framatome

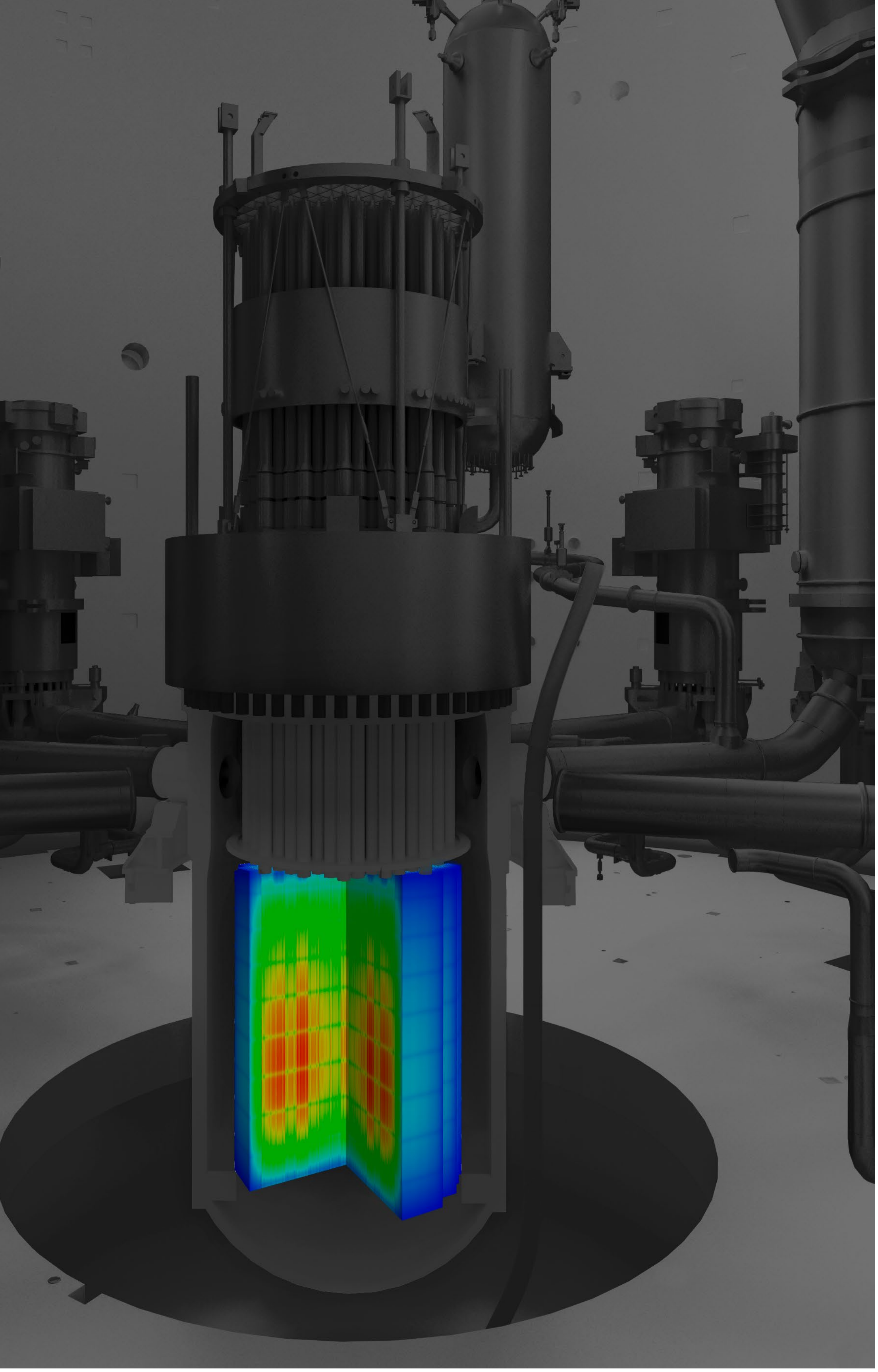
ARCADIA

Comprehensive code system & advanced methods for nuclear core design and safety analysis

For enhancing fuel cycle value and unlocking operational margins

Your performance
is **our** everyday **commitment**

Contact: sales-fuel@framatome.com



Your performance
is **our** everyday **commitment**

Safety verification, core design, fuel management, and operation of nuclear power plants are facing an increasingly more demanding and dynamically evolving environment than ever before.

We understand the kind of operational challenges you are facing – increasing economical pressure on fuel cycle costs, the need for operational flexibility as well as increasing safety requirements in an uncertain and complex environment.

Therefore, it is vital to optimize the fuel value and margin management in a secured-licensed frame, either to face new regulatory challenges, increase fuel utilization or gain more flexibility in the operation of nuclear power plants.

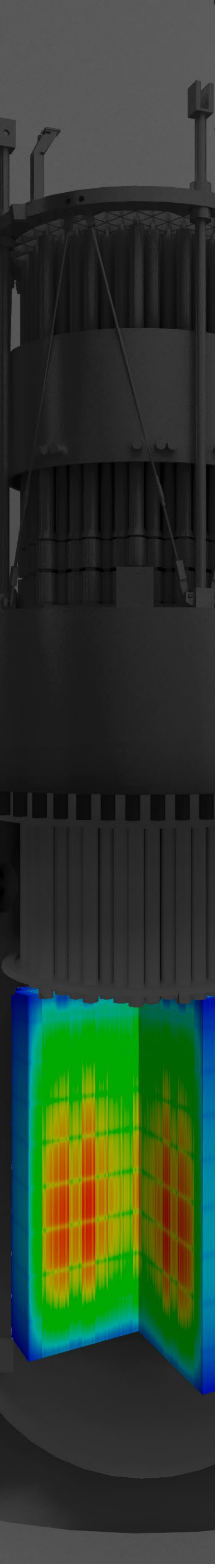
Our promise to you – being prepared for upcoming challenges.

Advanced codes & methods are an essential part of Framatome's answer to your challenges. The ARCADIA code system offers a modern and multi-functional platform for core design and safety analyses.

ARCADIA's advanced multi-physics coupling based on modern software architecture and algorithms enables industrial use of advanced methodologies to improve the profund understanding of plant behavior & enable a superior resolution of the true nature of the events to

- **address emergent regulatory criteria and changes to comply with high nuclear safety standards.**
- **enable liberation of existing performance margin and remove barriers to significant economic performance improvement initiatives.**

ARCADIA is ready for use



The power of ARCADIA codes & methods provides the industry with a leading core design and operational margin facilitator to profit in many areas, such as safety, operational margins, flexibility and enhancement of the cycle economics.

ARCADIA
is ready for use

Table of content

ARCADIA –
your most faithful companion enhancing fuel cycle value.

ARCADIA provides to utilities, designers, safety authorities, research centers and independent reviewers/consultants an industrial advanced multi-physics code system to efficiently and reliably cover numerous PWR engineering activities from fuel assembly through core design, core monitoring up to safety analysis.

§

Reactor analyses with ARCADIA allow **realistic modeling assumptions** and maximize the **accuracy** of core models to **release new margins** and **reduce safety justification**.

§

Unlike other core design and safety codes that require intensive trainings, a high amount of time to handle raw data and a very high level of expertise to manage several separated task-specific codes, ARCADIA provides **one single comprehensive platform**.

§

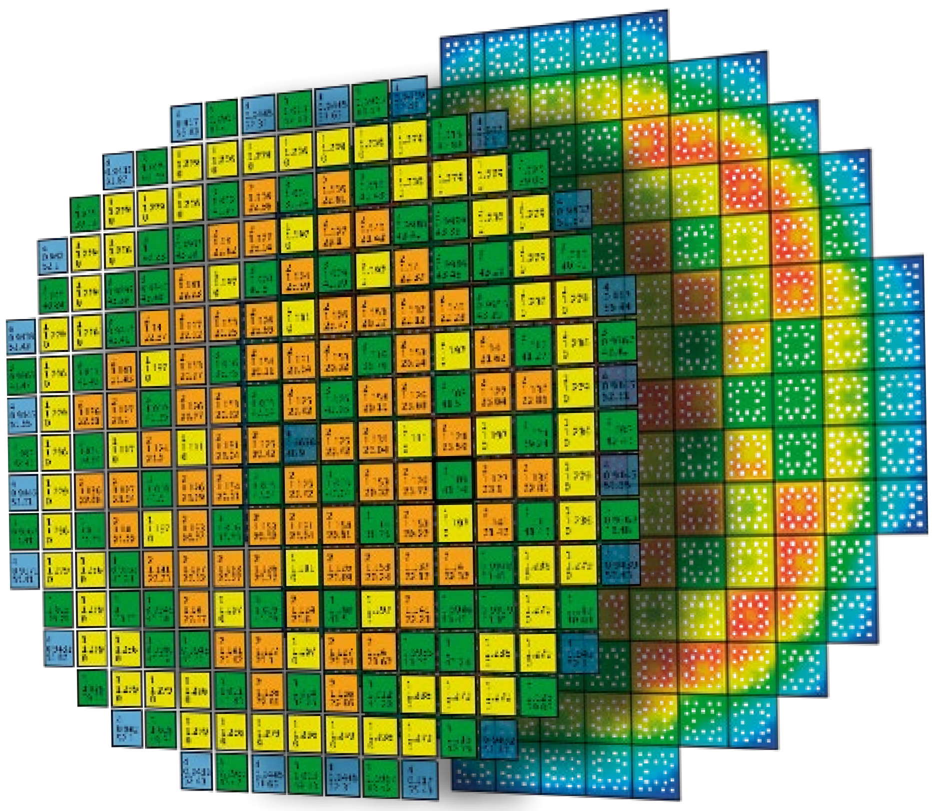
It provides **continuity** through coupled modules associated to an **efficient, flexible and consistent workflow** throughout the different phases of the core design and safety analysis, significantly **reducing training period, engineering and computational efforts, and improving quality**.

§

All tasks and processes are fully integrated in **one comprehensive Graphical User Interface** (GUI), allowing for **easy and intuitive interaction with the code package**.

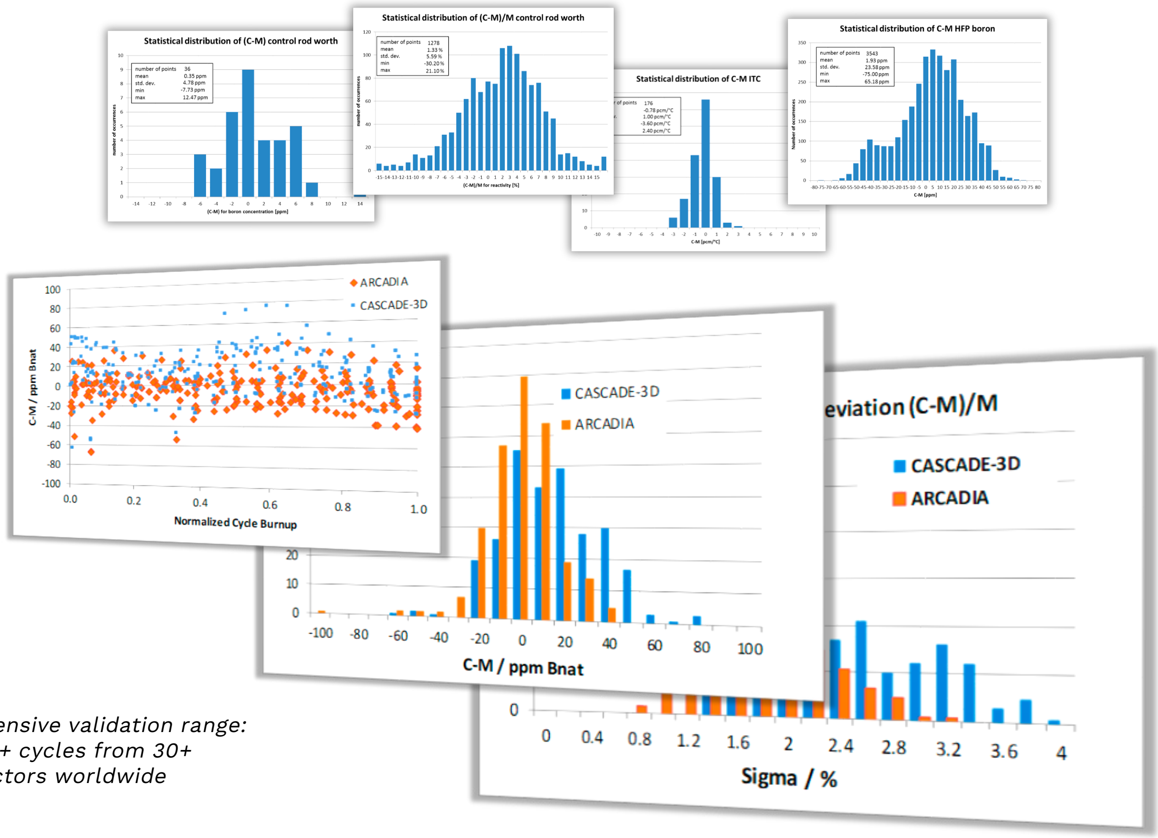
ARCADIA – a proven reference

LEARN MORE ›



Powerful & comprehensive application range

- Nuclear fuel assembly and core loading pattern design are performed in one single user-friendly modular platform for both steady state and transients analyses.
- With ARCADIA you profit from the most realistic ab initio physics models to obtain the most accurate modelling of challenging core designs with increased heterogeneities and aggressive operating strategies.
- ARCADIA enables optimized fuel management & performance (concerning cycle lengths, batch sizes, stretch-in & stretch-out cycle phase, flexible operation and power uprate).
- ARCADIA is built to meet the needs of reactor engineers and core designers, with functionality to support reactivity insertion analysis, dynamic rod worth calculations, and past operational events, startup physics testing, power manoeuvre guidance, thermal limit assessment, shutdown margin, and much more.
- ARCADIA supports established and emerging methodologies for performing PWR-specific safety analyses in compliance with various modern licensing frameworks: e.g., ejected rods and inadvertent bank withdrawals (RIA), rod drop accident, boron dilutionaccidents, locked-rotor, pump coast down, steam line break accident.



