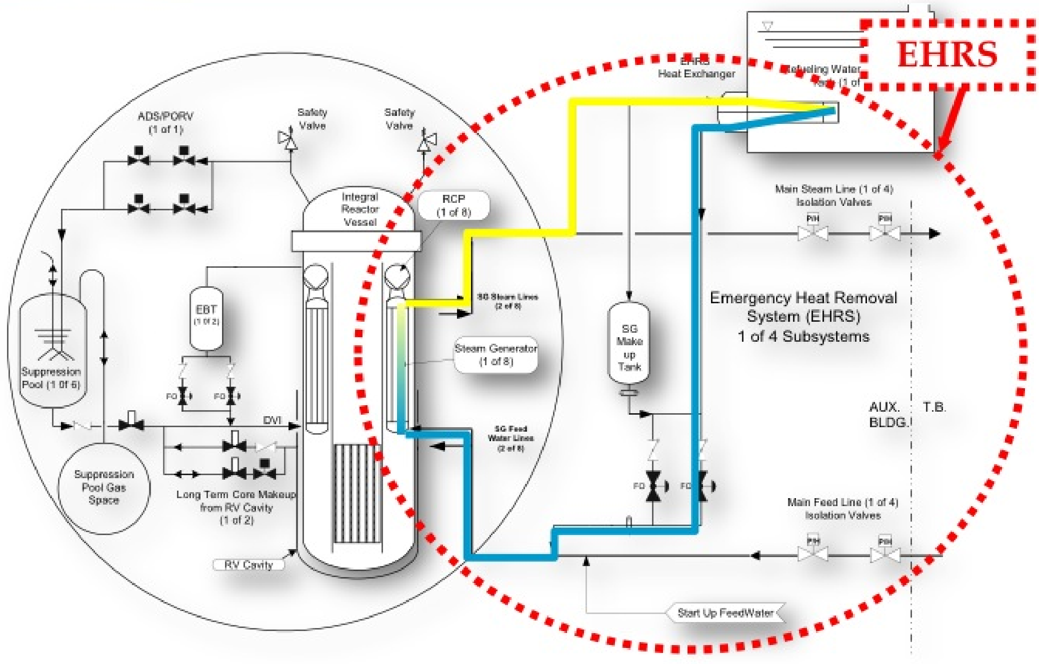

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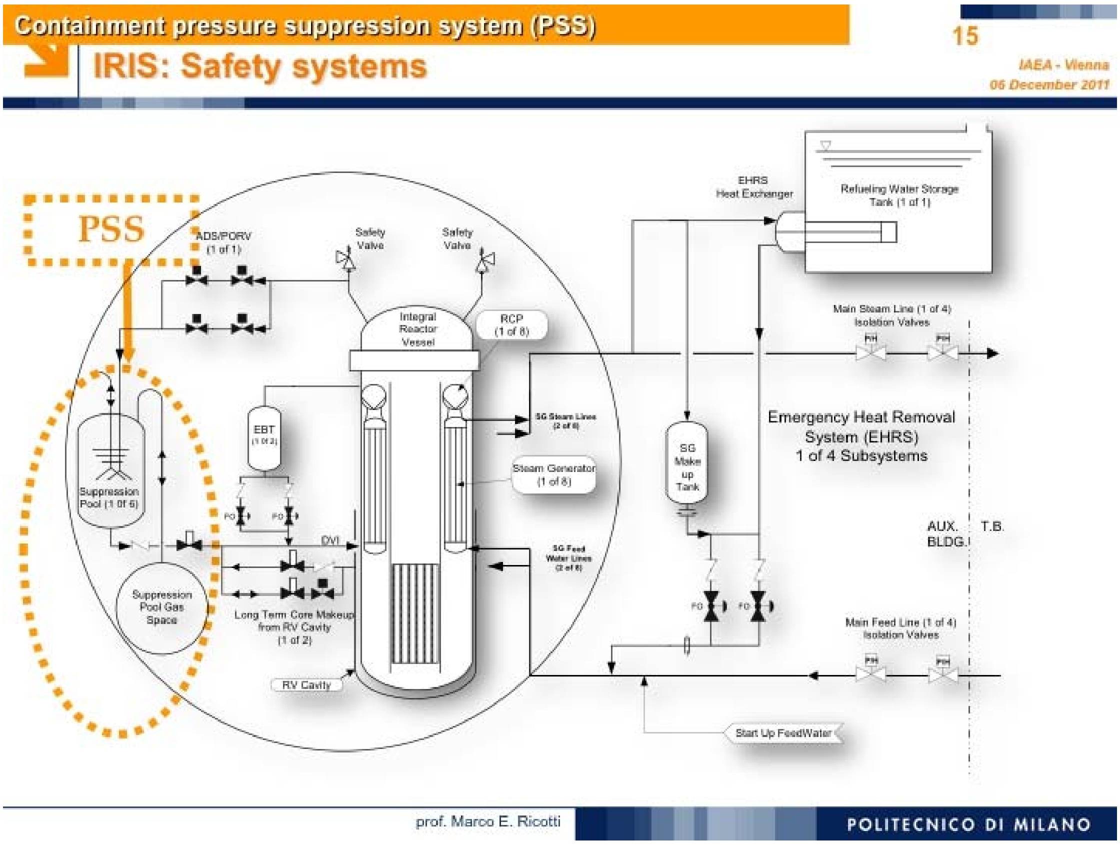
Containment pressure suppression system (PSS)
IRIS: Safety systems
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PSS
ADS/PORV
(1 of 1)
Safety Valve
Safety Valve
EHRS Heat Exchanger
Refueling Water Storage Tank (1 of 1)
Integral Reactor Vessel
RCP (1 of 8)
Main Steam Line (1 of 4) Isolation Valves
EBT
SG Steam Lines (2 of 8)
Steam Generator (1 of 8)
SG Make up Tank
Emergency Heat Removal System (EHRS)
1 of 4 Subsystems
Suppression Pool (1 Of 6)
DVI
SG Feed Water Lines (2 of 8)
AUX. BLDG.
T.B.
Suppression Pool Gas Space
Long Term Core Makeup from RV Cavity (1 of 2)
Main Feed Line (1 of 4) Isolation Valves
RV Cavity
Start Up FeedWater
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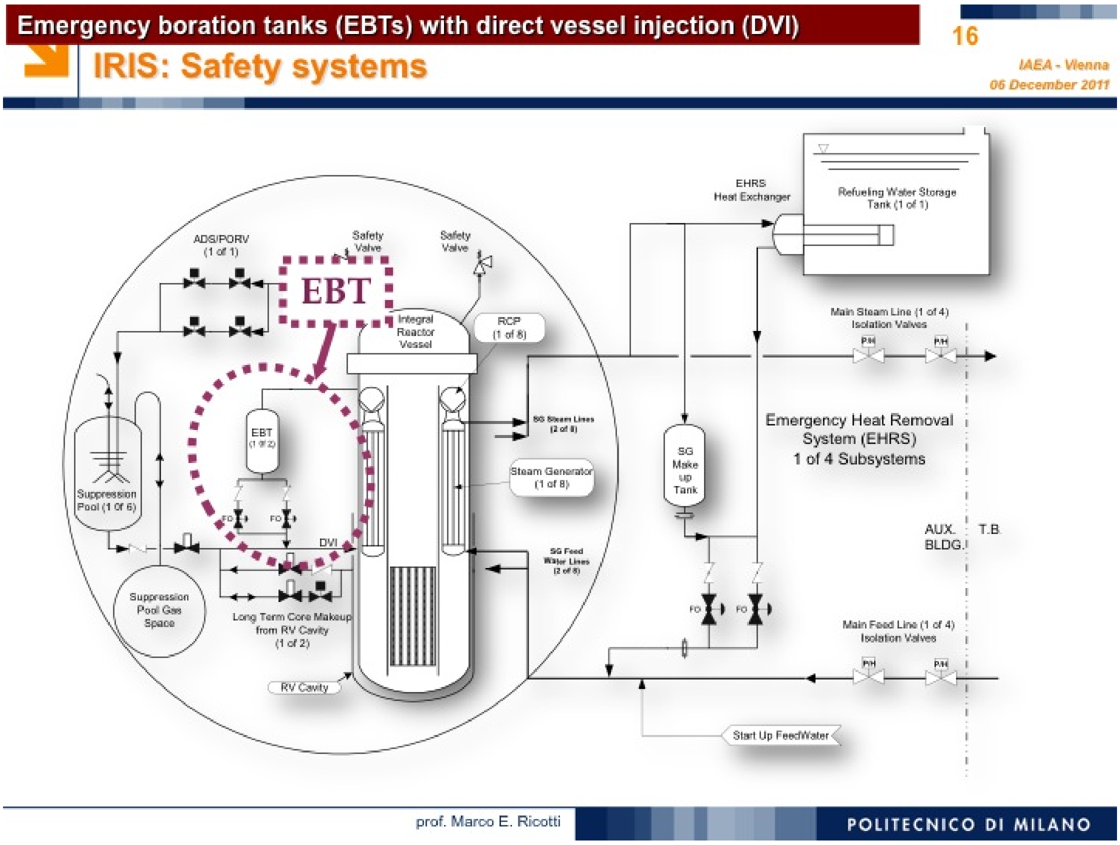
Emergency boration tanks (EBTs) with direct vessel injection (DVI)
IRIS: Safety systems
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EHRS Heat Exchanger
Refueling Water Storage Tank (1 of 1)
ADS/PORV (1 of 1)
Safety Valve
Safety Valve
EBT
Integral Reactor Vessel
RCP (1 of 8)
Main Steam Line (1 of 4) Isolation Valves
SG Steam Lines (2 of 8)
Steam Generator (1 of 8)
SG Make up Tank
Emergency Heat Removal System (EHRS)
1 of 4 Subsystems
Suppression Pool (1 Of 6)
DVI
SG Feed Water Lines (2 of 8)
AUX. BLDG.
T.B.
Suppression Pool Gas Space
Long Term Core Makeup from RV Cavity (1 of 2)
Main Feed Line (1 of 4) Isolation Valves
RV Cavity
Start Up FeedWater
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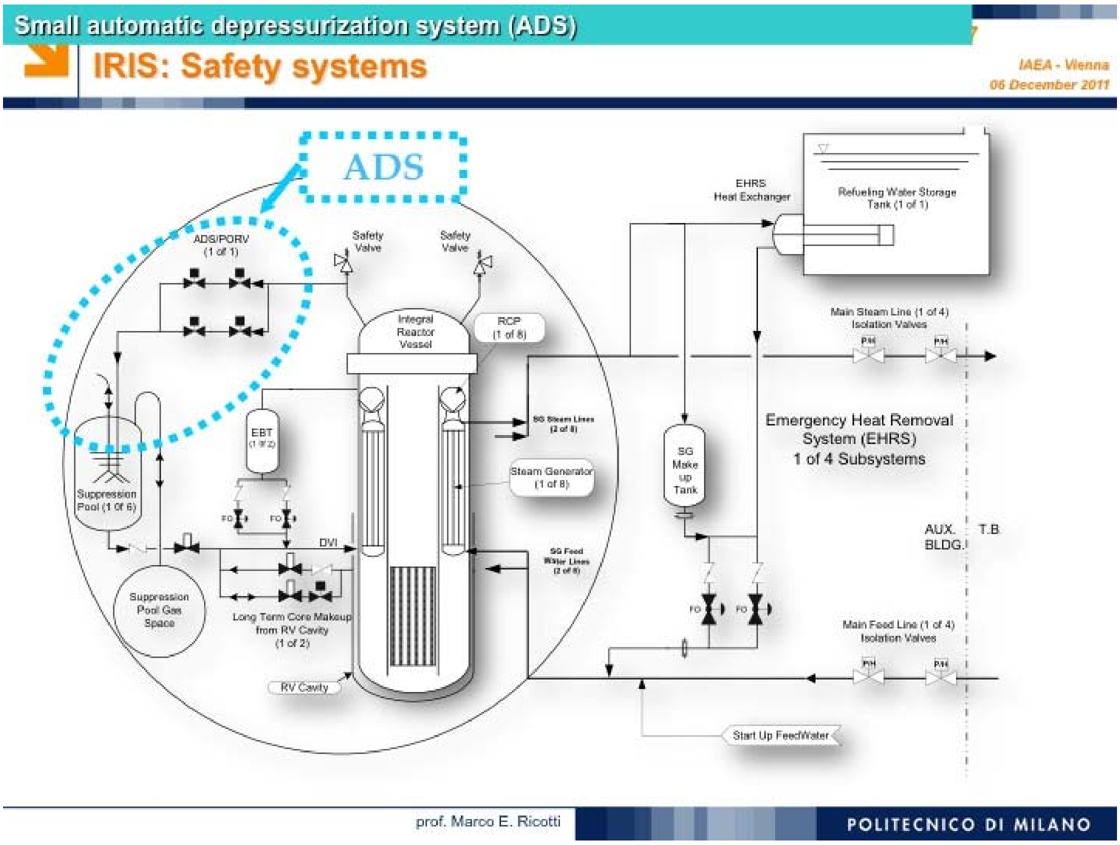
Small automatic depressurization system (ADS)
IRIS: Safety systems
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ADS
ADS/PORV (1 of 1)
Safety Valve
Safety Valve
Integral Reactor Vessel
RCP (1 of 8)
EHRS Heat Exchanger
Refueling Water Storage Tank (1 of 1)
Main Steam Line (1 of 4) Isolation Valves
SG Steam Lines (2 of 8)
Steam Generator (1 of 8)
SG Make up Tank
Emergency Heat Removal System (EHRS) 1 of 4 Subsystems
EBT
Suppression Pool (1 of 6)
DVI
SG Feed Water Lines (2 of 8)
AUX. BLDG.
T.B.
Suppression Pool Gas Space
Long Term Core Makeup from RV Cavity (1 of 2)
Main Feed Line (1 of 4) Isolation Valves
RV Cavity
Start Up FeedWater
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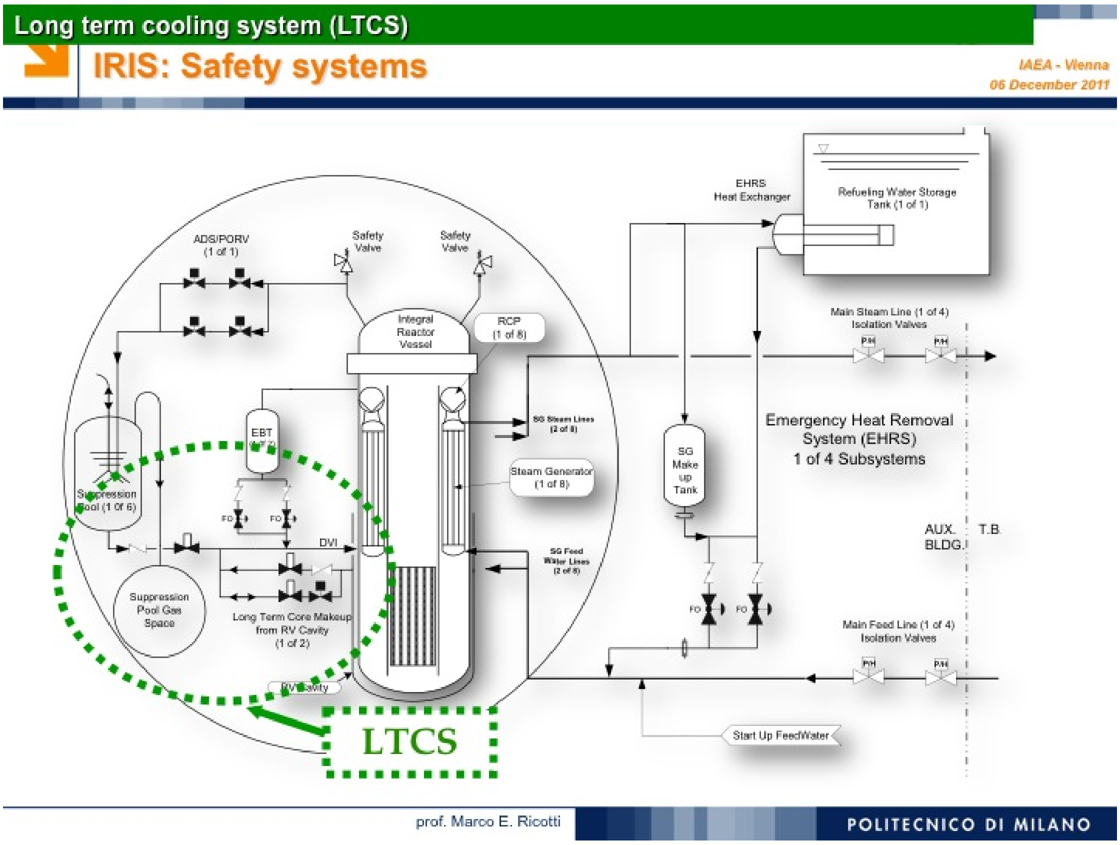
Long term cooling system (LTCS)
IRIS: Safety systems
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ADS/PORV (1 of 1)
Safety Valve
Safety Valve
Integral Reactor Vessel
RCP (1 of 8)
EHRS Heat Exchanger
Refueling Water Storage Tank (1 of 1)
Main Steam Line (1 of 4) Isolation Valves
SG Steam Lines (2 of 8)
Steam Generator (1 of 8)
SG Make up Tank
Emergency Heat Removal System (EHRS) 1 of 4 Subsystems
EBT
DVI
SG Feed Water Lines (2 of 8)
AUX. BLDG.
T.B.
Suppression Pool Gas Space
Long Term Core Makeup from RV Cavity (1 of 2)
Main Feed Line (1 of 4) Isolation Valves
Start Up FeedWater
LTCS
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Safety Systems and Functions

Emergency Heat Removal System (EHRS), 4 trains (redundant; only 1 needed to reject decay heat)
- Safety grade decay heat removal following SLB, FLB, LOHS events (2 trains actuated)
- Reactor and containment depressurization/cooling following LOCA events (4 trains actuated)

Main Feed and Steam Isolation Valves (MFIV/MSIV), redundant and fast closing
- Provides isolation following Steam Generator Tube Rupture event - terminating leak
- Part of EHRS actuation

Automatic Depressurization System (ADS), 1 stage
- Assists EHRS to equalize RV and containment pressures following LOCAs at low RV locations

Emergency Boration Tank (EBT), 2 tanks (redundant)
- Borates primary system to maintain reactor subcritical at low temperatures
- Provides diverse means of shutdown for ATWS events
- Provides a limited amount of water makeup following LOCA and cooldown event

Long Term Core Makeup System (LTCMS), 2 trains (redundant)
- Provide passive, long term, water makeup to RV from reactor cavity and suppression pools

Safety Systems and Functions (Cont'd)

Containment System
- **High Design Pressure (12 bar_g/175 psig) Steel Shell**
  - Pressurization following LOCA reduces break flow
  - Penetrations isolated automatically on high-high pressure
  - Low leakage - limits offsite dose
- **Suppression Pool**
  - Limits containment pressurization to 8 bar_g, following worst DBA
  - Floods RV cavity after pressure suppression function completed
  - Source of gravity-driven, borated, makeup water to RV
- **Reactor Vessel Cavity**
  - Assures bottom 1/3 of vessel externally flooded following LOCAs
  - Source of gravity-driven, borated, makeup water to RV for unlimited time

Refueling Water Storage Tank
- Provides out-of-containment heat sink for EHRS HXs
- Source of borated water for refueling and heat sink for shutdown accidents

IRIS: SBLOCA safety strategy

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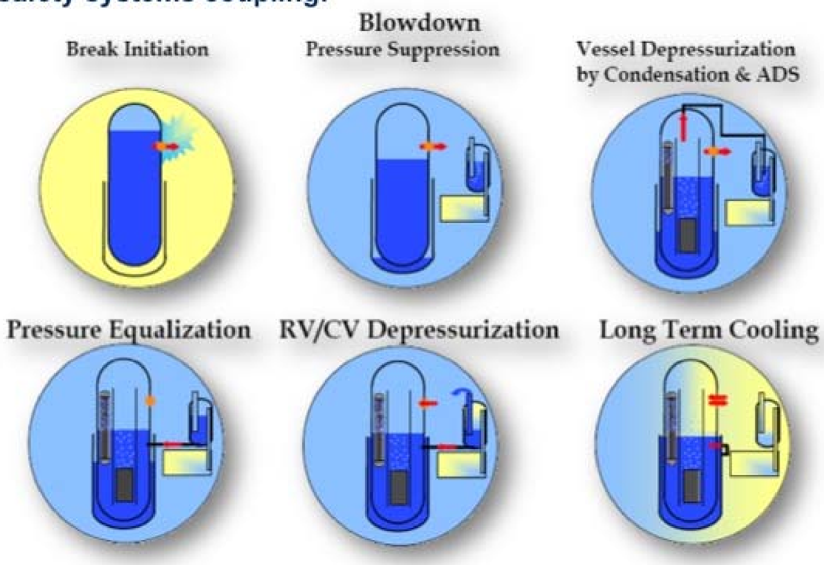
- **High pressure suppression containment + primary vessel + passive safety systems coupling:**



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SAFETY APPROACH

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- **Safety-By-Design approach**
- **Active, non-safety systems have passive, safety-related back-up to perform nuclear safety functions**
  - Safety functions automatically actuated, no reliance on operator action
  - Passive features actuated by stored energy (batteries, compressed air)
  - Once actuated, their continued operation relies only on natural forces (gravity, natural circulation) with no motors, fans, diesels, etc.
- **Core will remain covered under all accident sequences**
- **Heat sink designed to provide cooling for 7 days without operator action or off-site assistance for replenishing**
- **Additional diverse systems to minimize probability of Core Damage/Radioactivity Release**

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IRIS: Pressure Vessel Embrittlement eliminated

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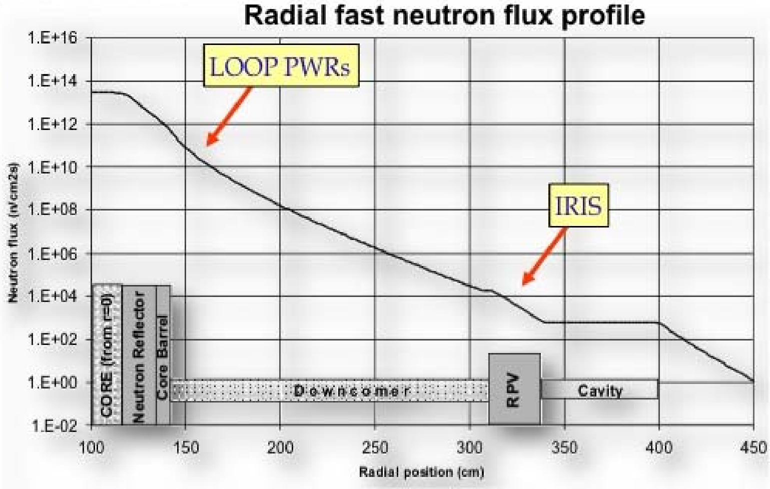
SG modules ➔ large Downcomer water thickness (core-vessel): 1.7 m

- Fast n flux on vessel: **~10^5 times less than in current PWRs** → "Cold vessel"
- **External dose practically avoided**
- **No embrittlement, no surveillance**
- "Aeternal" Vessel
- Decommissioning simplified

Radial fast neutron flux profile



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IRIS: Risk-Informed PROCESS

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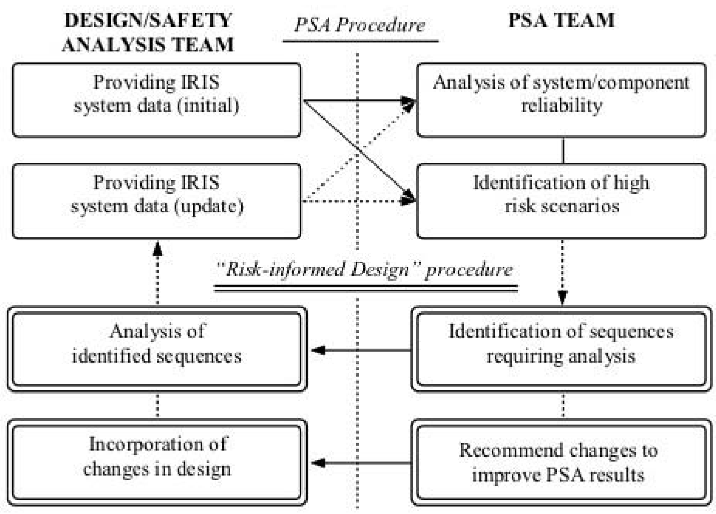
- **Deterministic safety analysis** and **PSA calculation during the development of the preliminary design**



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IRIS: Risk-Informed process – CDF reduction

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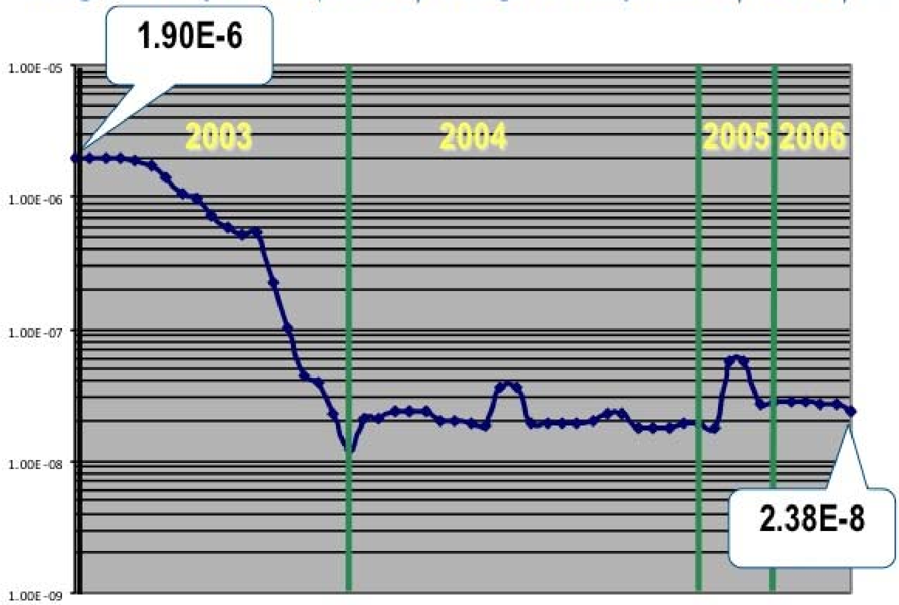
Design development ➡ PSA ➡ Design development ➡ PSA ➡ ...



