Nuclear Energy R&D in Finland

Workshop on R&D needs for current and future nuclear systems
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Prof. Riitta Kyrki-Rajamäki
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- Nuclear waste management studies in Finland
- National research programmes on operational safety:
  - Finnish research programme on NPP safety FINNUS 1999-2002,
  - Advanced light water reactors programme ALWR 1998 - 2003
  - Safety of nuclear power plants – Finnish national research programme SAFIR 2003 - 2006
Electricity supply in Finland

- Net imports
- Conventional condensing power
- Nuclear power
- Combined heat and power (CHP)
- Hydro power

Total nominal capacity in 2000 about 20 000 MW

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<th>Year</th>
<th>Net imports</th>
<th>Conventional condensing power</th>
<th>Nuclear power</th>
<th>Combined heat and power (CHP)</th>
<th>Hydro power</th>
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Demand for new electricity generating capacity

Nominal power, MW

21000
18000
15000
12000
9000
6000
3000
0


7500 MW

Demand for new capacity
CHP, industrial
CHP, district heat
Other condensing
Coal-condensing
Nuclear power
Hydro & wind power
Distribution of resources of nuclear energy R&D in Finland in 1999 (total € 27 million)

**Funding Sources**
- Power companies: 53%
- TEKES: 11%
- VTT: 10%
- EU: 6%
- STUK: 5%
- Others: 6%

**Research Areas**
- Waste Management: 50%
- Reactor Safety: 39%
- Fusion Research: 10%
- Others: 1%
- ALWR: 15%
- XVO: 4%
- JYT2001: 4%
- FINNUS: 4%
Overall situation of nuclear waste management in Finland

- Basic option is geological disposal for all types of wastes
  - polluter pays
- Repositories for low- and intermediate level waste are in operation at NPP sites
  - one in Olkiluoto and one in Loviisa
- Decommissioning waste will be disposed of in extensions to these repositories
- Preparations are underway for spent nuclear fuel disposal in one national repository in Olkiluoto - construction of the underground characterisation facility ONKALO will be started 2004
- Planned construction time of the encapsulation and final disposal facility 2010 - 2020
- JYT2001 public research programme was concluded in 2001
- KYT was launched 4.2.2002
Preliminary plan for ONKALO /http://www.posiva.fi/

ONKALON alustava tilasuunnitelma
Reference concept for Finnish spent nuclear fuel disposal
Main research areas of KYT: strategic studies

Strategic studies of nuclear waste management

- Fundamental options in nuclear fuel cycle and nuclear waste management
- General safety principles in nuclear fuel cycle and nuclear waste management
- Costs of nuclear waste management, transportations, decommissioning, low- and intermediate level waste
Main research areas of KYT: long-term safety of spent nuclear fuel disposal

Studies improving the long-term safety of spent fuel disposal

- Release of radionuclides from repository
- Methodology of safety assessment
- Bedrock and groundwater
- Migration of radionuclides in bedrock
- Biosphere studies
Main results of technical studies of JYT2001

- The idea of block-mosaic structure in crystalline bedrock was supported
  - possible bedrock movements occur via existing fracture zones
  - repository will be “safe” in a block surrounded by fracture zones

- Methodological progress in integrating geoscientific data in site investigations
  - groundwater flow modelling and geochemical groundwater studies support each other

- Behaviour of bentonite has been studied intensively but
  - more research is still needed on swelling mechanisms

- Migration studies in laboratory and on natural analogues provided further evidence that radionuclide retention mechanisms sorption and matrix diffusion occur in lab as well as in situ
Main results from social science studies of JYT2001

- Public participation was low in the EIA process despite extensive arrangements
  - participation was concentrated on a smallish number of individuals in all four sites
  - there was widespread uncertainty about the nature of the EIA
    - nuclear waste policy was actually decided in 1983 and the EIA at hand was really about the facility

- Media publicity had a limited effect in the DIP process
  - there was overall confidence in the expertise of both Posiva and regulators (i.e. KTM and STUK)
  - journalists generally considered the material provided by Posiva to be technically and scientifically well-founded

- Finnish nuclear waste management paradox:
  - low public involvement but high public confidence
FINNUS, the Finnish Research Programme on Nuclear Power Plant Safety 1999 - 2002

- Research fields: NPP ageing, accidents and risks aiming at integrity, safety and reliability
- Research Partners: VTT Processes, VTT Industrial Systems, VTT Building Technology and Lappeenranta University of Technology (LTKK)
- Annual volume Euro 3.6 million, 30 person-years, staff ~100
- 57 scientific articles, 233 international conference papers, 274 other reports
- 6 doctoral theses, 2 licentiate and 18 master’s theses completed
Co-operation between projects in FINNUS programme
FINNUS: Controlled-Distance Electrochemistry (CDE) arrangement

An experimental set-up enabling electrochemical studies of construction materials even in low-conductivity high-temperature water such as Boiling Water Reactor (BWR) coolant, with the option to detect dissolving species as well.