Extensive validation range: 600+ cycles from 30+ reactors worldwide

Proven reliable results through extensive validation database for steady-states & transients

ARCADIA is based on the largest validation and experience database worldwide for steady-state and transients, covering UO2, MOX, and ERU, for steady-state and transients.

The ARCADIA verification and validation base for transients covers international code and analytical benchmarks as well as benchmarks against measurements of actual transient cases.

As a result of its untuned approach and advanced models, ARCADIA brings high levels of accuracy and full consistency between steady state and transient calculations.

› International code and analytical benchmarks
- TWIGL-2D ramp transient analytical benchmark
- NEACRP rod ejection UOX benchmark
- NEACRP rod ejection MOX benchmark
- NEA/NSC bank withdrawal benchmark
- MSLB benchmark

› Benchmarks against measurements
- PWR 1300 MWe, rod drop transient
- SPERT rod ejection measurement
- PWR 1000MWe, coolant pump shaft break

› Benchmarks against measurements with system code coupling
- PWR 1300MWe, load rejection transient
- PWR 1300MWe, load rejection with temporary loss of one reactor coolant pump

› Code-to-code comparisons
- SCIENCE and CASCADE-3D

Recognition

ARCADIA is internationally acknowledged and recognized; it was NRC-licensed in 2013. It is now in use for safety studies and reload support at several U.S. and European Nuclear Power Plants (NPP), both for PWR and BWR.

ARCADIA – a coherent experience for all core activities

LEARN MORE ›

Purpose

ARCADIA is available for you and your engineering team, including personalized customer support to build up and sustain your ARCADIA projects for the long term.

ARCADIA key features

- A full core 3D pin-by-pin neutronic evaluation, subchannel-wise thermal hydraulic and thermal mechanic analysis.
- One single core simulator for a fully consistent evaluation of steady-state and transient application modes.
- Supports all core configurations and PWR / BWR fuel assembly geometries and designs.
- Advanced multi-physics coupling based on modern software architecture and algorithms to enable industrial use of advanced methodologies.
- Modern ergonomic productivity enhancing suite with graphical user interface (GUI) to manage any process from input-, calculation-, and outpout-processing, from core design up to spent fuel management & preparation of fuel end of life.
- Comprehensive validation base and NRC approval provide high degree of licensing certainty.
- ARCADIA can be directly coupled to plant system thermal hydraulics codes – such as S-RELAP or CATHARE to obtain an integral simulation of the nuclear core under realistic primary circuit flow conditions – a key feature for advanced accident modelling.

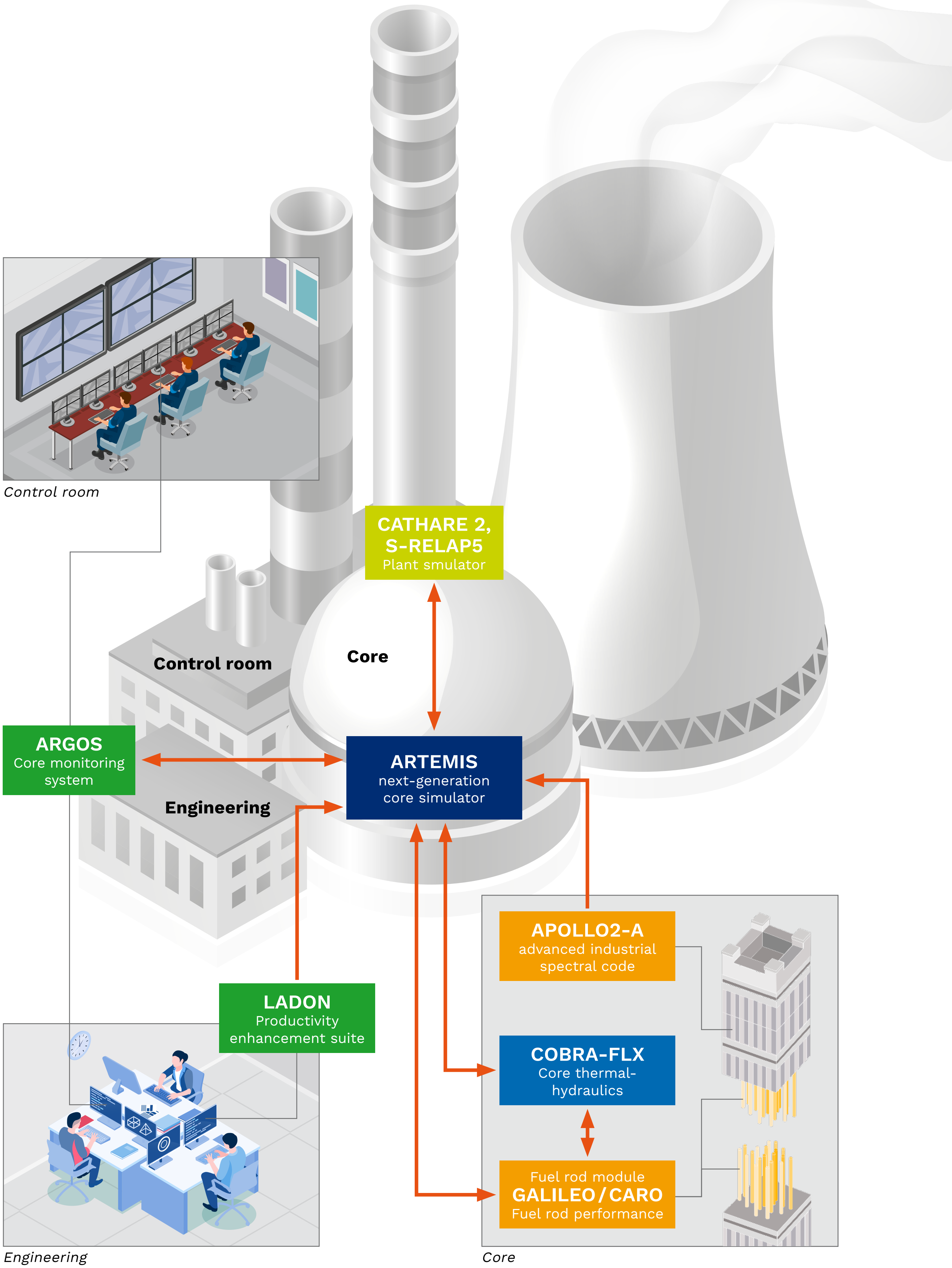
Large fuel design and configuration coverage

ARCADIA has a wide range of industrial modeling capabilities including:

- All rectangular PWR & BWR light water fuel design, including configurations with water holes and larger guide tubes as well as shielding fuel assemblies with part-length or full-length shielding rods in the assembly, independent of vendor, lattice size and core configuration, modeled with one uniform approach and cost-effective, repeatable process.
- UO_2, U/Gd, reprocessed uranium (ERU), high mixed-oxid concentrations (MOX).
- High burnable concentrations.
- Capability to model new materials for accident tolerant fuel as well as experimental set-ups and small modular reactors.
- Integrated burnable poisons (gadolinia, erbia, IFBA), removable poisons (WABA, Pyrex), and combinations of both.
- In-core instrumentation for power monitoring, including 235U fission chambers, rhodium and platinum detectors, gamma and neutron TIPs, vandadium aeroballs, and gamma thermometers.

Get more out of ARCADIA

- Included library of templates for many tasks featuring best practice from our expert teams.
- Customized & plant-specific implementation to match your exact needs.
- Dedicated training based on specific customer needs and pre-knowledge.



ARCADIA environment: one seamless experience with all the modules.

LADON – the productivity enhancement suite, access to the ARCADIA world

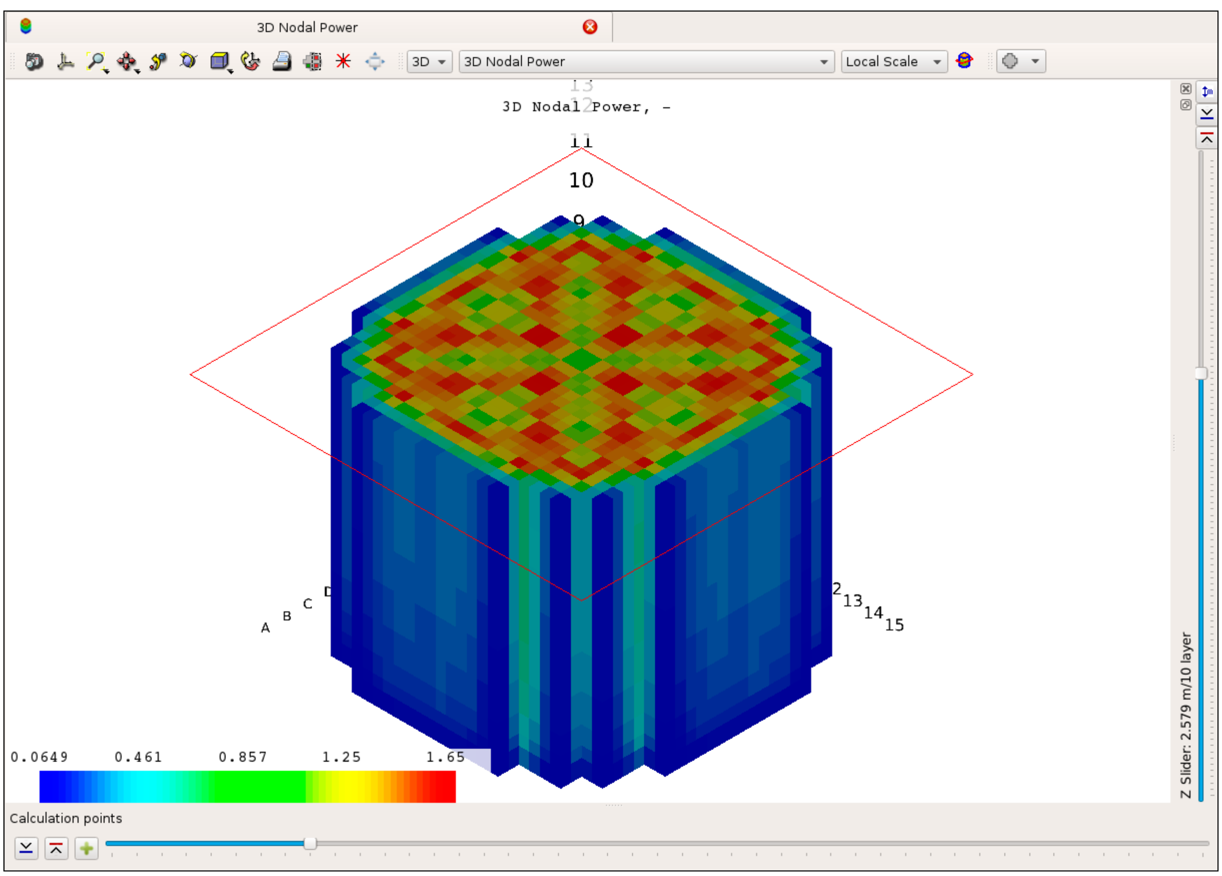
LEARN MORE ›

You are challenged to optimize core design, increase fuel value and operational flexibility while ensuring safety limits verification. Key elements of this challenge also include:

- Knowledge transfer from retiring experts to today's generation of engineers that require modern, graphical tools, i.e. you are looking for automatic and systematic work & know-how documentation.
- Continuous improvement of quality, i.e. you are required to have i) automated reporting and quality assurance tools, and ii) to demonstrate traceability & transparency.
- Data exchanges between disciplines, i.e. you expect no loss or approximations between codes.

