Modeling of Innovative Nuclear Energy Systems (INS) in International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

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Workshop on Modelling and Quality Control for Advanced and Innovative Fuel Technologies
International Centre for Theoretical Physics, ICTP, Triest, Italy, 14-25 November 2005
Innovative Nuclear Energy System (INS) – INPRO definition

• INS will position Nuclear Power to make Major Contribution to Energy Supply in the 21st Century

• INS includes Innovative and Evolutionary Designs.
  • Innovative design (= advanced design) incorporating radical conceptual changes in design approaches or system configuration in comparison with existing designs.
  • Evolutionary design (= advanced design) incorporating small to moderate modifications with strong emphasis on maintaining design proveness.

• INS includes all Components: Mining and Milling, Fuel Production, Enrichment, Fabrication, Production (incl. all types and sizes of reactors), Reprocessing, Materials Management (incl. Transportation and Waste Management), Institutional Measures (e.g. safeguards, etc.).

• INS includes all Phases (e.g. from cradle to grave)
Modelling. What for?

• Given time, resources and intellectual capacity, we can develop practically any nuclear reactor or any technology to meet all our requirements and needs.

• The question is how much society (the user) is prepared to pay for this, what sacrifices the user is prepared to make, what he is prepared to accept and what he is not prepared to compromise, no matter what opportunities are lost.
What is Methodology?

- The raison d’être of the methodology is to help society to select solutions that will be acceptable and justified in terms of both today’s perceptions and concerns for the future.
- In particular, the aim of the INPRO methodology is to help the developers of nuclear energy facilities to determine what is likely to be acceptable to society.
What is INPRO Methodology?

The key feature of the methodology is the information it provides about:

• nuclear energy’s potential
• the consequences of its use
• the development options for society and its energy requirements
• the associated expenditures in terms of efforts, resources and time.
What for is INPRO Methodology?

- Through simplified boundary conditions (basic principles, user requirements and criteria) linking the nuclear energy system to the natural world and the economic mechanism, the INPRO methodology should enable analysis not only of an individual part, facility or subsystem of the nuclear energy industry, but also of the global system (INS) in the framework of a holistic approach.
What to do?

INPRO approach:

To tackle NE opportunities and challenges we need global considerations and integrity of the approach at any definite and local action

to act locally and to think globally
Computer modelling for decision making

- Computer simulation of INS is as essential for decision making as good software for computers
- To shape an innovative nuclear energy system (INS) and to achieve some kind of agreement on the ways to develop it, we need a tool providing data-processing support in the decision making
Opportunities and challenges for large-scale global nuclear energy development presented by the global balance of demands and resources
Global future energy scenario + national power strategies
(time frame—100 years)

Electricity generation, MWh per capita

Electricity generation per capita:
NA-North America;
WE-Western Europe;
EE- Eastern Europe;
FEAP-Far East Asia (China, Korea, Japan);
MESA-Middle East & South Asia (Near East, India);
LA-Latin America;
AF- Africa

(DESAE code)
The Global Energy Imbalance

“Here in the developed world, the instant and plentiful availability of electricity is taken for granted. Not so in Ghana and Nigeria, where I visited earlier this year. The use of electricity in Ghana - per capita - is only about 300 kilowatt-hours per year. In Nigeria, 70 kilowatt-hours per year. That translates to an average availability of 8 watts for each Nigerian citizen -- roughly 100 times less than the average citizen in the developed world, and about 200 times less than the average here in the US.

Take a moment to visualize what this imbalance means in terms of living standards and access to modern technology. Approximately 1.6 billion people - one in four of our fellow human beings - lack access to modern energy services. This disparity in energy supply, and the corresponding disparity in standards of living, in turn creates a disparity of opportunity - and gives rise to the insecurity and tensions that plague many regions of the developing world.”