- The CDE arrangement makes it possible to assess the effect of anionic impurities, Fe/Ni ratio and other water chemistry parameters on material electrochemistry related e.g. to stress corrosion cracking and to activity incorporation.

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Model for materials embrittlement

The ability to estimate the effect of irradiation, annealing and reirradiation cycles on the mechanical properties of steels

- Techniques to utilise and interpret FEGSTEM microscopy in micro-mechanistic studies
- Chemical composition based correlation with mechanical properties

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FINNUS: The Master Curve approach

- The Master Curve (MC) method combines a theoretical description of the scatter, statistical size effect and temperature dependence of fracture toughness, which is thus described solely with the transition temperature $T_0$ in the transition region.

- The basic MC standard ASTM E1921 is the first standard that accounts for the statistical specimen size effect and variability in brittle fracture toughness.

- The MC methodology has evolved, from being a testing and analysis procedure, to a tool addressing many more structural integrity issues like constraint and parameter transferability.

Contact person: Kim Wallin, VTT Industrial Systems, kim.wallin@vtt.fi
FINNUS: Simulation of ultrasonic inspection

- Simulation is a fast and effective tool to examine basic requirements and conditions of an inspection task.
- Complicated inspection geometry can be visualised and examined using three-dimensional component models on which inspection simulations are performed.
- Simulations can be used to substitute practical trials thus fabrication of expensive test specimens and inspections on them can be reduced.
- Basic facilities to perform simulations that take into account the geometric conditions of component and defect location are established.

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FINNUS: Condensation pool experiments at LTKK

Direct connection to plant conditions
- Non-condensable gas blowdown to BWR suppression pool during Large Break Loss of Coolant Accident (LBLOCA)
- Gas may flow inside Emergency Core Cooling System (ECCS) strainers and disturb the performance of ECCS pumps

Experiments with a scaled down test rig
- Gas bubbles forming at the blowdown pipe vent touched the ECCS strainer but only a fraction of gas was transported through the strainer into the pump intake
- Threshold for critical gas volume fraction in the ECCS pump flow was measured
- Test rig relevant for passive safety system studies of the next generation plants

Contact person: Jani Laine, LTKK, jani.laine@lut.fi
FINNUS: Design calculations for condensation on pool experiments

Computational Fluid Dynamics (CFD)
- Fluent 5 code calculations supported the design of the test rig and the planning of the experiments
- Post test calculations confirmed the ability of CFD codes to simulate the behaviour of noncondensables in a water pool

Structural analyses
- Design and post test calculations with the ABAQUS Finite Element Method (FEM) code.
- Loading transients obtained from CFD results.

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Arja Saarenheimo, VTT Industrial Systems, arja.saarenheimo@vtt.fi
FINNUS: Thermal-hydraulics modelling

- **Piecewise Linear Interpolation Method (PLIM)** is a highly accurate hydraulic solution method developed at VTT
- **The solver CFDPLIM based on PLIM** further developed for the applications
- **CFDPLIM** to be implemented in reactor dynamics codes: improves e.g. tracking of boron and temperature fronts in transients and can also handle reversed flows
- Mathematical verifications performed and the potential of the method demonstrated by successfully calculating several demanding flow problems
- Improving the hydraulics models of VTT’s reactor dynamics codes is long-term research, challenging both scientifically and computationally, and continued effort is needed in this field to fulfil the inherent application promises of the new models.

Contact person: Markku Rajamäki, VTT Processes, markku.rajamaki@vtt.fi
FINNUS: Coupled fuel behaviour and thermal-hydraulics modelling

The FRAPTRAN-GENFLO coupled code development
- Elaborated fuel behaviour code FRAPTRAN (in collaboration with the USNRC) with high burnup effects modelled up to 60 MWd/kgU
- Advanced general five-equation flow model GENFLO developed by VTT

Test cases
- Loviisa VVER Large Break Loss-of-Coolant Accident (LBLOCA)
- BWR Anticipated Transients Without a Scram (ATWS)

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FINNUS: Validation and application of accurate Monte Carlo method