Value

LADON offers you an unparalled, intuitive, efficient & highly configurable graphical platform to manage the ARCADIA code system from solver input preparation to analytical process automation, post-processing, quality assurance, and document generation.



Slice through a 3D core view - example of 3D coolant temperature

Featuring direct customer benefits

Intuitive & user-friendly graphical interface
➜ GUI-based to improve user interface and reduce training time

- Graphical creation/execution/review of calculations.
- Macro tools to simplify creation of inputs to physics codes.
- 3D graphical simulation results including ‘movies’ of time evolving studies.
- Easy follow, review, retrieve process.
- Intuitive and easy navigation between different steps of analyses from scoping calculations to final core design & safety justification.
- From beginning … definition of input, to end … engineering document, and in between … execution, results analysis, QA review, etc.
- Automated report generation with text and figures.

Highly traceable and transparent support and quality tool
➜ Standard database format increases usability and quality

- QA tools to facilitate review.
- Presentations of results with business entities.
- Automated report generation with text and figures.
- Use of ARCADIA database to re-use QA data.
- Flexible automation with scripted reload work and free elements for FOAK design.
- Integrated help menus explain input keywords and calculations.

High customizable/configurable use from fully automated to manual
➜ Flexible modes to accomodate any user and any application

- Flexible work modes:
- Production mode … highly recurrent, standardized and therefore automated task and design mode … first-of-a-kind analysis, new core design, out-of-the-box analysis.
- Customizable automation tools improve efficiency and allow the analyst to focus on the physics.
- Python powers the automation so it is easy for your engineers to understand and adapt.
- Flexible building blocks allow any process to be quickly and easily realized.

Efficient and modern software architecture
➜ Computation on a cluster to expand solution space and improve solution times

- Robust and accurate calculations between different disciples & modules.

Seamless coupled & integration within ARCADIA
➜ 3D, coupled physics simulation + LADON is adaptable to your legacy simulation tools

- LADON GUIs: works with any codes or methods package.

Examples

Analysis with a boost

Project structures and organizes calculations in PLAN and Sub-PLAN.

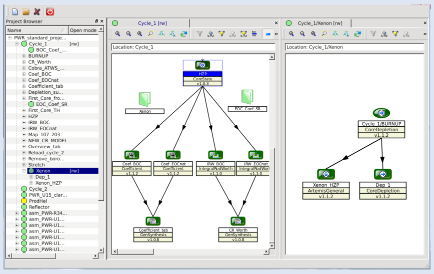
Create calculations from templates.

Link calculations in a flow.

Duplicate calculations already performed.

Share projects with other engineers.

QA checks and reports within the project.



Proof-check your inputs

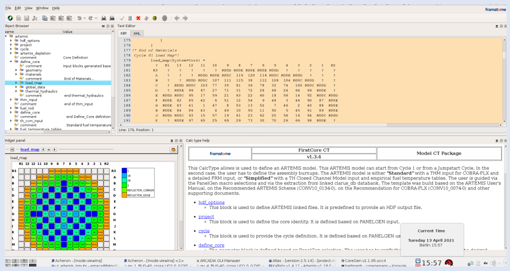
Develop input file with a context sensitive elements.

Object Browser represents the text input file in an “Explorer” like format.

Widgets guide the automatic development of the solver input.

Help window describes functionality.

Validate the input before calculation is executed.



Create in a few clicks a thermal-hydraulic mesh

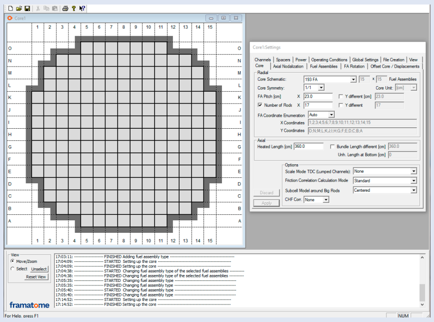
Establish **core mesh** and geometry for thermal hydraulic models.

Pick from **standard core maps** (193/157/etc.).

Define **sub-channels.**

Place **spacers.**

Zoom in and out of the mesh from the core view to the channel view.



Combine and assess your lattice mesh generation

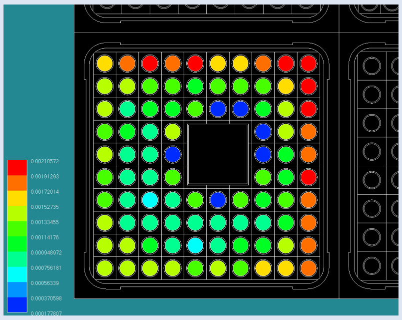
Create new meshes graphically.

Test design with APOLLO2-A or MCNP.

Evaluate the detailed results with plotting tools.

Batch mode permits execution using scripts.

Elements are created individually and then combined into the final mesh.

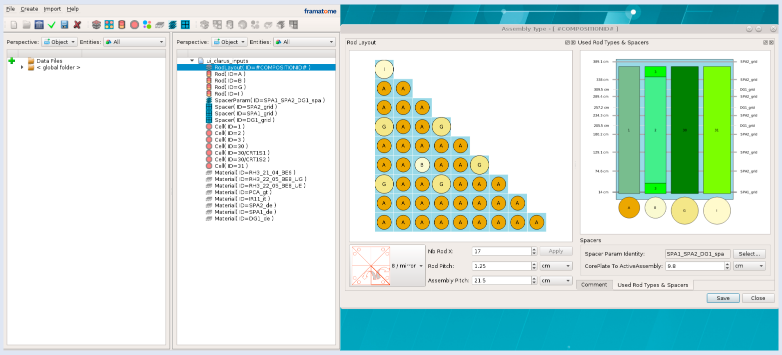


Easily created fuel design

Geometry created graphically.

Component library with global data files allows quick access to past and standard design elements.

Construct assembly from components starting with material definitions and build up step by step with pellets, rods, lattices, etc.



Examples

Analyze your result in one shot

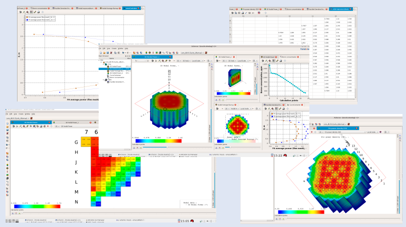
View solver results in a well-adapted and flexible format.

Many representations: core view, assembly view, assembly slice view.

Plots/Curves/Tables in multi-dimensions.

Scripting to recreate presentations automatically either in ACHERON or with python scripts.

Movies for transient events.

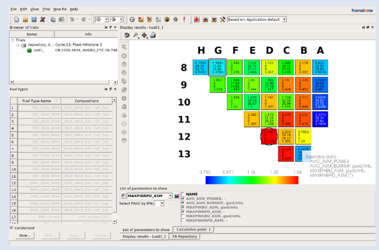


Explore core design

Interactively create new reload, test designs on the template series of calculations and review results.

Drag and drop fuel assemblies from the spent fuel pool to the new reload plan.

Update the spent fuel pool with repaired assemblies.



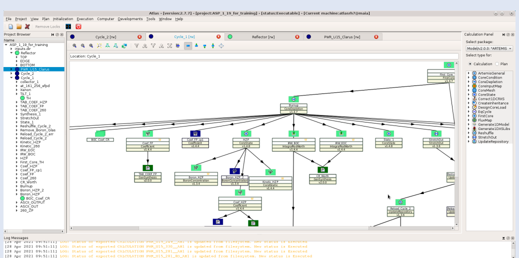
Easily scale up your calculations

Generic calculations form building blocks of the system.

Custom calculations to meet specific user need.

Plans generate sets of calculations.

Projects create a complete ATLAS project based on one input dialog.

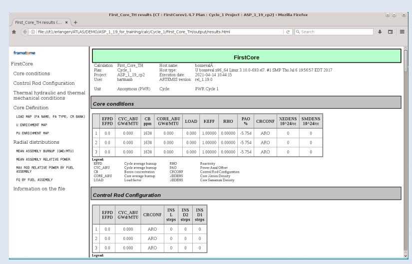


Profit from report automation

Templates are filled with calculation results (Word/LaTeX/HTML).

Create from short summary to full engineering document.

Extract the needed data, create the needed figures and tables.



Secure quality assurance

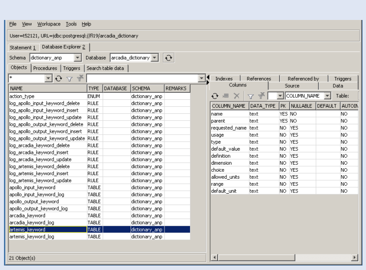
Store geometry input data, key output results and measured data.

Boost input definition by downloading database information.

Verify data once and safely use many times.

Share the data with the ARCADIA user community.

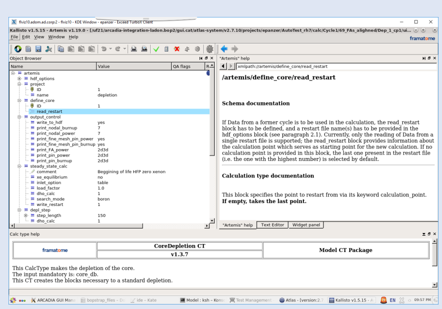
Provide **statistics** on wide range of data.



Rely on help function

Clear unambiguous definition of keyword improves quality and understanding.

Interface linked to input generation and output viewing GUIs.



ARTEMIS – the truly next-generation core simulator

LEARN MORE ›

Value

ARTEMIS is a powerful integrated coupled 3D neutronic/thermal-hydraulic/thermal-mechanic nodal multi-group core simulator with pin power reconstruction for both PWR & BWR.

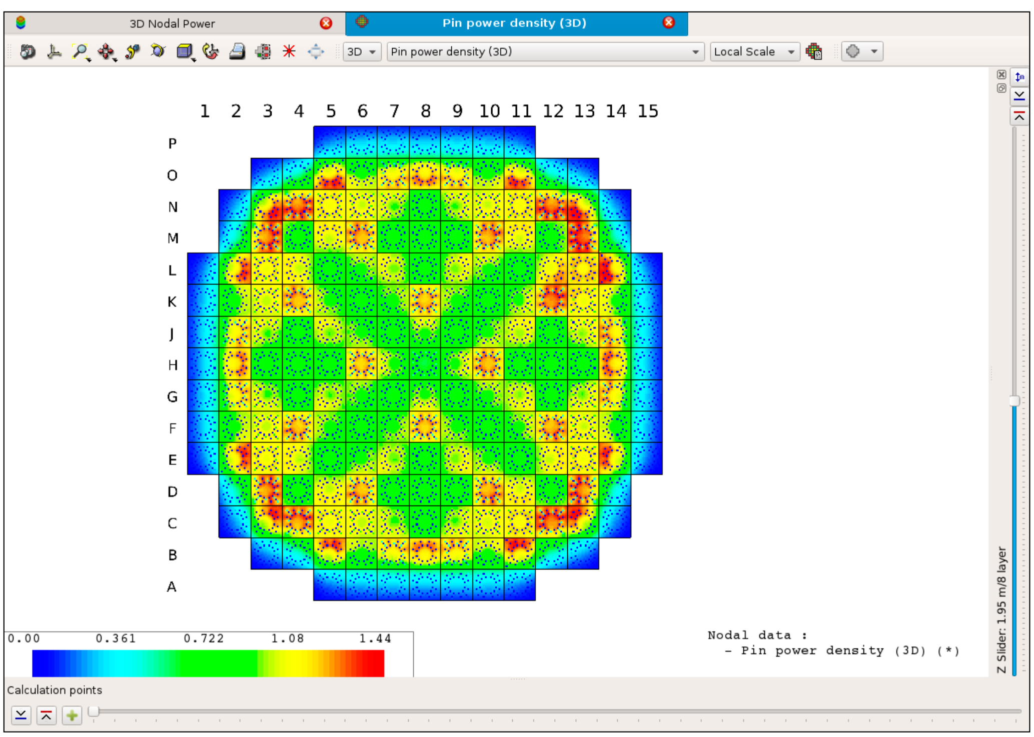
ARTEMIS is the central engine of the ARCADIA system to feature the most realistic, reliable and accurate description of the core.