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IRIS: auxiliary building seismically isolated

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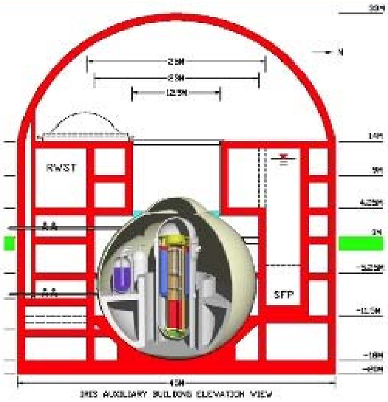
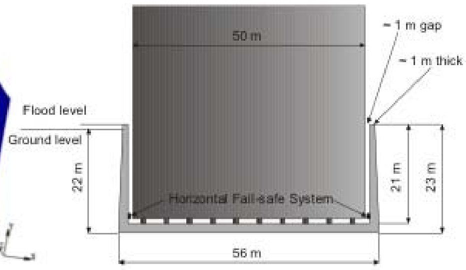
Numerical and experimental study:

- 120 rubber-steel isolators (High Damping Rubber Bearings-HDRBs), 1 m diam, 84 mm height
- PGA = 0.3 g, isolation frequency = 0.7 Hz
  - lateral displacements < 12 cm
  - 25% reduction PGA at vessel supports **level**, 5 times reduction at roof level
- **HDRB** experimental campaign already carried out





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IRIS: results of the Safety-by-Design™ & Risk-Informed approaches

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Criterion	Typical Advanced LWRs	IRIS
Defense-in-Depth (DID)	Redundant and/or diverse active systems or Passive systems	No active 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)	~10^{-5} - 10^{-7} events per year	~10^{-8} events per year
Large Early Release Frequency (LERF)	~10^{-6} - 10^{-8} events per year	~10^{-9} events per year

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IRIS Safety-by-Design™: The 5 Most Severe Accident Precursors since 1979 as ranked by NRC

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(Cannot Occur or are Intrinsically Mitigated in IRIS)

Rank	Year	Plant	Accident Precursor	IRIS
1	1979	Three Mile Island	Pressurizer Power Operated Relief Valve stuck open **Partial Core Meltdown occurred**	Same accident **cannot occur**: IRIS has integral pressurizer and no power operated relief valve. Similar accidents (any small break LOCA) have intrinsic mitigation (core always covered)
2	1985	Davis Besse	Total Loss of Feedwater (main and auxiliary) **Core Damage Probability = $7*10^{-2}$**	**Cannot occur**: IRIS safety grade decay heat removal system (EHRS) does not require any source of water injection to the steam generators; also, increased primary side thermal inertia inherently mitigate loss of main feedwater events
3	1981	Brunswick	Residual Heat Removal (RHR) U-tubes Heat Exchanger Failure due to blockage (oyster shells) **Core Damage Probability = $9*10^{-3}$**	BWR Event; **eliminated by design** and operational procedures for RHR, **inherent mitigating features**
4	1991	Shearon Harris	Unavailability of high pressure safety injection (HPSI) pump **Core Damage Probability = $6*10^{-3}$**	**Cannot occur**: IRIS does not need, thus does not have safety related HPSI pumps
5	2002	Davis Besse	Degraded vessel head; unqualified coatings and debris in containment; potential HPSI pump failure during recirculation **Core Damage Probability = $6*10^{-3}$**	**Cannot occur**: IRIS has no vessel head penetrations by adoption of internal CRDMs and has no HPSI pumps

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IRIS response to Fukushima-like events

- Full exploitation of simple, passive safety systems, no need for energy/electricity supply
- Grace period: >1 week; beyond 1 week: air-cooling, eventually supply of water (not electricity or oil for DG) in the Auxiliary Building (not in the containment), plug-in solutions under study
- Fully seismically isolated Auxiliary Building

OPERATION & MAINTENANCE

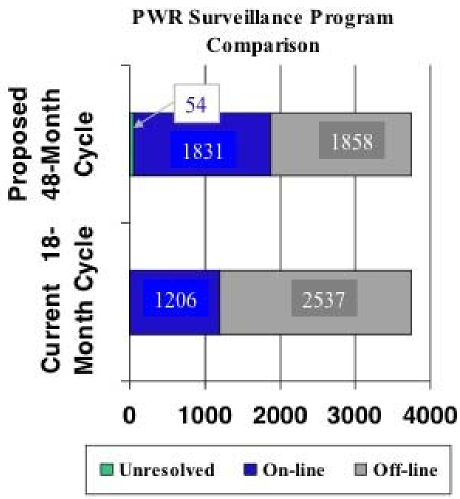
•Main Goal: Perform maintenance shutdowns no sooner than each 48 months

•MIT study completed in 1996 investigated extending PWR to 48 month cycle

•3743 maintenance items (on-line and off-line) identified

•By recategorizing 625 items from off-line to on-line, only 54 were left unresolved for PWR

•Accounting for IRIS configuration, unresolved items are reduced to 7



After MIT study, only 7 items unresolved

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1. Relief valve testing
2. Steam generator inspection
3. Main condenser cleaning
4. Safety system testing
5. Main turbine throttle control
6. Rod control system testing
7. Reduced power window items

In 2003, TVA addressed and resolved or found resolution programmes for all 7 items

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IRIS: EPZ reduction

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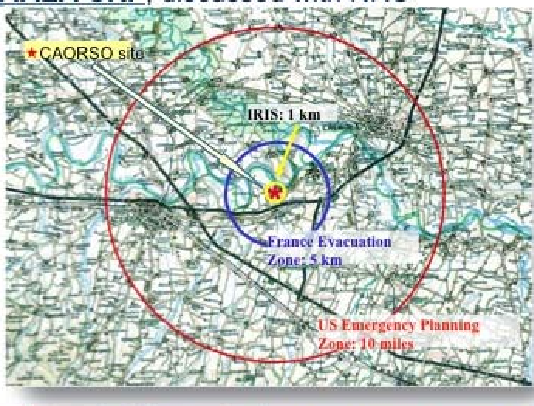
Once you have reached a sound safety level for SMR, to support the claim "EPZ reduction", a new scientific-based approach/method is needed

Risk-Informed approach: No Emergency Planning Zone

- Elimination/strong reduction (NPP fences) of the Emerg. Planning Zone
- New procedure developed: **Deterministic + Probabilistic** evaluation of the EPZ, as a function of radiation dose limit and NPP safety level
- **Procedure developed within a IAEA CRP**; discussed with NRC



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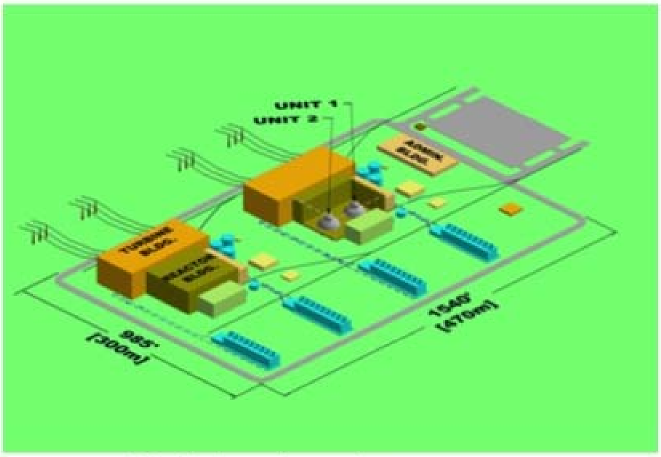
IRIS - Site Plot Arrangement Example



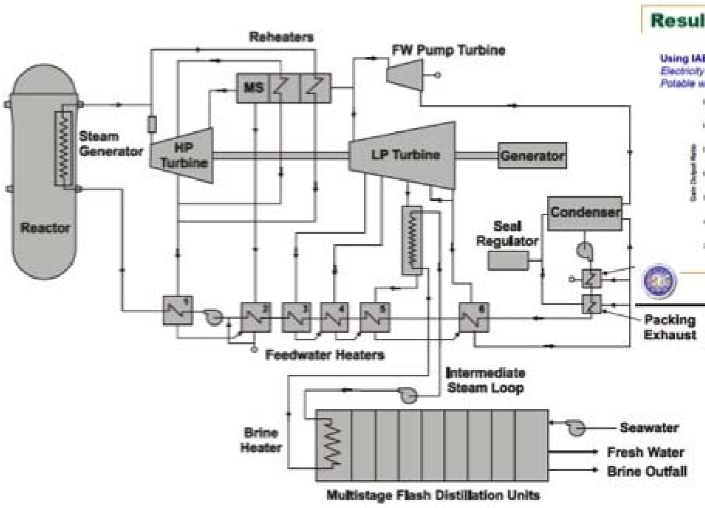
Multiple twin-units
(2 twin-units, 1340 MWe)

- Very compact
- Low profile
- Modular construction
- Shared buildings and systems (except containment)

- Also well suited for co-gen (desalination, district heating, agro-industrial steam)

Co-generation: Desalination, District Heating, Ethanol production

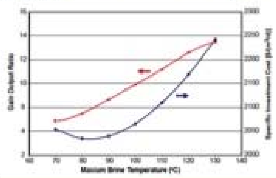
IRIS Coupled to an MSF Plant



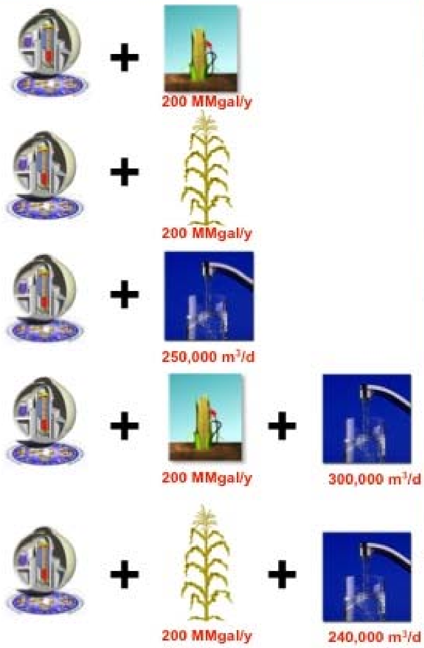
Results for IRIS + MSF Plant

Using IAEA DEEP Code:

Electricity cost (using standard PWR option)	0.038	$/kWh(e)
Potable water cost	1.44	$/m³



Ethanol + Desalination: Outputs and Energy Balance

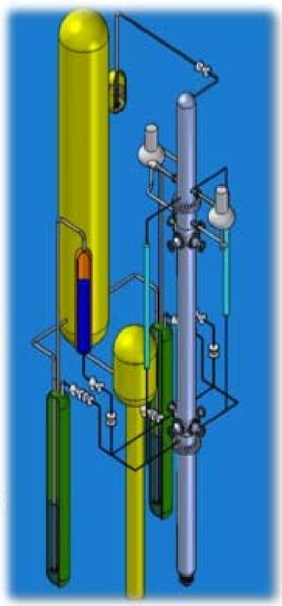


Exchanged Thermal Power		
Ethanol 256 MW_{th}	(10% Surge capacity)	270 MWe
Ethanol + HP bleeding 385 MW_{th}	(10% Surge capacity)	240 MWe
Desalination 520 MW_{th}		208 MWe
Ethanol 253 MW_{th}	(10% Surge capacity)	110 MWe
Desalination 635 MW_{th}		
Ethanol + HP bleeding 389 MW_{th}	(10% Surge capacity)	105 MWe
Desalination 506 MW_{th}		

IRIS Prototypic Components & Test Facilities for Design Certification

Prototypic 20 MW bundle, tested originally for ISIS Ansaldo reactor and having the same diameter as one of the IRIS Steam Generators

IETI (SIET Italy) Facility: thermal-fluid-dynamics experiments on a full-scale helical-coil tube of the IRIS Reactor Steam Generator



SPES-3 at SIET (Piacenza, Italy) will be used to demonstrate IRIS integrated system performance and to support design approval (AP600 testing was performed at SIET)

IRIS: experimental campaigns on SG and Safety Systems (basic set)

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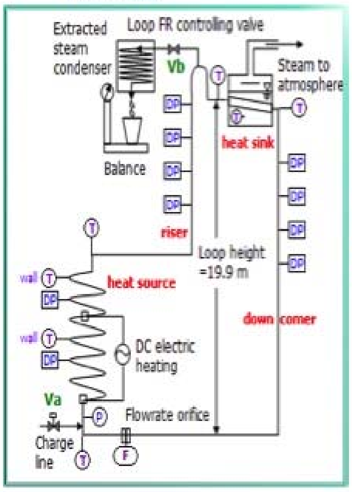
ENEA + POLIMI in collaboration with SIET labs (Piacenza)

1. **Steam generator helical coil tubes – full scale**
2. **EHRS passive safety systems – scaled on power/ volume**



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SPES-3 facility

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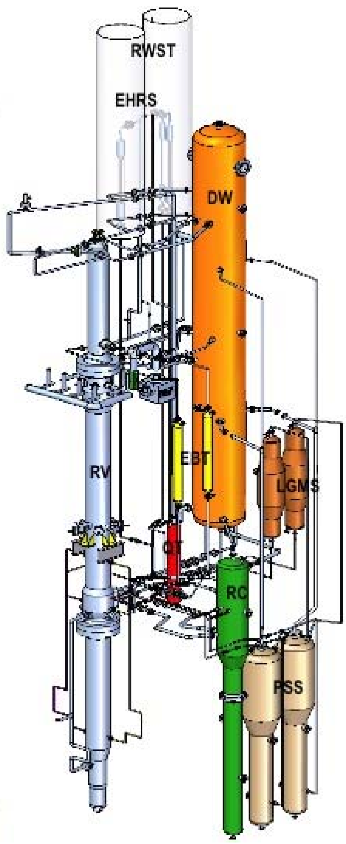
Primary circuit

RV and internals:
core simulator (electrically heated rod bundle), riser and CRDM zone, pressurizer, downcomer, riser-to-downcomer connection check valves, lower plenum,
an outer circulation pump (simulating eight IRIS pumps)

Secondary circuits (three loops simulating four IRIS loops)
- **Steam generators (3 SGs simulating 8: 2/8, 2/8, 4/8)**
- **Feed Lines**
- **Steam Lines**

Emergency systems components and piping
- **EBT** (2 Emergency Boration Tanks)
- **EHRS** (3 Emergency Heat Removal Systems)
- **RWST** (2 Refuelling Water Storage Tanks)
- **ADS** (2 trains Automatic Depressurization Systems, simulating three)
- **DVI** (2 Direct Vessel Injection lines)

Containment system simulated by separate tanks and piping
- **DW** (1 Dry Well),
- **QT** (1 Quench Tank),
- **PSS** (2 Pressure Suppression Systems)
- **RC** (1 Reactor Cavity)
- **LGMS** (2 Long Term Gravity Make-up Systems)
- **PCC** (1 Passive Containment Cooling inside the DW)



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SPES3 facility design and construction steps

IAEA - Vienna
06 December 2011

- Technical specification for IRIS testing;
- SPES3 facility preliminary design (layout, components, instrumentation);
- RELAP5 simulation of SPES3;
- Comparison with IRIS results by RELAP5 and GOTHIC coupled code;
- Review of the Technical specification to adjust component volumes.
- SPES-3 design modification and optimization to match the IRIS results.
- RV final design by Mangiarotti Nuclear;
- Containment components preliminary design by SIET; final design by outer suppliers → assembling/installation by mid-2012;
- Supporting tests on: electrical heaters simulating the reactor core, single and double helicoidal tube of the IRIS SG, EHRS system tests;
- Data Acquisition System definition by SIET (National Instruments products);
- Special instrumentation for two-phase flow measures under development by SIET/POLITO;
- Load bearing structure design and construction by outer suppliers.

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SPES-3: area preparation for components installation, heating rods testing

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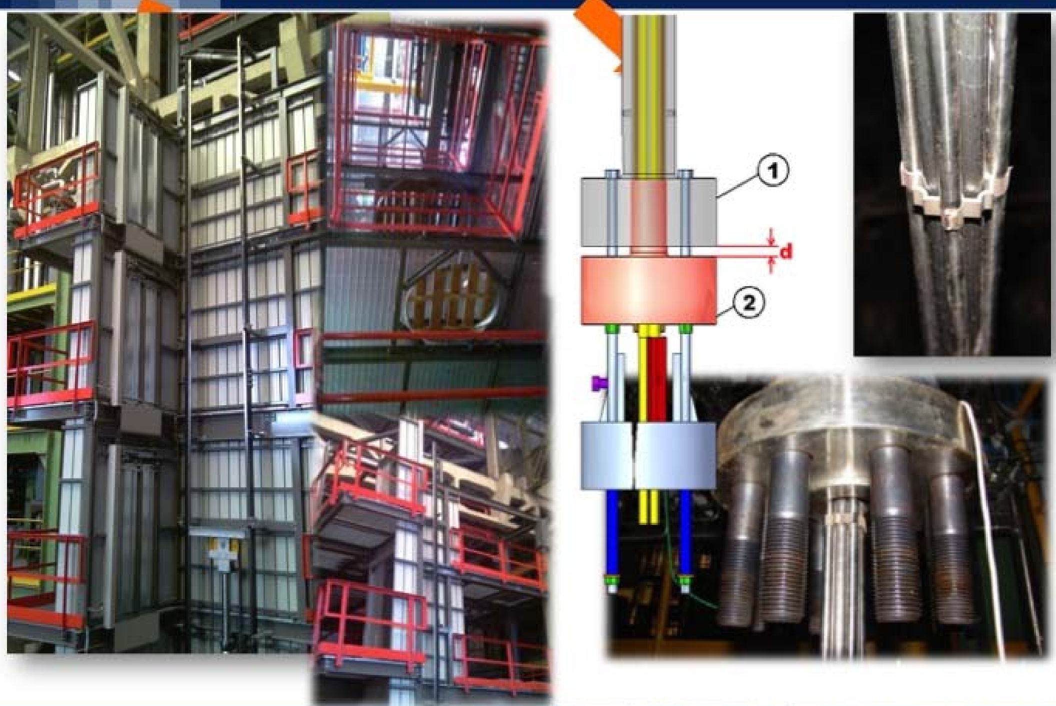

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SPES3 nodalization: Primary, secondary and RWST (RELAP, GOTHIC, TRACE)

(11/21)

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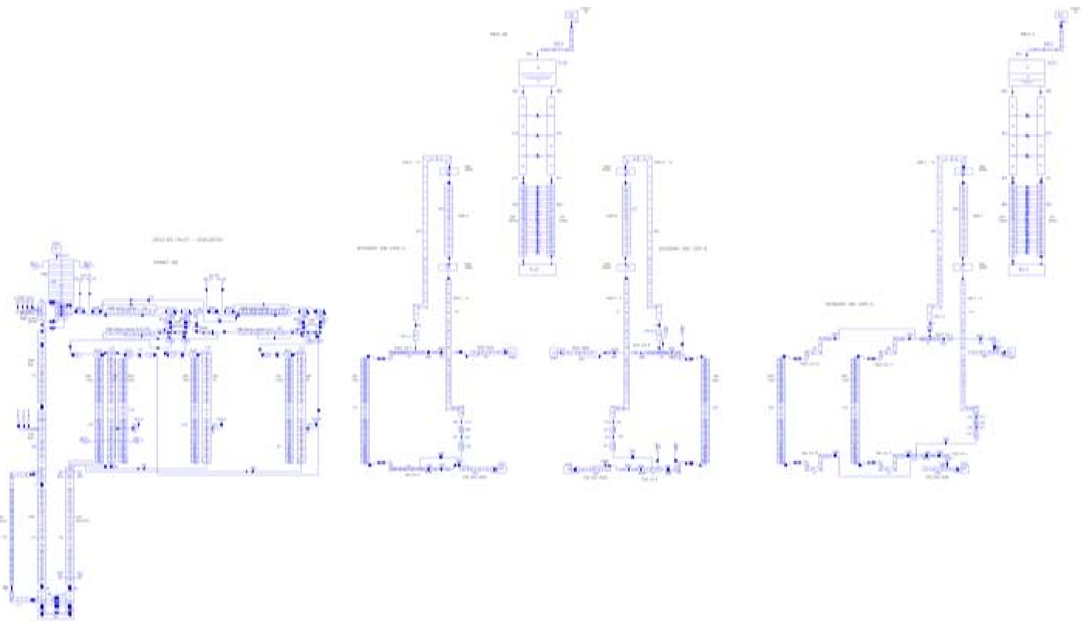

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SPES3 nodalization: containment (RELAP, GOTHIC, TRACE)

(12/21)

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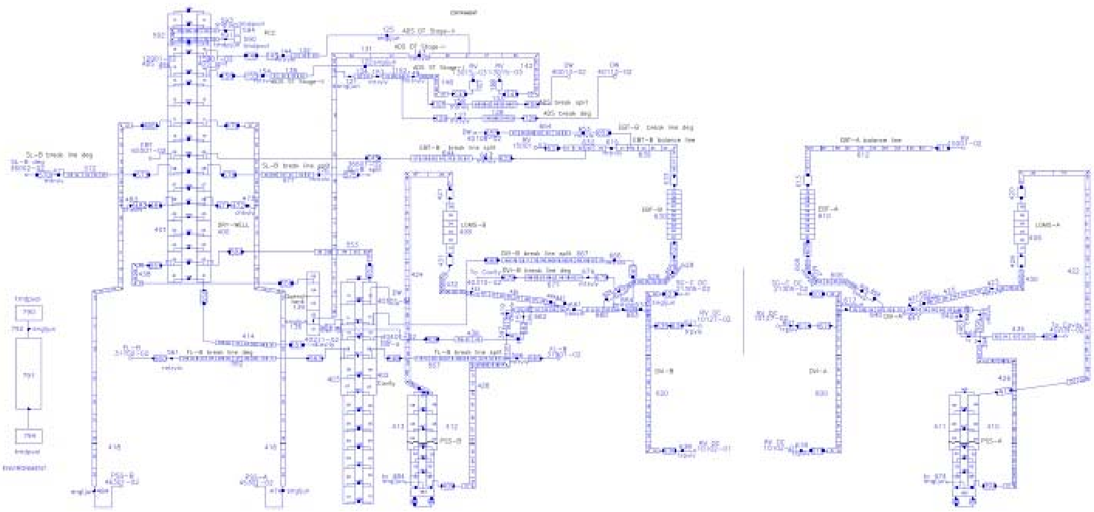

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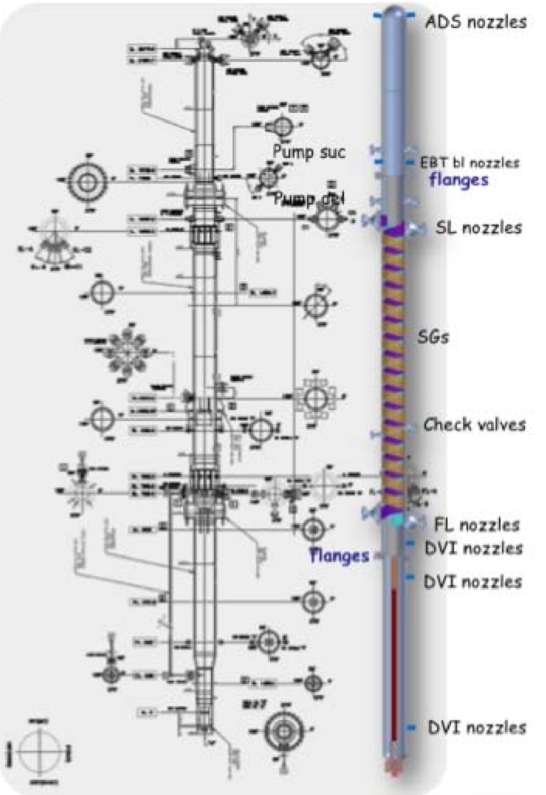
SPES-3: reactor simulator

- 3 forged pieces + 4 helical coil SG simulators
- Detailed design provided by italian manufacturing enterprises
- Co-funding (50%) by same industries
- Estimated cost: >5 M€
- Co-funding: discussions with Regional Government, Ministry of Economic Development
- Partnership: Industries, ENEA, SIET labs, POLIMI



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IRIS R&D on SMRs' ECONOMICS

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Multi-dimensional concept:

QUANTITATIVE FACTORS: Technological + Financials.

- Discounted Cash Flow Model captures: Net Present Value, Internal Rate of Return, Levelized Unit Electricity Cost, Pay Back Time, etc.

RISK EVALUATION: uncertainties in the input/ output parameters.

- Sensitivity to different scenario conditions, different investment strategies
- Stochastic distribution of input/output parameters and variance analysis

"EXTERNAL FACTORS": non-monetary strengths and weaknesses, not fully quantifiable, but relevant for the success of the project.