- **Monte Carlo method** is used in neutronics to solve complex problems in criticality and radiation shielding
- Advanced features of the MCNP Monte Carlo code and use of Monte Carlo method in burnup calculations studied
- **Monte Carlo method applied to calculate e.g.**
  - Efficiency of VVER-440 control assembly
  - Tokaimura criticality accident
  - Kernels of the out-of-core detector signal model in the three-dimensional reactor dynamics code HEXTRAN developed by VTT (figure)
- **NJOY nuclear data processing code** applied to generate multi-temperature cross section data for MCNP
- Several applications in contract research

Contact person: Markku Anttila, VTT Processes, markku.anttila@vtt.fi
FINNUS: Pressure vessel lower head integrity

PASULA / FEM model for two- and three-dimensional mechanical analyses

- Detailed assessment of pressure vessel failure mode during a severe accident for PWR and BWR
- Fast-running code, efficient and flexible visualisation of results
- Both two- and three-dimensional models give excellent agreement with experimental data from Sandia's 1/5th scale OLHF lower head tests with and without penetrations and with KTH's FOREVER creep rupture tests
- Applications to Loviisa and Olkiluoto plants

Contact person: Kari Ikonen, VTT Processes, kari.ikonen@vtt.fi
FINNUS: Reliability assessment methods for modern Instrumentation and Control (I&C) systems

A method for the reliability estimation of software-based I&C systems

- Combines both quantitative and qualitative reliability evidence from the whole life cycle of the I&C system
- Based on the use of Bayesian networks
- Provides support for the licensing of software-based I&C systems

Contact person: Atte Helminen, VTT Industrial Systems, atte.helminen@vtt.fi
FINNUS: Risk-informed applications of Probabilistic Safety Assessment

Qualification of PSA applications

- A generic approach to be applied in various safety-related decision contexts
- PSA evaluators can use it as a decision aid for approving PSA applications
- Practitioners can find guidance to QA, modelling, analyses, and documentation

Expert panel methodology

- Approach to achieve a balanced utilisation of information and expertise from several disciplines in decision making, including PSA as one decision criterion
- Tested in categorisation of piping segments in Olkiluoto and Loviisa (RI-ISI i.e. Risk-Informed In-Service Inspection applications)

Contact person: Kaisa Simola, VTT Industrial Systems, kaisa.simola@vtt.fi
FINNUS: Probabilistic fire simulator

A general Monte Carlo simulation tool to estimate loss probabilities for fire scenarios

- General Monte Carlo simulation tool PDF developed to calculate probability estimates for given fire scenarios
- Commercial @RISK program + fire simulation tool CFAST
- Realistic data bank collected
- Application to incomplete physical partition between redundances in Olkiluoto cable tunnels
- Shows efficiency of partial screens for preventing ignition on the opposite side of tunnel

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Olavi Keski-Rahkonen, VTT Building and Transport, olavi.keski-rahkonen@vtt.fi
FINNUS: Contextual Assessment of Organisational Culture (CAOC) methodology

Why study culture
- Culture has an influence on the safety and efficiency of organisations
- Culture is not self-evident, it consists of conceptions and working practices that are taken-for-granted and not easily questioned
- Culture strives to resist outside influences but can develop deficient practices

CAOC methodology developed by VTT
- Identifies organisation's strengths and targets for development

Contributes to the:
- Design and allocation of work
- Design of organisational structures and processes
- Development of working practices and cooperation

Contact person: Teemu Reiman, VTT Industrial Systems, teemu.reiman@vtt.fi

• Concentrating on those reactors which can be built within 5-10 years

• Participating and sponsoring organisations:
  VTT, TVO, Tekes, Fortum, STUK, LTKK, HUT from Finland
  Framatome ANP, GE, Westinghouse Atom, EC

“to increase understanding of the next generation nuclear reactors so that the Finnish organisations can evaluate their economics and safety on an independent and solid technical basis”

“to gather experience and to develop tools for effective design and safety assessment”

“to support graduate and postgraduate education of nuclear experts
ALWR programme conclusions and outlook:

• Research within ALWR has concentrated on the safety aspects
• Economics of new plants has not been explicitly studied.
  - understanding the measures needed to meet Finnish safety requirements set for safety systems provides more reliable basis also for plant cost estimates.
• Development and testing of new models for APROS thermal-hydraulic code
  - condensation, thermal stratification, ...
• Wide practical experiences gained on the use of CFD tools for design and safety analyses
  - special features of safety systems imply deep understanding of the capabilities of CFD codes
• New experimental capabilities developed
• Close co-operation between experimental research and modelling
• Capabilities of fuel loading analysis tools demonstrated for ALWRs
• Educational work concentrated on getting new challenges for senior experts
  - some diploma thesis done but less than originally planned
• Most of the studied reactors are candidates for the new Finnish plant
  - tools and capabilities developed will be in heavy use during evaluation of the new plant
SAFIR - the mid-field of research and education