Unlike many other core design codes, the complex interplay between neutronic, thermal hydraulic and thermal mechanical effects is addressed within ARCADIA by integrating the COBRA-FLX thermal-hydraulics code and a fuel rod module directly into the ARTEMIS neutronic flux for taking into account thermal mechanical feedback effects.

This intimate most realistic coupling of the underlying physical effects allows for a most realistic description of the reactor core.

It replaces the legacy approach where neutronic, thermalhydraulic and thermal mechanic parameters have been studied in a separated manner which requested for each parameter an unrealistic over-conservative penalization compensating the limitations of the decoupled model.

ARTEMIS overcomes the drawbacks of existing codes and therefore allows a massive release of operational margin – the primary key to optimize safety, plant utilization, and extende fuel economy.



3D pin power density on a core cross-section

ARTEMIS: truly first-in-class

- Full core 3D pin-by-pin coupled neutronic/ thermal-hydraulic/thermal-mechanic simulator.
- Fully consistent steady-state and transient solution.
- Macroscopic and microscopic depletion models, optionally freely configurable.
- Advanced dehomogenization method and pinwise burnup model to analyze all core features down to the pinlevel:
  - Enhanced pin reconstruction techniques (interpolation and modulation) up to high burnup.
  - Application of multigroup power form functions for improved pin power accuracy.
  - Application of spacer grid form functions for power and group fluxes.
  - Time integration of 3D pin burnup based on pin powers (consistent to nodal burnup).
  - Reconstruction of pin-wise 3D power and group-wise fluxes.
  - Application of spacer grid form functions for power and group fluxes.
- Calculation of in-core detector signals for AMS, MIPS, FIDS.
- Calculation of ex-core detector signals.
- Parallel multithread processing for fast and efficient use of modern computer hardware.
- New features include
  - Advanced multigrid convergence accelera-tion techniques.
  - New search algorithms to support opera-tional strategy generation (planning of op-erational event, eg Load Follow or part load operation).
  - Axial offset and axial shape control (inclu-ding search algorythms for control rod bank position and / or boron concentrations).

Built in physics models for couple core physics evaluation

- COBRA-FLX:
  - Models TH feedback under static and transient conditions and allows for 3D full core sub-channel by subchannel TH and DNB evaluation.
  - Improved best-estimate post-DNB model.
  - Advanced CHF correlations developed and ready for implementation (all current cor-relations remain available).
  - Cutting edge ORFEO GAIA CHF correlation available.
- Fuel rod module provides fuel and clad temperature.
  - Based on ab initio thermal mechanical models.
  - Heat conduction equation solved in steady-state or transient condition.
  - Radial temperature distribution within fuel rod.
  - Effective fuel temperature evaluated from pellet temperature distribution.
  - Surface heat flux to coolant.
  - Specific heat capacity under transient conditions.
  - Thermal conductivity and specific heat evaluated using empirical correlations.
  - Optional use of default fuel temperature rise tables for UO2 and MOX fuel.
- Core monitoring – MEDIAN.

Broader evaluation environment: Direct interfaces to other codes

- Interface to thermo-mechanics codes
  - GALILEO, CARO-E.
  - Easy file coupling (2D/3D pin power histories in different formats – e.g. PINDAT).
- Interface to shielding applications
  - MCNP, DORT.
- File coupling (2D pinwise time integrated neutron source distribution).
- Interface to decay heat calculation
  - DINUM (DIN 25463).
  - ANSI/ANS-5.1-2005 for application in transient mode.
- Interface to system thermal-hydraulics codes
  - S-RELAP5, CATHARE2.
  - Communication via message passing interface (MPI).

APOLLO2-A – the advanced industrial spectral code

Value

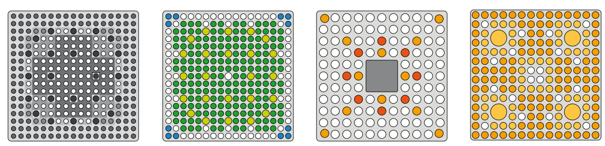
APOLLO2-A is the most advanced spectral code developed by Framatome based on the APOLLO2 kernel developed by the french commissariat à l'énergie atomique et aux énergies alternatives (CEA).

It was adapted by Framatome for PWR & BWR industrial applications while comprising high level physics enhancements in comparison to other lattice codes available on the market.

APOLLO2-A is widely based on first principle physics providing unparalleled accuracy for a large range of advanced applications.

A major application of APOLLO2-A is the generation of nuclear cross-section libraries which can be used in APOLLO2-A standalone applications (e.g colorset studies, reflector modeling) or be used as input for the core simulator ARTEMIS.

APOLLO2-A supports PWR / BWR fuel assembly geometries and designs. Furthermore, APOLLO2-A may also be used for special applications, like criticality aspects of fuel assembly storage.



APOLLO2-A allows spectral evaluation of all light-water reactor fuel assembly geometries

Ahead of competition modeling/accuracy

- Nuclear data libraries based on JEFF 3.1.1 for neutron transport and gamma production (filled up for missing nuclides with other evaluations) and EPDL97 for gamma transport.
  - Kinetic data based on JEFF 3.1.1 (8 delayed groups).
  - Refined multi-group energy mesh for neutrons (281 groups) and gammas (94 groups).
- Improved self-shielding model.
  - Equivalence methods for spatial heterogeneity ("homogenization" – yielding reaction rates) and multigroup equivalence (yielding cross sections).
  - Treatment of resonances with collision probability tables.
  - Explicitly takes into account the "dancoff effect" by a dedicated 2D computation.
- Enhanced multi-level scheme strategy.
  - Three flux calculation levels : CP 281 g / IDT 44 g / MOC 35 g.
  - Advanced flux reconstruction method to combine all flux results.
  - Use of 281 group fundamental mode (critical) neutron spectrum for output of XS and for depletion.
- Extended depletion chain.
  - Explicit account of 26 fissile isotopes an 131 fission products.
  - Dedicated chains for special materials like Gadolinium (73 isotopes).
- Detailed gamma calculation.
  - Prompt and delayed gamma production (281 neutron groups -> 94 gamma groups).
  - Gamma transport equation based on own schema: CP (94g), IDT (18g) and optionally (e.g. for gamma detectors) MOC (18g).
- Refined physics models.
  - Energy deposition model (from fission fragments, neutrons and gammas).
  - Pin detector model (neutron and gamma).
  - Reflector model: 1D and 2D, including output for response functions used in ERM1 and ERM4 procedures as basis for equivalent reflector XS.
  - Kinetic data in 8 delayed groups.
  - Colorset model – calculation of individual weighting fluxes for each fuel assembly, while the MOC step is done for the whole geometry.
- Core geometries.
  - Dedicated schema to achieve high accuracy: P3 and MOC in 281 groups.

- Colorsets up to 1/8 core including reflector.
- Used (as 11x11 core mock-ups) e.g. for validation of special fuel assembly (e.g. radially inert and partially inert shielding assemblies) and reflector models (ERM1, ERM4).

› Advanced modelling capabilities for operational challenges.

- Fuel assembly repair capability (replacement of defective pins with new ones (fuel or inert) from several donor fuel assemblies, impact on heterogeneous form functions).
- Pin replacement also usable for comparisons with isotopic measurements.
- 1D+2D "quasi 3D" model for the spacer effect.

Large range of fuel design applicability

APOLLO2-A has a wide range of industrial modeling capabilities:

› PWR & BWR light water fuel design.

› for UO2, U/Gd, ERU, high mixed-oxid concentrations (MOX).

› High burnable concentrations.

› Single lattice to multi-assembly effects.

› Extensive application modes: single assembly, up to 1/8 core with reflector (heterogeneous pin cells), single cell, 1D slab reflectors, full 2D reflectors.

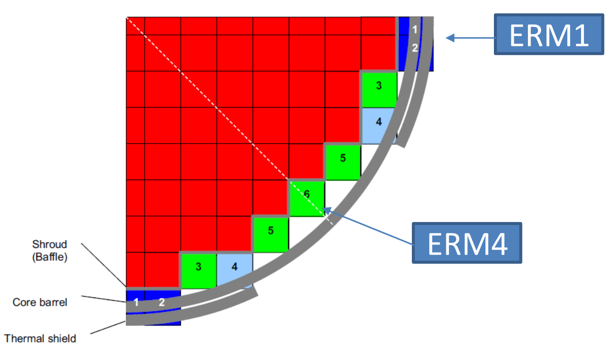
› Covers a wide range of cold hot reactor states including challenging accidental conditions.

Advanced high accuracy reflector modelling

The accuracy of the neutronic modelling capabilities of a core simulator depends crucially on the quality of the applied reflector model.

Various water gap geometries baffle and core barrel configurations must be realistically modelled and additional features like thermal shields or additional steel elements (e.g EPR heavy reflector) need adequate description.

ARCADIA comes with sophisticated and versatile reflector modelling capabilities which can be customized to realistically describe many reflector geometry configurations of all types of commercial LWRs.



Typical reflector geometry configuration for core and core baffle

The ARCADIA equivalent reflector model (ERM)

› Is based on ab initio physics in APOLLO-2A, extensively validated with mont carlo methods and reference experimental setups.

› Provides reliability and robustness in application to a large variety of reactor types.

› Spans a wide range of cold to hot operational conditions and boron 10 concentrations.

Sophisticated response properties

› ARCADIA features the ERM1 and ERM4 reflector model.

› ERM1 is suited to describe 1D slab geometries, taking into account only direct reflection responses.

› ERM4 features a sophisticated extension to 2D explicit geometries, taking into account straight and side transmissions, allowing for computing surface fluxes.

› ERM4 is crucial for obtaining the best modelling of flux conditions at inner corners with two sides facing fuel.

Application in practice

› ERM1 is applied for generation of axial and radial shroud-water reflectors.

› ERM4 is applied for generation of radial shroud-water and heavy reflectors and has been successfully used for modelling a shielding fuel assembly.

› The most realistic modeling of neutronic fluxes & its interaction with the core buffle is integrated in the ERM4 model for accurate predictions of the neutronic leakage.

Did you know?

› Together with you, Framatome builds the most suited customized reflector model for your plant.

› The ARCADIA reflector model is best suited for designing and evaluating advanced shielding fuel assembly solutions.

Built-in add-ons

LEARN MORE ›

COBRA-FLX – the performing thermal-hydraulic core simulator

Value

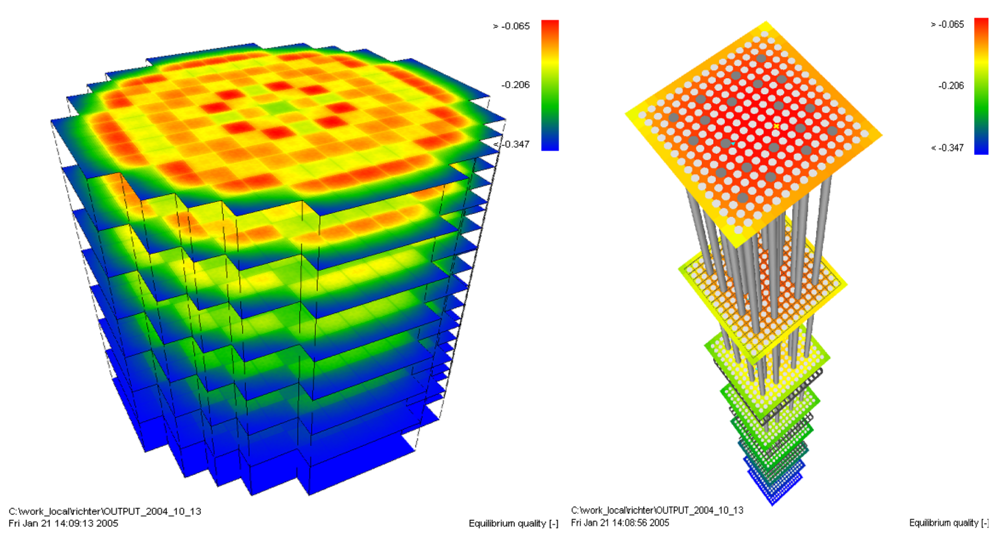
COBRA-FLX is the most performant sub-channel code to predict 3D distributions of coolant flow and temperature in the core and to perform accurate 3D steady-state and transient full core analyses in reasonable computing time and in a flexible way for homo-geneous and mixed cores.