- Typical features of strategic projects

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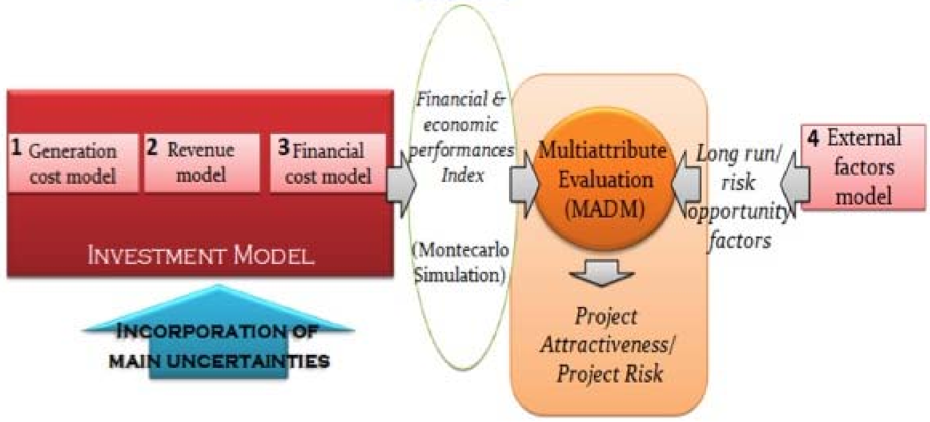
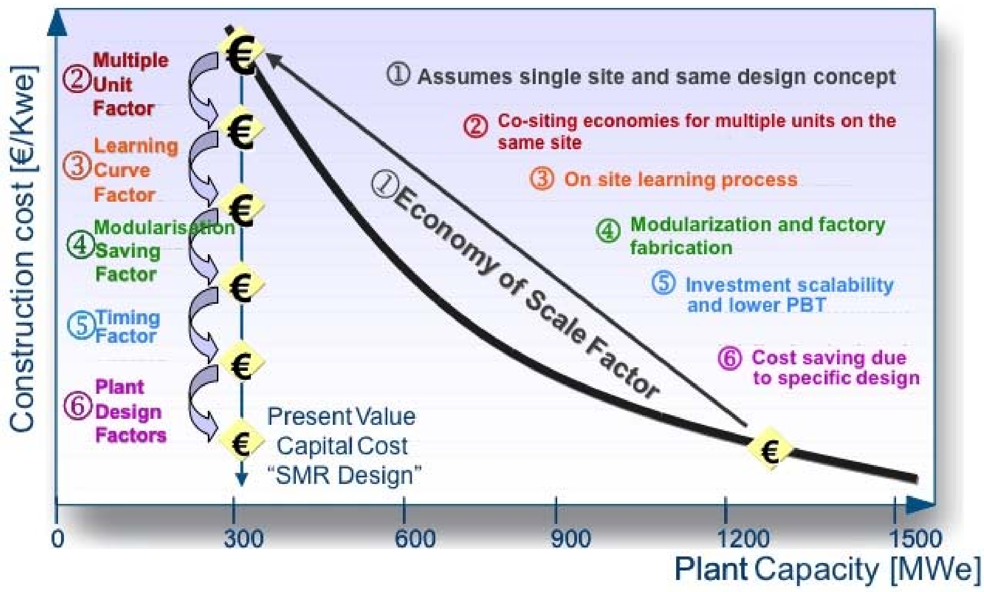
INCAS as a tool for an integrated evaluation

INtegrated model for the **C**ompetitiveness **A**nalysis of **S**mall-medium modular reactors



INCAS conceived for the competitiveness analysis of SMRs vs. LR (IRIS project and IAEA CRP)
Economic parametric model to calculate capital costs
"Economy of Multiples" vs. "Economy of Scale"

INVESTMENT MODEL: parametric model for capital costs



INVESTMENT MODEL: parametric model for capital costs

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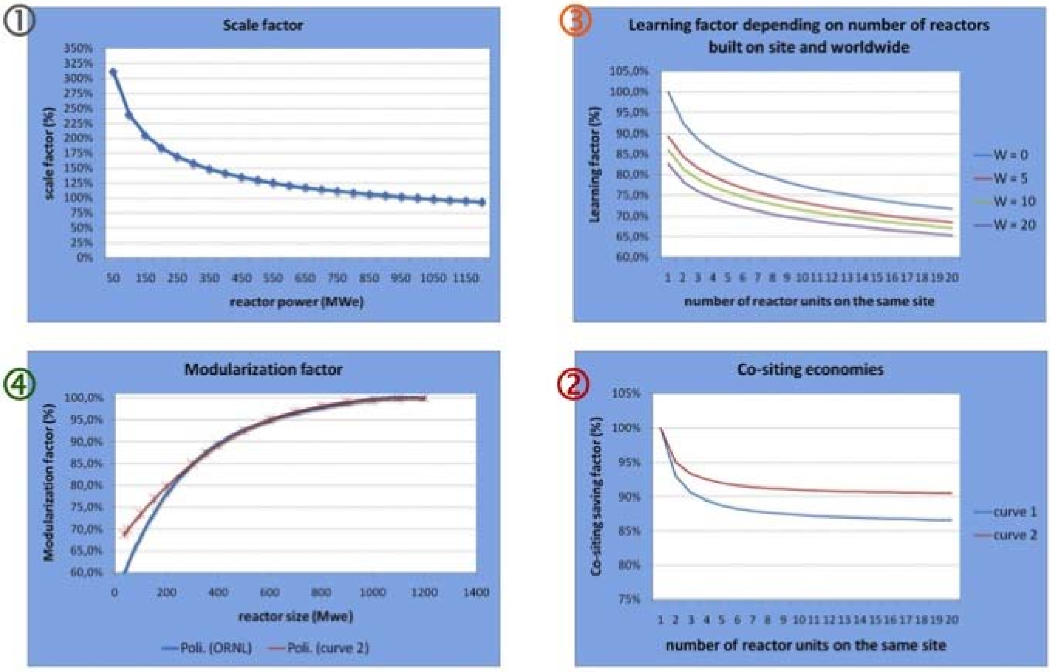

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INVESTMENT MODEL: other modelling assumptions

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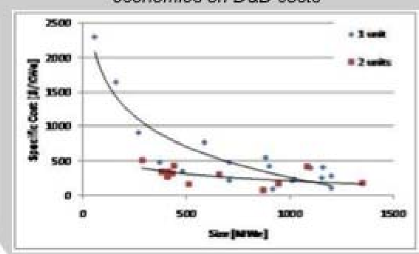
⑥ Design Saving factor:
"expert elicitation",
base assumption: lower NPP size ⇒ enhanced design simplification

O&M and D&D: (dis)economy of scale for SMRs, learning and co-siting economies apply as well

Diseconomy of scale and co-siting economies on D&D costs



- **Revenue Model**: based on capacity factor (differential between LR and SMR) and constant electricity price in real monetary terms
  - *INCAS-revenue model could be linked to country-specific forecast models (electricity price time series)*
- **Financial Model**: based on Discounted Cash Flow with cash-transfer mechanism between successive NPP units
  - "Construction of a new NPP is financed first with cash flow from operation of early deployed units (self-financing), then with new debt and equity financing mix"
- **"Top-Down" approach** (substantial lack of suitable, open data on current SMR projects)

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SMRs comparison, size & design saving factor: trade-off investigation

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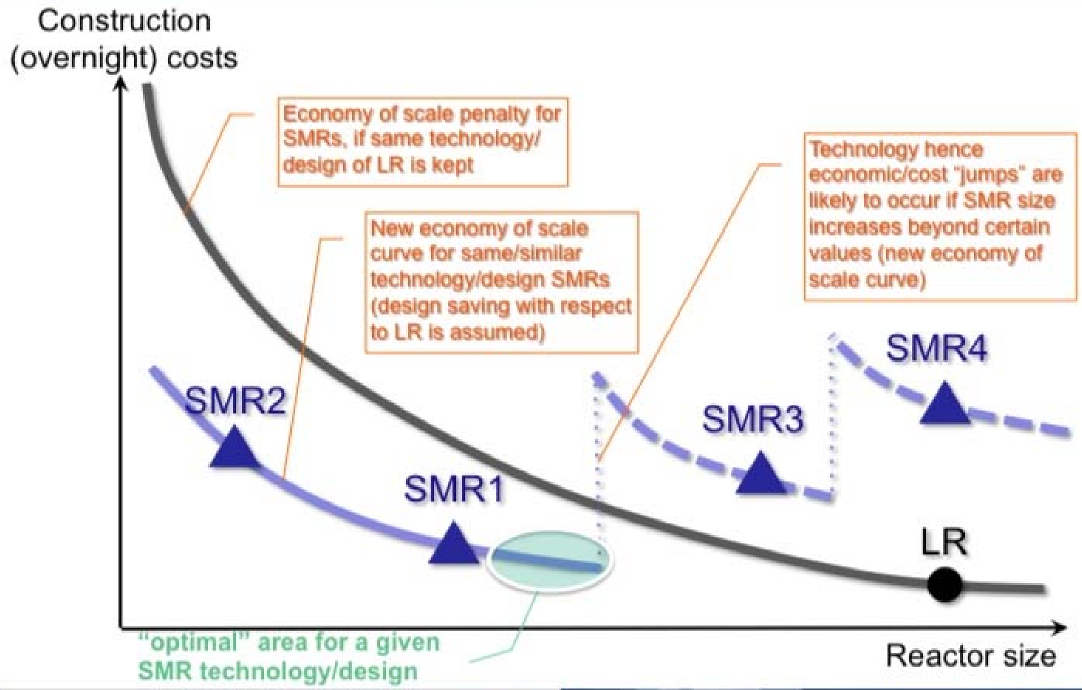

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Conclusions on economics

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INCAS conceived as a tool for comparative evaluation of economic performance of SMR versus LR: "Economy of multiples" vs. "Economy of Scale".

- *Preliminary results: "**scenarios seem to exist where deployment of multiple SMRs may compensate for loss of economy of scale** (vs. LR of equivalent power), i.e. economic performance gap reduction"*

INCAS ver.1.1 is currently under testing / validation at IAEA-PESS and at JRC-Petten.

Further developments:

- **from "Top-Down" to "Bottom-Up" approach (SMR design - related costs breakdown)**
- uncertainties/sensitivity analysis & risk evaluation
- external factors & MADM
- real options model

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R&D role in the IRIS project

Universities' collaboration:

- **Within University labs and/or through Company internships**
- **Thesis work (3-6-12 months), PhD program (6 months-3 years)**
- **Post-graduation period (6 month-1 year)**

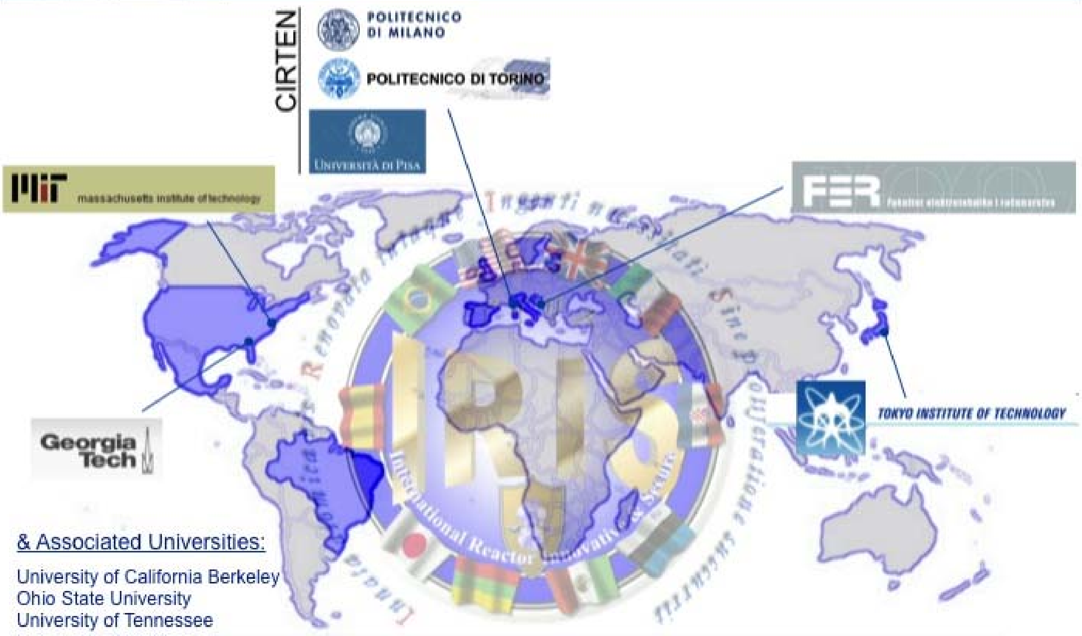
>120 students worked on IRIS

Professors/permanent researchers involved: >25

Open Literature – Open Knowledge:
~400 papers

(2 reference papers on 10 years of R&D history on IRIS to be published in apr-may 2012 on “Nuclear Technology” - ANS)

The “IRIS Universities”



& Associated Universities:

University of California Berkeley
Ohio State University
University of Tennessee
University of Michigan
Iowa State University
University of Illinois

Dimension of the students' involvement

University	Under-graduate	Master	Doctorate& post-doc
FER - Univ. of Zagreb	3	1	3
Georgia Tech		2	
Massachusetts Inst. of Technology	1	4	1
Polytechnic of Milan (CIRTEN)	1	28	10
Polytechnic of Turin (CIRTEN)		3	
Univ. of Pisa (CIRTEN)	28	8	1
Tokyo Inst. of Technology		6	6
Univ. of California at Berkeley		2	
Univ. of Tennessee	1	4	
Ohio State Univ.		4	1
Univ. of Michigan	6	2	
Sub-total	*40*	*63*	*22*
TOTAL		125	

Feedbacks from ten years of SMR R&D activity

- **"(re)think different" - a non-bias approach**
- **innovation - no technological jump**
- **international cooperation and team**
- **involve young, talented, motivated people**
- **address all items at the same time ("parallel & loop design")**

CRITICAL ITEMS

On the path to deployment (currently in stand-by mode):

- **find a vendor**
- **keep open collaboration approach (to prepare for international market)**
- **involve countries interested into deployment (to share R&D activities, knowledge)**
- **complete large scale testing phase for licensing purposes**

Newcomer Countries’ Exercise and Feedback Presentation
Friday, 9 December 2011:

Group C for LWR - SMRs

Economics, Constructability

Presenter: Francis Ibitoye (Nigeria)

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Structure of Group C for LWR – SMRs

- SMR Designs, Technology Developers:
  - **IRIS**, *Politecnico di Milano* – Italy (M. Ricotti)
  - **NuScale**, NuScale Power – USA (J.N. Reyes)
  - **Westinghouse SMR**, Westinghouse – USA (M. Anness)

Newcomer Countries:

- Bangladesh
- Kenya
- Nigeria
- Thailand
- Uruguay

- Expert Facilitators:
  - J. Cleveland (Consultant, Austria)
  - D.T. Ingersoll (ORNL, USA)

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Assessment Summary on IRIS (1)

- On Economics
  - Capital cost: A simulation tool was used to estimate costs in a top-down approach. Penalty is of the order of 70% but can be reduced to 7% by multiple saving factors. Need to conduct a bottom-up approach.
  - Preliminary estimate of overnight cost is 7-10% more than for LRs in terms of $/kW installed.
  - Costs will be reduced if SMRs are constructed in sequence. Costs can be lower than for an equivalent LR on the long run.
  - Fuel costs for multiple units should be about the same for an equivalent LR.
  - O&M: e.g consider 4 SMRs; penalty: 4 control rooms, staffing. Compared with one large reactor, O&M cost can be reduced for equivalent SMRs because of higher CF. Shutting down 1 unit for maintenance still enable generation from 3 other units. This may eventually override the penalty.
  - Need to compare costs of SMRs with other options, not just LRs.
  - Because of much lower n flux on the PV, decommissioning costs should be lower than for LRs

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Assessment Summary on IRIS (2)

- On Constructability
  - Modularization: Each IRIS system is an independent plant, in terms of safety systems and control.
  - Key systems are separated. Administration and services can be shared.
  - The footprint of 4 SMRs is about the same as that for 1 LR.
  - Construction time: 3 years is assumed, but this is not yet optimized.

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Assessment Summary on NuScale (1)

- On Economics
  - Need to understand what is included in the costs.
  - Costs can be reduced by "economy of small"
    - Design Simplicity and Scalability
    - Simpler Safety Systems and Analyses
    - Factory Fabrication
    - Modular Parallel Construction
    - Innovative Operations
  - O&M cost: cost of labour different for different countries. Savings on staffing and infrastructure, since a 12-module unit can be controlled from one control room.
  - Decommissioning cost is only small fraction of total cost. Module includes PV & containment. Decommissioning is matter of lifting out the module. A new module can actually be reinstalled in same location immediately.
  - Cost estimates made available only on request following a non-disclosure agreement.

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Assessment Summary on NuScale (2)

- On Constructability
  - Factory constructed
  - Units can be transported by truck, rail or barge.
  - Skid-mounted turbines and easily replaceable.
  - Highly scalable
  - Adding more units is an installation, not a major construction project.
  - Construction time 36 months for a base unit of 12 modules

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Assessment Summary on Westinghouse SMR (1)

- On Economics
  - Capital costs 75% of total cost. High level of certainty for the estimates.
  - Operating costs 15%. B/c of less systems, passive safety systems, reduction in the amount of cables, length of piping etc. result in lower O&M costs. Reduction of the amount of labour.
  - Standardization: robust global network for replacement of components.
  - Fuel costs 10%: No striking differences b/w conventional LWR and SMR in terms of burnup; security of fuel supply and price stability reduces prices uncertainties.
  - Localization: cost efficiency will mean less localization. Simplifications, more local resources to be used hopefully in the future.
  - Detailed cost estimates can be released to potential clients after signing a confidentiality agreement.

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Assessment Summary on Westinghouse SMR (2)

- On Constructability
  - Draws experience from on-going AP1000 projects in US and China. Construction time is 40 mths for AP1000.
  - Construction time for SMR : 18 -24 mths for first module, and12 mths for site excavation before construction.
  - Cost effective deployment scheme: optimizing use of labour, concrete, welders etc. Local industry can be used for deployment

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Specific Requirements from Newcomer Countries (if any)

- Bangladesh
  - Construction time and capital costs are main concerns
  - Regulatory requirement does not prevent us from turning to nuclear.
  - Spent fuel and High Level waste concerns
  - Support for financing.
- Kenya
  - Regulatory authority since 1982. Collaboration with US NRC. Nuclear option already identified in a national energy master plan. NEPIO also setup. At tail phase of milestone 1.
  - Bilateral agreements preferred compared to multilateral approach through IAEA.
  - Need for information about the price that countries are expected to offer.
- Nigeria
  - Wants developers to take into consideration the adverse weather conditions in some countries – high ambient temperature and humidity.
  - Need to provide estimates for transportation costs, since these could become quite significant for some locations.
- Thailand
  - If vendors are ready to sell internationally, they should have a proposal for financing options.
- Uruguay
  - Modularization is important because Uruguay has small grid and small population and nuclear contribution can grow as demand grows
  - Constructability: Increase in costs because of delays.

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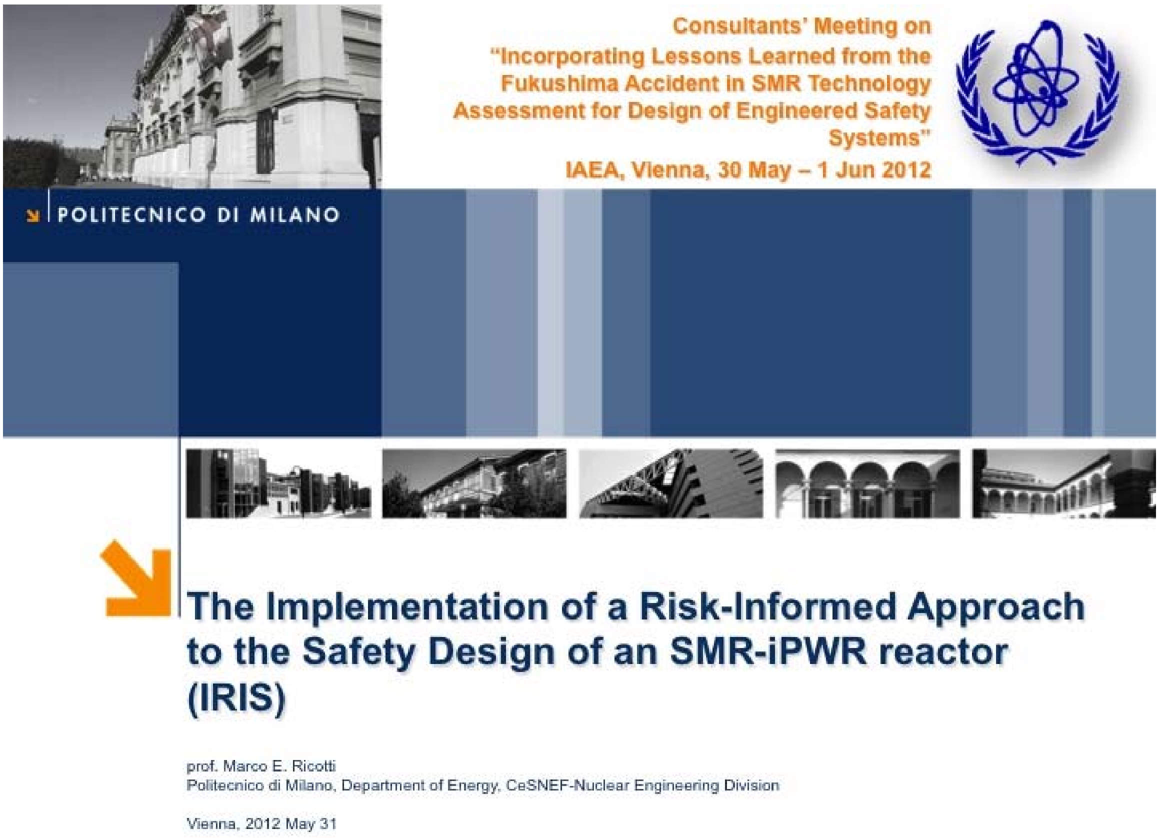
INTERNATIONAL ATOMIC ENERGY AGENCY

Consultants' Meeting on "Incorporating Lessons Learned from the Fukushima Accident in SMR Technology Assessment for Design of Engineered Safety Systems"

IAEA Headquarters, Vienna, Austria, 30 May – 1 June 2012

List of the presentations, contributions and discussions

• Engineered Safety Features adopted in Advanced SMR Designs for Near Term and Future Deployment	**Mr. H. Subki,** NENP/NPTDS
• Overview of the IAEA Activities on Severe Accident Management in response to the Fukushima Accident	**Mr. M. Kim** NSNI/SAS
• Overview of the Recent International R&D Activities on Reactor Safety	**Mr. L. Meyer** NENP/INPRO
• INPRO project on Review of Innovative Reactor Concepts for Prevention and Mitigation of Severe Accidents	
• Applying Lessons-Learned from the Fukushima Accident to Water Cooled Reactor Technology Development	**Mr. K. Yamada** NENP/NPTDS
• What really happened at the Fukushima Daiichi nuclear Power Plants?	**Mr. M. Aritomi** Tokyo Institute of Technology, Japan
• Concepts to Enhance Safety Systems' Performance in SMRs on the Basis of Lessons-Learned from the Fukushima Accident	
• Prevention of recurrence of the Fukushima Accidents	**Mr. M. Aritomi** Tokyo Institute of Technology, Japan
• R&D activities in Japanese universities on reactor safety; advanced study on two-phase flow dynamics	
• Evolution of **BWR** designs and technologies; operating fundamentals; suppression-pool containment performance;	**Mr. W. Marquino** GE Power & Water, USA
• Advanced concepts of passive safety cooling systems of **ESBWR** to cope with various DBA and severe accidents	**Mr. W. Marquino** GE Power & Water, USA
• Design Characteristics and Advanced Safety Features of the **AHWR300-LEU** reactor	**Mr. A. K. Nayak** BARC, India
• **Technical requirements of Newcomer Countries** on Reactor Safety; R&D activities in PRA of small reactors	**Mr. S. Syarip** BATAN, Indonesia
• The Implementation of a Risk-Informed Approach to the Safety Design of the **IRIS** reactor	**Mr. M. Ricotti** Politecnico di Milano, Italy
• Design Characteristics and Advanced Safety Features of the **SMART** reactor	**Mr. S. Choi** KAERI, Republic of Korea
• Provisions for **KLT-40S** Reactor Plant Safety Performance under Extreme External Hazards	**Mr. I. Bylov** and **Mr. K. Veshnyakov** OKBM Afrikantov, Russian Federation
• Discussion on the Available **Deterministic** and **Probabilistic Analyses Methodologies** for Advanced Reactors	All
• Consultants Input to the IAEA on identification of safety lessons-learned to be incorporated in the design of advanced SMRs of integral water-cooled reactor type	All
• Identification of subjects of near-term and long-term international R&D activities in SMR technology development, in the area of advanced engineered safety features designs	All
• Wrap Up Session, Meeting Conclusions and Action Plan	**H. Subki** NENP/NPTDS
• **Closing Remarks**	**T. Koshy,** SH-NPTDS


Consultants' Meeting on
"Incorporating Lessons Learned from the Fukushima Accident in SMR Technology Assessment for Design of Engineered Safety Systems"
IAEA, Vienna, 30 May – 1 Jun 2012
POLITECNICO DI MILANO
The Implementation of a Risk-Informed Approach to the Safety Design of an SMR-iPWR reactor (IRIS)
prof. Marco E. Ricotti
Politecnico di Milano, Department of Energy, CeSNEF-Nuclear Engineering Division
Vienna, 2012 May 31

"Risk-Informed": a suitable/obliged approach after Fukushima events?

2

IAEA – Vienna
31 May 2012

Example of R-I applied to a SMR (iPWR-type): IRIS

1 **IRIS safety features**

2 **Risk-Informed process in a SMR design phase: internal events, seismics, EPZ**

3 **Tools for "Risk-Informed" SMRs: probabilistic + deterministic**

4 **Final/Personal considerations**

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"Risk-Informed": a suitable/obliged approach after Fukushima events?

3

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Meaning of "**Risk-Informed approach**" in this example:

Concurrent use of deterministic + probabilistic safety tools and analysis, aiming at providing the highest, robust, balanced, optimised safety features for new reactor systems, at all levels (design, operation, accident management)

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The IRIS (International Reactor Innovative & Secure) project: 10 years of R&D

4

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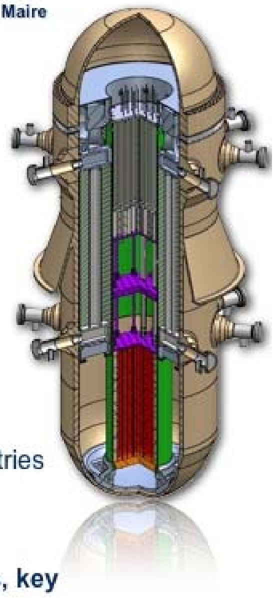
- Westinghouse, MIT, Oak Ridge Nat.Lab. (UCBerkeley)
- **Ansaldo Nucleare, Politecnico di Milano, Univ. di Pisa, Politecnico di Torino, ENEA, Mangiarotti Nuclear, Maire Tecnimont, ATB Riva Calzoni, SAIPEM (ENI)**
- Rolls Royce
- CNEN research center, NUCLEP Industries
- ENSA Industries, Empresarios Agrupados
- Univ. of Zagreb
- Tokyo Inst.of Technology
- Lithuanian Energy Institute
- ININ research center
- EESTI Energia



- Growing interest on the project: at 2009, 20 partners from 10 countries
- **Key italian contribution**
- 2010: Westinghouse decided to abandon the initiative
- **The IRIS project kept on going by Italy-Croatia-Japan partners, key activity: large scale testing (SIET labs) for licensing phase**

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IRIS Three-Tier Safety

5

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Safety-by-Design™

-aims at eliminating by design possibility for accidents to occur,
-eliminates systems/components that were needed to deal with those accidents,
-at reducing probability of occurrence for remaining accidents,
-at reducing consequences.

Passive Safety Systems

-protect against still remaining accidents and mitigate their consequences,
-fewer and simpler than in passive LWRs.

Active Systems

-no active safety systems are required,
-but, active non-safety systems may contribute to reducing the probability of CDF (Core Damage Frequency) in Accident Management.

