Validation of European computer codes for fusion safety analysis

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"Fusion Power Plant Safety"
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Structure of the lecture

- Short introduction and objectives
- The various types of codes developed recently
  - Neutronics and activation analysis
  - Activated corrosion products
  - Accident analysis:
    - INTRA developments and validation
    - CONSEN validation against EVITA
    - MAGS development and analysis
    - Validation exercise through EVITA programme
  - Dose to the population: validation of the developed code
- Future needs and developments for fusion power plants
- Some conclusions
Short introduction and objectives

- Safety relevant fusion specific computer codes are needed for licensing future fusion plants
  - use of validated codes developed for the 400+400 fission reactors worldwide
  - but fusion specific codes and models needed (neutron flux and energy, presence of tritium, specific materials, cryogenic fluids, vacuum condition, presence of large magnetic fields, etc…)

- Codes and models adapted to fusion need to be qualified and validated
  - by conducting representative experiments
  - by benchmarking and cross checking different codes

- This paper will focus on European latest developments and EFDA supported program
The safety approach of a fusion plant

Diagram:

- Normal working conditions and maintenance
  - Effluents
    - Dose to public mSv
  - Occupational dose
    - Dose to workers Person-Sv

- Initiating Events Accident Sequences
- Thermodynamic transients Aerosols and H3 transport
- Release from the Containments
  - Dose to public mSv

- Radioactive Inventory
- Overall Plant Analysis
  - Failure Mode and Effect Analysis (FMEA)

- Radiactive waste: Operational & Decommissioning Identification & Classification
  - On-site waste management
  - Quantity and Waste categories
The safety computer codes and models development follows the same logic

- assessment of radioactive **source terms** and energies
- **impact** during normal operation (**releases** to the public and **occupational radiation exposure**)
- radioactive releases and relevant doses following the **dominant accident sequences** identified through a systematic approach like FMEA/FFMEA
- radioactive **waste** quantification and characterization
What will be covered and not covered

• This lecture will thus cover:
  – most of the topics involved by safety analysis
  – recent developments and validation exercises performed in E.U.

• …but the lecture will not...
  – be a comprehensive review
  – evaluate the various codes and compare them
  – be focused on one plant type (although the mention of ITER safety analysis cannot be avoided)
Safety assessment

Neutronic calculations as input for further handling

Normal working conditions and maintenance

- Effluents
  - Dose to public: mSv/yr
  - Occupational dose: Dose to workers: Person-Sv/yr

- Initiating Events Accident Sequences
  - Thermodynamic transients Aerosols and H3 transport
  - Release from the Containments
    - Dose to public: mSv

Overall Plant Analysis
Failure Mode and Effect Analysis (FMEA)

Radioactive waste: Operational & Decommissioning Identification & Classification

On-site waste management

Quantity and Waste categories

Radioactive Inventory
Assessment of radioactive source term

- by the **neutronics analysis** and calculations
  - activation estimate and radiation field evaluation
- evaluation of the **activated corrosion products (ACP)**
  - follow up of the spread of activity within the cooling systems
- **other mechanisms** participating to the source term (dust, tritium, …)
Neutronics scoping calculation (1D): input for activation, decay heat, radiation levels,…

- 1D calculations allow for scoping approach and fast answer to questions.
- 1D-Sn deterministic SCALENEA calculation sequence:
  - Nuclear data processing ➔ Data libraries, problem dependant
  - Radiation (n, γ) transport analysis ➔ neutron and gamma spectra
  - Radiation transport results post processing ➔
    - Radioactive inventories
    - Radiation damages (dpa, appm He)
    - Dose rate
    - Nuclear heating
- Use of activation code packages (ANITA-2000 and FISPACT)
- The code and libraries were validated against various experiments (incl. 14 MeV neutron sources)
Activation calculation principle and results (example)

ANITA-2000 neutron activation library

Decay and Hazard data library

256-group neutron fluxes from radiation transport calculation

Unconditional Clearance Level Data Library

ANITA-2000 Activation code

Radioactive inventories

Decay gamma library

Specific activity (Bq/Kg)

SS-316 (C/E) calculation to experiment ratios Main isotopes contributions
ITER CAD to MCNP benchmark model

From 1D to 3D analysis and calculations

One of the difficulties is the input data set

CAD model (CATIA)

MCNP model (converted by CAD to MCNP interface)

Courtesy by Association FZK-Euratom
Source Terms – Inventories
Neutronics

**Neutronic Analysis**

- Nuclear heating and component decay heat
- Activation and dose rates
- Damage in components and He production
- Wastes quantification and characterisation

Poloidal contour of the nuclear heating in different materials of the high heat flux components. Values are in W/cm³
Activated Corrosion Products (ACP) behaviour: PACTITER + CORELE

- Evaluation of the ACP formation, release, migration and deposition
- important for source term evaluation in case of accidents (involving the cooling systems), for occupational exposure evaluation and for the waste management
- the evaluation is based on fission codes and models
Development of the PACTITER code