Advanced technical features

- Subchannel-by-subchannel DNB analyses.
- Low and even reverse flow modelling capability.
- Full core pin and sub-channel wise steady-state and transient neutronic and thermal-hydraulic evaluations.
- Fuel and cladding temperature distributions based on ARTEMIS fuel rod module.
- High-performance computing: Users can perform pin-by-pin full core transient calculations in only a few minutes.
- Enhanced pre-processing and core generation with user-friendly and flexible graphical user environment.

Dedicated application

- Reload analyses for a variety of fuel assembly designs; for that numerous critical heat flux (CHF) correlations are implemented.
- Lift force calculation for steady-state conditions.
- Crud risk assessment.
- Steaming rate prediction.



Examples of COBRA-FLX results.

Built-in add-ons

Spent fuel pool manager

Value

Framatome's spent fuel pool manager facilitates the management of the inventory of the spent fuel pool, making a direct link between the management of the core loading and the management of fuel assemblies in the spent fuel pool.

This feature makes the spent fuel pool manager to a most valuable tool for all engineers who are engaged in loading pattern design and fuel management activities.

The tool hereby optimizes the use of the fuel in the core and in the spent fuel pool. This optimization is performed via LADON GUI, which relies directly on the core model data from ARCADIA.

The interface allows considerations of other material constraints such as retired control rods or disabled assembly locations. In addition, this tool also offers direct services such as generation of an automated spent fuel pool inventory report.

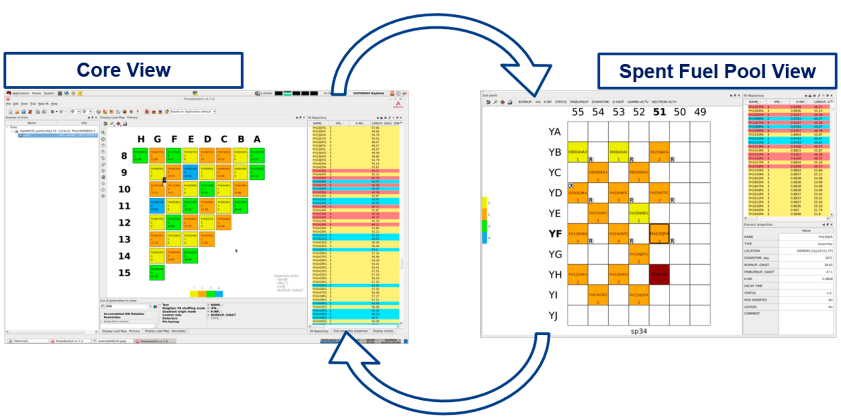
Benefits from ARCADIA suite power

- Benefits from LADON powerful capabilities being an intuitive tool: : very easy to use – even with limited training, it provides fast and secure pool management.
- Is fully integrated all-in-one ARCADIA tool – from core modeling to spent fuel pool management – to reduce risks related to additional interfaces.

Versatile use

LADON offers a dual view of both the core and the spent fuel pool. Once the geometry models are established, the user can switch the visualization mode between the core model view and the spent fuel pool model view. The repository file is the link between these models.

- **Core model view:** the user can define new core loading pattern and launch core calculation tests to evaluate the core loading. The core designer can focus on using his/her skills and experience to optimize the core loading pattern for a new core cycle. The selected loading pattern can then be exported to pursue even more complete analyses.
- **Spent fuel pool view:** the user can simulate the placement of fuel assemblies and other elements within pool locations. This mode is of interest for site engineers who manage the positioning of fuel assemblies in the spent fuel pool.



Versatile use of the spent fuel pool manager and its dual views (core view and spent fuel pool view).

Opening the perspective for multiple applications

- Support to criticality analysis.
- Support for core unloading and loading sequence between two definitions (before and after) of the pool inventory and the core loading.
- Characterization of the fuel assemblies for potential dry storage, identifying potential candidates for extraction from the pool, based on their characteristics as calculated by the core simulator.

ARGOS – the universal core monitoring system

LEARN MORE ›

Value

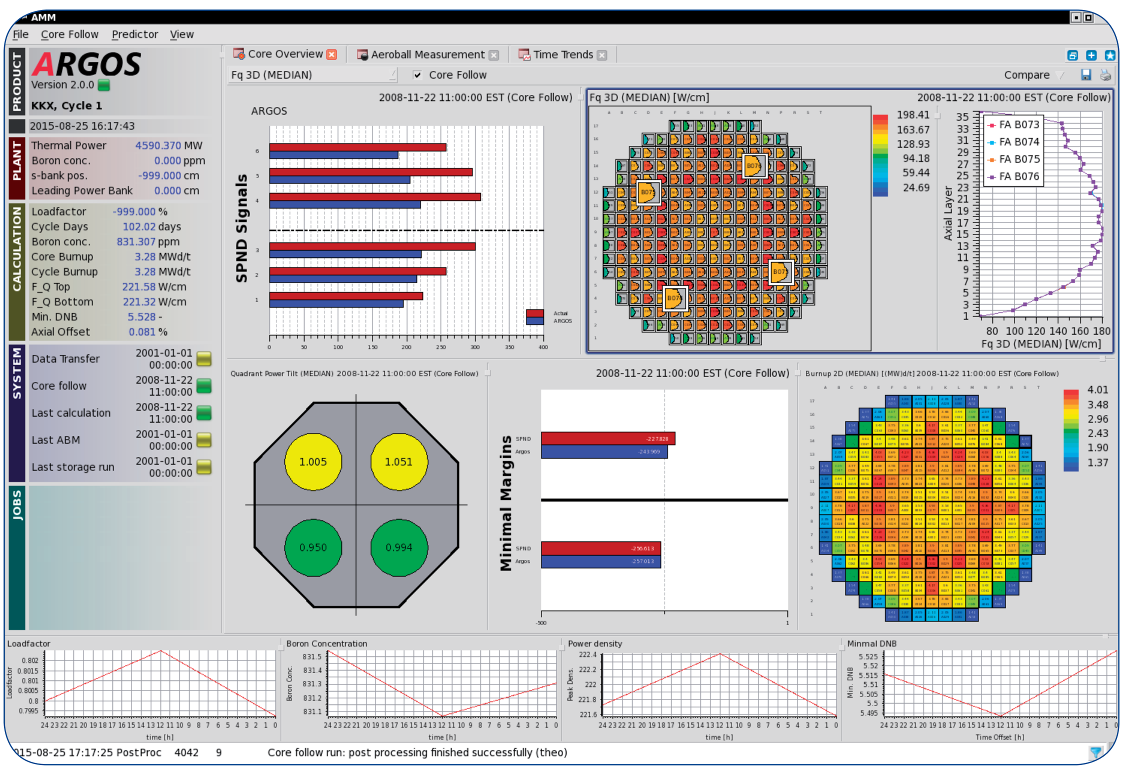
NPP are increasingly seeking efficiency, margin & flexibility for their core surveillance & operational maneuvers. This requires a tedious exchange of data between plant operators and core designers, providing a incomplete & discontinuous past view on the core conditions.

The solution has to fit onto existing platforms & core design codes on one side, and has to be fully intuitive for non-experts of core design such as plant operators.

ARGOS is the first and unique universal core monitoring system to support all types of commercial light water reactors.

The proven accuracy and robust performance of ARGOS efficiently supports plant operators for core monitoring, technical specifications surveillance and in planning & optimizing short-term and long-term cycle operating projections.

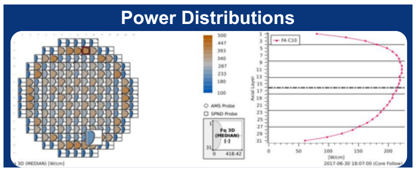
The innovative software architecture is completely intuitive, on-the-fly customizable & modular, allowing additional services & coupling to other codes.



ARGOS GUI can be easily configured to fit individual needs.

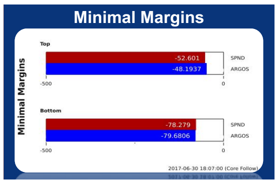
Provides diagnostics & reactivity monitoring to plant operators

- Various power reconstruction methods available to provide instantaneous & continuous 3D core power distribution.
- Modular design – possible coupling with all common neutronic simulators – customizable solution independent of the core simulator & power reconstruction methodology.
- Flux trace data from various measurement systems.
- Ex-core/in-core detector calibration.
- Reactivity and xenon monitoring.
- Isotopic tracking.
- Proven MEDIAN methodology – safely applicable for all LWRs.
- 3D power reconstruction based on in-core measurements for the different measurement systems.
- Optional, on-line burnup calculation with adaptation factors between measurements.
- Operation strategy generator.



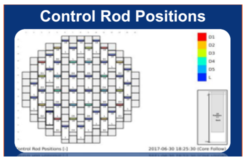
Increases operational flexibility by continuous margin control to operational limits

- Automatic on-line core follow calculations with core parameter trending and monitoring of thermal limits compliance & comparison between predicted and observed core behavior.
- Any calculation the core simulator is capable of estimated critical conditions, shutdown boron concentrations & margin, reactivity monitoring, predictive core calculations in (non-) adaptive mode, flux mapping for steady state conditions, flux mapping based on accurate time and power dependent xenon calculations for operational transients.



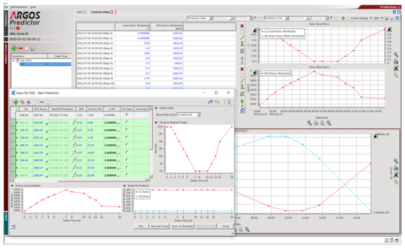
Supports planning of more efficient load follow maneuvers, lower operational costs by reducing boron processing through optimized power maneuvers & save time in return to full power

- Predictive capability: the predictor module of ARGOS has been designed to easily set up and virtually calculate all thinkable core states and operational transients via an interactive GUI Interface.
- Function to transfer executed transients from core follow as input to the prediction module to analyze planned or executed load transients and to apply them to other time points.