IMPROVES SAFETY WHILE SIMPLIFYING DESIGN

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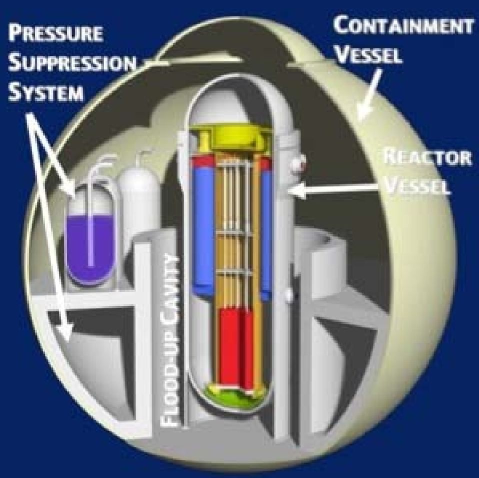
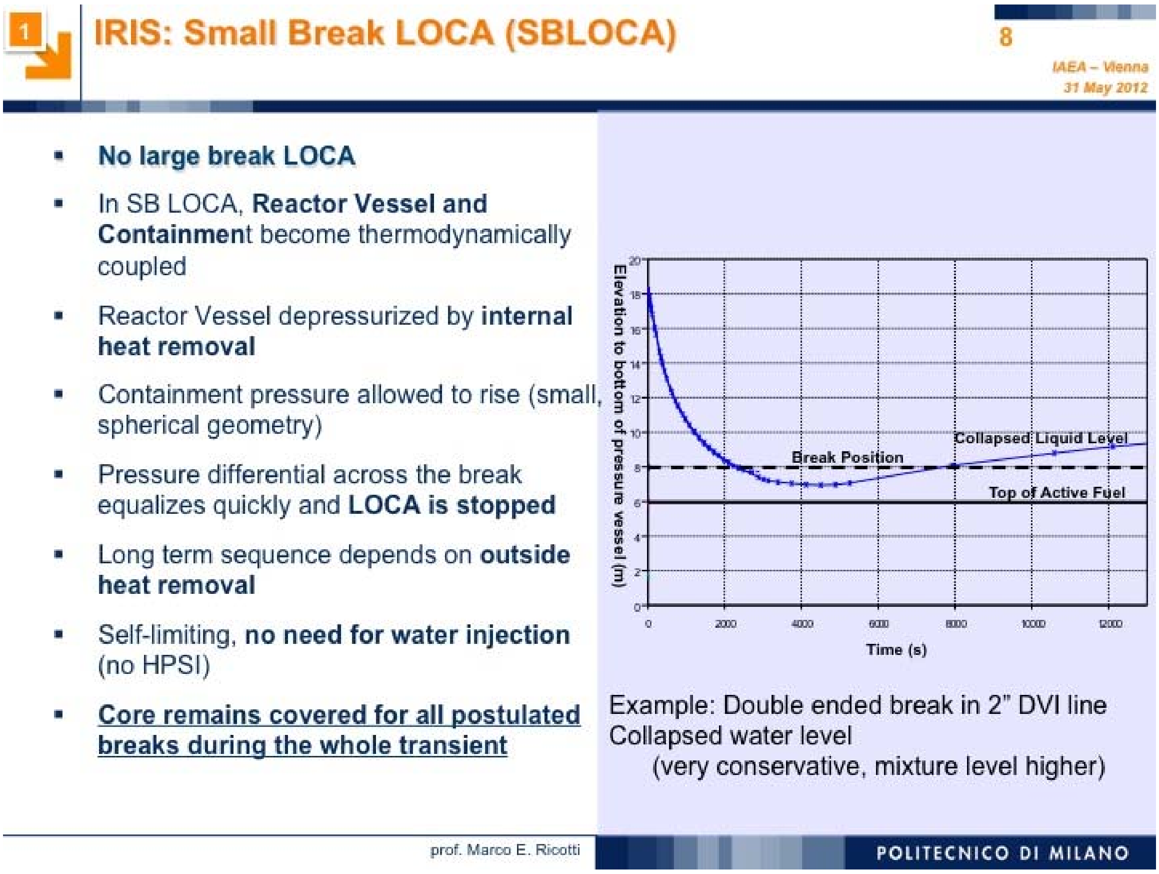
IRIS Design Features

- **Integral PWR module 335 MWe, Safety-by-Design™ approach**
- **Long Life Core** (~4 years, no maintenance outage within it)
- **8 helical-coil steam generators** (compressed tubes, no crud: no Stress Corrosion Cracking)
- **8 axial flow fully immersed primary coolant pumps** (low ΔP, no leakages, no maintenance, self-cooled, already used at 500°C in chemical industry)
- **Internal Control Rod Drive Mechanisms** (no penetrations/leakages, no Rod Ejection Accident)
- **Integral Pressurizer** (high prz volume / reactor power ratio, no sprays)
- **Probabilistic target: CDF 10^{-8} event/r y** (internal+seismic)

IRIS: Containment Vessel integrated into Safety Strategy

- **Pressure Suppression Containment,** spherical, steel, 25 m diam.
- **Design Pressure 15 bar (rel.)**
- **Suppression Pool limit peak pressure to 9 bar (rel.);** water injection by gravity in case of LOCA
- **Self-limiting LOCA** due to containment-RPV pressure equalization
- **Heat-sink:** external air cooling of steel shell rejects heat to atmosphere
- **Auxiliary building seismically isolated**




IRIS: Small Break LOCA (SBLOCA)
8
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No large break LOCA
In SB LOCA, Reactor Vessel and Containment become thermodynamically coupled
Reactor Vessel depressurized by internal heat removal
Containment pressure allowed to rise (small, spherical geometry)
Pressure differential across the break equalizes quickly and LOCA is stopped
Long term sequence depends on outside heat removal
Self-limiting, no need for water injection (no HPSI)
Core remains covered for all postulated breaks during the whole transient
Elevation to bottom of pressure vessel (m)
Time (s)
Collapsed Liquid Level
Break Position
Top of Active Fuel
Example: Double ended break in 2" DVI line
Collapsed water level
(very conservative, mixture level higher)
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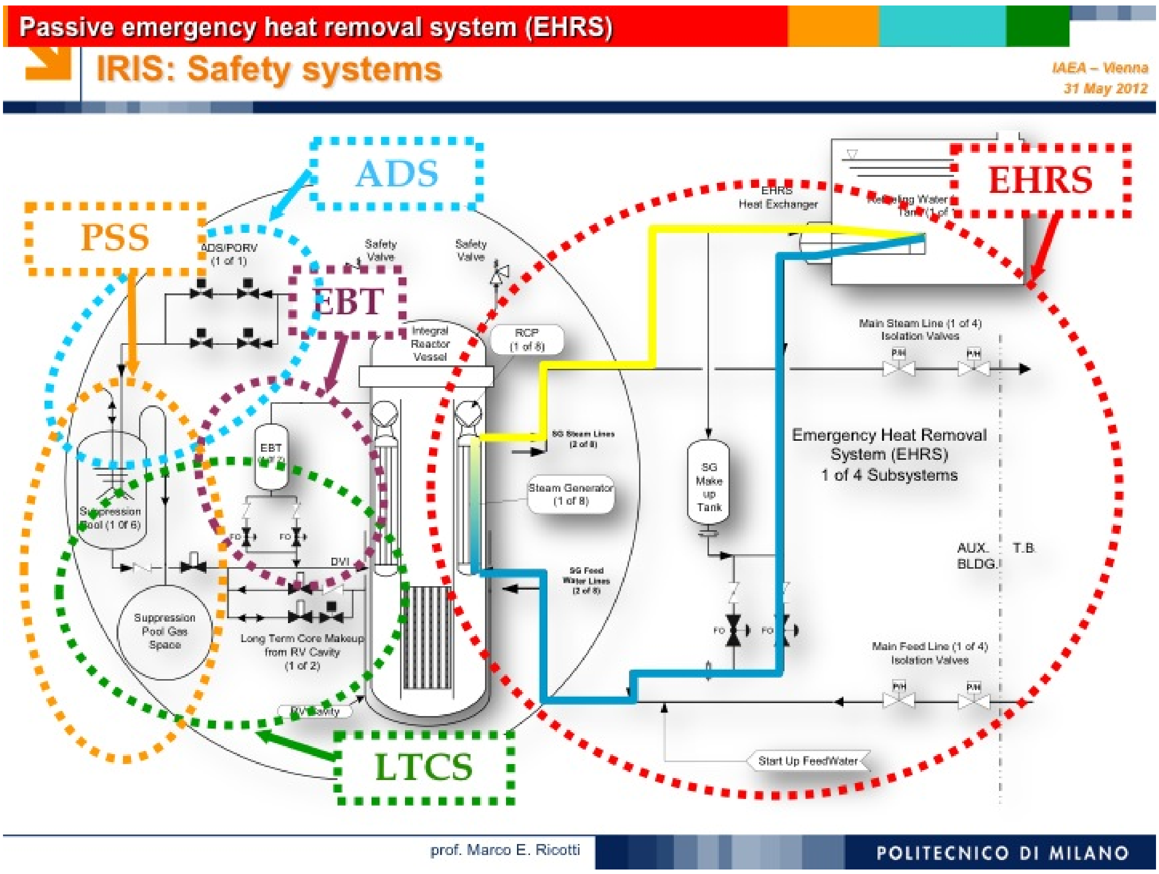
Passive emergency heat removal system (EHRS)
IRIS: Safety systems
IAEA – Vienna
31 May 2012
ADS
PSS
EBT
EHRS
LTCS
ADS/PORV (1 of 1)
Safety Valve
Safety Valve
EHRS Heat Exchanger
Integral Reactor Vessel
RCP (1 of 8)
Main Steam Line (1 of 4) Isolation Valves
Emergency Heat Removal System (EHRS) 1 of 4 Subsystems
SG Make up Tank
Steam Generator (1 of 8)
Suppression Pool (1 of 6)
Suppression Pool Gas Space
DVI
Long Term Core Makeup from RV Cavity (1 of 2)
AUX. BLDG.
T.B.
Main Feed Line (1 of 4) Isolation Valves
Start Up FeedWater
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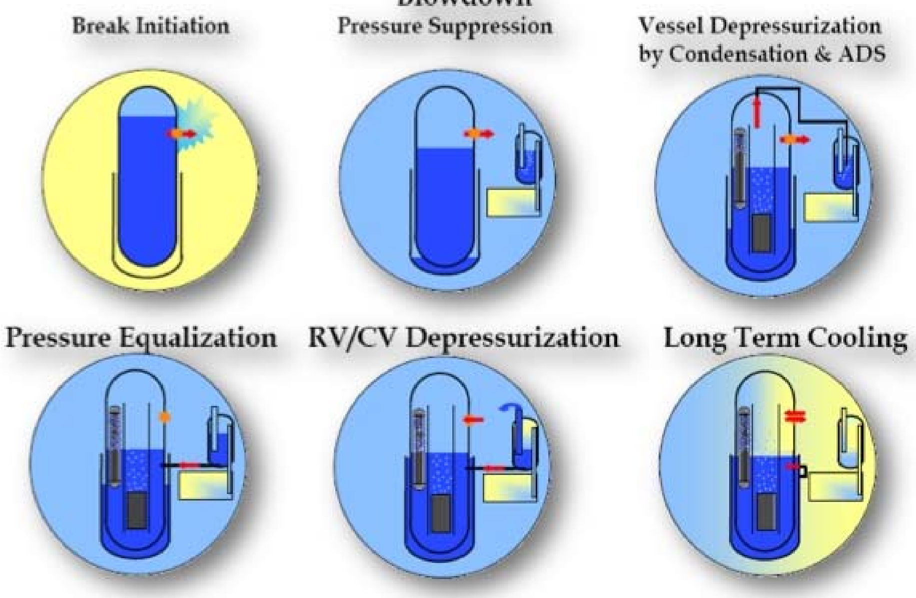
IRIS: SBLOCA safety strategy

- High pressure suppression containment + primary vessel + passive safety systems coupling:



SAFETY APPROACH

- **"Safety-By-Design" approach**
- **Active, non-safety systems have passive, safety-related back-up to perform nuclear safety functions**
  - Safety functions automatically actuated, no reliance on operator action
  - Passive features actuated by stored energy (batteries, compressed air)
  - Once actuated, their continued operation relies only on natural forces (gravity, natural circulation) with no motors, fans, diesels, etc.
- **Core will remain covered under all accident sequences**
- **<u>Heat sink designed to provide cooling for 7 days without operator action or off-site assistance for replenishing</u>**
- **Additional diverse systems to minimize probability of Core Damage/Radioactivity Release**

IRIS: other useful safety-related features

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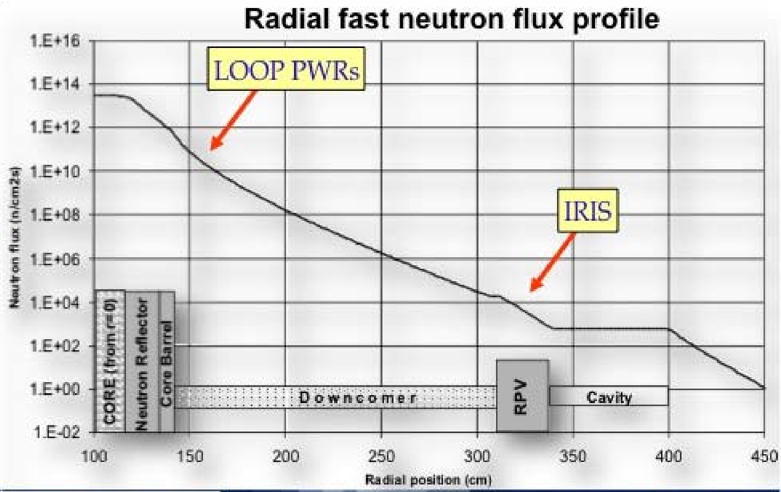
SG modules ➔ large Downcomer water thickness (core-vessel): 1.7 m

- Fast neutron flux on vessel: **~10^5 times less than in current PWRs** → "Cold vessel"
- **External dose practically avoided**
- **No embrittlement, no surveillance**
- "Aeternal" Vessel
- Decommissioning simplified

Useful feature to reduce environment severity during accident managmt



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Risk-Informed process in a SMR design phase: the IRIS case

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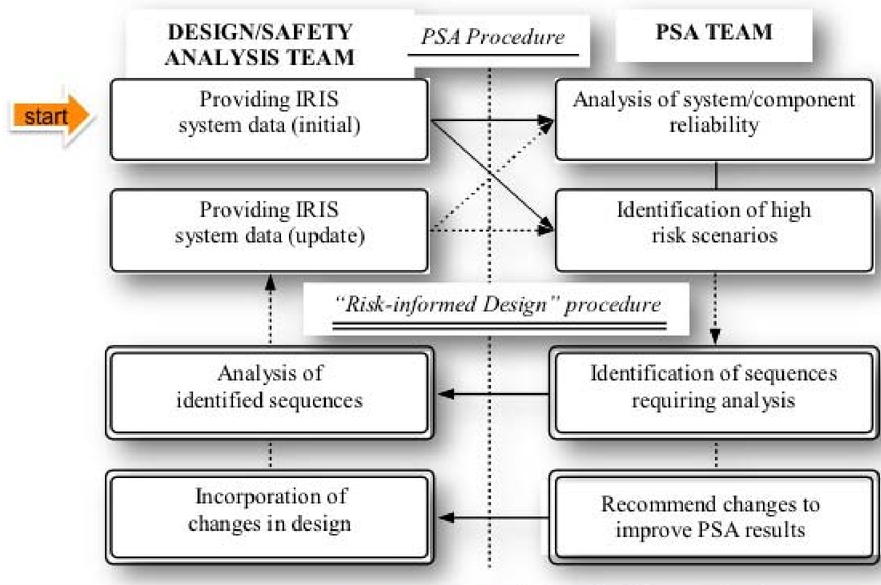
- **Deterministic safety analysis** and **PSA calculation during the development of the preliminary design**



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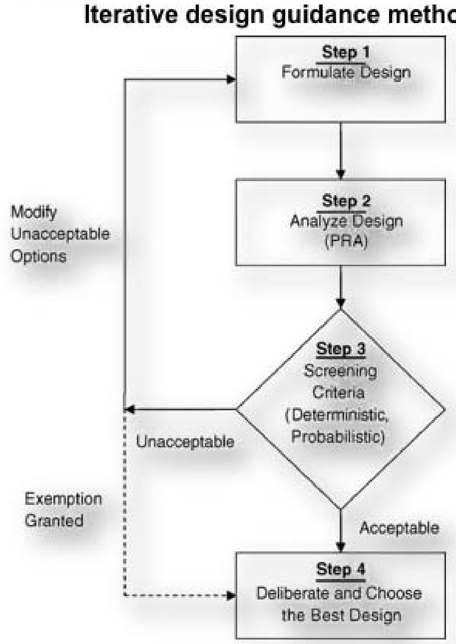
Risk-Informed approach: other examples

Iterative design guidance methodology



Nuclear Engineering and Design 235 (2005) 1537–1556
Risk-informed design guidance for future reactor systems
Michael J. Delaney, George E. Apostolakis, Michael J. Driscoll

Risk-Informed process: design + deterministic safety + PSA level-1

- Improvements from starting phase to iterative phase

Initiating event categories for IRIS PRA

The conceptual phase PRA	The preliminary design phase PRA for risk-informed design
1. General LOCA	1. General LOCA
2. Automatic depressurization system line break	2. Spurious automatic depressurization system actuation
N/A	3. Emergency boration line break
3. Long-term gravity makeup system line break	4. Direct vessel injection line break
(General LOCA)	5. Reactor coolant system leakage
4. Steam generator tube rupture	6. Steam generator tube rupture
5. Reactor vessel rupture	7. Reactor vessel rupture
6. Interfacing system LOCA	8. Interfacing system LOCA
7. Transients with main feed water	9. Transients with main feedwater
8. Transients without main feed water	10. Loss of main feedwater
9. Loss of condenser/turbine bypass system	11. Loss of condenser
(Loss of condenser/turbine bypass system)	12. Loss of component cooling/service water/compressed air
10. Loss of offsite power	13. Loss of offsite power
11. Steam line break	14. Main steam line break downstream of MSIVs
(Steam line break)	15. Main steam line break upstream of MSIVs
(Transient without main feed water)	16. Core power excursion
12. ATWS precursor: to be analyzed	17. ATWS precursor with main feedwater: to be analyzed
(ATWS precursor: to be analyzed)	18. ATWS precursor without main feedwater: to be analyzed
(ATWS precursor: to be analyzed	19. ATWS precursor with safety injection: to be analyzed

Risk-Informed process: design + deterministic safety + PSA level-1

- Improvements from starting phase to iterative phase

The post-accident mitigation system

Function	The conceptual phase PRA		The preliminary design phase PRA for risk-informed design	
	LOCA	Transients	LOCA	Transients
Reactor sub-criticality	Control rod insertion	Control rod insertion	Control rod insertion, and/or EBS or CVCS	Control rod insertion, and/or EBS or CVCS
Emergency core cooling (short/long-term)	EHRS	MFWS with turbine bypass, or SFWS with turbine bypass, or EHRS	EHRS	MFWS with turbine bypass, or SFWS with turbine bypass, or EHRS
Primary system depressurization	EHRS or ADS	EHRS or ADS	EHRS or ADS	EHRS or ADS
Feed and bleed	N/A	N/A	N/A	CVCS and NRHR with ADS successful
Long-term core makeup	LGMS	LGMS	LGMS	LGMS
Containment depressurization	CPSS or PCCS	CPSS or PCCS	CPSS or PCCS	CPSS or PCCS
Containment cooling	PCCS	PCCS	PCCS	PCCS

ADS: automatic depressurization system, CPSS: containment pressure suppression system, CVCS: chemical and volume control system, EHRS: emergency core cooling system, MFWS: main feed water system, NRHR: normal residual heat removal system, PCCS: passive containment cooling system.

Risk-Informed process: design + deterministic safety + PSA level-1

- Improvements from starting phase to iterative phase

Results of the preliminary design phase PRA for risk-informed design

Case #	Description	CDF	Δ (%)
00	Base case	1.98×10^{-6}	±00.00
01	ADS valves quarterly tested	5.88×10^{-7}	-70.15
02	EHRS (4/4 working) credited as a success criteria for DVI Line break	9.62×10^{-7}	-51.17
03	ADS provided with a third identical line	1.06×10^{-6}	-46.19
04	ADS provided with a third line with two solenoid valves	5.18×10^{-7}	-73.71
05	EHRS provided with a solenoid valve instead of one of the two air-operated valves	1.74×10^{-6}	-11.67
06	ADS with one of the two line substituted with two solenoid valves	7.37×10^{-7}	-62.59
07	EHRS credited of successfully working also without closure of main steam isolation valves	1.42×10^{-6}	-27.92
08	EHRS provided with a stop-check valve instead of one of the two check valves	1.87×10^{-6}	-5.56
09	EBS provided with a solenoid valve instead of one of the two air-operated valves for train	1.97×10^{-6}	-0.50
10	EBS provided with different kind of motor-operated valves	1.98×10^{-6}	–
11	EBS not required for LOCA mitigation	1.98×10^{-6}	–
Combined cases			
12	01+02	5.33×10^{-7}	-73.08
13	01+02+07	2.26×10^{-7}	-88.59
14	01+02+05+07	1.04×10^{-7}	-94.75
15	01+02+05+07+08	4.51×10^{-8}	-97.72
16	01+02+05+07+08+09	3.87×10^{-8}	-98.04
17	01+02+05+07+08+09+10	2.32×10^{-8}	-98.83
18	01+02+05+07+08+11 (new base case)	1.21×10^{-8}	-99.39

ADS: automatic depressurization system, EBS: emergency boration system, EHRS: emergency heat removal system, DVI: direct vessel injection.

Risk-Informed process
IRIS CDF reduction

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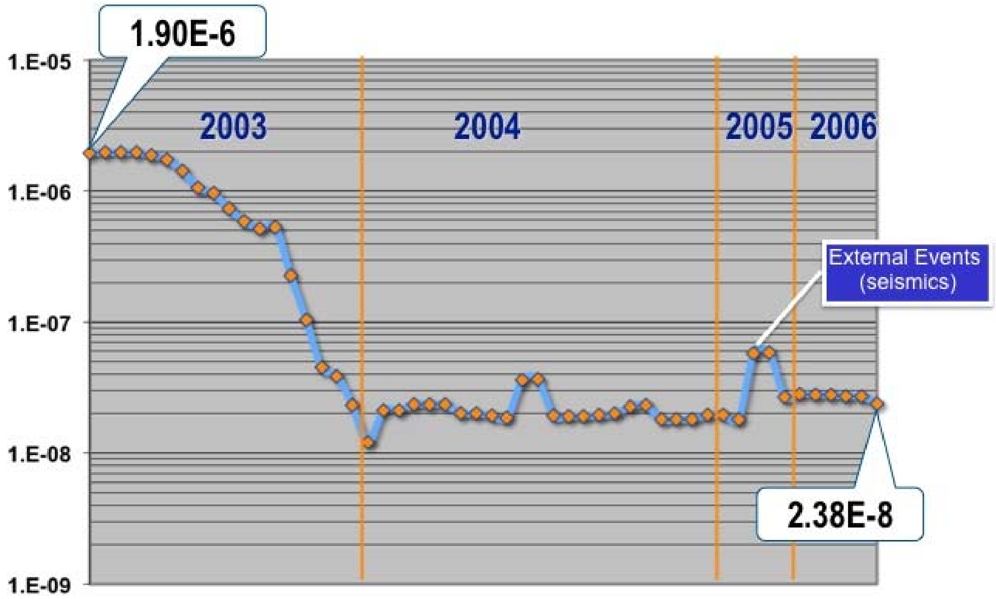
Design development ➜ PSA ➜ Design development ➜ PSA ➜ ...