Statement by IAEA Director General Dr. Mohamed ElBaradei
3 November 2005 | Massachusetts, USA
Export and Import

Of Oil and Gas in the World

Oil

Gas

International Atomic Energy Agency
Oil Prices in 1970-2025

![Chart showing oil prices from 1970 to 2025, with historical data and future projections under different case scenarios.]
Why INPRO needs global analysis?

• To understand boundary conditions for INS assessments at national level (global energy demand; economic data; resources; environmental issues; non-proliferation; safety)

• To estimate role of NE for sustainable development at global level

• To define effective institutional and technology development responses having global impact
Nuclear electricity production (EJ) for the four selected SRES scenarios

![Graph showing nuclear electricity production (EJ) for the four selected SRES scenarios from 2000 to 2070. The scenarios are A1T, A2, B1, and B2, with projections for each year up to 2070.]
Opportunities for Nuclear Energy

• Limited amounts of available fossil fuels
• Rates of economic growth
• Ecological constraints
• Extension of the effective use of potential fossil resources
• Huge amount of U-238 and Th-232
• Experience in Nuclear Power Technology
Scheme of coexistence of different energy technologies

Task for modeling

\[
\frac{\partial W(t)}{\partial t} = -\lambda \cdot W(t) + \left( \alpha \cdot \frac{\partial Q(t-t)}{\partial t} + \beta \cdot \frac{\partial Q(t)}{\partial t} \right)
\]

were:

- \( W \) - wealth;
- \( Q \) - resources;

Resources, Rate of consumption

\( Q_{\text{nuclear}}(U^{235-233}) \)

\( Q_{\text{fossil}}(\text{heavy}) \)

\( Q_{\text{fossil}}(\text{light}) \)

\( Q_{\text{fossil}}(U^{238}) \)

Fossil

Thermal Reactors

Transition

Breeding

Nuclear and Hidrocarbon

Competition

Coexistence

Wealth

\( t, \) time
Asymptotic view of Sustainable Energy Future

10^5 mlnrd t.o.e./year

Renewables
2 mlnrd t.o.e./year

Photosynthesis
100 mlnrd t.o.e./year

Fossil Energy
10 mlnrd t.o.e./year

Nuclear Energy
10 mlnrd t.o.e./year

Electricity

Light hydrocarbons: 500 mlnrd t.o.e.

Heavy hydrocarbons > 5000 mlnrd t.o.e.

U_{235} = 60 mlnrd t.o.e.
U_{238} + Th_{232} > 20000 mlnrd t.o.e.

Mining: > 10 – 14 decays per atom
Burying: < 0.2 decays per mining atom
Argentina, Armenia, Brazil, Bulgaria, Canada, Chile, China, Czech Republic, France, Germany, India, Indonesia, Morocco, Netherlands, Republic of Korea, Pakistan, Russian Federation, South Africa, Spain, Switzerland, Turkey, Ukraine and the European Commission (USA announced joining INPRO)
UN Concept of Sustainability and INPRO

UN General Concept of Sustainable Development
including sustainable development of ENERGY supply

- Economic Dimension
- Environmental Dimension
- Social Dimension
- Institutional Dimension

Sustainable development of Nuclear Energy

- Economics
- Environment
- Waste Management
- Safety
- Proliferation Resistance
- Infrastructure

INPRO Objectives and Methodology:
 MODELLING of energy systems
 Assessment using a holistic approach
 Decision on Innovative Nuclear Energy System (INS)

- Energy supply is fundamental to sustainable development of the world
- Sustainable energy supply needs significant contribution by NE
- INPRO assures that NE is available in a sustainable manner in the 21st century
- INPRO addresses all dimensions of the concept of Sustainability
Conditions for sustainable development of energy system

- Rate of consumption of exhaustible resources should not be higher than the rate of development of substitutive resources
- Utilisation of renewable resources should not destroy renewability of natural processes
- Waste production and waste quality should not destroy possibility of nature to assimilate them in acceptable way.
Three phases of INS lifecycle