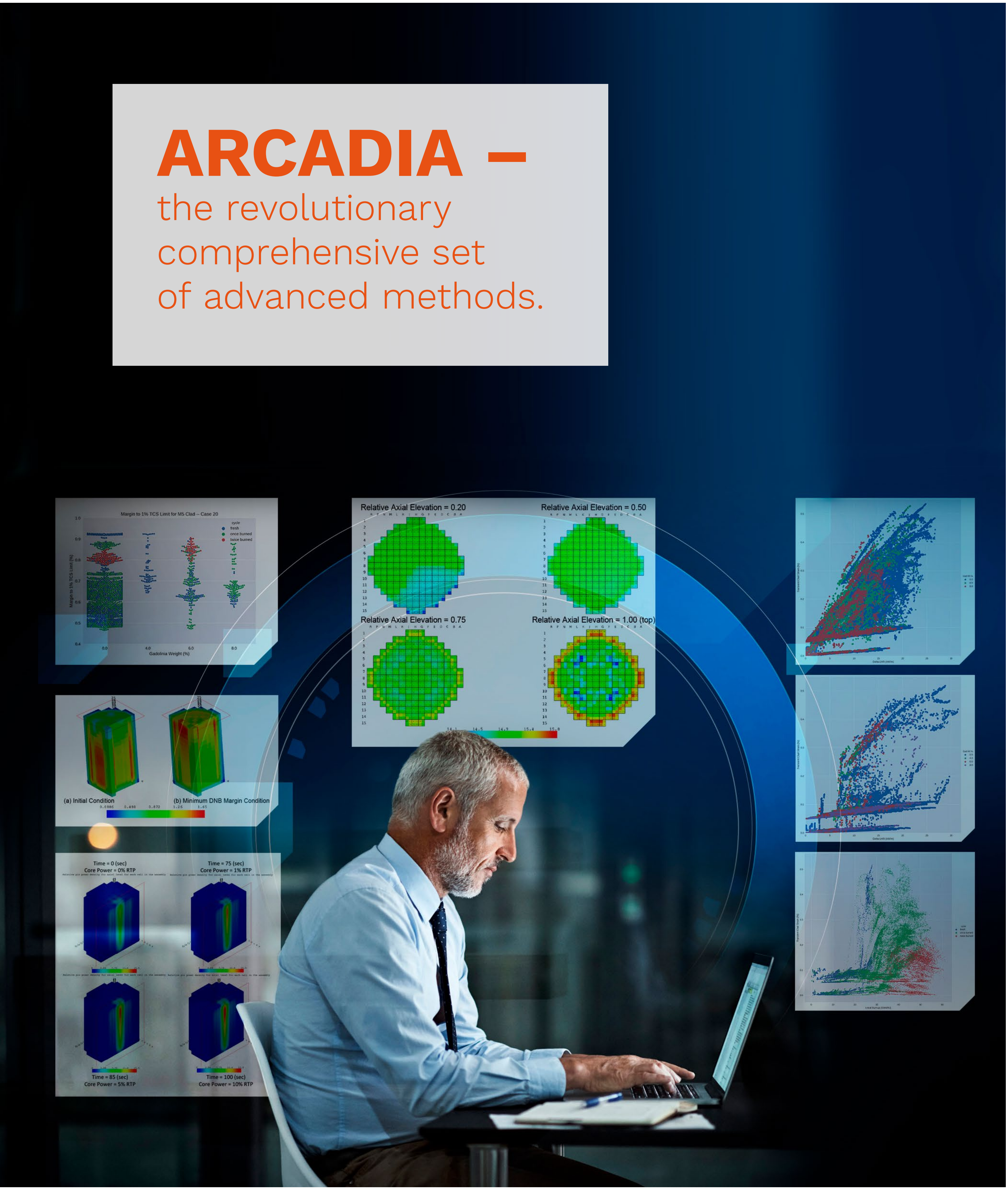


Facilitates access to all available measured and calculated data for the plant operator, as well as the engineering work, in a safe manner

- State-of-the-art & intuitive graphical user interface with improved ergonomics through flexibly configurable GUI interface including Automated report generation and on-the-fly capabilities.
- Offer a fleet-wide solution with common look and feel, independent of the core simulator or power reconstruction methodology (coupling to different core simulators possible, supports different power reconstruction methodologies, comprehensive user configurable GUI for core follow and prediction, can be adapted to all nuclear power plants).
- Security concept.



ARCADIA –
the revolutionary comprehensive set of advanced methods.



Utilities are expecting from the fuel suppliers to provide solutions to increase fuel cycle performance and operational flexibility while maintaining safety to a very high level. Safety authority requirements are also evolving, e.g. new reactivity-initiated accident (RIA) criteria or reinforced request for enlarged qualification database.

Value

Framatome has anticipated the evolution and come up with methods properly meeting the new utility and safety needs, such that product and operation performance are making a new breakthrough.

This is made possible by leveraging ARCADIA code capabilities:

- Best-in-class model accuracy of the ARCADIA code system which reduces conservatisms from potential outdated methodologies and provides more accurate assessments of events.
- Modern architecture of the ARCADIA code system using up-to-date computing capabailities; codes and methods are no longer constrained by the limitations of past decades, which are still currently defining the plant performance.
- Breakthrough features & functionalities that enable the realization of embedded advanced methods deliver a better understanding and a substantial across-the-board performance margin for operational performance and flexibility.

Value

With ARCADIA´s methods, you profit from its support of operational initiatives. Unlike any nuclear code developer, core designer or fuel supplier in the world who provide only part of the answer, Framatome offers a complete set of advanced codes and methods to utilities for accidental transients empowered to:

- **Provide a response to changes and challenges in regulatory environments.**
- **Secure the high commitment to safe operation of your nuclear power plant.**
- **Deliver a better understanding and a substantial across-the-board performance margin for operational performance and flexibility.**

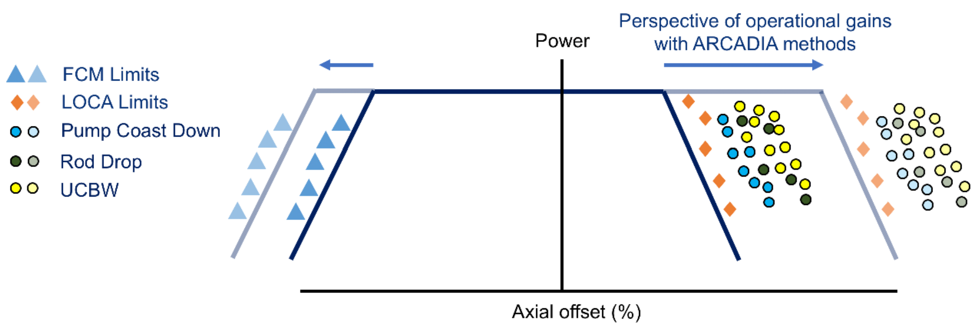
Developer core team of ARCADIA advanced methods.

ARCADIA methods – the path for unlocking margins

Your utility has a current design that works?

Managing value from margin gain can be tricky: as one obstacle is removed, the next is usually not far behind.

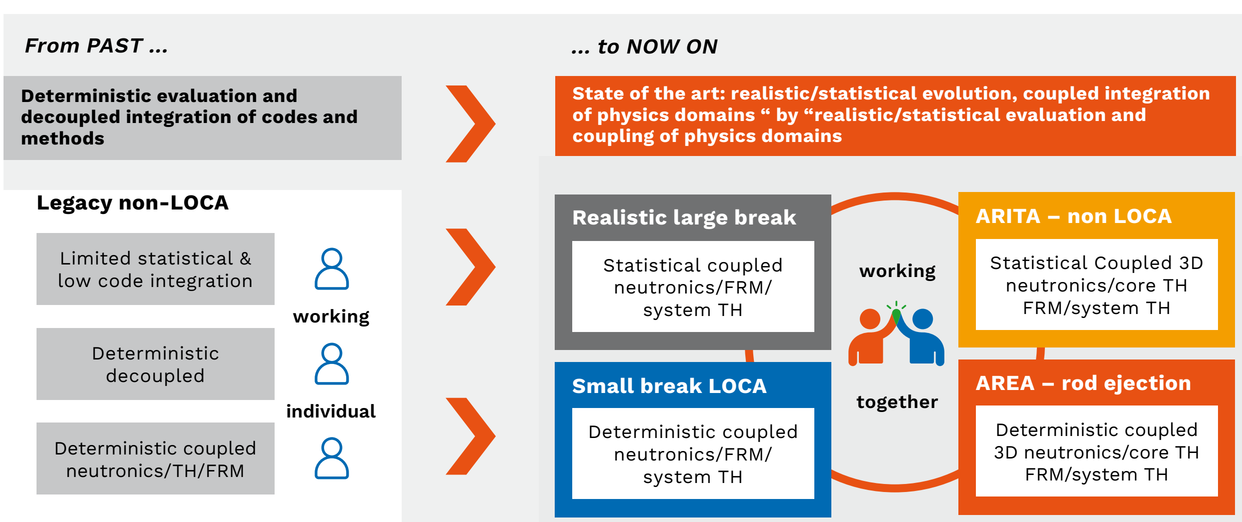
Example (dark- and light-colored symbols represent the domain of operation and its associated constraints before and after use of ARCADIA methods, respectively):



The blue line limits your reactor's domain for normal operation and therefore your operational flexibility. The domain is constrained by operating conditions (marked by dark-colored symbols in the picture) which could result in an event severely challenging the plant's safety, e.g. in case of an accidental transient emerging from these initial conditions (such as LOCA, rod drop, UCBW – uncontrolled bank withdrawal, pump coast Down, FCM – fuel centerline melting).

Framatome has developed breakthrough methods using the unique features of ARCADIA to perform the most realistic evaluations of such limiting accidental scenarios, while removing legacy over-conservative assumptions and reducing uncertainties. Therefore, the re-evaluation of limiting events with ARCADIA allows to considerably offset these constraints and to enlarge the normal operating domain (marked by light-colored symbols in the picture). This is key to enhanced operability gains and to unlock substantial product performance.

ARCADIA methods offer the potential to unlock substantial product performance and operability gains.



The advanced ARCADIA methods cover all the different aspects of safety analysis and can be modularly used based on utility needs.

§

AREA – Arcadia rod ejection analysis significantly reduces the severity of the rod ejection event primarily by using an advanced evaluation model

- Deterministic fully coupled 3D transient simulation.
- Equipped to handle enthalpy rise, system pressure, and DNBR portions of the RIA analysis scope.
- Positioned to address future RIA criteria changes.
- Approved in Dec. 2017 for application in PWR plant licensing bases.

§

ARITA – ARTEMIS/RELAP integrated transient analysis delivers performance margin for the full spectrum of non-LOCA events while still respecting the existing safety limits

- Fully coupled statistical 3D transient simulation.
- Rigorous uncertainty evaluation method based on Monte Carlo simulation, uncertainty propagation, and non-parametric statistics.
- Submitted Aug. 2018.

§

Advanced LOCA methods to address new criteria

- Realistic large break LOCA revision 3 approved in 2016, moved LOCA based cycle design restrictions out years ago.
- Small break LOCA method supplement approved in 2015.

Validation

The advanced ARCADIA codes and methods package has been validated to the following events:

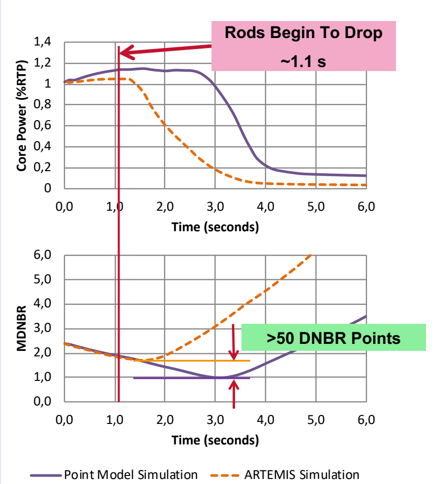
- Locked rotor
- Rod ejection
- Complete loss of flow
- Partial loss of flow
- Increase in steam flow
- Single rod withdrawal
- Uncontrolled bank withdrawal at power
- Post scram main steam line break
- Inadvertent opening of power operated relief valve
- Loss of condenser vacuum
- Inadvertent operation of the emergency core cooling system

Example

This kind of event is traditionally modeled using a point model simulation with constant moderator feedback. The scram reactivity was derived from the steady state balance.

With ARCADIA, the event is modeled using 3D full core steady-state and transient analyses with dynamical feedback and dynamical modelling of the control rod drop. This model calculates the core power and MDNBR with much higher accuracy.

Due to the precise modeling of the rod drop, the calculated core power is reduced much earlier and, consequently, the minimum DNBR starts to increase at a significantly earlier time, resulting in a gain of 50 DNBR points, compared to the legacy method.



AREA – the method addressing regulatory criteria while improving margin

LEARN MORE ›

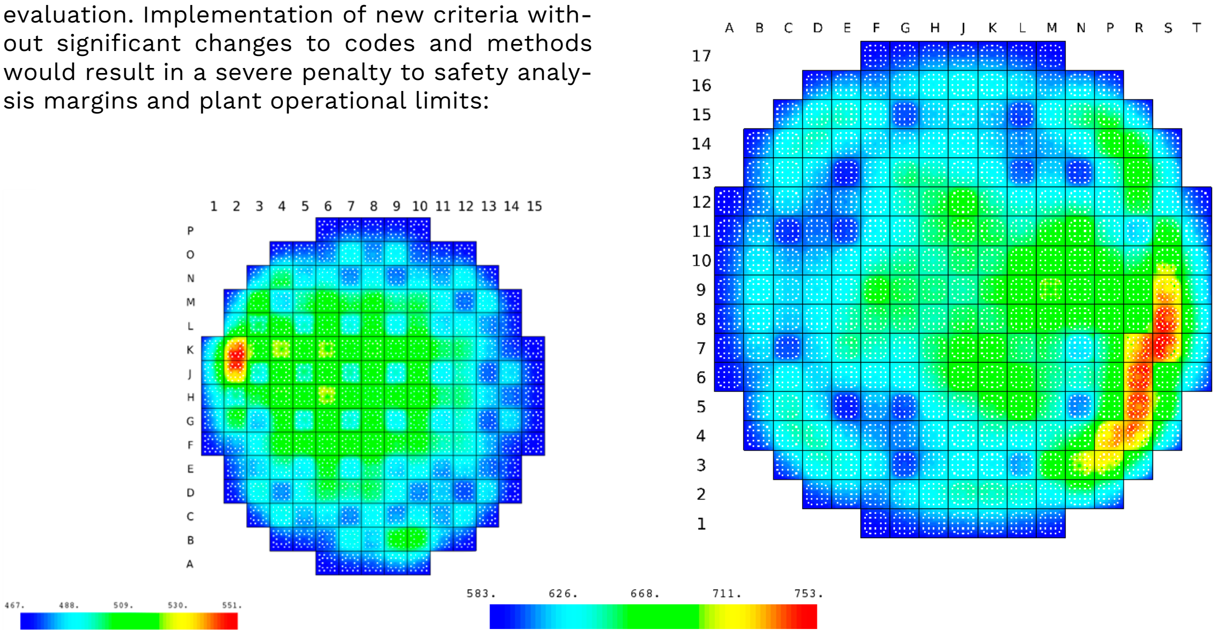
In recent years, the legacy processes for analyzing reactivity insertion transients have been questioned. The NRC revisited the specified limits making changes to the standard review plan in 2006, and then issuing a draft regulatory guidance document in 2016.