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Risk-Informed process
Current IRIS CDF value

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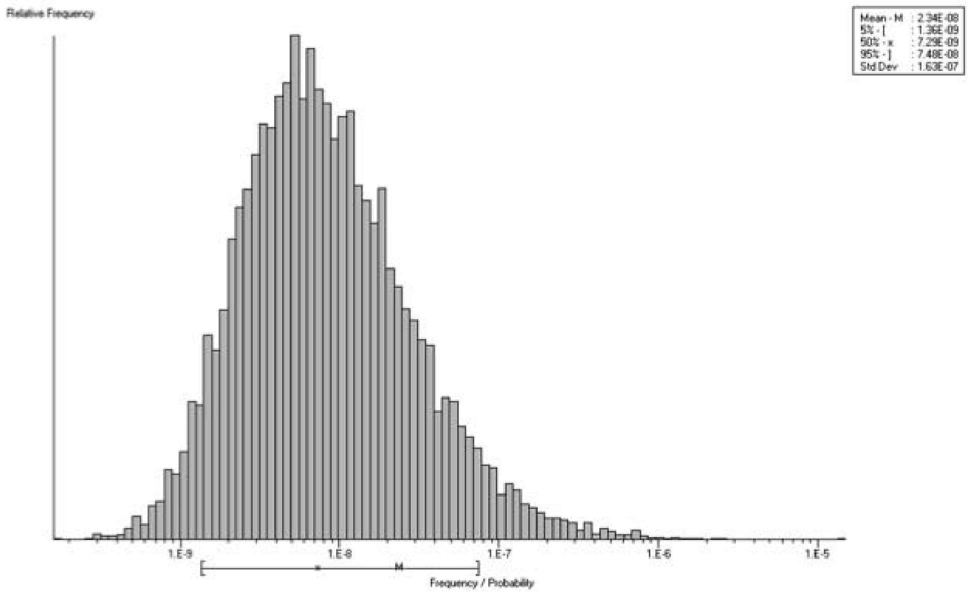

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Risk-Informed and seismics
IRIS: auxiliary building seismically isolated

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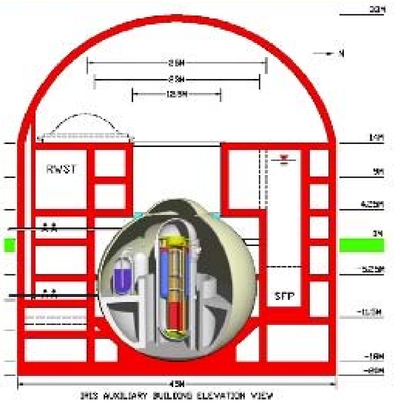
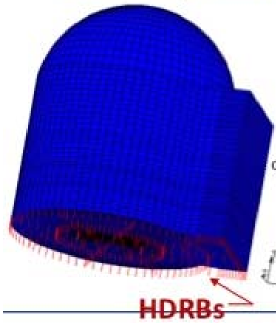
Deterministic solution to overcome prob. results

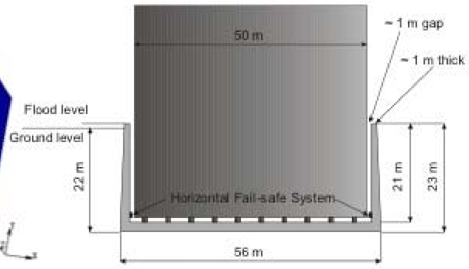
Numerical and experimental study:

- 120 rubber-steel isolators (High Damping Rubber Bearings-HDRBs), 1 m diam, 84 mm height
- PGA = 0.3 g, isolation frequency = 0.7 Hz
  - lateral displacements < 12 cm
  - 25% reduction PGA at vessel supports **level**, 5 times reduction at roof level

HDRB experimental campaign already carried out







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IRIS: results of the Safety-by-Design™ & Risk-Informed approaches

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Criterion	Typical Advanced LWRs	IRIS
Defense-in-Depth (DID)	Redundant and/or diverse active systems or Passive systems	No active 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)	~10^{-5} - 10^{-7} events per year	~10^{-8} events per year
Large Early Release Frequency (LERF)	~10^{-6} - 10^{-8} events per year	~10^{-9} events per year

10^{-8}, 10^{-9}… to be interpreted as "robust, balanced, optimal design" of the reactor safety level

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Risk-Informed approach and O&M

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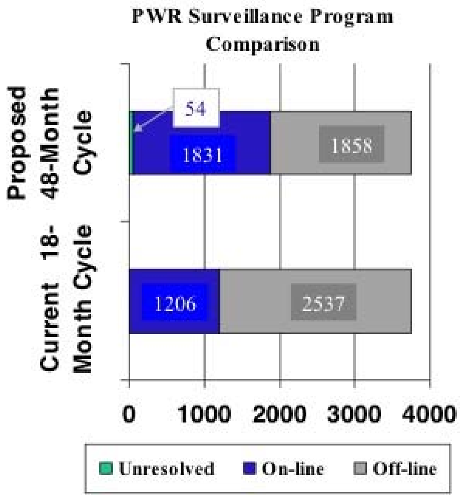
•Main Goal: Perform maintenance shutdowns no sooner than each 48 months
(wide use of In-Service Inspection solutions)

- MIT study in 1996 investigated extending PWR to 48 month cycle
- 3743 maintenance items (on-line and off-line) identified
- By recategorizing 625 items from off-line to on-line, only 54 were left unresolved for PWR
- Accounting for IRIS configuration, unresolved items are reduced completed to 7

•In 2003, TVA addressed and resolved or found resolution programmes for all 7 items



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Risk-Informed approach and EPZ reduction

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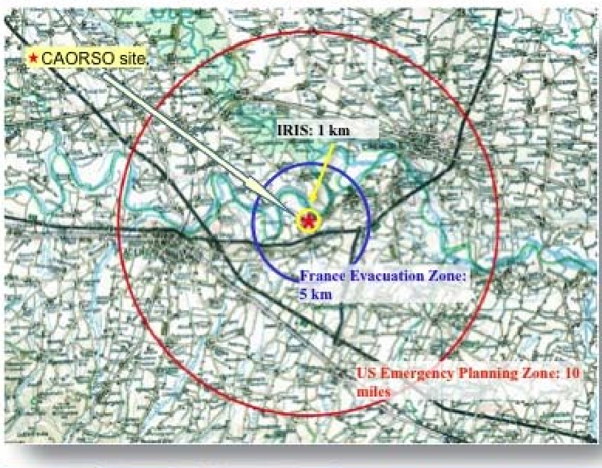
Risk-Informed approach to "No (or reduced) Emergency Planning Zone"

- Elimination/strong reduction (NPP fences) of the Emerg. Planning Zone
- New procedure developed: **Deterministic + Probabilistic** needed to evaluate EPZ (function of radiation dose limit and NPP safety level)
- **Procedure developed within a IAEA CRP**; discussed with NRC


IAEA-TECDOC-1667

Small Reactors without On-site Refuelling: Neutronic Characteristics, Emergency Planning and Development Scenarios

IAEA



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Risk-Informed approach
EPZ Redefinition Methodology

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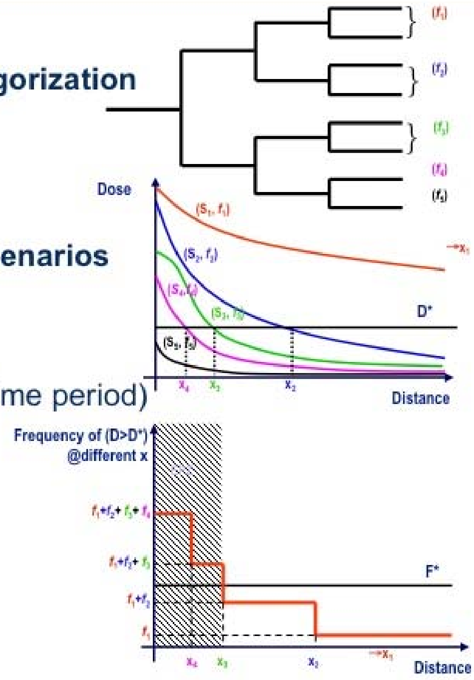
- Step1
  PRA accident sequences re-categorization and release scenario definition
- Step2
  Deterministic dose vs distance evaluation for relevant release scenarios
- Step3
  Identify Limiting dose, D*
  (eg 1 rem or 10-100 mSv, and the time period)
- Step4
  Identify Limiting frequency, *f**
  (eg 10^{-7} e/y)
- Step5
  EPZ definition



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Risk-Informed process: design + deterministic safety + PSA level-2 and -3

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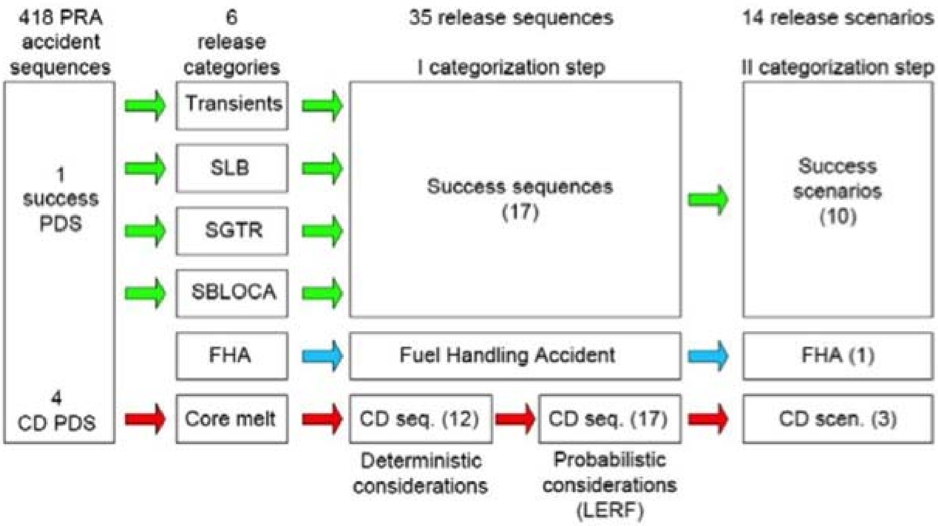

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Risk-Informed process: design + deterministic safety + PSA level-2 and -3

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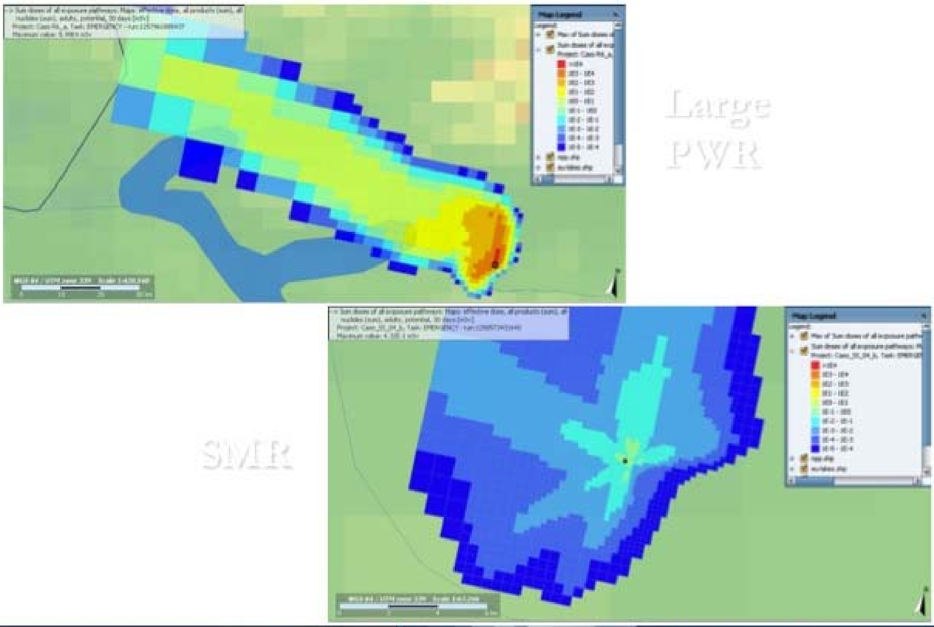
- Effective dose at 30 days: rain conditions (RODOS code)



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Risk-Informed process: design + deterministic safety + PSA level-2 and -3

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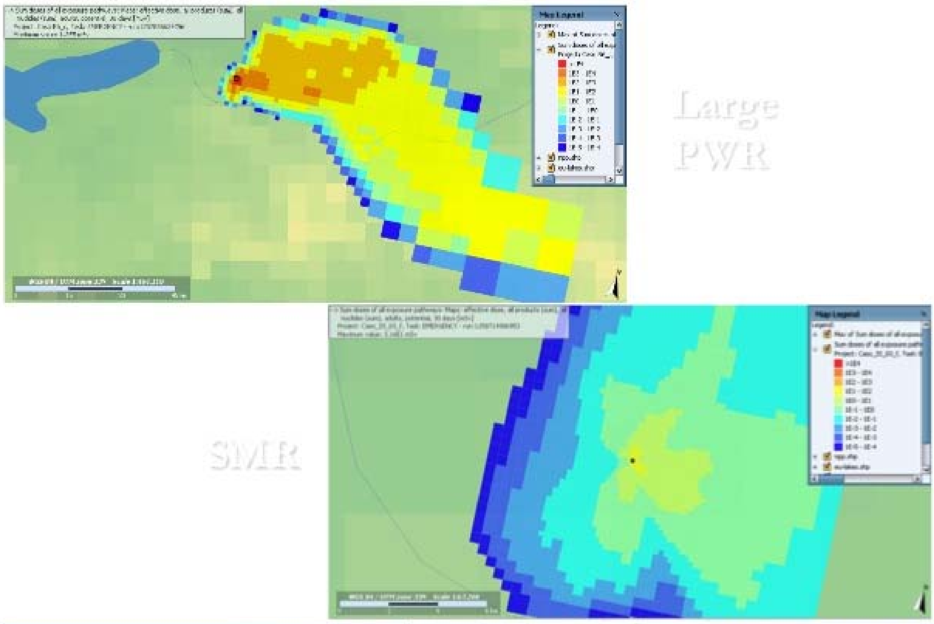
- Effective dose at 30 days: stability conditions (RODOS code)



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Risk-Informed process: design + deterministic safety + PSA level-2 and -3

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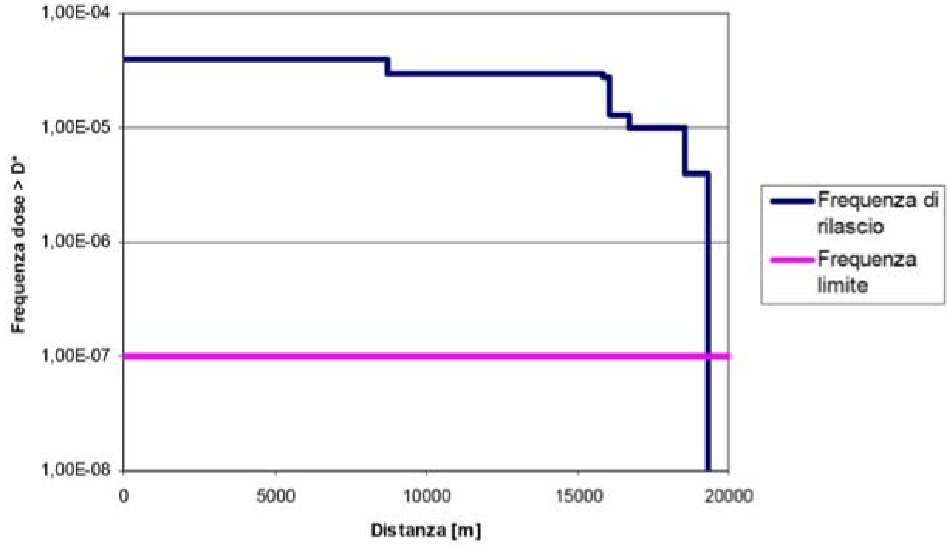
- Large PWR - Effective dose at 30 days: 100 mSv (rain conditions)



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Risk-Informed process: design + deterministic safety + PSA level-2 and -3

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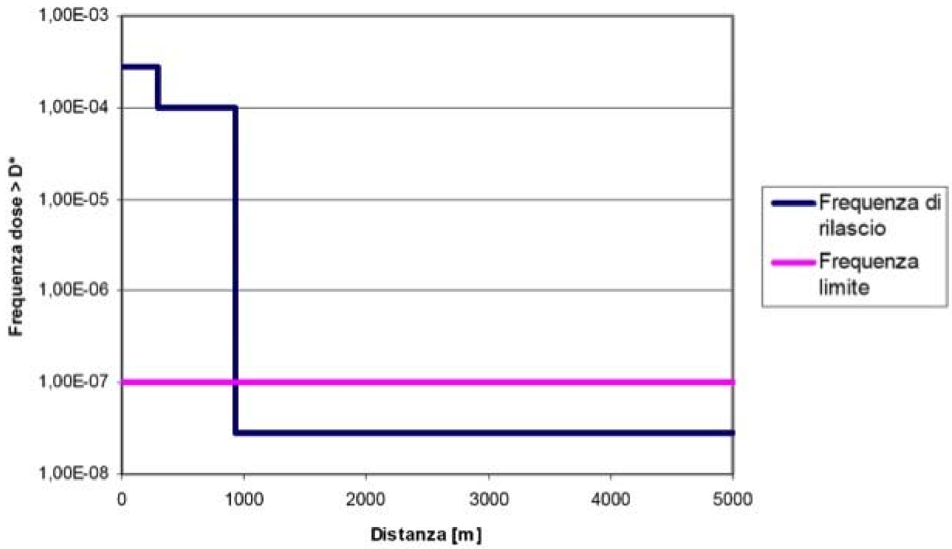
- SMR - Effective dose at 30 days: 10 mSv (rain conditions)



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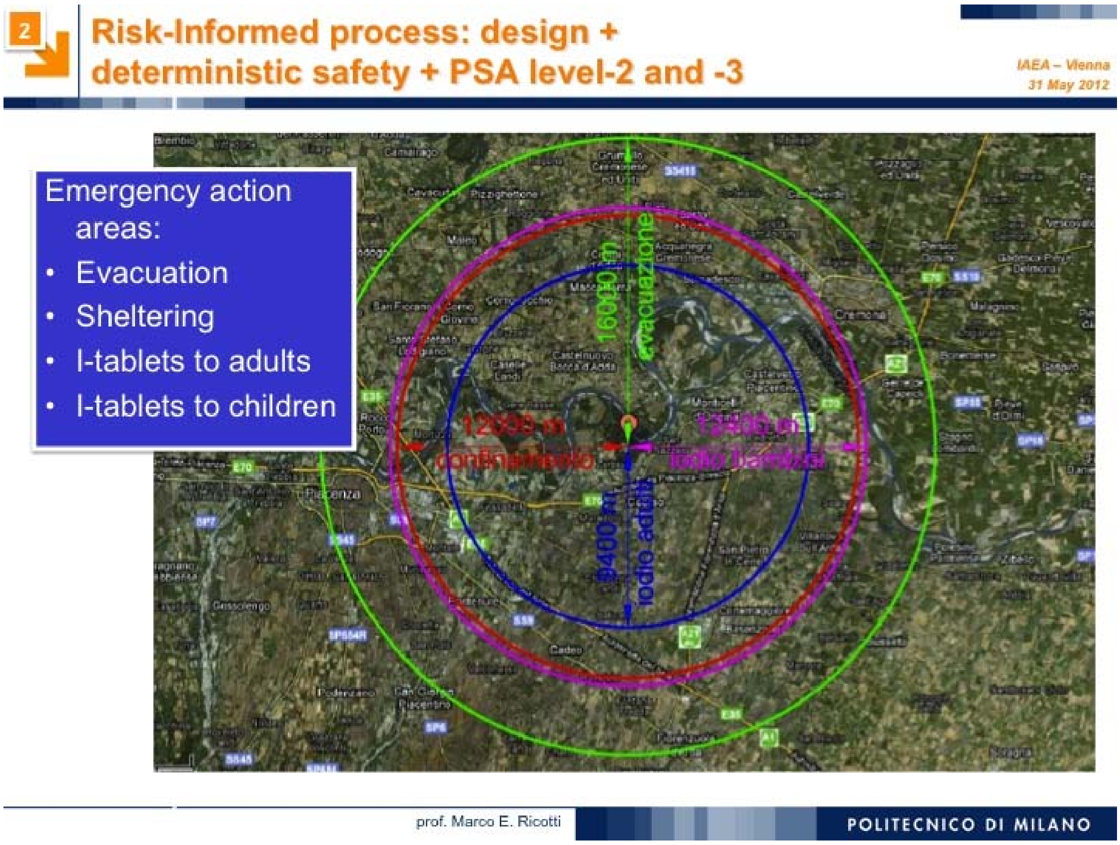
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Risk-Informed process: design + deterministic safety + PSA level-2 and -3
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Emergency action areas:
• Evacuation
• Sheltering
• I-tablets to adults
• I-tablets to children
16000 m
evacuazione
12000 m
confinamento
12400 m
iodio bambini
9400 m
iodio adulti
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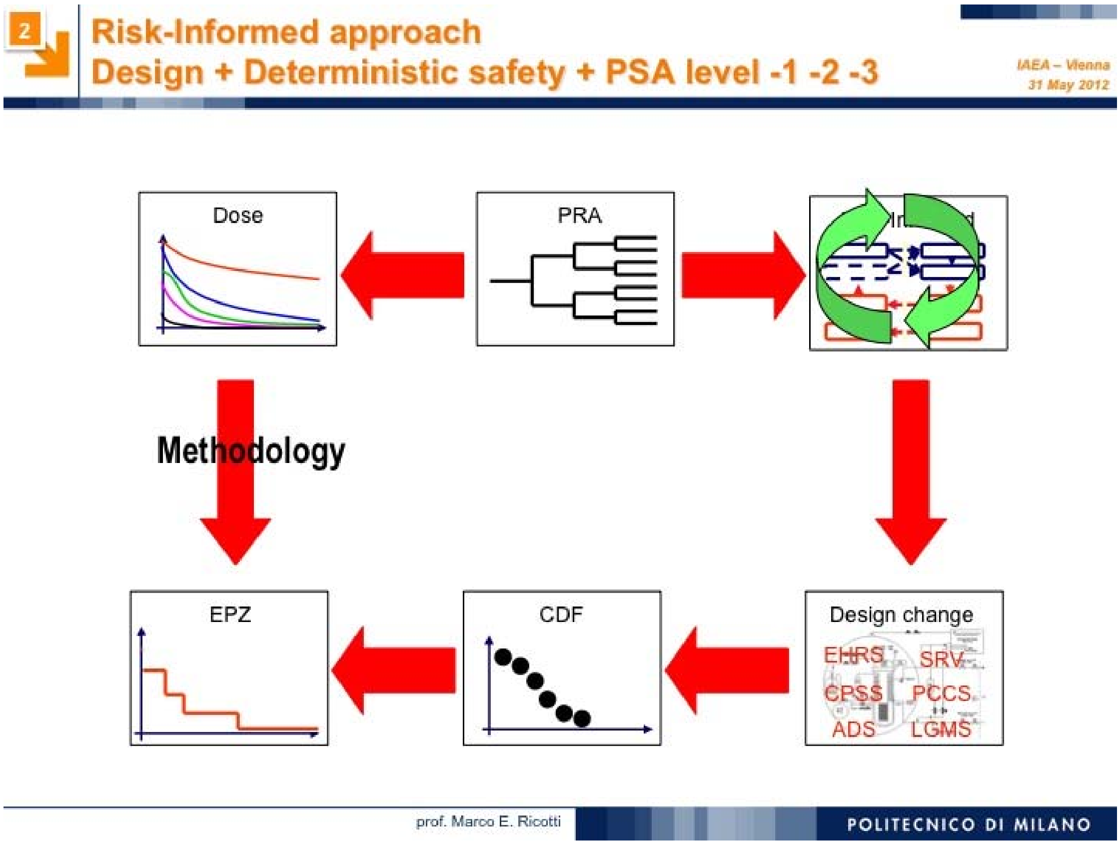
2
Risk-Informed approach
Design + Deterministic safety + PSA level -1 -2 -3
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Dose
PRA
Methodology
EPZ
CDF
Design change
EHRS
SRV
CPSS
PCCS
ADS
LGMS
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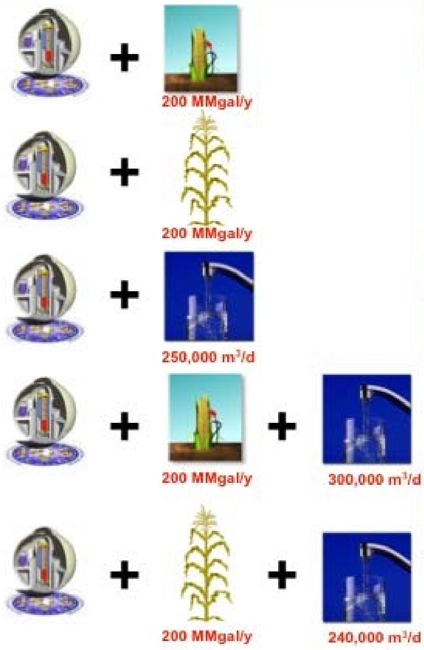
Risk-Informed approach and use of SMRs for co-production



Exchanged Thermal Power		
Ethanol 256 MW_{th}	(10% Surge capacity)	270 MWe
Ethanol + HP bleeding 385 MW_{th}	(10% Surge capacity)	240 MWe
Desalination 520 MW_{th}		208 MWe
Ethanol 253 MW_{th}	(10% Surge capacity)	110 MWe
Desalination 635 MW_{th}		
Ethanol + HP bleeding 389 MW_{th}	(10% Surge capacity)	105 MWe
Desalination 506 MW_{th}		

Tools for Risk-Informed SMRs: probabilistic + deterministic analysis

- Probabilistic side:
  - PSA tools are available, dynamic & living PSA are under development
  - **uncertainties** have to be taken into account
  - **Human Factors** to be included since the beginning
  - concurrent evaluation of complex systems besides NPP (SMRs are suitable for co-generation/co-production)
- Deterministic side:
  - Identification and consideration of **extreme boundary conditions in the area**, following extreme external events
  - Suitable **modelling tools** and **experimental validation** for passive safety systems and integral layout (eg for SMR-iPWR)

Tools: deterministic needs
Experimental investigation & validation

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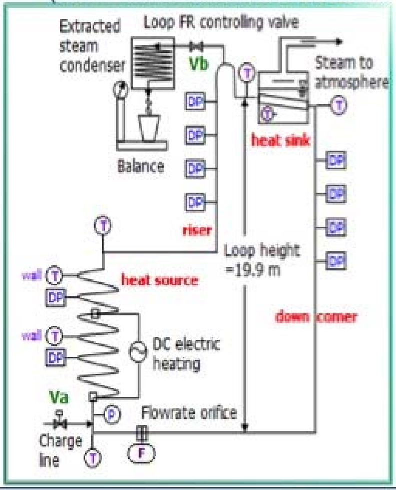
ENEA + POLIMI in collaboration with SIET labs (Piacenza)

1. **Steam Generator Helical Coil tubes –** full scale
2. **EHRS Passive Safety System –** scaled on power/ volume

(New correlations for RELAP code; validation)



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SMR-iPWR (IRIS): SPES-3 large scale integral test facility

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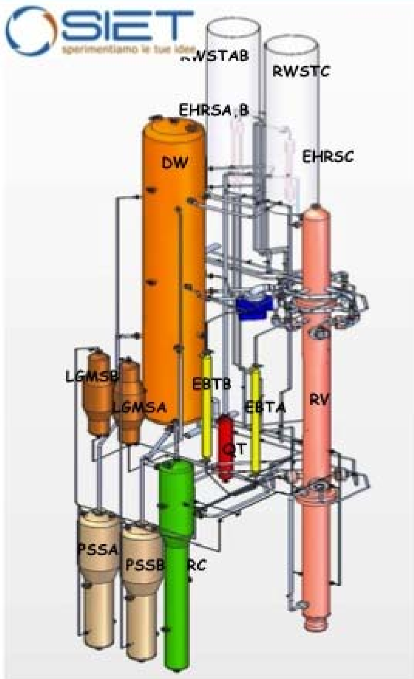
3. **Integral Test Facility**
   - Full scale (1:1) in height – temperature – pressure
   - Scaled 1:100 in power – volume
   - Testing of most accident scenarios
   - **Validation of codes and behavior of passive safety systems and containment-vessel coupling**
   - **>** 700 measurement points, new instrumentation developed

2010: scaling phase and design phase completed

2011: site preparation and control room completed, bid for components except RPV simulator

2012: start construction phase



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3 SPES-3 facility

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1 May 2012

Primary circuit

- **RV and internals**:
  - core simulator (electrically heated rod bundle), riser and CRDM zone, pressurizer, downcomer, riser-to-downcomer connection check valves, lower plenum,
  - an outer circulation pump (simulating eight IRIS pumps)

Secondary circuits (three loops simulating four IRIS loops)

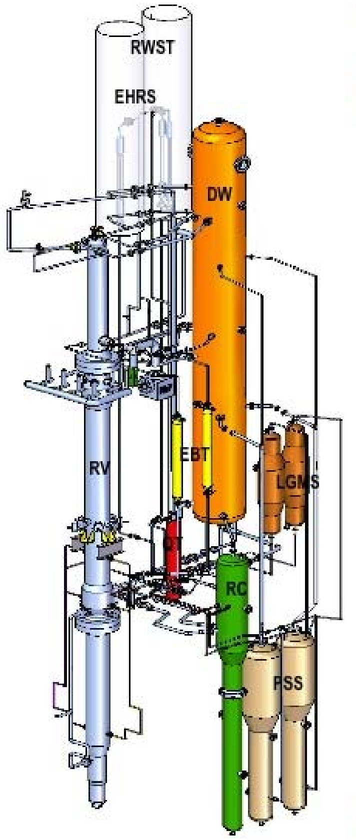
- **Steam generators (3 SGs simulating 8: 2/8, 2/8, 4/8)**
- **Feed Lines**
- **Steam Lines**

Emergency systems components and piping

- **EBT** (2 Emergency Boration Tanks)
- **EHRS** (3 Emergency Heat Removal Systems)
- **RWST** (2 Refuelling Water Storage Tanks)
- **ADS** (2 trains Automatic Depressurization Systems, simulating three)
- **DVI** (2 Direct Vessel Injection lines)