Fig. 1. Three phases of Nuclear Power development and corresponding reactor types.
Reasons for closing of fuel cycle
Physical basis for meeting long term requirements in the areas of waste environment, non-proliferation, economics and safety

Control of nuclide composition

Fig. 3. The typical rates of radionuclide
Example of INS - Multi component nuclear energy system
(RRC “Kurchatov institute”, Russia)
Contemporary Situation

~ $\sum 200$ men Sv

~150 men Sv

U-natural
200 t

177 t depleated U

1GWe year

~40 men Sv transmuted 0.1-0.3 t nuclides

NES
LWR

23 t - spent fuel
~ 10 men Sv

~1 t - fission products
~0.2 t - TRU
21.8 t - U
Perspective balance $\leq 10$ men·Sv

- $\sim 1$ men Sv
  - $(1 + \omega)$, t
  - natural or depleated U
  - or/and Th

- LWR NES FBR MSR-B

- 1 Gwe year
  - Heat
  - $\gamma$ - energy

- Transmuted nuclides
  - $< 0.1$ t
  - $< 5$ men Sv

- Fission products

- Losses
  - $< 1$ t

- Products

- $\omega$ (U + TRU losses)
  - $(20 - 200)$ kg - U
  - $(2 - 20)$ kg - TRU
Physical basis for INS sustainable development

**Neutron efficiency**

\[
N(U; \text{Th}) \rightarrow (Pa; Np; Pu; Am; Cm; \ldots)
\]

\[
\begin{align*}
\text{LWR} + \text{FR} + \text{BR} & \\
\text{Losses} & \\
1\% & \\
0.1\% & \\
\end{align*}
\]

Neutron gain: \( \text{NG} = (n_f - n_0)/N \)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>FR</th>
<th>LWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>U - 238</td>
<td>0.62</td>
<td>0</td>
</tr>
<tr>
<td>U - 235</td>
<td>0.88</td>
<td>0.62</td>
</tr>
<tr>
<td>Th-232</td>
<td>0.39</td>
<td>0.24</td>
</tr>
</tbody>
</table>
INS sustainable development:

Process of increasing of neutron potential is provided by **breeding**—production of plutonium from uranium - 238 and uranium - 233 from thorium - 232.

Growth of neutron potential is connected not only to characteristics of reactors and their neutron spectrum, but also with characteristics of NE system as a whole: **nuclides losses, external fuel cycle time, a share of neutron absorption outside of fuel.**
Innovations are needed for sustainable, large-scale long-term energy development
Priority areas for innovations can be established by means of modelling of various options of global energy development.

These innovations will be a basis for sustainable development in this century. The areas of innovations include:
Understanding NE challenges

In line with RES PESS developed 4 reference NE scenarios (RNES) analysed by region.

Objectives of this activity is to clarify NE specific challenges for each RNES. It will include incorporation of factors to be identified such as

• Key Indicators (KI) to measure success in addressing NE challenges in different areas of concern
• Institutional measures and technical features of NE having major impact on these KI globally and regionally
• Time dependent desirable targets for KI in different areas for NE to play an important role for SD
Nuclear Energy Growth in 21st Century

- A1 (Rapid Economic Growth)
- A2 (Heterogeneous World)
- B1 (Convergent World)
- B2 (Local Solutions)

Projection by IPCC-SRES
Understanding NE challenges
Modelling needs

- Geographic coverage - regional and global
- Time horizon – 21st century, benchmarks at 2030 and 2050
- Areas of analysis – nuclear energy system
- Type of nuclear energy services - electricity, transport, heating, desalination and other
- Areas of concern (resources, Proliferation resistance, waste management, infrastructure, safety? environment? other?)
- Key Indicators and criteria to measure success in addressing NE specific challenges - TBD.
- Model availability – DESAE or any other NE model with detailed fuel cycle description applicable for analysis of economics, infrastructure, resources, waste and Proliferation resistance challenges.
No sustainable NE development with open NFC