The original energy deposition limit of 280 calories/gram was lowered to 230 calories/gram and additional failure thresholds including high temperature and pellet clad mechanical interaction (PCMI) were defined.

Past models struggle to adequately capture key phenomena in this event and produce a thorough evaluation. Implementation of new criteria without significant changes to codes and methods would result in a severe penalty to safety analysis margins and plant operational limits:

- Limits are decreasing and becoming more complex.
- Increased complexity by burnup dependent limits.
- Legacy methods were not built to support limits like these.

What is at stake? The strong risk to have adverse effects on fuel cycle.



Pellet center temperature in rod ejection event.

Value

Framatome's U.S. NRC-approved AREA methodology provides analysis methods for all of the relevant aspects of the rod ejection accident from calculation of local peak and total energy deposition to the calculation of peak system pressure.

AREA methodology introduces a coupled core and system evaluation model that brings substantial margin through accurate modeling and simulation of the overall transient progression. This method addresses the regulatory changes while using advanced modeling techniques to greatly improve analysis margins.

ARITA – the the industry´s leading method for performing non-LOCA safety analysis

LEARN MORE ›

Nuclear plants are continually challenged to improve economic performance to compete with other energy sources. This has led to a demand for an updated methodology which addresses regulatory issues, but also provides utilities, increased operational margin and flexibility.

Core simulator – ARTEMIS

- Internal coupling of neutronics, thermal-hydraulics, and fuel rod model.

Plant simulator – S-RELAP5

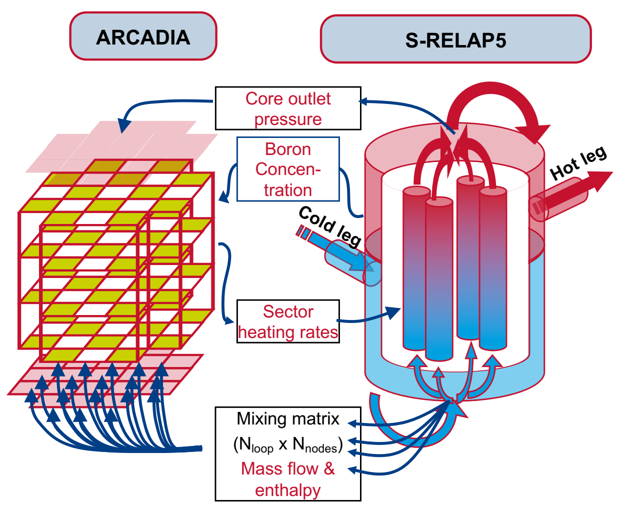
- Coupled to ARTEMIS via message passing interface (MPI).

Monte Carlo simulation & order statistics

- Random sampling of important input parameters.
- Generation of a sample set of outcomes using the evaluation model.
- Identification of tolerance limit using order statistics.
- ARITA – Framatome is the industry leader in this domain by implementing for the first time world-wide statistical non-LOCA methods in PWRs.

ARITA – culmination of benefits of advanced ARCADIA codes & methods – aimed at game changing analysis capabilities

- Taking advantage of ARITA does not require a new consistent analysis of all non-LOCA design transients and accidents.
- It is sufficient to re-analyze the most limiting scenarios.



Coupling of ARCADIA with thermal-hydraulics system codes.

Value

The ARITA method harnesses the capability of modern programming to couple the ARTEMIS 3D core simulator with the S-RELAP5 plant simulator, resulting in a 3D-coupled transient evaluation model including an extended statistical approach applicable to the whole bunch of uncertainties of a transient analysis at one shot.

Example

ARITA in numbers:

- 50% margin gains through combination of coupled evaluation model and statistical process.
- 100% of the large collection of non-LOCA events analyzed have seen significant margin gain.

Your benefit with the AREA method

Parameters in rod ejection accident analyses, in particular enthalpy rise in the context of the pellet clad mechanical interaction failure threshold, have limit values depending on the clad oxide thickness or the burnup. Thus, the appropriate limit for a given fuel rod is a function of local conditions and the clad type itself.

With legacy methods where the local fuel rod conditions for each rod in the core are not known, a limiting composite pin method would be required where the worst combinations of fuel rod conditions would be assumed to exist simultaneously. While this practice simplifies the analysis, performance margin is locked away by the bounding assumptions and limited resolution of these methods.

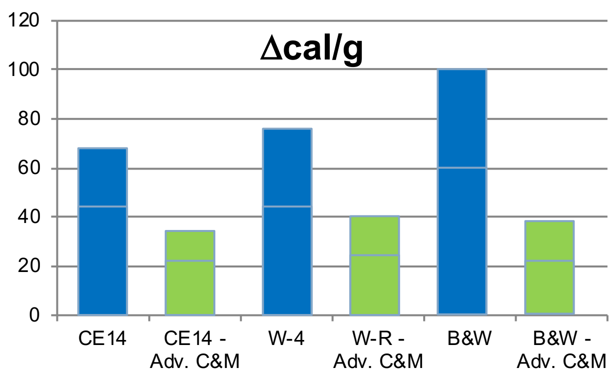
With the application of the AREA methods 3D full-core coupled pin-by-pin model, the safety relevant parameters can be resolved on the pin level accounting for the local oxide thickness/burnup and the fuel and cladding material. The local feedback mechanisms can be individually and accurately modeled.

The higher resolution due to the accurate modeling allows to generate truly local results without overly bounding assumptions, accessing existing margins that have been hidden before with legacy methods.

Value

Using ARCADIA with the AREA rod ejection methodology greatly reduces the impact of the control rod ejection event. Enthalpy deposition magnitudes are effectively half of those assessed by legacy analyses.

The margin created by this advanced analysis process removes control rod ejection from the list of limiting events for all plant types evaluated to date.



Comparison of enthalpy deposition rate with legacy methods (blue bulk) and AREA method (green bulk) for different types of PWR reactors.

Your benefits with the AREA & ARITA methods:

Your benefit with the ARITA method

Application of the advanced 3D transient evaluation model to non-LOCA events presents a significant challenge of managing the large number of conditions that must be considered in the analysis. The realistic approach of the ARITA method provides an analysis framework that is well suited for the analysis of complex events such as the uncontrolled bank withdrawal at power.

Historically, uncontrolled bank withdrawal has been highly ranked among the most limiting anticipated operational occurrences. The multitude of initial states, control bank configurations, and the potential for control rod movement create a very large initial condition & outcome space with many degrees of freedom.

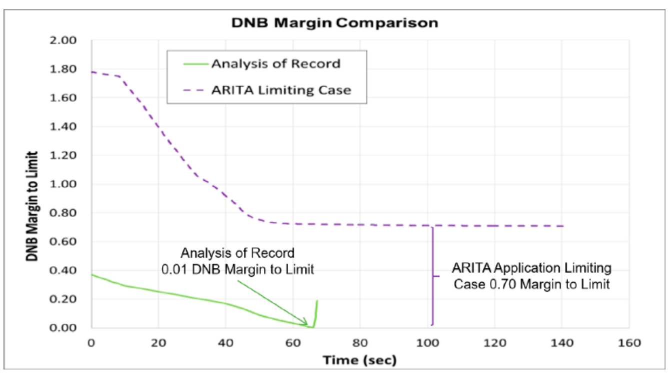
The event can affect the core in many ways: Long, slow transients can challenge DNB limits, part power cases with deep rod insertion may challenge FCM limits, while large changes in power may challenge TCS limits.

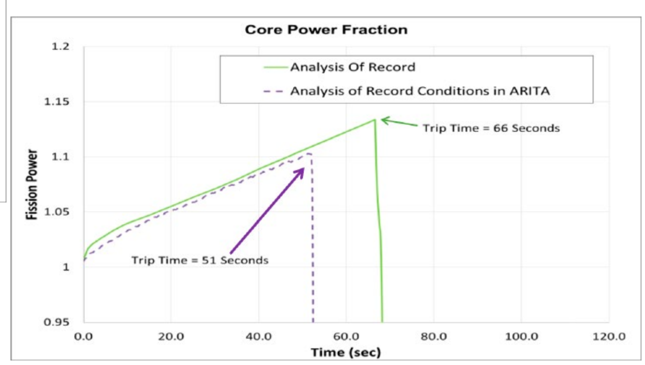
ARITA provides a way to perform comprehensive analyses without assumptions on limiting cases and overly bounding conditions as required by legacy methods.

The realistic approach of the ARITA method also provides insight in the transient evolution of events that has been so far hidden by layers of simplifications and conservatisms in legacy methods.

Value

Framatome's coupled non-LOCA method, ARITA, can provide a substantial margin gain in comparison to overly conservative legacy methods to all non-LOCA events.



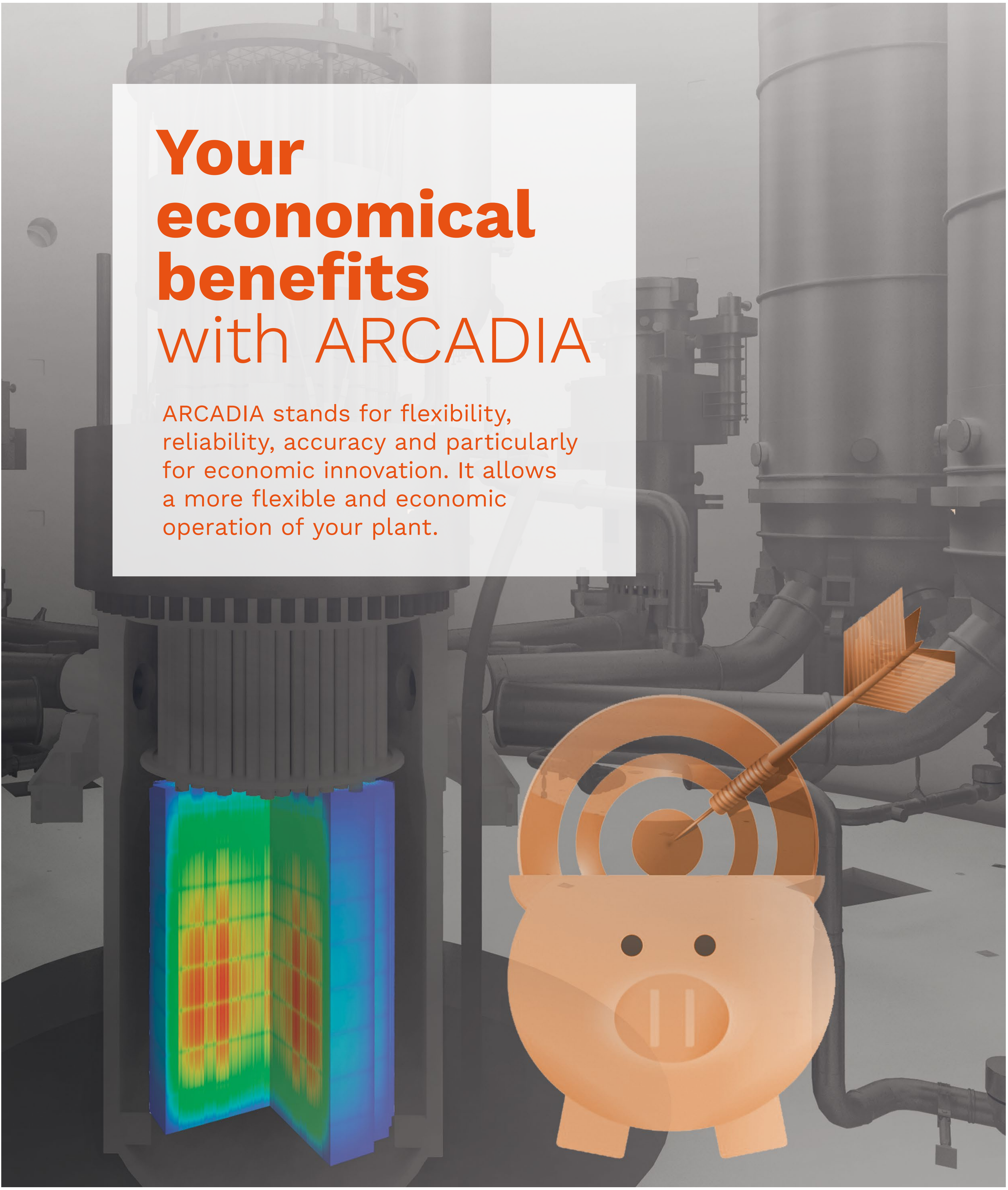


Example of reactivity insertion accident (RIA) applying the ARITA method.