- PACTOLE code developed (by CEA) for PWR cooling loops (for about 30 years)
- the PHTS of ITER being based on pressurized water ➔ natural to use PACTOLE
- but operating conditions, materials composition and water chemistry are different in fusion facilities
- This lead to adapt the code and develop the « PACTITER » (Pactole for ITER) version
Validation of the PACTITER code

- The validation and development was mainly carried out through 2 experiments:
  - one launched in 1996 (in CEA Fontenay-aux-Roses) to get the copper solubility at defined conditions
  - using the CORELE experimental loop (in CEA Cadarache) run in 2001 and 2004 (foreseen in 2006) in conditions close to ITER cooling loops
Schematic view of the Corele loop

Hot Line

Test sections

Mixed bed ion exchange resins

Millipore filters 1µm

1 3 2 4

Mixed bed purification resins

Cold Line

Millipore filter 6µm

Circulating pump

Feed water

Feed water

Circulating pump

Heating line
Main EU computer codes developed/adjusted, validated and used for accident analysis inside the S&E Programme

**INTRA**  In-vessel chemical reactions, gas/steam transport and distribution, pressurization of containments;

**PAXITR** Thermal hydraulics and containment pressurization;

**CONSEN** Simplified thermal hydraulics and pressurization of volumes and cryogenics;

**ECART** Integrated code for accident sequence analysis, including radionuclide transport;

**MAGS** Assessment of thermal failure propagation in superconducting magnets and cryogenics;

**PACTITER** Corrosion products generation and transport in water coolant loops;

**GASFLOW/DET3D, CAST3M**
3-D hydrogen and dust transport, and hydrogen and dust explosion.
INTRA: IN vessel TRansient Analysis

• developed, and used, through 1996-2006
• general containment systems code based on lumped parameters
• handles thermal hydraulic behaviour in buildings and vessels, chemical reactions and distribution of non-condensable gases
• Validation of INTRA Mod-6 was carried out against
  • ICE experiment (first wall breaks, pressure drop and condensation in VVPSS), Japan
  • LOVA experiment
  • Marviken test (full scale blowdown events), Sweden
  • EVITA experiment (steam injection), France
  • ThAI experiment (wall condensation, natural circulation, turbulent diffusion and atmospheric stratification).
Validation of INTRA Mod-6

INTRA nodalization of the ICE test facility

THAI facility

Typical INTRA results for ICE (Case P2): VV, Suppression Tank and Drain Tank pressure transient result
CONSEN: CONservation of ENergy.

- The CONSEN code evaluates temperature and pressure trends in interconnected volumes affected by a LOCA.
- It solves the equations of mass and energy conservation for fluids (water, helium, oxygen, nitrogen and non-condensable gases)
  - including change of phase, also in cryogenic conditions
  - it can also simulate chemical reactions between Be, W, C and steam or air
- The critical flow model and the jet impingement heat transfer model are included into the code.
CONSEN : validation exercises

• Validation of various aspects carried out in 1997-2003 using experimental data of the ICE (Inlet of Coolant Event) experiment in Japan

• Validation against EVITA experiment, with cryogenic plate, with and without uncondensable gas.
  – new model developed to evaluate the ice porosity
  – iterative algorithm for ice thickness evaluation

Example of simulation against EVITA experiment

Ice mass: experimental (EVITA) and simulated (CONSEN) results for water injection test with tank heated walls
MAGS: MAGnet Systems

- Development triggered by the available energy within the magnet systems in case of accidents: in ITER e.g., 40 GJ in TF circuit able to melt 4 m³ or 30 T of steel...

- In fusion plant there are several protection measures which are making the accidents unlikely, but licensing asks for clarifying possible consequences

- MAGS analyses the 3D quench behavior of superconducting forced flow cooled magnet coils of cable in conduit conductor type
MAGS: structure of the code

**HEAT3D:**
heat conduction in coil winding pack

**EFFI:**
magnet field

**EDDY:**
AC-losses

**GANDALF:**
helium thermohydraulics in manifold

**LINKUP:**
helium thermohydraulics in manifold

**OHM:**
check conditions for superconductivity
ohmic power in case of quench

**SHORTARC:**
electric arc inside coil

**MSCAP:**
electric circuit, inductive effects

To complete: MOVEMESH, HEXAN, COINLOSS, CRYOSTAT
MAGS : validation exercises

- Several components of the code (not own developments) were validated separately
- The validation of the MAGS system with several interacting modules was done using experiments with superconducting test coils and gave satisfactory results:
  - QUELL: QUench Experiments at Long Length performed in the SULTAN facility at the Paul Scherrer Institut in Villigen in 1995
  - Q3D experiments at the STAR facility (in 1996) at FzK
  - TFMC (Toroidal Field Model Coil) experiments in 2000 at the TOSKA facility at FzK
Validation of the codes through the EVITA experiment