Uranium Consumption and Repositories in Large-Scale Development of NE in Open NFC
Installed capacities of INS: LWR, FR (2020)
Uranium – 6 mln t, BR=1.05
Installed capacities of INS: LWR, FR (2020)
Uranium – 6 mln t, BR=1.6
Installed capacities of INS: LWR, FR (2020)
Uranium – 16 mln t, BR=1.05
Installed capacities of INS: LWR, FR (2040)
Uranium – 16 mln t, BR=1.05
Installed capacities of INS: LWR, FR (2020)
Uranium – 16 mln t, BR=1.6
Installed capacities of INS: LWR, FR (2040)
Uranium – 16 mln t, BR=1.6
Installed capacities of INS: LWR, FR (2070)
Uranium – 40 mln t, BR=1.05
Installed capacities of INS: LWR, FR (2070)
Uranium – 40 mln t, BR=1.6
INS: LWR and FBR (BR ~ 1.6)
Example of sustainable INS based on LWR, FBR + LWRs + small and middle capacity reactors (SMR)
NE Specific Challenges

Large scale global NE development may face some nuclear specific challenges in areas such as:

• Natural resource availability (Pu–internal resource)
• Assurance of proliferation resistance
• Assurance of safe nuclear waste management
• Nuclear safety assurance
• Specific NE environmental issues

A need for dynamic NE modelling
U-Th-Pu closed fuel cycle

- Enrichment U
- LWR-U
- FBR(Pu-Th)
- Thermal Reactor (U3-Th)
- Pu
- U-233
Closed fuel cycle: LWR(U); FR(core-U-Pu, blanket-Th); HTGR(Th-233U)
Total consumption of natural Uranium – 11 mln t
### Some parameters of NFC for INS with power capacity of 1000 GWe

<table>
<thead>
<tr>
<th></th>
<th>Open NFC (current)</th>
<th>Closed NFC (BTP)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>U-Pu</td>
<td>U-Pu-Th</td>
</tr>
<tr>
<td>Mining of fuel, t/year, Uranium Thorium</td>
<td>200 000</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>SWU, mln t/year</td>
<td>150</td>
<td>-</td>
</tr>
<tr>
<td>Fabrication of fuel, t/year, core blanket</td>
<td>20 000</td>
<td>18 000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19 000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>Reprocessing SNF, t/year, core Blankets of FR MSR</td>
<td>-</td>
<td>18 000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2000</td>
</tr>
<tr>
<td>Final disposing, t/year</td>
<td>20 000</td>
<td>30-100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30-100</td>
</tr>
<tr>
<td>Quantity of nuclides in disposals, t/year: Pu</td>
<td>200</td>
<td>1,5</td>
</tr>
<tr>
<td>NP</td>
<td>10</td>
<td>0,01</td>
</tr>
<tr>
<td>Am</td>
<td>10</td>
<td>0,05</td>
</tr>
<tr>
<td>Cm</td>
<td>1</td>
<td>0,02</td>
</tr>
<tr>
<td>Cm</td>
<td></td>
<td>0,003</td>
</tr>
<tr>
<td>Expected collective effective dose (10^4 years), be 1000 GWe year of electricity, 10^3 men Sv</td>
<td>100-150</td>
<td>10-15</td>
</tr>
</tbody>
</table>
Innovations:

Development of efficient breeders on the basis of fast spectrum neutron reactors:

- at the initial stage - specific loading of plutonium into the reactor to a minimum (up to 3–4 t per GWe), breeding ratio of 1.2–1.3; duration of the external fuel cycle for plutonium is not more than 5–6 years;

- after 15–20 years, the plutonium breeding level in a fast reactor has to be raised up to 1.5–1.6; duration of the external fuel cycle for plutonium is not more than 3 years
Innovations:

More **efficient fuel utilization in thermal reactors** (breeding ratio 0.9) through:

- closed plutonium fuel cycle;

- improved reactor core design;

- transition to a uranium-thorium fuel cycle, particularly for high-temperature reactors.
Innovations:

Development of non-aqueous methods of reprocessing spent nuclear fuel for:
  • shortening of external fuel cycle;
  • reduction of amount of waste.
This will allow to:
  • reduce amount of fuel in the nuclear energy system;
  • solve the problems of:
    • non-proliferation;
    • ecological acceptability;
    • fuel utilization
reduce the share of fast reactors in the system
Innovations:

The development of liquid fuel reactor-waste incinerators (burners of minor actinides) to close the nuclear fuel cycle for minor actinides, which will significantly ease the problems of:

- disposal and minimization of the quantities of hazardous nuclides in the nuclear energy system;
- non-proliferation;
- ecological acceptability;
- effective utilization of the neutron potential of nuclear fuel.
Innovations:

Development of low-power capacity reactors for providing high-quality reliable energy supply services in regions of the world where normal, efficient economic activity would be impossible without them.

These nuclear power facilities should be transportable and be operated without any fuel and radioactive waste management procedures at their sites.
Innovations:

Development of nuclear energy technology complexes for production of hydrogen and various chemical compounds based on its use, including the production of high-quality liquid fuels from low-quality fossil resources.

The total output of these nuclear power facilities will be thousands of GW.

To raise the energy conversion efficiency, these will most likely be thermal neutron spectrum nuclear power facilities (ceramic structural materials), and to improve their fuel utilization parameters a gradual transition to thorium fuel (more efficient in the thermal neutron spectrum than uranium-238) will be necessary.
Introducing thorium to the nuclear energy system for:
• increasing the thermal reactor share (up to 80%) and
• reducing the quantity of plutonium and minor actinides (by approximately a factor of ten per unit of power) in the nuclear energy system.

This will toughen up the requirements for neutron-efficient nuclide losses (uranium-233, plutonium-239 and 241, uranium-235) up to 0.1%;
Development of methods for assessing the neutron efficiency of the nuclear energy system.

Efficient utilization of nuclear energy resources (uranium-238 and thorium-232) will be possible only if for each uranium and thorium nucleus consumed at least 0.3 neutrons will be obtained. This indicator depends on:

- reactor design (ranging from 0.25 for molten salt cooled reactors to 0.4 for transport nuclear power facilities with a high fuel burn-up);
- time fuel is kept in the external fuel cycle (decay of plutonium-241 and curium-244);
- irretrievable loss of actinides during reprocessing (a reduction in plutonium loss from 1 to 0.1% would mean that the fast reactor share of the nuclear energy system could be reduced by a factor of roughly one and a half).
In the same way as economic requirements are derived from a “market mechanism” for seeking price “consensus”

**A “humanitarian” process needs to be organized for reaching agreement between interested parties on key questions** including:

- criteria for safety, non-proliferation, ecological damage;
- necessary criteria for multivariant analysis and the selection of acceptable options.

Scientists identify the dangers, evaluate them, provide information and give recommendations, but it is not they who take decisions on requirements and limitations.
Innovations in the aforementioned areas will enable the **basic physical principles of sustainable nuclear energy development** to become a reality:

- The long-term risk is proportional to nuclear energy capacity and not to overall energy output;
- The neutron efficiency of nuclear energy is increasing;
- The lifetime of the hazardous radio nuclides in the system is becoming shorter;
- All the radio nuclides are being used efficiently, including utilization of all the extracted fuel;
Example of INS -Multi component nuclear energy system (RRC “Kurchatov institute”, Russia)
Example of INS -Multi component nuclear energy system
(RRC “Kurchatov institute”, Russia)
Multi-product model of INS
INPRO Methodology

Can be used:

• to screen an Innovative Nuclear Energy System (INS) for its compatibility with the energy needs of the 21st century and sustainability considerations;

• to compare different INSs;

• to identify the RD&D required to improve and validate the performance of an INS.