Containment system simulated by separate tanks and piping

- **DW** (1 Dry Well),
- **QT** (1 Quench Tank),
- **PSS** (2 Pressure Suppression Systems)
- **RC** (1 Reactor Cavity)
- **LGMS** (2 Long Term Gravity Make-up Systems)
- **PCC** (1 Passive Containment Cooling inside the DW)



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3 SPES-3 nodalization: Primary, Secondary and RWST (RELAP, GOTHIC, TRACE)

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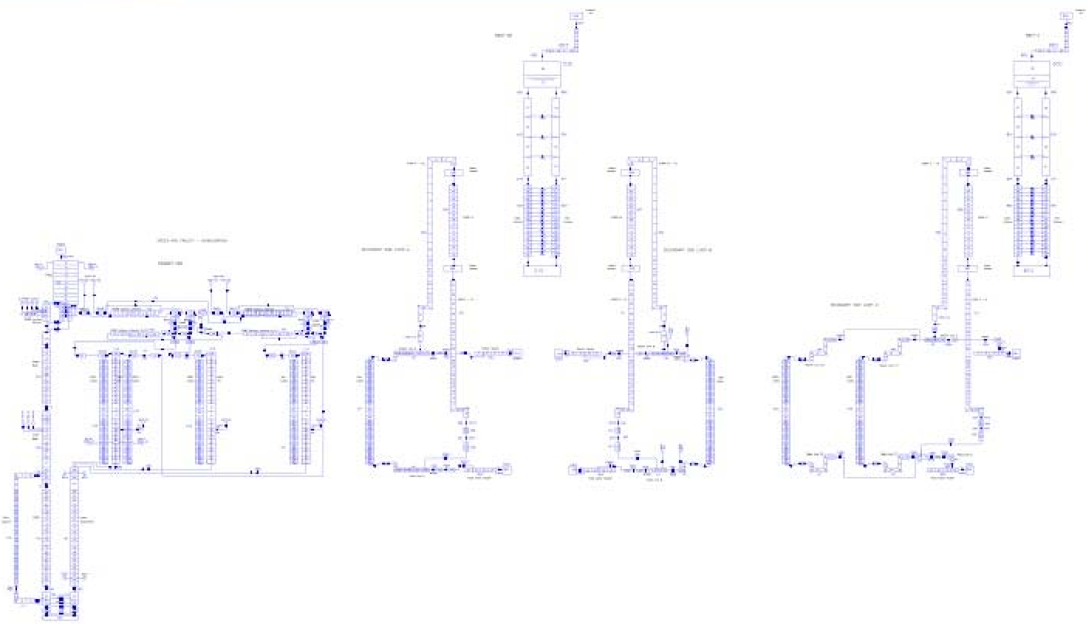

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SPES-3 nodalization: Containment (RELAP, GOTHIC, TRACE)

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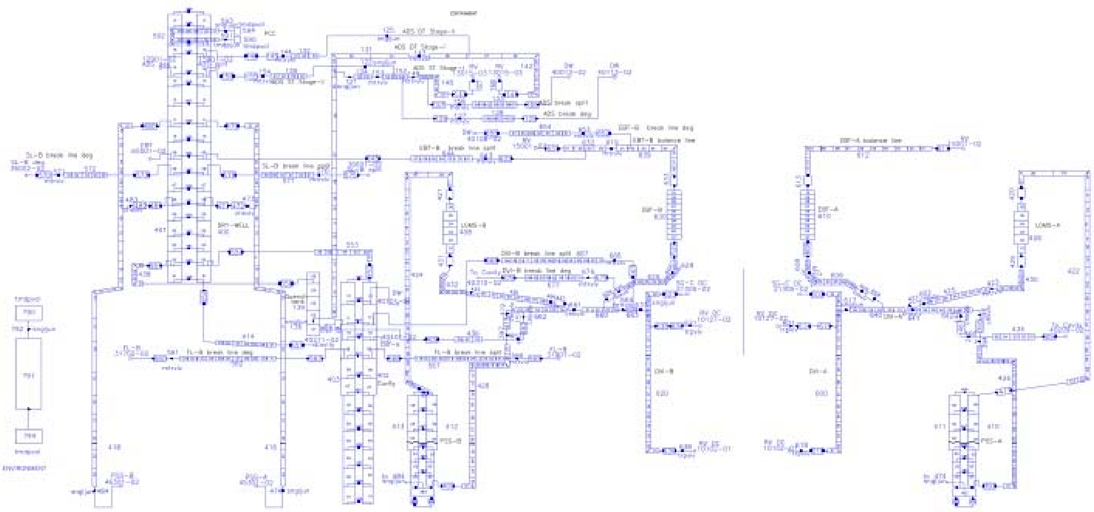

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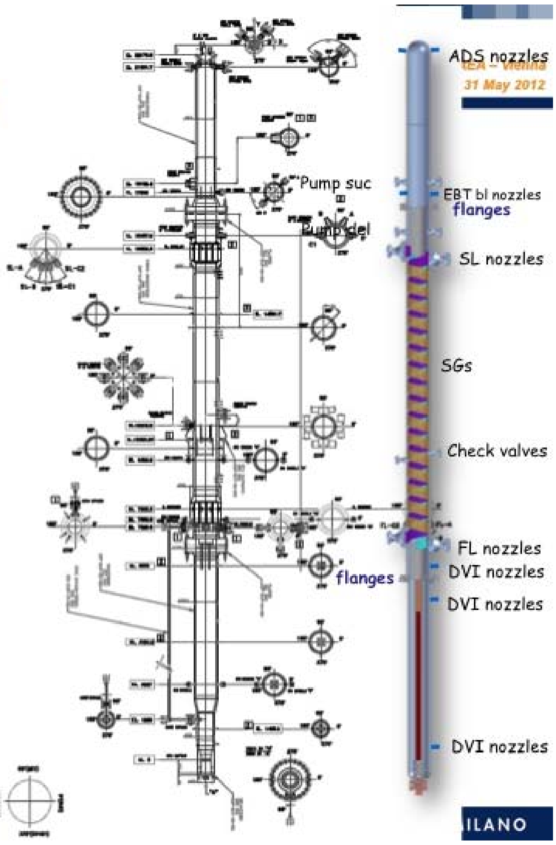
SPES-3: integral reactor simulator

- 3 forged pieces + 4 helical coil SG simulators
- Detailed design provided by italian manufacturing enterprises
- Co-funding (50%) by same industries
- Estimated cost: 5 M€
- Co-funding: discussions with Regional Government, Ministry of Economic Development
- Partnership: Industries, ENEA, SIET labs, POLIMI



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3

SPES-3 large scale integral test facility

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Possible evolution of the facility:

▪become an **"International" facility for SMR-iPWR** studies & testing
- Investment cost: supplied by Italy
- Experimental campaign cost: shared among organisations (industries, authorities, R&D organisations)
- lead by an International Scientific Committee (IAEA collaboration)
- provide experimental data to validate codes (licensing; design), eg ISP

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4

FINAL COMMENTS on SMRs after Fukushima events (1/3)

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31 May 2012

- Risk-Informed: a suitable approach to implement **since the early stage of design** phase the key safety requirements (internal + external + extreme + HF)
- For IRIS (SMR-iPWR) example:
  - Full exploitation of **simple, passive safety systems,** no need for energy/electricity supply
  - **Grace period: 1 week**;
    beyond 1 week: air-cooling, eventually supply of water (no needs for electricity or oil for DG) in the Auxiliary Building (not in the containment), by means of plug-in solutions
  - **Fully seismically isolated Auxiliary Building** (ie Control Room included)
  - In-vessel core retention

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FINAL COMMENTS on SMRs after Fukushima events (2/3)

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- SMRs are **likely** to be more robust (with respect to current technology) towards extreme boundary conditions in the area, following severe external events: **this potentiality has to be demonstrated (implementing Fukushima lessons learned is a critical test bed)**
  - More easy to extend grace period? (3 ➔ 7 days with no intervention); to set up "plug-in" supply systems? (water, electricity); to cope with extreme boundary conditions? (transportation, communications)
  - Warnings: multiple modules (common cause failure, HF)
- A new approach? "***Progressive safety***", to avoid cliff-edge effects?
  - Example: main building seismically isolated
  - Designed for a reference PGA
  - Later in time, **new knowledge** on the site may require to increase, even sensibly, the ref. PGA
  - New seismic isolators designed, tested and substituted

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"Progressive Safety": is the answer already suggested in Fukushima?

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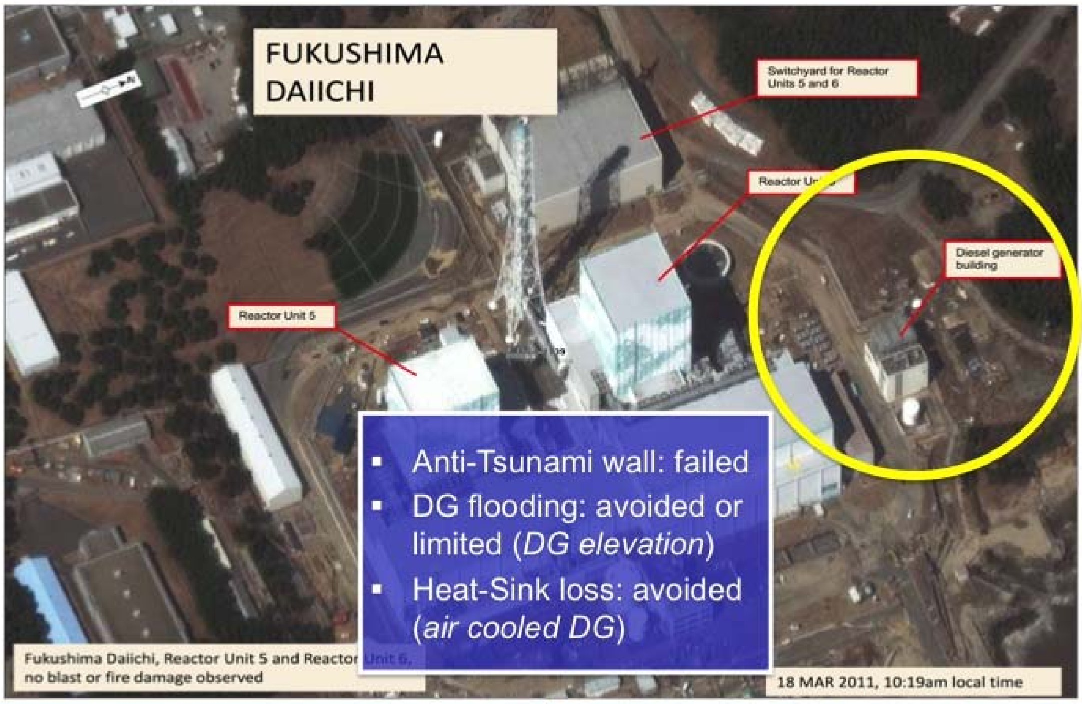

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Lessons Learned from Fukushima Accident to Apply to Nuclear Power Technology Development

Additional Input from the Consultancy on SMR Engineered Safety Features on 30 May- 01 June 2012

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 **+ June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
1. Design and siting	**External Hazards:** There is a need to ensure that in considering external natural hazards: • the siting and design of nuclear plants should include sufficient protection against infrequent and complex combinations of external events and these should be considered in the plant safety analysis – specifically those that can cause site flooding and which may have longer term impacts; • plant layout should be based on maintaining a 'dry site concept', where practicable, as a defence-in-depth measure against site flooding as well as physical separation and diversity of critical safety systems; • common cause failure should be particularly considered for multiple unit sites and multiple sites, and for independent unit recovery options, utilizing all on-site resources should be provided; • any changes in external hazards or understanding of them should be periodically reviewed for their impact on the current plant	IAEA Lesson 1	**1.1 Strengthen measures against extreme external events and subsequent events** **- Excess of design basis earthquake did not cause any known significant damage (*will apply also to SMRs*)** **- Design basis tsunami height is less than actual (*could apply also to SMRs*)** **- Extensive tsunami and explosion damage and debris created significant logistical difficulties and inhibited response actions (*could apply, to a less extent -H2 explosions could be avoided in SMRs- also to SMRs*)** **- Repeated earthquakes and tsunami threats stopped work on occasions (*could apply also to SMRs*)** **[Note] Positive lessons** **Negative lessons** **Neutral lessons**	**A**				**SMR countermeasures / developments:** -usually SMRs have small footprint for the containment building/main building; some SMRs adopt the seismic isolation option; in case of re-evaluation of the seismic grade of the site (see NRC recommendation), the isolators could be re-designed and substituted, allowing further flexibility in updating the seismic resistance of the containment building/main building -cliff-edge effects, eg due to tsunami exceeding protective walls, can be avoided by use of passive safety systems (eg no DG, use of air cooling systems, etc.), or by incorporating by design suitable solutions (water-tight rooms, high elevation for critical safety systems outside the main building, H2 passive recombiners, explosion-proof secondary building, etc.) **warnings:** -in case of underground site (positive solution for seismics), water tightness of safety critical SSC and access paths (corridors, stairs, rooms, etc.) should be ensured -in case of safety critical SSC moved to higher elevation, other hazards should be addressed (aircraft crash, tornadoes, seismics, etc.)

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				LWR	HWR	HTGR	FR	
	configuration; and • an active tsunami warning system should be established with the provision for immediate operator action.							
	Strengthen measures against earthquakes and tsunamis: we will consider the handling of plurally linked seismic centers as well as the strengthening of the quake resistance of external power supplies. Regarding tsunamis, from the viewpoint of preventing a severe accident, we will assume appropriate frequency and adequate height of tsunamis in consideration of a sufficient recurrence period for attaining a safety goal. Then, we will perform a safety design of structures, etc. to prevent the impact of flooding of the site caused by tsunamis of adequately assumed heights, in consideration of the destructive power of tsunamis. While fully recognizing a possible risk caused by the flooding into buildings of tsunamis exceeding the ones assumed in design, we will take measures from the viewpoint of having defenses-in-depth, to sustain the important safety functions by considering flooded	Japanese Government Lesson 1						

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	sites and the huge destructive power of run-up waves.							
	Consideration of NPS arrangement in basic designs: Japan will promote the adequate placement of facilities and buildings at the stage of basic design of NPS arrangement, etc. in order to further ensure the conducting of robust cooling, etc. and prevent an expansion of impacts from the accident, in consideration of the occurrence of serious accidents. In this regard, as for existing facilities, additional response measures will be taken to add equivalent levels of functionality to them.	Japanese Government Lesson 7						
	Ensuring Protection: The Task Force recommends that the NRC require licensees to reevaluate and upgrade as necessary the design-basis seismic and flooding protection of structures, systems, and components for each operating reactor.	NRC Recommendation 2						
	Ensuring Protection: The Task Force recommends, as part of the longer term review, that the NRC evaluate potential enhancements to the capability to	NRC Recommendation 3						

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				LWR	HWR	HTGR	FR	
	prevent or mitigate seismically induced fires and floods.							
	Enhancing Mitigation: The Task Force recommends that the NRC strengthen SBO mitigation capability at all operating and new reactors for design-basis and beyond-design-basis external events.	NRC Recommendation 4						
	Impact of Natural Hazards: The UK nuclear industry should initiate a review of flooding studies, including from tsunamis, in light of the Japanese experience, to confirm the design basis and margins for flooding at UK nuclear sites, and whether there is a need to improve further site - specific flood risk assessments as part of the periodic safety review programme, and for any new reactors. This should include sea - level protection.	ONR IR-10						
	Seismeic Resilience: Once detailed information becomes available on the performance of concrete, other structures and equipment, the UK nuclear industry should consider	ONR IR-15						

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				LWR	HWR	HTGR	FR	
	any implications for improved understanding of the relevant design and analyses.							
	Extreme External Events: When considering the recommendations in this report the UK nuclear industry should consider them in the light of all extreme hazards, particularly for plant layout and design of safety - related plant.	ONR IR-16						
	Safety Case: All nuclear site licensees should give appropriate and consistent priority to completing Periodic Safety Reviews (PSR) to the required standards and timescales, and to implementing identified reasonably practicable plant improvements.	ONR FR-1						
	Extreme External Events: The UK nuclear industry should ensure that structures, systems and components needed for managing and controlling actions in response to an accident, including plant control rooms, on - site emergency control centres and off - site emergency centres, are adequately protected against hazards that	ONR FR-2						

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				LWR	HWR	HTGR	FR	
	could affect several simultaneously.							
	Extreme External Events: Structures, systems and components needed for managing and controlling actions in response to an accident, including plant control rooms, on‐site emergency control centres and off‐site emergency centres, should be capable of operating adequately in the conditions, and for the duration, for which they could be needed, including possible severe accident conditions.	ONR FR-3						
	External Hazards: There is a need to ensure that in considering external natural hazards: • .....; • .....; • common cause failure should be particularly considered for multiple unit sites and multiple sites, and for independent unit recovery options, utilizing all on-site resources should be provided;	IAEA Lesson 1	**1.2 Consider issues concerning multiple reactor sites and multiple sites** **- Benefit from twin units (allowed temporary cross connection with electrical systems between unit 5 and unit 6) (*will apply also to SMRs*)** **- Unexpected problem from twin units (H2 explosion in unit 4)** **- Multi-unit failure caused unexpected challenges (*may apply also to SMRs*)**	**A**				**SMR countermeasures / developments:** -some SMRs are proposed in multiple units: some safety related SSC could be designed in order to supply endangered units on the site **warnings:** -multiple SMR units on the same site or in the same building have to duly address the common cause failure issues and related accident management concerns

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				LWR	HWR	HTGR	FR	
	• .....; and •							
	Severe accidents: External events have a potential of affecting several plants and several units at the plants at the same time. This requires a sufficiently large resource in terms of trained experienced people, equipment, supplies and external support. An adequate pool of experienced personnel who can deal with each type of unit and can be called upon to support the affected sites should be ensured.	IAEA Lesson 7						

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				LWR	HWR	HTGR	FR	
	Response to issues concerning the siting with more than one reactor: Japan will take measures to ensure that emergency operations at a reactor where an accident occurs can be conducted independently from operation at other reactors if one power station has more than one reactor. Also, Japan will assure the engineering independence of each reactor to prevent an accident at one reactor from affecting nearby reactors. In addition, Japan will promote the development of a structure that enables each unit to carry out accident responses independently, by choosing a responsible person for ensuring the nuclear safety of each unit.	Japanese Government Lesson 6						
	Strengthening Emergency Preparedness: The Task Force recommends that the NRC require that facility emergency plans address prolonged SBO and multiunit events.	NRC Recommendation 9						
	Strengthening Emergency Preparedness: The Task Force recommends, as part of the longer term review, that the NRC pursue additional	NRC Recommendation 10						

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	emergency preparedness topics related to multiunit events and prolonged SBO.							
	Multi-reactor Sites: The UK nuclear industry should ensure that safety cases for new sites for multiple reactors adequately demonstrate the capability for dealing with multiple serious concurrent events induced by extreme off - site hazards.	ONR IR-11						
	Ensure power supplies: Japan will secure a power supply at sites for a longer time set forth as a goal even in severe circumstances of emergencies, through the diversification of power supply sources by preparing various emergency power supply sources such as air-cooled diesel generators, gas turbine generators, etc., deploying power-supply vehicles and so on, as well as equipping switchboards, etc. with high environmental tolerance and generators for battery charging, and so on.	Japanese Government Lesson 2	**1.3 Ensure off-site and on-site electricity supplies** **- All emergency D/Gs started as designed after off-site power loss (*will apply also to SMRs that use DGs*)** **- Location of switchboards low in the building with little margin to external flooding design level was critical to the outcome of the accident (*could be avoided by SMRs*)** **- Complete loss of DC power was not considered (e.g. LOCA closure of IC AC valves) (*could be considered by SMRs*)** **- Signal was generated by loss of all DC power and caused IC valves to close (LOCA signal) disabling passive systems (*could be avoided by SMRs*)**	**A**				**SMR countermeasures / developments:** -usually SMRs rely on passive safety, thus on-site and off-site electricity should not be needed for the grace period; DG systems could be avoided (at least as safety grade systems) -SMRs could incorporate since the design phase the adoption of "plug-in" water+electricity supply, *and the adoption of renewables+storage systems (?!?)* **warnings:** -the identification of a suitable grace period (without need of intervention from operators and of electricity supply) should be duly addressed

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	Enhancing Mitigation: The Task Force recommends that the NRC strengthen SBO mitigation capability at all operating and new reactors for design-basis and beyond-design-basis external events.	NRC Recommendation 4						
	Strengthening Emergency Preparedness: The Task Force recommends that the NRC require that facility emergency plans address prolonged SBO and multiunit events.	NRC Recommendation 9						
	Strengthening Emergency Preparedness: The Task Force recommends, as part of the longer term review, that the NRC pursue additional emergency preparedness topics related to multiunit events and prolonged SBO.	NRC Recommendation 10						
	Off-site Electricity Supplies: The UK nuclear industry should undertake further work with the National Grid to establish the robustness and potential unavailability of off‐site electrical supplies under severe hazard conditions.	ONR IR-17						

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	On-site Electricity Supplies: The UK nuclear industry should review any need for the provision of additional, diverse means of providing robust sufficiently long ‑ term independent electrical supplies on sites, reflecting the loss of availability of off ‑ site electrical supplies under severe conditions.	ONR IR-18						
	External Hazards: There is a need to ensure that in considering external natural hazards: • the siting and design of nuclear plants should include sufficient protection against infrequent and complex combinations of external events and these should be considered in the plant safety analysis – specifically those that can cause site flooding and which may have longer term impacts; • plant layout should be based on maintaining a 'dry site concept', where practicable, as a defence-in-depth measure against site flooding as well as physical separation and diversity of critical safety systems; • common cause failure should be particularly considered for multiple unit sites and multiple sites, and for independent unit	IAEA Lesson 1	**1.4 Ensure design of safety-related structures, systems and components** **- All control rods successfully inserted (*will have to apply also to SMRs*)** **- Non-electrically-driven systems (IC, RCIC) started as designed (*will have to apply also to SMRs*)** **- Containment vessel integrity was lost on all at power units (1,2,3) (*should be avoided by design by SMRs*)** **- Once-through cooling system in a damaged reactor creates a large amount of radioactive liquid waste (*could apply also to SMRs*)** **- Access to some manual valves was difficult due to radiation concerns (*should be avoided by design by SMRs*)** **- If unit 1 IC had been kept in service (and water makeup to tanks) the core damage would have been delayed or avoided** **- Unit 2 and unit 3 would have needed to bleed (vent) and feed to avoid core**	**A**				**SMR countermeasures / developments:** -SMRs can implement since the design phase the safety related SSC needed to cope with CV integrity, diverse shutdown, core cooling and decay heat removal, with positive features easily exploitable by SMRs: *reduced decay heat and sorce term (due to small size), *wide use of passive safety features (eg air cooling or easily externally cooling containment vessel, large pools/large amount of water per MWth, with respect to current reactors), *reduced radiation field (internal shielding), *positioning of manually-activate safety components/systems in suitable areas, *in-vessel core retention and cooling **warnings:** -once through cooling system should be addressed and possibly eliminated, especially in case of underground siting

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	recovery options, utilizing all on-site resources should be provided; • ......; and •		**damage - limited by water supply and power to pump (steam)**					
	Severe accidents: Particularly in relation to preventing loss of safety functionality, the robustness of defence-in-depth against common cause failure should be based on providing adequate diversity (as well as redundancy and physical separation) for essential safety functions.	IAEA Lesson 9						
	Ensure robust cooling functions of reactors and PCVs: Japan will secure robust alternative cooling functions for its reactors and PCVs by securing alternative final heat sinks for a durable time. This will be pursued through such means as diversifying alternative water injection functions, diversifying and increasing sources for injection water, and	Japanese Government Lesson 3						

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	introducing air-cooling systems.							
	Ensuring the water tightness of essential equipment facilities: Japan will ensure the important safety functions even in the case of tsunamis greater than ones expected by the design or floods hitting facilities located near rivers. In concrete terms, Japan will ensure the water-tightness of important equipment facilities by installing watertight doors in consideration of the destructive power of tsunamis and floods, blocking flooding routes such as pipes, and installing drain pumps, etc.	Japanese Government Lesson 8						
	Ensuring the independence and diversity of safety systems: the Japanese Government will ensure the independence and diversity of safety systems so that common cause failures can be adequately addressed and the reliability of safety functions can be further improved.	Japanese Government Lesson 26						

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				LWR	HWR	HTGR	FR	
	Enhancing Mitigation: The Task Force recommends that the NRC strengthen SBO mitigation capability at all operating and new reactors for design-basis and beyond-design-basis external events.	NRC Recommendation 4						
	Site and Plant Layout: The UK nuclear industry should review the plant and site layouts of existing plants and any proposed new designs to ensure that safety systems and their essential supplies and controls have adequate robustness against severe flooding and other extreme external events.	ONR IR-13						
	Extreme External Events: When considering the recommendations in this report the UK nuclear industry should consider them in the light of all extreme hazards, particularly for plant layout and design of safety - related plant.	ONR IR-16						
	Exteme External Events: Structures, systems and components needed for managing and controlling actions in response to an accident, including plant control rooms, on - site emergency control centres and off - site emergency centres, should be capable of operating adequately in	ONR FR-3						

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				LWR	HWR	HTGR	FR	
	the conditions, and for the duration, for which they could be needed, including possible severe accident conditions.							
	Severe accidents: The risk and implications of hydrogen explosions should be revisited and necessary mitigating systems should be implemented.	IAEA Lesson 8	**1.5 Ensure measures for prevention and mitigation of hydrogen explosions** **- Radioactive release was significantly reduced on unit 1 and unit 3 due to water scrubbing (*could apply also to SMRs*)** **- Extensive tsunami and explosion damage and debris created significant logistical difficulties and inhibited response actions (*could apply, to a less extent -H2 explosions could be avoided in SMRs- also to SMRs*)** **- Venting did not prevent containment failure due to inability to properly implement** **o Venting delay due to practical difficulties;** **High dose** **Lack of control air** **Lack of DC** **Lack of light** **Communication difficulties** **(*could be avoided by SMRs*)**	**A**				**SMR countermeasures / developments:** -SMRs could exploit reduced H2 production due to smaller size **warnings:** -SMRs probably cannot avoid by design the H2 concerns

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				LWR	HWR	HTGR	FR	
	Enhancement of measures to prevent hydrogen explosions: we will enhance measures to prevent hydrogen explosions such as by installing of flammability control systems that would function in the event of a severe accident in reactor buildings, for the purpose of discharging or reducing hydrogen in the reactor buildings, in addition to measures to address hydrogen within the PCVs.	Japanese Government Lesson 9						
	Enhancement of containment venting system: we will enhance the containment venting system by improving its operability, ensuring its independence, and strengthening its function of removing released radioactive materials.	Japanese Government Lesson 10						
	Enhancing Mitigation: The Task Force recommends requiring reliable hardened vent designs in BWR facilities with Mark I and Mark II containments.	NRC Recommendation 5						
	Enhancing Mitigation: The Task Force recommends, as part of the longer term review, that the NRC identify insights about hydrogen control and mitigation inside containment or in other buildings as additional information	NRC Recommendation 6						