Safety of nuclear power plants – Finnish national research programme

SAFIR

Regulatory research
- Regulatory inspections and reviews
  - not in SAFIR

Utility research
- Safety case and licensing evidence
  - not in SAFIR

National research programme

2003-2006
Future safety challenges for SAFIR

1. New fuel designs and enhanced use
2. Ensurance of integrity of an ageing reactor circuit
3. Ensurance of containment integrity and leak-tightness
4. New types of nuclear power plants
5. Uncertainties associated with process safety functions
6. Automation modernizations
7. Control room modernizations
8. Operational development with modern technology
9. Plant lifetime management
10. Development of organisational culture and safety management
11. Risk analysis of external effects
12. Risk-informed safety and operational management
SAFIR 1. Reactor fuel and core
## SAFIR 2. Reactor circuit

### Reactor circuit integrity

- **Reactor pressure vessel with joints and internals**
  - Loadings
  - Material properties
  - Faults
  - Criteria
  - Re-embrittlement
  - Data
  - Methods
  - Integrity

- **Reactor circuit pipelines**
  - Loadings
  - Material properties
  - Geometry
  - LBB
  - Environment
  - Cumulative effects
  - Operating experiences

- **Other reactor circuit components**
  - Loadings
  - Materials
  - Failure types
  - Faults
  - Criteria

- **Water chemistry effects**
  - Base material
  - Oxide film
  - Flow conditions
  - Impurities

### Plant lifetime management

- Requirements – design – manufacturing
- Inspection – characterisation – predictions

### Risk-informed safety management

- Operational development with modern technology
SAFIR 3. Containment and process safety functions

Containment

Process safety functions
- Passive systems
- Balanced safety

Integrated assessment of containment and process safety functions

Severe accidents
- Coolability
- Shutdown conditions
- Long-term aspects
- Plant-specific questions
- Chemistry
- Fission products

Effects of ageing on containment function

Integrity

Leak-tightness

External threats

Potential releases, environmental effects
SAFIR 4. Automation, control room and information technology

**Automation**
- Requirements engineering
- Qualification process
- Design evaluation
- Lifetime management

**Control room**
- Changes in control room work
- Verification and validation process
- Human system interaction (interface design)

**IT**
- Reference model for the work processes
- Configuration and requirements management
- Knowledge and information management
SAFIR 5. Organisations and safety management

Theoretical development

- understanding cultural aspects
- management and decision making
- preventing routine effects
- changing procedures and habits

Practical problems

- bringing new technology into operation
- maintaining knowledge and expertise
- work load and wearout

Pressure for change

- implementation of changes
- development of technology
- improved productivity & efficiency
- changes in age structure
SAFIR 6. Risk-informed safety management

Development of risk analysis

- Level 1 PSA: plant design
- Level 1 PSA: plant operation
- Level 2 PSA: severe accident management

Dynamic reliability and risk models

- Structural reliability and failure models
- Risk-informed maintenance strategies

Multidisciplinary, risk-informed practices involving different technical areas

Cost-benefit evaluations in design, operation and monitoring

Multidisciplinary risk analysis related to plant lifetime

Fire safety and risk analysis

Risk analysis of external effects
SAFIR summary 1 (2)

- Supports the safety use of nuclear energy by
  - developing thorough understanding (engineering science)
  - educating new experts
  - maintaining knowledge and cautiousness in important areas.

- The framework has been designed based on future safety challenges, which are many and which highlight the importance of SAFIR
  - in research and education
  - in attracting new generation experts to the field.

- Collects national resources by
  - active exchange on information also on activities outside the hard core of SAFIR
  - efficient information exchange to all organisations
  - providing an open discussion forum for participation in internal co-operation, resource allocation and planning of new activities.
SAFIR summary 2 (2)

- The framework plan identifies the research needs based on future safety challenges:
  - This creates the basis for detailed annual plans and the activity proposals needed for this.
  - The framework looks at least 4 years ahead, and in practice, it covers a period of about 10 years.
  - The framework allows fast well-targeted activities, activities continuing over the SAFIR programme period, and even more long-term research and development work.

- SAFIR will need to be flexible:
  - The safety demonstration and the regulatory review of the fifth NPP unit will require considerable resources ("in the penalty areas")!
  - In this case, the SAFIR programme needs to be focused more on education ("this is mid-field")!
  - Such refocusing needs to be reflected in annual research plans.
  - The steering committee and the reference groups have to be active in identifying the above-mentioned needs for flexible refocusing.