The assessment must include in the evaluation all components of the INS to achieve a holistic view and ensure that the overall system is sustainable.
Set of basic principles, user requirements and criteria is defined in the areas of sustainability, economics, environment, safety, waste management, proliferation resistance, infrastructure.
Scheme of time dependence of weighting factors for different groups of user requirements

Task for modeling
Nuclear electricity production (EJ) for the four selected SRES scenarios

The graph illustrates the trend of nuclear electricity production (EJ) for the four selected SRES scenarios (A1T, A2, B1, B2) from the year 2000 to 2070.

- **SRES**

The scenarios are represented as follows:
- **A1T**
- **A2**
- **B1**
- **B2**

The y-axis represents the energy in EJ, and the x-axis represents the years from 2000 to 2070. The graph shows a clear projection of nuclear electricity production for each scenario.
1st Scientific and Technical Committee Meeting: 16-17 March 2005, Obninsk, Russia

* Draft JS Concept presented, discussed and approved in general;
* National development/deployment strategies presented:

- **JS MS identified technologies to be considered as INS CNFC-FR components:**
  - **France** – Gas and Na cooled reactor technologies with appropriate fuel cycle technologies
  - **India** – Na cooled reactor technologies with involvement of Th fuel and appropriate fuel cycle technologies with high breeding
  - **Korea** – Na cooled reactor technologies with appropriate fuel cycle technologies
  - **Russia** – Na, Pb, Pb-Bi and gas cooled reactor technologies with dry and aqueous reprocessing technologies
  - **Japan** – Any promising fast reactor technologies with appropriate fuel cycle technologies
Modelling needs

• INPRO needs dynamic modelling at energy system level, and at national, regional or global levels. Different model structures and levels of modelling will be required.

• Several models may be needed to help define future nuclear energy systems at national, regional or global levels.
• MESSAGE is a scenario-based optimisation model that can be used for energy analysis. It can also be used for fuel cycle analysis at a given level of aggregation, encompassing closed nuclear fuel cycle.

• DESAE is a simulation model that can be used for detailed nuclear energy system analysis, based on input of nuclear reactor type, scenarios, fuel cycle leading to assessment of material and isotopic flows and radio-activities. DESAE presently can be used for analysis of different closed fuel cycle options.
Production and Trans-regional Flows of Fresh and Irradiated Nuclear Fuel in 2100, t/year; $N \approx 5000$ GWe ("Traditional" Model)

**Table: Production and Flows**

<table>
<thead>
<tr>
<th></th>
<th>NA + WE + EE</th>
<th>LA + AF + MESA + FEAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production 2005</td>
<td>16 000</td>
<td>5 000</td>
</tr>
<tr>
<td></td>
<td>4 800</td>
<td>1 100</td>
</tr>
<tr>
<td>Production 2010</td>
<td>72 000</td>
<td>47 000</td>
</tr>
<tr>
<td></td>
<td>64 000</td>
<td>41 000</td>
</tr>
<tr>
<td>Flows 2010</td>
<td>53 000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>42 000</td>
<td></td>
</tr>
</tbody>
</table>

NF – nuclear fuel flow; SNF – spent nuclear fuel flow; NPP – nuclear power plant; NFP – nuclear fuel plant; SNFR – spent nuclear fuel reprocessing plant
INPRO methodology, formalized in the form of cybernetic models with the corresponding adaptable data bases (incorporating basic principles, users’ requirements and criteria), will be a necessary condition for the effective development and functioning of nuclear energy on a global scale.
Conclusions
INPRO Modelling

• Modelling tools can be developed on the basis of cybernetic simulation of the INPRO methodology;
• On the basis of the knowledge gained through application of such data-processing support tools, we will be able to make various judgements, and use these as the starting point for a readily comprehensible debate about development problems, including the outlook for a global nuclear energy system.
General objective of INPRO task 4

Analyse **Opportunities and Challenges for Large-scale Global NE** to define responses that have to be done today in institutional and technology development areas:

• to facilitate global NE use in medium term and

• to prepare basis for NE to play an important role for global sustainable development.
Thank you!

WWW.iaea.org/INPRO