- **EVITA** (European Vacuum Impingement Test Apparatus): simulation of coolant ingress in the cryostat
- **Main features of EVITA:**
  - the pressurizer (7g/s water/steam flowrate at 165°C, until 40 bar)
  - the vacuum vessel (0.22 m³, heated at 165°C)
  - the cryogenic system (liquid N2 (77K) flowrate up to 100 g/s) including a cryogenic plate
  - the ratio between the volume of the vessel and the surface of the cryogenic plate is similar to the one in the ITER reactor
  - phase separator allowing to evaluate the quantity of nitrogen vaporized during a test
  - simultaneous ingress of water or steam and non condensable gas (165°C, 2 g/s) can be simulated.
Schematic view of the EVITA experiment

Pressurizer

Vacuum Vessel

Phase separator
EVITA - Inside view of the vacuum vessel

Deflector plate and the cryogenic plate

Heated deflector plate
Main objectives of the experiments:

- Analysis of the steam condensation on the cryogenic plate:
  - ice formation kinetics
  - heat transfer characteristics
  - condensed water mass
  - cryogenic surface temperature
  - temperature and pressure in the vessel

- Each test is characterized by:
  - initial pressure
  - temperature of the injected fluid
  - injected mass flow rate
  - initial temperatures of internal structures
  - operating conditions of the cryogenic loop
EVITA tests: steam injection example of results of benchmark exercise

- **Test 5.3**
  - 0.7 g/s at 7.5 bar, 165 °C
  - CONSEN, MELCOR, PAXITR
  Vs experiment

- **Test 5.5**
  - 2.6 g/s at 7.5 bar, 165 °C
  - CONSEN, PAXITR
  Vs experiment

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**EVITA complementary cryogenic tests 5.3**

**EVITA - complementary cryogenic tests 5.5**
Dose to the population: validation of European computer code UFOTRI

- Tritium might dominate dose to public from accidental releases from fusion plants
- In the 90's studies were performed to define the most important exposure pathway for tritium
- UFOTRI investigated the contribution of various exposure pathways:
  - It highlighted the importance of the food chain part
  - The OBT (Organically Bounded tritium) dominated the doses in all calculations
Validation by benchmarking

- Validated against French and Canadian tritium release experiments
- IAEA’s BIOMOVS II (BIOsheric MOdel Validation Study - phase II)
  - comparison between codes and some experimental data
  - very good performance of UFOTRI
- IAEA’s EMRAS (Environmental Modelling for Radiation Safety) program
  - launched in 2003 (still on-going)
  - to test models of the uptake, formation and translocation of organically bound tritium (OBT) in food crops, animals and aquatic systems
Some typical results of UFOTRI

Countermeasure criteria achieved (%)
Countermeasure criteria in [mSv]: Evacuation: 100, Sheltering: 10
Rel. Height [m]: 10  Precip. [mm/h]: 0  Diff. Cat: F  Wind [m/sec]: 1

<table>
<thead>
<tr>
<th></th>
<th>Early Phase</th>
<th>Sheltering (%)</th>
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<tbody>
<tr>
<td>ACP</td>
<td>2.63E+01</td>
<td>2.63E+00</td>
</tr>
<tr>
<td>1.00E+01</td>
<td>5.93E+00</td>
<td>5.93E+01</td>
</tr>
<tr>
<td>3.00E+00</td>
<td>8.27E+00</td>
<td>8.27E+01</td>
</tr>
<tr>
<td>HT</td>
<td>3.56E+02</td>
<td>3.56E+02</td>
</tr>
<tr>
<td>DUM</td>
<td>6.83E+00</td>
<td>6.83E+01</td>
</tr>
</tbody>
</table>

Individual short term dose as a function of distance
(for ACP, DUST, HT, HT and their sum)
Rel. Height [m]: 10  Precip. [mm/h]: 0  Diff. Cat: F  Wind [m/sec]: 1
Future needs and developments for future power plants

- Most accidental situations pointed out to be considered for deterministic assessment are initiated by loss of coolant (LOCA) or loss of flow (LOFA) accidents.
- This requires thermal-hydraulic codes which are validated for fusion relevant conditions.
- A significant effort has been devoted to the validation of thermal-hydraulic codes for ITER, which could be used for water-cooled fusion power plants.
Future needs and developments for future power plants (continued)

- He cooled divertor and blanket may require specific efforts on codes development and validation
  - some benefits to be taken from fission Gen IV studies (high temperature reactors)
- What need mainly to be handled:
  - Pressurisation of a volume at low initial pressure
  - Critical flow
  - Heat transfer between walls and fluids
  - Helium flow inside complex arrangements
- **Accuracy** required for the analysis of the accidental sequences to provide sufficient margin for the design of
  - safety features (expansion volume) and
  - cooling loops (loop inventory).
Concluding remarks

- Since many years Europe is preparing, studying and developing fusion, through various research facilities and pilot plants
- The development and validation of safety relevant computer codes has been considered since long time, and their validation also
- The presently available and validated computer codes and models seem to be adequate for the licensing of ITER and the preliminary study of future fusion power plants
- Further developments and updating can still improve the quality of the results
- For instance, partners are encouraged to participate to benchmark exercises inside the implementing agreement within the IAE
Thank you for your attention