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	is revealed through further study of the Fukushima Dai-ichi accident.							
	Combustible Gases: The UK nuclear industry should review the ventilation and venting routes for nuclear facilities where significant concentrations of combustible gases may be flowing or accumulating to determine whether more should be done to protect them.	ONR IR-21						
	Severe accidents: Emergency Response Centres should have available as far as practicable essential safety related parameters based on hardened instrumentation and lines such as coolant levels, containment status, pressure, etc., and have sufficient secure communication lines to control rooms and other places on-site and off-site.	IAEA Lesson 5	**1.6 Ensure hardened instrumentation and lines for safety-related parameters and monitoring equipment** **- Loss of reactor instrumentation data hampered operator understanding and response (also from TMI)** **- Situation awareness was very difficult under these conditions** **(*situation may apply also to SMRs*)**	**A**				**SMR countermeasures / developments:** SMR simplification in design and O&M should help in reducing that type of concern; also "mild and slow accident evolution" transients should help **warnings:** the topic requires innovative solutions - ie reliable instrumentation should be developed anyway for all the NPPs
	Off-site Emergency Arrangements to Protect the Public and Environment: Greater consideration should be given to providing hardened systems, communications and sources of monitoring equipment	IAEA Lesson 10						

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	for providing essential information for on-site and off-site responses, especially for severe accidents.							
	Enhancement of instrumentation to identify the status of the reactors and PCVs: we will enhance the instrumentation of reactors and PCVs, etc. to enable them to function effectively even in the wake of severe accidents.	Japanese Government Lesson 14						
	Enhancing Mitigation: The Task Force recommends enhancing spent fuel pool makeup capability and instrumentation for the spent fuel pool.	NRC Recommendation 7						
	Emergency Control Centres, Instrumentation and Communications: The UK nuclear industry should review the provision on‐site of emergency control, instrumentation and communications in light of the circumstances of the Fukushima accident including long timescales, wide spread on and off‐site disruption, and the environment on‐site associated with a severe accident.	ONR IR-22						

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	Ensure robust cooling functions of spent fuel pools: Japan will secure robust cooling measures by introducing alternative cooling functions such as a natural circulation cooling system or an air-cooling system, as well as alternative water injection functions in order to maintain the cooling of spent fuel pools even in case of the loss of power supplies.	Japanese Government Lesson 4	**1.7 Enhance robustness of spent fuel cooling**	**A**				**SMR countermeasures / developments:** several SMRs solutions use spent fuel pit below grade; due to the size of the core, less decay heat and less source term should be considered
	Enhancing Mitigation: The Task Force recommends enhancing spent fuel pool makeup capability and instrumentation for the spent fuel pool.	NRC Recommendation 7						
	Spent Fuel Strategies: The UK nuclear industry should ensure the adequacy of any new spent fuel strategies compared with the expectations in the Safety Assessment Principles of passive safety and good engineering practice.	ONR IR-12						
	Fuel Pond Design: The UK nuclear industry should ensure that the design of new spent fuel ponds close to reactors minimises the need for bottom penetrations and lines that are prone to siphoning faults. Any that are necessary should be as robust to faults as are the ponds	ONR IR-14						

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	themselves.							
	Cooling Supplies: The UK nuclear industry should review the site contingency plans for pond water make up under severe accident conditions to see whether they can and should be enhanced given the experience at Fukushima.	ONR IR-20						
	Effective use of probabilistic safety assessment (PSA) in risk management: the Japanese Government will further actively and swiftly utilize PSA while developing improvements to safety measures including effective accident management measures based on PSA.	Japanese Government Lesson 27	**1.8 Use PSA effectively for risk assessment and management** **- Analysis of plant had not previously considered all the failure modes that occurred (*in principle, that may apply to any NPP technology, GenIV included...*)** **-The physical consequence of the events were largely in line with previous understanding**	**A**				**SMR countermeasures / developments:** SMRs can/must exploit risk-informed approach since the design phase, to encrease robustness of the safety level

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	Safety Case: The nuclear industry should ensure that adequate Level 2 Probabilistic Safety Analyses (PSA) are provided for all nuclear facilities that could have accidents with significant off - site consequences and use the results to inform further consideration of severe accident management measures. The PSAs should consider a full range of external events including "beyond design basis" events and extended mission times.	ONR FR-4						
2. On-site emergency preparedness and response	Severe accidents: For severe situations, such as total loss of off-site power or loss of all heat sinks or the engineering safety systems, simple alternative sources for these functions including any necessary equipment (such as mobile power, compressed air and water supplies) should be provided for severe accident management.	IAEA Leson 2	**2.1 Ensure on-site emergency response facilities, equipment and procedures** **- On-site emergency response center (seismically isolated) was very useful (*should apply also to SMRs*)** **- The use of Non-Safety related systems limited damage (*should apply also to SMRs*)** **- Loss of power supplies removed some communication equipment and delayed actions** **- Lack of information limited external advice** **- Recovery of heavily damaged equipment was not achieved** **- Failure of some on-site communication systems delayed and complicated actions (specifically**	**A**				**SMR countermeasures / developments:** SMRs usually provide simplification as a common characteristic: that should help significantly in reducing the problems (eg seismically isolated buildings, passive safety systems with active non-safety-related systems, standardised "plug-in" systems) **warnings:** the problem of communications and supply of emergency energy for light and instrumentation is probably a common issue for all the NPP technologies (innovative solutions are needed)

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			mobile systems) **- Lack of standardized external connections could have delayed re-energization** **- Lack of light was a major issue** **- Loss of HVAC created access difficulties** **(*in principle, some could apply also to SMRs - eg communication lost, some could be avoided by design by SMRs - eg standardised external connections*)** **- The ability to physically locate and manually operate valves and equipment under difficult circumstances on the plant was very important**					
	Severe accidents: Such provisions as are identified in Lesson 2 should be located at a safe place and the plant operators should be trained to use them. This may involve centralized stores and means to rapidly transfer them to the affected site(s).	IAEA Lesson 3						
	Severe accidents: Nuclear sites should have adequate on-site seismically robust, suitably shielded, ventilated and well equipped buildings to house the Emergency Response Centres, with similar capabilities to those provided at Fukushima Dai-ni and Dai-ichi, which are also secure	IAEA Lesson 4						

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	against other external hazards such as flooding. They will require sufficient provisions and must be sized to maintain the welfare and radiological protection of workers needed to manage the accident.							
	Severe accidents: Emergency Response Centres should have available as far as practicable essential safety related parameters based on hardened instrumentation and lines such as coolant levels, containment status, pressure, etc., and have sufficient secure communication lines to control rooms and other places on-site and off-site.	IAEA Lesson 5						
	Severe accidents: Severe Accident Management Guidelines and associated procedures should take account of the potential unavailability of instruments, lighting, power and abnormal conditions including plant state and high radiation fields.	IAEA Lesson 6						

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	Thorough accident management (AM) measures: we will change the accident management measures from voluntary safety efforts by operators to legal requirements, and develop accident management measures to prevent severe accidents, including a review of design requirements as well, by utilizing a probabilistic safety assessment approach.	Japanese Government Lesson 5						
	Improvements to the accident response environment: we will enhance the accident response environment that enables continued accident response activities even in case of severe accidents through measures such as strengthening radiation shielding in the control rooms and the emergency centers, enhancing the exclusive ventilation and air conditioning systems on site, as well as strengthening related equipment, including communication and lightening systems, without use of AC power supply.	Japanese Government Lesson 11						

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	Enhancement of the radiation exposure management system at the time of the accident: we will enhance the radiation exposure management system at the time of an accident occurs by storing the adequate amount of personal dosimeters and protection suits and gears for accidents, developing asystem in which radioactive management personnel can be expanded at the time of the accident and improving the structures and equipment by which the radiation doses of radiation workers are measured promptly.	Japanese Government Lesson 12						
	Enhancing Mitigation: The Task Force recommends strengthening and integrating onsite emergency response capabilities such as emergency operating procedures, severe accident management guidelines, and extensive damage mitigation guidelines.	NRC Recommendation 8						
	Off - site Infrastructure Resilience: The UK nuclear industry should review the dependency of nuclear safety on off - site infrastructure in extreme conditions, and consider whether enhancements are necessary to sites' self sufficiency given for the reliability of the grid	ONR IR-8						

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	under such extreme circumstances.							
	Cooling Supplies: The UK nuclear industry should review the need for, and if required, the ability to provide longer term coolant supplies to nuclear sites in the UK in the event of a severe off‐site disruption, considering whether further on‐site supplies or greater off‐site capability is needed. This relates to both carbon dioxide and fresh water supplies, and for existing and proposed new plants.	ONR IR-19						
	Safety Case: The UK nuclear industry should review, and if necessary extend, analysis of accident sequences for long‐term severe accidents. This should identify appropriate repair and recovery strategies to the point at which a stable state is achieved, identifying any enhanced requirements for central stocks of equipment and logistical support.	ONR IR-25						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	Extreme External Events: Structures, systems and components needed for managing and controlling actions in response to an accident, including plant control rooms, on - site emergency control centres and off - site emergency centres, should be capable of operating adequately in the conditions, and for the duration, for which they could be needed, including possible severe accident conditions.	ONR FR-3						
	Severe accidents: External events have a potential of affecting several plants and several units at the plants at the same time. This requires a sufficiently large resource in terms of trained experienced people, equipment, supplies and external support. An adequate pool of experienced personnel who can deal with each type of unit and can be called upon to support the affected sites should be ensured.	IAEA Lesson 7	**2.2 Enhance human capabilities and capacities** **- Manual stop of HPCI in unit 3 prior to confirmation that the alternative system was effective**	**A**				**SMR countermeasures / developments:** passive safety systems automatically actuated should avoid this concern; Human Factors can be taken into account since SMR design phase
	On-site Emergency Arrangements to Protect Workers: Large scale radiation protection for workers on sites under severe accident conditions can be effective if appropriately organized and with well led and suitable	IAEA Lesson 14						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	trained staff.							
	On-site Emergency Arrangements to Protect Workers: Exercises and drills for on-site workers and external responders in order to establish effective on-site radiological protection in severe accident conditions would benefit from taking account of the experiences at Fukushima.	IAEA Lesson 15						
	Enhancement of training responding to severe accidents: we will enhance training to respond to severe accidents by promptly building a structure for responding to accident restoration, identifying situations within and outside power plants, facilitating the gathering of human resources needed for securing the safety of residents and collaborating effectively with relevant organizations.	Japanese Government Lesson 13						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 **+ June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	Human resources for nuclear safety and nuclear emergency preparedness and responses: the Japanese Government will enhance human resource development within the activities of nuclear operators and regulatory organizations along with focusing on nuclear safety education, nuclear emergency preparedness and response, crisis management and radiation medicine at educational organizations.	Japanese Government Lesson 25						
	Human Capabilities and Capacities: The UK nuclear industry should review existing severe accident contingency arrangements and training, giving particular consideration to the physical, organisational, behavioural, emotional and cultural aspects for workers having to take actions on - site, especially over long periods. This should take account of the impact of using contractors for some aspects on - site such as maintenance and their possible response.	ONR IR-24						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
3. Off-site emergency preparedness and response	Severe accidents: For severe situations, such as total loss of off-site power or loss of all heat sinks or the engineering safety systems, simple alternative sources for these functions including any necessary equipment (such as mobile power, compressed air and water supplies) should be provided for severe accident management.	IAEA Leson 2	**3.1 Strengthen off-site infrastructure resilience** **- The use of off-site resources limited damage** **- Recovery of a heavily damaged plant is dependent on external equipment**	**A**				**SMR countermeasures / developments:** less dependence on off-site infrastructure should be implemented by design, passive safety features help
	Severe accidents: Such provisions as are identified in Lesson 2 should be located at a safe place and the plant operators should be trained to use them. This may involve centralized stores and means to rapidly transfer them to the affected site(s).	IAEA Lesson 3						
	Off-site Emergency Arrangements to Protect the Public and Environment: Greater consideration should be given to providing hardened systems, communications and sources of monitoring equipment for providing essential information for on-site and off-site responses, especially for severe accidents.	IAEA Lesson 10						
	Central control of emergency supplies and equipment and setting up rescue team: we will introduce systems for centrally controlling emergency	Japanese Government Lesson						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	supplies and equipment and setting up rescue teams for operating such systems in order to provide emergency support smoothly even under harsh circumstances.	15						
	Responses to combined emergencies of both large-scale natural disasters and prolonged nuclear accident: we will prepare the structures and environments where appropriate communication tools and devices and channels to procure supplies and equipment will be ensured in the case of concurrent emergencies of both a massive natural disaster and a prolonged nuclear accident. Also, assuming a prolonged nuclear accident, we will enhance emergency response preparedness including effective mobilization plans to gather human resources in various fields who are involved with accident response and support for affected persons.	Japanese Government Lesson 16						
	Off‐site Infrastructure Resilience: Once further relevant information becomes available, the UK nuclear industry should review what lessons can be learnt from the comparison of the events at the Fukushima‐1 (Fukushima Dai‐	ONR IR-9						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 **+ June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	ichi) and Fukushima‐2 (Fukushima Dai‐ni) sites.							
	Emergency Control Centres, Instrumentation and Communications: The UK nuclear industry, in conjunction with other organisations as necessary, should review the robustness of necessary off‐site communications for severe accidents involving widespread disruption.	ONR IR-23						
	Safety Case: The UK nuclear industry should review, and if necessary extend, analysis of accident sequences for long‐term severe accidents. This should identify appropriate repair and recovery strategies to the point at which a stable state is achieved, identifying any enhanced requirements for central stocks of equipment and logistical support.	ONR IR-25						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	External Hazards: There is a need to ensure that in considering external natural hazards: • .....; • .....; • .....; • …..; and • an active tsunami warning system should be established with the provision for immediate operator action.	IAEA Lesson 1	**3.2 Strengthen national arrangements for emergency preparedness and response** **- Fire engines were successful in injecting water to systems but limited to low pressure** **- Off-site radiation monitoring posts did not consider loss of power condition** **- SPEEDI has to be used to be useful**					probably no difference from SMR to LR
	Off-site Emergency Arrangements to Protect the Public and Environment: The use of IAEA Safety Requirements (such as GS-R-2) and related guides on threat categorization, event classification and countermeasures, as well as Operational Intervention Levels, could make the off-site emergency preparedness and response even more effective in particular circumstances.	IAEA Lesson 11						
	Central control of emergency supplies and equipment and setting up rescue team: we will introduce systems for centrally controlling emergency supplies and equipment and setting up rescue teams for operating such systems in order to provide	Japanese Government Lesson 15						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	emergency support smoothly even under harsh circumstances.							
	Responses to combined emergencies of both large-scale natural disasters and prolonged nuclear accident: we will prepare the structures and environments where appropriate communication tools and devices and channels to procure supplies and equipment will be ensured in the case of concurrent emergencies of both a massive natural disaster and a prolonged nuclear accident. Also, assuming a prolonged nuclear accident, we will enhance emergency response preparedness including effective mobilization plans to gather human resources in various fields who are involved with accident response and support for affected persons.	Japanese Government Lesson 16						
	Reinforcement of environmental monitoring: the Government will develop a structure through which the Government will implement environmental monitoring in a reliable and well-planned manner during emergencies.	Japanese Government Lesson 17						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	Enhancement of communication relevant to the accident: we will reinforce the adequate provision of information on the accident status and response, along with appropriate explanations of the effects of radiation to the residents in the vicinity. Also, we will keep in mind having the future outlook on risk factors is included in the information delivered while incidents are still ongoing.	Japanese Government Lesson 19						
	Adequate identification and forecasting of the effect of released radioactive materials: The Japanese Government will improve its instrumentation and facilities to ensure that release source information can be securely obtained. Also, it will develop a plan to effectively utilize SPEEDI (System for Prediction of Environmental Emergency Dose Information) and other systems to address various emergent cases and disclose the data and results from SPEEDI, etc. from the earliest stages of such cases.	Japanese Government Lesson 21						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	Strengthening Emergency Preparedness: The Task Force recommends, as part of the longer term review, that the NRC should pursue emergency preparedness topics related to decisionmaking, radiation monitoring, and public education.	NRC Recommendation 11						
	National Emergency Response Arrangements: The Government should consider carrying out a review of the Japanese response to the emergency to identify any lessons for UK public contingency planning for widespread emergencies, taking account of any social, cultural and organisational differences.	ONR IR-2						
	National Emergency Response Arrangements: The Nuclear Emergency Planning Liaison Group should instigate a review of the UK's national nuclear emergency arrangements in light of the experience of dealing with the prolonged Japanese event.	ONR IR-3						
	Openness and Transparency: Both the UK nuclear industry and ONR should consider ways of enhancing the drive to ensure more open, transparent and trusted	ONR IR-4						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 **+ June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	communications, and relationships, with the public and other stakeholders.							
	Planning Controls: The relevant Government departments in England, Wales and Scotland should examine the adequacy of the existing system of planning controls for commercial and residential developments off the nuclear licensed site.	ONR FR-5						
	National Emergency Response Arrangements: The nuclear industry with others should review available techniques for estimating radioactive source terms and undertake research to test the practicability of providing real‐time information on the basic characteristics of radioactive releases to the environment to the responsible off‐site authorities, taking account of the range of conditions that may exist on and off the site.	ONR FR-6						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	National Emergency Response Arrangements: The Government should review the adequacy of arrangements for environmental dose measurements and for predicting dispersion and public doses and environmental impacts, and to ensure that adequate up to date information is available to support decisions on emergency countermeasures.	ONR FR-7						
	Openness and Transparency: The Government should consider ensuring that the legislation for the new statutory body requires ONR to be open and transparent about its decision‐making, so that it may clearly demonstrate to stakeholders its effective independence from bodies or organisations concerned with the promotion or utilisation of nuclear energy.	ONR FR-8						
	Research: ONR should expand its oversight of nuclear safety‐related research to provide a strategic oversight of its availability in the UK as well as the availability of national expertise, in particular that needed to take forward lessons from Fukushima. Part of this will be to ensure that ONR has access to	ONR FR-10						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	sufficient relevant expertise to fulfil its duties in relation to a major incident anywhere in the world.							
	Off-site Emergency Arrangements to Protect the Public and Environment: The international nuclear community should take advantage of the data and information generated from the Fukushima accident to improve and refine the existing methods and models to determine the source term involved in a nuclear accident and refine emergency planning arrangements.	IAEA Lesson 13	**3.3 Enhance communication and contacts with the international community**	**A**				

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	Enhancement of responses to assistance from other countries and communication to the international community: the Japanese Government will contribute to developing a global structure for effective responses, by cooperating with the international community, for example, developing a list of supplies and equipment for effective responses to any accident, specifying contact points for each country in advance in case of an accident, enhancing the information sharing framework through improvements to the international notification system, and providing faster and more accurate information to enable the implementation of measures that are based upon scientific evidence.	Japanese Government Lesson 20						
	International Arrangements for Response: The Government should approach IAEA, in co‑operation with others, to ensure that improved arrangements are in place for the dissemination of timely authoritative information relevant to a nuclear event anywhere in the world.	ONR IR-1						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
4. Nuclear safety culture and infrastructure	Global Nuclear Safety: The UK Government, nuclear industry and ONR should support international efforts to improve the process of review and implementation of IAEA and other relevant nuclear safety standards and initiatives in the light of the Fukushima‐1 (Fukushima Dai‐ichi) accident.	ONR FR-9	**4.1 Review and clarify regulatory and emergency response framework - Consideration between evacuations and venting decision**					**SMR countermeasures / developments:** emergency response needs and ares should be limited by SMR source term and level of safety
	Off-site Emergency Arrangements to Protect the Public and Environment: The use of long term sheltering is not an effective approach and has been abandoned and concepts of 'deliberate evacuation' and 'evacuation-prepared area' were introduced for effective long term countermeasures using guidelines of the ICRP and IAEA.	IAEA Lesson 12						
	Establishment of a clear division of labor between relevant central and local organizations: we will review and define roles and responsibilities of relevant organizations including the NERHQs (Nuclear Emergency Response Headquarters), clearly specify roles, responsibilities and tools for communication while also improving institutional mechanisms.	Japanese Government Lesson 18						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	Clear definition of widespread evacuation areas and radiological protection guidelines in nuclear emergency: the Japanese Government will make much greater efforts to clearly define evacuation areas and guidelines for radiological protection in nuclear emergencies.	Japanese Government Lesson 22						
	Clarifying the Regulatory Framework: The Task Force recommends establishing a logical, systematic, and coherent regulatory framework for adequate protection that appropriately balances defense-in-depth and risk considerations.	NRC Recommendation 1						
	Safety Assessment Approach: Once further detailed information is available and studies are completed, ONR should undertake a formal review of the Safety Assessment Principles to determine whether any additional guidance is necessary in the light of the Fukushima accident, particularly for "cliff - edge" effects.	ONR IR-5						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	External Hazards: There is a need to ensure that in considering external natural hazards: • .....; • .....; • .....; • any changes in external hazards or understanding of them should be periodically reviewed for their impact on the current plant configuration; and •	IAEA Lesson 1	**4.2 Reinforce safety regulatory bodies and legal structures**	**A**				
	Off-site Emergency Arrangements to Protect the Public and Environment: The use of IAEA Safety Requirements (such as GS-R-2) and related guides on threat categorization, event classification and countermeasures, as well as Operational Intervention Levels, could make the off-site emergency preparedness and response even more effective in particular circumstances.	IAEA Lesson 11						
	Follow-up IRRS (Integrated Regulatory Review Service) Mission: Nuclear regulatory systems should ensure that regulatory independence and clarity of roles are preserved in all circumstances	IAEA Lesson 16						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	in line with IAEA Safety Standards.							
	Thorough accident management (AM) measures: we will change the accident management measures from voluntary safety efforts by operators to legal requirements, and develop accident management measures to prevent severe accidents, including a review of design requirements as well, by utilizing a probabilistic safety assessment approach.	Japanese Government Lesson 5						
	Reinforcement of safety regulatory bodies: the Japanese Government will separate NISA (Nuclear and Industrial Safety Agency) from METI (Ministry of Economy, Trade and Industry) and start to review implementing frameworks, including the NSC (Nuclear Safety Commission) and relevant ministries, for the administration of nuclear safety regulations and for environmental monitoring.	Japanese Government Lesson 23						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	Establishment and reinforcement of legal structures, criteria and guidelines: the Japanese Government will review and improve the legal structures governing nuclear safety and nuclear emergency preparedness and response, along with related criteria and guidelines. During this process, it will reevaluate measures taken against age-related degradation of existing facilities, from the viewpoint of structural reliability as well as the necessity of responding to new knowledge and expertise including progress in system concepts. Also, the Japanese Government will clarify technical requirements based on new laws and regulations or on new findings and knowledge for facilities that have already been approved and licensed, in other words, it will clarify the status of retrofitting in the context of the legal and regulatory framework. The Japanese Government will make every effort to contribute to improving safety standards and guidelines of the IAEA by providing related data.	Japanese Government Lesson 24						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	Human resources for nuclear safety and nuclear emergency preparedness and responses: the Japanese Government will enhance human resource development within the activities of nuclear operators and regulatory organizations along with focusing on nuclear safety education, nuclear emergency preparedness and response, crisis management and radiation medicine at educational organizations.	Japanese Government Lesson 25						
	Improving the Efficiency of NRC Programs: The Task Force recommends that the NRC strengthen regulatory oversight of licensee safety performance (i.e., the Reactor Oversight Process) by focusing more attention on defense-in-depth requirements consistent with the recommended defense-in-depth framework.	NRC Recommendation 12						
	Emergency Response Arrangements and Exercises: ONR should consider to what extent long - term severe accidents can and should be covered by the programme of emergency exercises overseen by the regulator.	ONR IR-6						

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	Emergency Response Arrangements and Exercises: ONR should review the arrangements for regulatory response to potential severe accidents in the UK to see whether more should be done to prepare for such very remote events.	ONR IR-7						
	Thoroughly instill a safety culture: the nuclear operators whose organization and individuals have primary responsibility for securing safety should look at every knowledge and every finding, and confirm whether or not they indicate a vulnerability of a plant. They should reflect as to whether they have been serious in introducing appropriate measures for improving safety, when they are not confident that risks concerning the public safety of the plant remain low. organizations or individuals involved in national nuclear regulations, as those who responsible for ensuring the nuclear safety of the public, should reflect whether they have been serious in addressing new knowledge in a responsive and prompt manner, not leaving any doubts in terms of safety.	Japanese Government Lesson 28	**4.3 Thoroughly improve and instil safety culture** **- Operators performed above and beyond call of duty** **- Operators stayed within approved dose limits (except for limited inadvertent events)** **- Operators/utility had no hesitation in carrying out actions to the benefit of the public but economic detriment to the facility** **- Appropriate operational response was not constrained by fear of personal harm** **- Operators initiated non-standard procedures early in the event (e.g. fire engines)**	**A**				**SMR countermeasures / developments:** simplicity usually adopted in SMRs should help

Category	Individual Lessons Learned and Recommendations	Sources	Integrated Lessons Learned /CM Lessons (April 2012 + **June 1, 2012**)	Applicable Reactor Type				Possible Countermeasures / Technology Development
				LWR	HWR	HTGR	FR	
	Japan will establish a safety culture by going back to the basics, namely that pursuing defenses-in-depth is essential for ensuring nuclear safety, by constantly learning professional knowledge on safety, and by maintaining an attitude of trying to identify weaknesses as well as room in the area of safety.							
	Strengthening Emergency Preparedness: The Task Force recommends, as part of the longer term review, that the NRC should pursue emergency preparedness topics related to decisionmaking, radiation monitoring, and public education.	NRC Recommendation 11						
	Human Capabilities and Capacities: The UK nuclear industry should continue to promote sustained high levels of safety culture amongst all its employees, making use of the National Skills Academy for Nuclear and other schemes that promote "nuclear professionalism".	ONR FR-11						

OECD-NEA

Committee for Technical and Economic Studies on Nuclear Energy Development and The Fuel Cycle (NDC)

7th Meeting of the Working Party on Nuclear Energy Economics, 10 November 2011

List of the presentations, contributions and discussions

• Report on Work of the International Atomic Energy Agency in the Areas of Economics and Finance (Presentation by the IAEA Secretariat)
• Results of the Workshop on "Enhancing the Contribution of Nuclear Power to a Low-carbon Electricity Future" held on 9 November 2011 (Open discussion) [Agenda – NEA/NDC(2011)26]
• Feedback on Presentations and Sales of the WPNE study on "Carbon Pricing, Power Markets and the Competitiveness of Nuclear Energy" [NEA/NDC(2011)36]
The System Effects of Nuclear Power:
• Detailed Outline: Update and Status of Activities in the Context of the System Effects Study [NEA/NDC(2011)21/REV] (Presentation by Secretariat)
• Chapter 1. "The System Effects Engendered and Experienced by Nuclear Power" [NEA/NDC(2011)27] (Presentation by Secretariat of advanced draft for comment and discussion)
• Chapter 3. "The Contribution of Nuclear Power to the Minimisation of Long-Run and Short-Run System Effects" [NEA/NDC(2011)37]
• Chapter 4. "A Comparaison of the Grid and System Costs of Different Technologies" (Presentation by Secretariat and discussion)
• Chapter 5. "The Institutional and Regulatory Framework for Integrating System Effects and Flexibility Services" [NEA/NDC(2011)29]. (Presentation by Secretariat of advanced draft for comment and discussion)
• Chapter 6a. "Smart Electricity Grids" [NEA/NDC(2011)30] (Presentation of advanced draft for comment and discussion, Dirk Van Herten, University of Leuwen)
• Chapter 6b. "SMR Economic Potential in Integrated Electricity Systems" [NEA/NDC(2011)38] (Presentation of draft for comment and discussion, Marco Ricotti, Politecnico Di Milano)
• Proposed New Title for the WPNE Project on "The System Effects of Nuclear Power" [NEA/NDC(2011)31] (Initiating discussion about title and policy conclusions of study)
• "Economics of Long-term Operation of Nuclear Power Plants" [NEA/NDC(2011)34] (Summary Record of the 1st Meeting of the Expert Group) (Presentation by Secretariat)
• "Economics of the Back-End of the Nuclear Fuel Cycle" [NEA/NDC(2011)24] (Draft Agenda of the 1st Meeting of the Expert Group). (Presentation by Secretariat).