- Proactively address emergent regulatory criteria, provide responses to NRC feedback and due diligence with respect to regulatory certainty.
- Improve understanding of plant behavior to remove obstacles to significant economic performance improvement initiatives.
- Provide industry leading safety analysis margins which can be used in many areas: operational margins, operating flexibility, enhance cycle economics, bound cyclic variation.

Your economical benefits with ARCADIA

ARCADIA stands for flexibility, reliability, accuracy and particularly for economic innovation. It allows a more flexible and economic operation of your plant.



1. Your challenge

Preserving and increasing the design space of your plant

The design space represents a comprehensive set of possible design options and operational modes for your plant. Its boundaries are defined by various requirements and constraints (legal requirements, technical requirements such as codes & methods limitations, plant specific initiatives, etc.) which restrict the range and flexibility of operation for your plant.

Increasing the design space corresponds to creating more freedom for nuclear design, margin release and operational modes (e.g. cycle length variation, enrichment or burnup increase, release of margins hidden in inherited legacy methods).

Shifting the boundaries of the design space enables in general more economic and flexible operation. The design space is defined by:

Regular requirements
Restrictions set by regulator based on the present licensing landscape can create severe limitations. Emerging rules (e.g., NRC LOCA and RIA criteria) could even shrink the design space.

Technical limitations (code & methods limitations)
Are the technical framework (e.g., computational and modeling) to operate a reactor safely.

Plant specific limitations / constraints
Each plant has a unique configuration (hardware and applicable methods), often accumulated during decades of operation. This heritage can bring constraints to flexibility and more economical operation if not revised regularly.

And many more

Reliability and flexibility during operation
Requirements of the grid and electricity demand are getting more and more challenging: e.g., due to coexistence with renewables.

Optimal utilization of the fuel
Increasing economic pressure due to competition with alternative energy sources (renewables and cheap oil / gas) or high tax load creates an unfavorable environment.

Safe reactor operation
Safe reactor operation is our overall goal. Nevertheless, today's modeling capabilities reveal over-conservative legacy assumptions and provisions which can be today released.

Each plant has its own unique positioning. The distance from the border of the current position to the limits of the design space is the margin for that parameter. Fuel and core designs that fit within the design space are then acceptable.

The margin and flexibility for fuel assembly and core design is defined by the evaluation models and the associated methods used.

However, the design space is at risk of shrinking due to emerging advanced safety criteria, e.g. for LOCA or RIA or new economical requirements, e.g. flexible operation.

Your challenge as a utility is to secure and enlarge the design space!

2. The solution for you

ARCADIA – advanced code system & methods.

The application of Framatome's ARCADIA advanced codes and methods can help you to favorably change or extend the design space of your plant. The enhanced modeling capabilities of ARCADIA support the preservation and the extension of the design space, through the gain of further margins by breakthrough physical models and coupled core physics evaluations, both for steady states and transients,

ARCADIA's advanced codes and methods unlock margins and positively act on a broad set of parameters, such as:

Fuel assembly placement
e.g. increasing average discharge burnup.

Spent fuel pool
e.g. optimize your spent fuel pool for coolant, discharge etc.

BOC boron
e.g. best boron prediction speeds up start up and minimizes material consumption.

Enrichment 4,95%
e.g. higher enrichments like 6 or 7 wt% are now reachable.

Radiological release
Improved modelling capabilitiesfor severe accidents improves prediction for radiological release.

FCM / TCS
e.g. highest prediction accuracy opens more margins.

Max Gd wt%
e.g. precise calculations allow optimally adjusted gadolinium content.

Max. number of Gd pins
e.g. higher flexibility of Gd rod placement.

Placement of Gd pins
e.g. higher flexibility for cycle design.

Total peaking
e.g. most accurate prediction unlocks margins to safety limits due to reduced uncertainty.

Radial peaking
e.g. higher flexibility of to position limiting Fuel assemblies for better fuel utilization.

Moderator temperature coeffiecient (MTC)
Precise knowledge increases flexibility of the NPP.

Axial power shapes
e.g. reduction of conservatism due more realistic prediction.

Burnup limits
e.g. Arcadia allows highest burn up limits.

... and many more

3. Your profits

How can you profit from expanding your design space - and how can you master the challenge?

Operational margin, flexibility and economical operation depend on the evaluation models and the associated methods (i.e. the accuracy and capability of the applied codes and methods).

Adopting advanced codes and methods overcomes legacy boundaries of the design space by providing most realistic description of the core physics and provides the needed flexibility to minimize impact of future changes.

The ARCADIA advanced code system & methods offer you multiple options and solutions to support your customized and demanding plant operation, such as:

- **Reload batch size reduction**
  Use of the fuel design space might reduce the number of reloaded fuel-assemblies due to better fuel utilisation.
- **Margin for operational flexibility**
  Higher operational flexibility allows faster adjustements to the grid requirements.
- **Operating space expansion**
  Please see p. 33.
- **Cycle length extension**
  A longer cycle length improves the overall availability of the nuclear power plant.
- **Inlet temperature increase**
  The increase of the coolent inlet temperature might increase the efficiency of the whole nuclear powerplant.
- **Margin for power uprate**
  Better codes and methods might improve margins for power uprates.
- **Solutions for hardware removal & reclassification**
  A better solution for hardware removal & reclassification leads to lower operating and maintenance costs.
- **Solutions for plant aging issues**
  Better solutions for aging issues, e.g. shielding fuel assemblies or low leakage fuel management, can support lifetime extension.

ARCADIA extends the design space and opens new economical benefits for utilities.

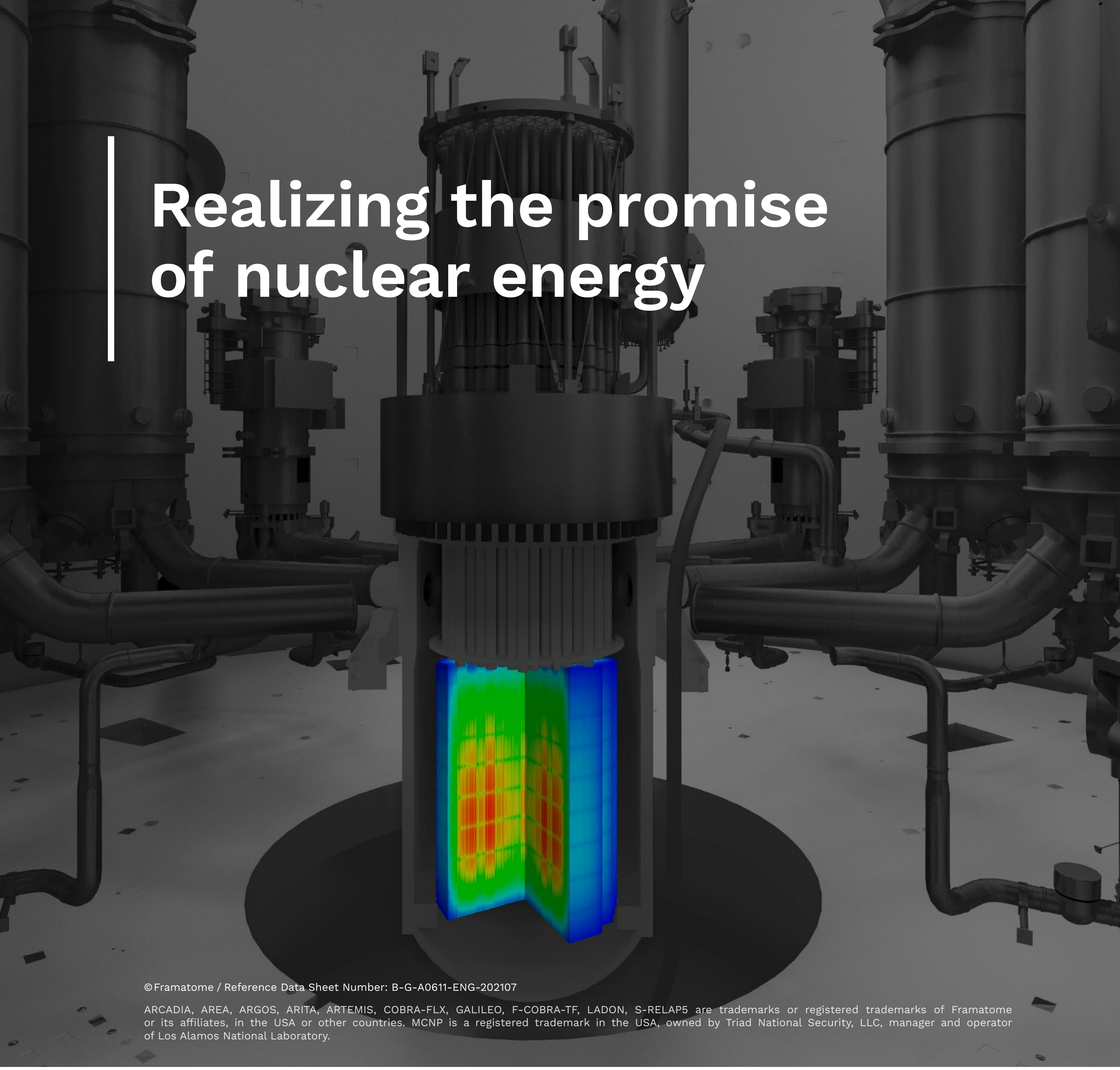
Example

Framatome's ARCADIA advanced code system & methods have shown a 50 DNB point margin in some cases – what does that mean?

As a rule of thumb, 8 to 12 DNB point margin is roughly equivalent to 4 bundle savings. Would this mean that 50 DNB points are equivalent to 16-24 bundle savings?

It is not possible to save that many assemblies before encountering other limits such as enrichment, fuel pin burnup, alternate source term.

Some U.S. PWR plants can reduce the batch size by 4 to 8 assemblies.



Realizing the promise of nuclear energy

©Framatome / Reference Data Sheet Number: B-G-A0611-ENG-202107

ARCADIA, AREA, ARGOS, ARITA, ARTEMIS, COBRA-FLX, GALILEO, F-COBRA-TF, LADON, S-RELAP5 are trademarks or registered trademarks of Framatome or its affiliates, in the USA or other countries. MCNP is a registered trademark in the USA, owned by Triad National Security, LLC, manager and operator of Los Alamos National Laboratory.

About Framatome
Framatome is an international leader in nuclear energy recognized for its innovative solutions and value added technologies for the global nuclear fleet. With worldwide expertise and a proven track record for reliability and performance, the company designs, services and installs components, fuel, and instrumentation and control systems for nuclear power plants. Its more than 14,000 employees work every day to help Framatome's customers supply ever cleaner, safer and more economical low-carbon energy.

Visit us at: www.framatome.com
Follow us on Twitter and Linkedin: @Framatome_

Framatome is owned by the EDF Group (75.5%), Mitsubishi Heavy Industries (MHI – 19.5%) and Assystem (5%).

For more info please contact: **sales-fuel@framatome.com**

ARCADIA
is ready for use

Your performance
is **our** everyday **commitment**