WPNE meeting
Paris, 10 Nov. 2011

POLITECNICO DI MILANO

SMR economic potential in Integrated Electricity Systems

POLIMI nuclear economics research group
Prof. Marco E. Ricotti, PhD
Prof. Mauro Mancini, PhD
Prof. Paolo Trucco, PhD
Mr. Giorgio Locatelli, PhD
Ms. Sara Boarin
Mr. Andrea Trianni

Economic evaluation of SMRs deployment

WPNE meeting
Paris, 10 Nov. 2011

SMRs are gaining increasing interest all around the "nuclear" world

But, since the nuclear "business as usual" is Large Size NPPs:

- **Are SMRs economically-financially competitive?**
- **Are SMRs' technology & deployment representing a "similar" or "scaled" business with respect to LRs?**
- **How can we evaluate and quantify penalties/advantages of SMRs vs LRs?**
- **Are there already suitable tools to compare such deployments?**

Origin of the work: IRIS project opportunity + collaboration with IAEA

Scope: comparison of deployments (SMRs vs LRs)

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INCAS economic evaluation tool

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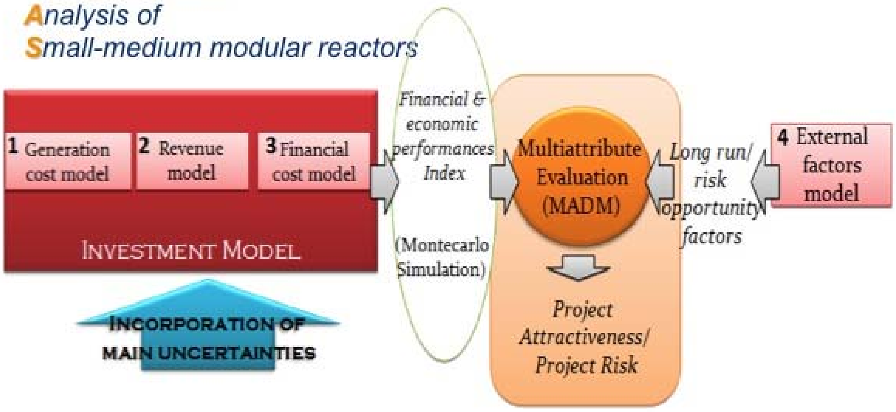
INtegrated model for the
Competitiveness
Analysis of
Small-medium modular reactors



- INCAS applies to the comparative evaluation of SMR vs. LR with equivalent total power output installed

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EXTERNAL FACTORS

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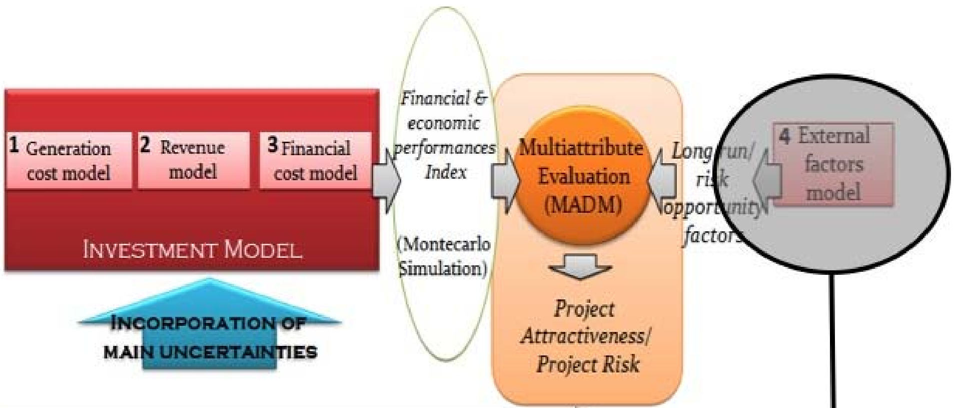

- Factors not fully quantifiable and not explicitly considered in an investment evaluation (technical, social,…)
- Impossible to manage or control in some or all the phases of the project
- Able to influence the economic performances or the feasibility of the project

Evaluation of the impact on LR and SMR: differential?

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EXTERNAL FACTORS - Introduction

- An "**external factor**" is a factor usually not directly considered within the investment evaluation, because is not directly controllable from the investor and it results hardly accounted. However it strongly influences the life cycle and the feasibility of the project itself.

- Examples of external factors are: **supply chain, public acceptability, system effects, competences required to run the plant,** etc.

EXTERNAL FACTORS - List

- External Factors differential between LR and SMR

SITE RELATED

Qualitative	Sub- Factors	Evaluation	Result
Spinning Reserve Management	-	Quantitative	Differential
Electric Grid Vulnerability	-	Mixed	Differential
Public acceptability	Overall population's attitude	Qualitative	Not Differential
	Local population's attitude	Qualitative	Differential
Technical Siting Constraints	SMR stand alone	Qualitative	Differential
	Each configuration	Qualitative	Differential

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EXTERNAL FACTORS - List

➢ External Factors differential between LR and SMR

PROJECT LIFE CYCLE RELATED

Qualitative	Sub- Factors	Evaluation	Result
Risks Associated to the Project	FOAK risks	Qualitative	Differential
	Supply Chain	Qualitative	Differential
	Construction	Qualitative	Differential
Design Robustness	-	Quantitative	Differential
Historical and Political Aspects	-	Qualitative	Differential
Competences Required for the Operations	-	Qualitative	Differential

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EF Example-1: Spinning reserve

➢ Ancillary services are in charge to **maintain the security and the quality of electricity supply**

➢ To **control the system frequency** is the most important of them: it requires that a certain amount of **active power be kept in reserve**, to re-establish the balance between load and generation in continuous. Such reserve is usually named as "spinning reserve",

SPINNING RESERVE DEFINITION:

*Unutilized generation capacity which can be activated **by the TSO** (Transmission System Operator) to control the electric system frequency, **independently** from the time window of availability.*

Size ⇧ Spinning Reserve Required ⇧

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EF Example-1: Spinning reserve

QUANTIFICATION ALGORITHM

1. Split electric system in different areas which can be considered like isolated systems
2. Calculate the LC (Largest Contingency) for every area: it's the sum of the **two** largest generating unit. The WE (Worst Event) is the contemporary outage of the two main autonomous groups of generation in the area.
3. Hypothesize to establish in each area a 1340 MWe LR or four stand-alone 335 MWe. Calculate new LC for each of new cases and the difference from the actual LC. If difference is not zero, new NPPs increase required spinning reserve and the burden for TSO.
4. Sum the differences of all areas for each configuration: one LR and four SMRs. Results measure the increase of reserve due to LRs or SMRs construction on the whole territory. The nearer to one the ratio between sums is, the smaller the differential impact will be.

Advantage SMR

$$0 < \frac{\sum \Delta LC_{SMR}}{\sum \Delta LC_{LR}} < 1$$

Advantage LR

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EF Example-1: Spinning reserve

IMPLEMENTATION ON THE ITALIAN SCENARIO

Step 1

8 reference areas in Italy

TERNA (grid manager), 2009

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EF Example-1: Spinning resereve

IMPLEMENTATION ON THE ITALIAN SCENARIO

Step 2 | Step 3

AREA	ACTUAL WE	ACTUAL LC	1 LR			4 SMR		
			WE	LC	DIFF.	WE	LC	DIFF.
Turin	790+800	1.590	1.340+800	2.140	550	As actual	1.590	0
Milan	800+850	1.650	1.340+850	2.190	540	As actual	1.650	0
Venice	660+660	1.320	1.340+660	2.000	680	As actual	1.320	0
Florence	390+390	780	1.340+390	1.730	950	As actual	780	0
Rome	770+660	1.430	1.340+770	2.110	680	As actual	1.430	0
Naples	660+660	1.320	1.340+660	2.000	680	As actual	1.320	0
Palermo	376+376	752	1.340+376	1.716	964	As actual	752	0
Cagliari	575+350	925	1.340+575	1.915	990	As actual	925	0
SUM		9.767		15.801	6.043		9.767	0
RATIO		Step 4		+61,8%			+0,0%	0

EF Example-1: Spinning resereve

- The construction of LR would require 61,8% more spinning reserve than today
- The construction of SMR does not cause any increments
- **Impact on required spinning reserve supports SMR option**

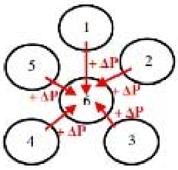
(assumption: 1 LR built in each area;
penalty increase if 2 LRs per area are built;
penalty reduces if >2 LRs are built per area)

EF Example-2: Grid Vulnerability

- Vulnerability Index (VI) of the Power System (with LRs or with SMRs)

1. *LRs / SMRs must be located in the different generation nodes of the grid;*
2. *for each new configuration, the calculation of VIs evaluates the effect of outages of different transmission lines.*

- At same level of lines' congestion: the larger the site's output, the higher the risk of overloads. Differential impact (LR-SMRs) higher in case of generation nodes connected to the most congested transmission lines.



CONDITION	POWER (*MWe*)	AREAS 1-5	AREA 6
Normal working	Generation	100	100
	Load	100	100
Instant of unit #6 outage	Generation	100	0
	Load	84	80
After activation of reserves	Generation	120	0
	Load	100	100

- *Electric grid vulnerability is not differential considering multiple SMRs on the same site, with total equivalent power installed than LR.*

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EF Example-3: Mean Variance Portfolio

- Mean Variance Portfolio theory (MVP) is the most widely used method for the optimization of the electricity generation mix.
- Identify the best power plants portfolio from the investor point of view towards risk attitude: IRR as key profitability indicator, with its probability distribution.
- Optimal portfolio: the higher IRR expected value, with given IRR variance;
  OR
  Optimal portfolio: lowest variance, with given IRR.
- Best mix on IRR/variance: optimum frontier match the investor risk aversion and profitability requirements.

Large Electricity Markets: MVP analysis theoretical (best portfolio is a public governance issue)

Investment decisions taken by each Utility (in a liberalized market).
Generation capacity is limited, similar to Small Electricity markets (e.g. 2 GW)

"Large markets" made up by "Small Markets"

EF Example-3: Mean Variance Portfolio

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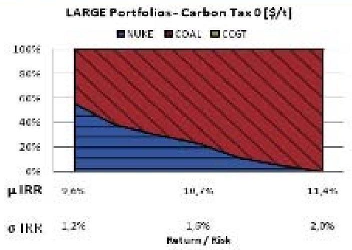


Figure 4 - Large market Portfolio - Electricity Price 50$/MWh - Carbon Tax 0$/t

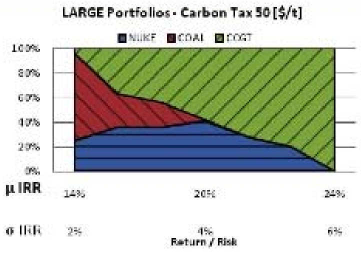
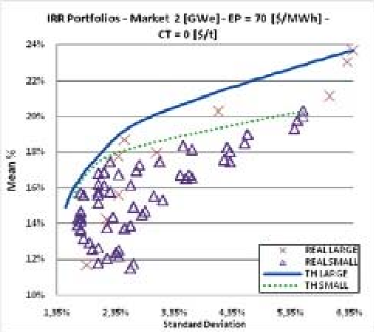


Figure 7 - Large market Portfolio - Electricity Price 90 $/MWh - Carbon Tax 50 $/t



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EF Example-4: Investment Flexibility

REAL OPTIONS APPROACH – why?

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- The DCF is a capital budget method, which looks at projects in isolation. It determines the future cash flows the project may generate, and discounts those to today's value at a project-specific discount rate that reflects the perceived risk of the cash flows.
- DCF assumes that the firm will embark on a rigid and inflexible path forward, ignoring and failing to respond and adjust to any changes in the market place.
- DCF ignores the value of managerial flexibility to react to future uncertainties. In the future new information may arrive and the original investment plan will change.
- DCF ignores the fact that investments often come in natural, sequential steps with multiple "go" or "no-go" decisions

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REAL OPTIONS – why?

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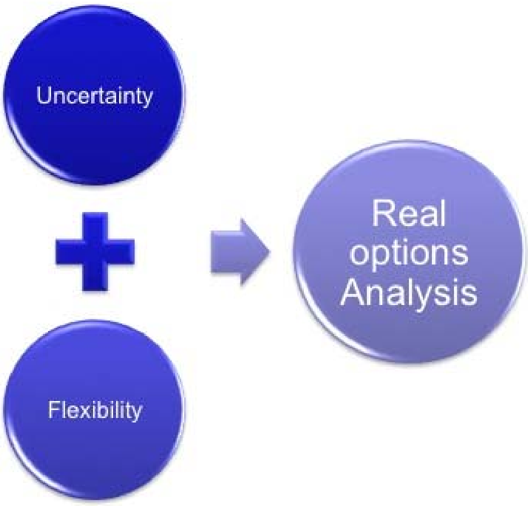

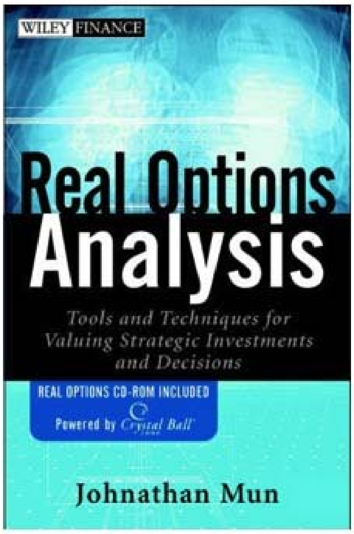

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REAL OPTIONS - Introduction

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- Real option is defined as **the right but not the obligation to acquire the present value of the expected cash flows** by making an investment when the opportunity is available.
- The real option concept applies financial option theory to real life investments such as investments in manufacturing plants, information technology projects, pharmaceutical research and development, new ventures, etc.
- **An option arises when information can modify the outcome of future investment decisions**. This methodology is particularly applicable when there is a high degree of uncertainty, some managerial flexibility, and not all the information is known at a given time.

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REAL OPTIONS - Introduction

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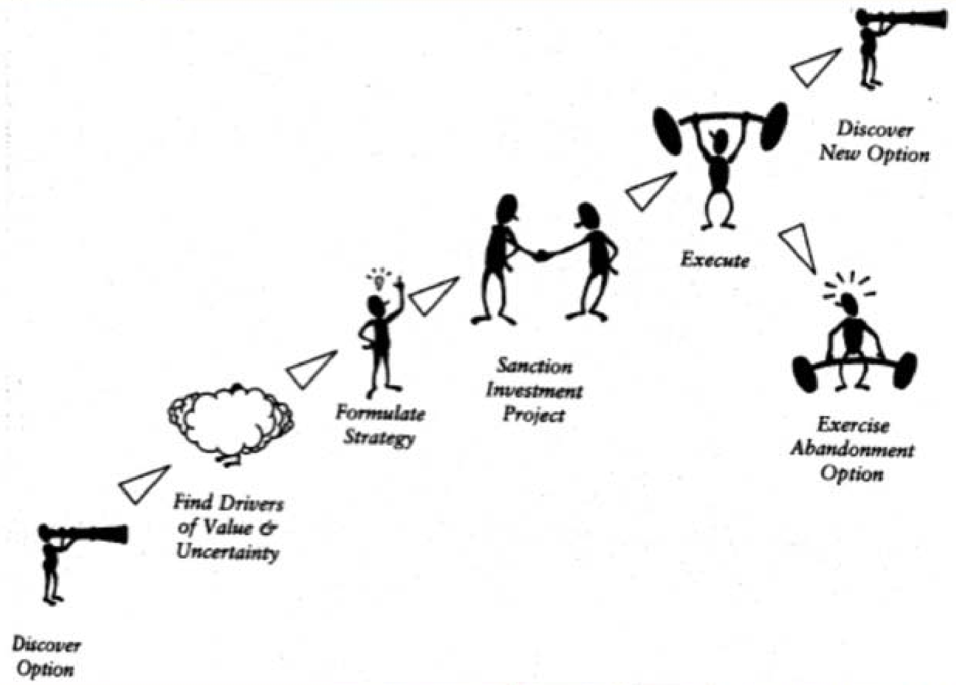

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REAL OPTIONS – Example for nuclear case

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Options	Description
Abandon	Creating an abandonment option you have the right not to continue a project should the business conditions be negative (Brach, M.A. 2003), (Mun, Johnathan 2002).
Expand	Management can expand production or increase resource deployment if the market environment develops favorably (Rogers, Jamie 2002).
Delay/Defer	The option to delay is exercised when the firm owning the rights to the project decides when to invest on it (Brach, M.A. 2003), (Mun, Johnathan 2002).
Stage	It is the ability to break up investment into incremental, conditional step (Brach, M.A. 2003).
Learn	It is the firm's ability to reduce technical uncertainty through investment to obtain a reliable and precise understanding of the future (Brach, M.A. 2003).

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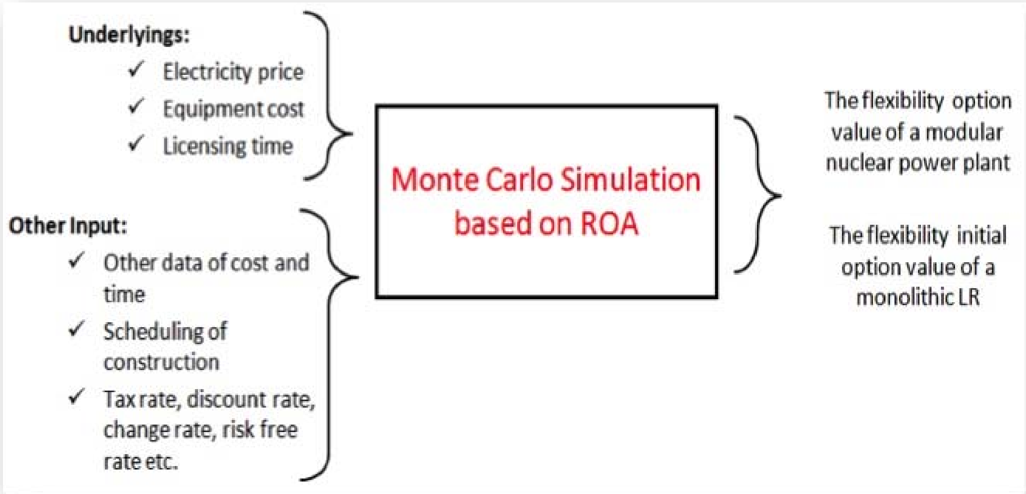
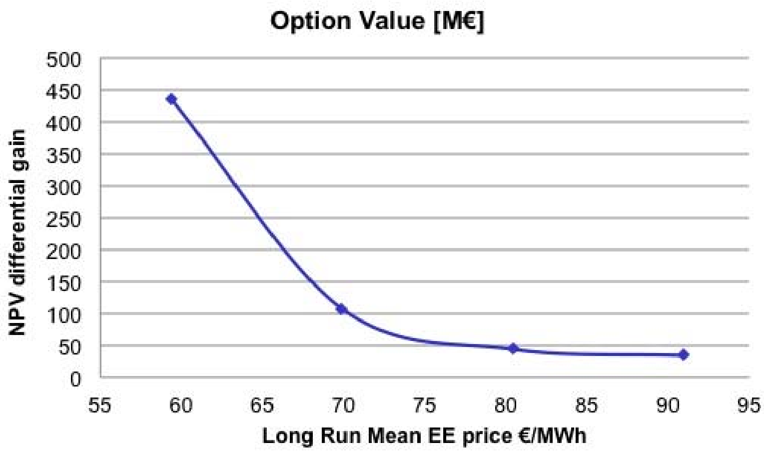
REAL OPTIONS – macro approach



REAL OPTIONS – preliminary results

Electricity Long run mean

Electricity Long Run Mean	FCFO without option	FCFO with option	% Option Value
59,4 €/MWh	-317,9	117,9	137%
69,9 €/MWh	502,8	610,2	21%
80,4 €/MWh	1293,8	1337,8	3,4%
90,9 €/MWh	2054,3	2088,7	1,7%



REAL OPTIONS – preliminary results

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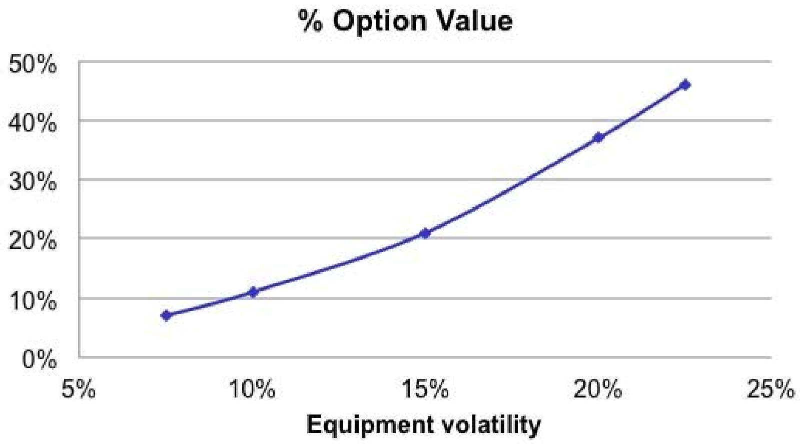
Equipment Volatility

Equipment volatility	FCFO without option	FCFO with option	% Option Value
7,5%	501,3	536,7	7%
10%	499,8	556,4	11%
15%	502,8	610,2	21%
20%	488,3	670,3	37%
22,5%	487,4	712,1	46%



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EF Example-4: Investment Flexibility

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- The flexibility allows the investor to react in an environment affected by uncertain conditions
- The DCF techniques underestimate the value of SMR
- An investment in SMR has more degrees of freedom than an investment in LR
- The intrinsic SMR' investment flexibility can be fully quantified by Real Options
- Real Options do not aim to predict the future, but evaluate in financial terms [€] the value of catching opportunities and/or heading negative risks

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Summary & further developments

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Model development is still on-going, in the following areas:

- **Risk evaluation & stochastic approach (✔ DONE – oct. 2011)**
- **Bottom-up cost-estimation of different SMR size and design**
- **External factors integration & MADM**
- **Real Options model**

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Short Info on the Collaboration Agreements between Politecnico di Milano and some Small Modular Reactor projects

In the recent period, and due to the expertise gained by POLIMI in the last 10 years through the participation to the IRIS international project, some Collaboration Agreements have been signed by POLIMI with some Small Modular Reactor projects, paving the way for possible R&D activities in the very next future.

In particular:

- with DCNS company, a French organisation involved in the design of the FlexBlue reactor, an SMR of 100MWe size, PWR integral type, mounted into a submarine hull and to be located 100m deep in the sea, interested in collaborating on the design of passive safety systems and on experimental activities devoted to thermal fluid dynamics investigation of the passive systems;
- with NuScale company, a US organisation involved in teh design of the NuScale reactor, an SMR of 45MWe per module, PWR integral type, natural circulation, to be deployed in cluster of 12 modules, interested in collaborating on the design and investigation, both modelling and experimental, of helical coil steam generators and of passive safety systems, as well as on the investigation of the profitability and other financial and economic features for a multi-module deployment strategy.

Recently, also another US company, Flibe Energy, asked for a collaboration on the modellig of molten salt modular reactors, for the investigation of fluid dynamics and neutronics behavior, with Thorium as a reference fuel cycle.

Other relationships are under development and consolidation, mainly for the use, for R&D purposes, of the INCAS code, developed by POLIMI for the simulation of different strategies of deployment of SMRs and the analysis of the corresponding costs, profitability and other financial and economic features. An Agreement with the Ghana Atomic Energy Commission has been already signed, others are under discussion (e.g. with Finland, China, South Korea, Russia).

CURRICULUM SCIENTIFICO DEL GRUPPO DI LAVORO

Il gruppo di lavoro impegnato nell'attività è costituito da un professore ordinario di Impianti Nucleari del Politecnico di Milano (Dipartimento Energia), Marco Enrico Ricotti, e da una Assegnista di Ricerca, Sara Boarin.

Il prof. Ricotti svolge attività di ricerca da più di 20 anni al Politecnico nel campo della Ingegneria Nucleare, con particolare riferimento alla termoidraulica, alla sicurezza, agli aspetti economici dell'energia nucleare ed ha svolto o coordinato ricerche teorico-modellistiche e sperimentali nel gruppo Reattori Nucleari del Dipartimento di Energia del Politecnico di Milano, che attualmente guida, pubblicando i risultati su rivista e in atti di Congresso, quasi esclusivamente internazionali. Insieme all'ing. Boarin è anche autore di diversi rapporti nell'ambito dei PAR trascorsi.

L'ing. Boarin ha una esperienza pluriennale di collaborazione di ricerca con il Politecnico sulle tematiche economico-finanziarie dei reattori nucleari, nonché una esperienza lavorativa presso banche di affari internazionali. E' coautrice di paper scientifici e report per organizzazioni internazionali (OECD, IAEA).

Maggiori dettagli sulle attività di ricerca nonché l'elenco delle pubblicazioni più recenti si possono trovare sul sito Web del gruppo di ricerca del Politecnico di Milano (http://www.nuclearenergy.polimi.it).