Evolutionary Design Studies of PHWR Fuel Rods

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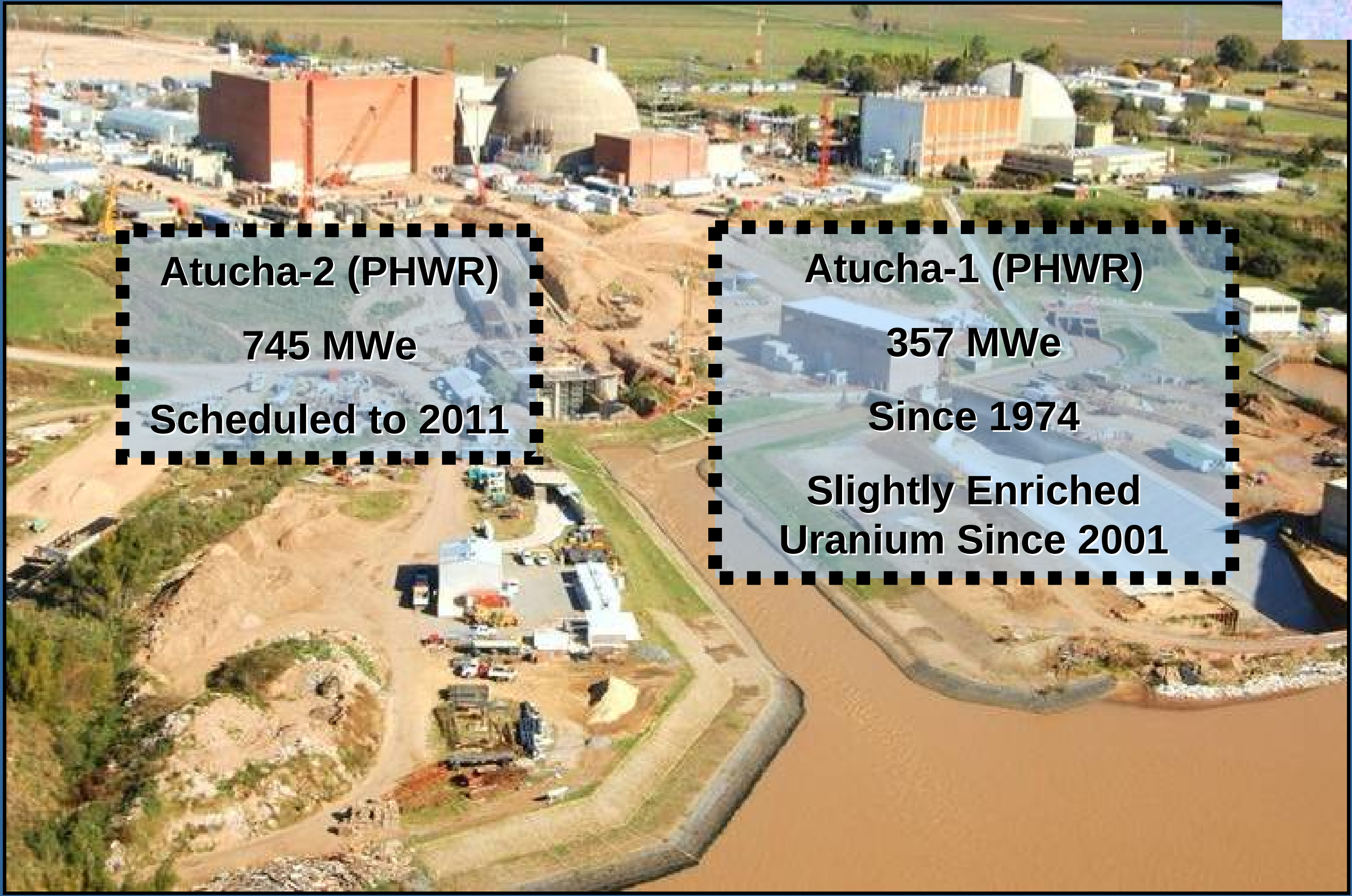
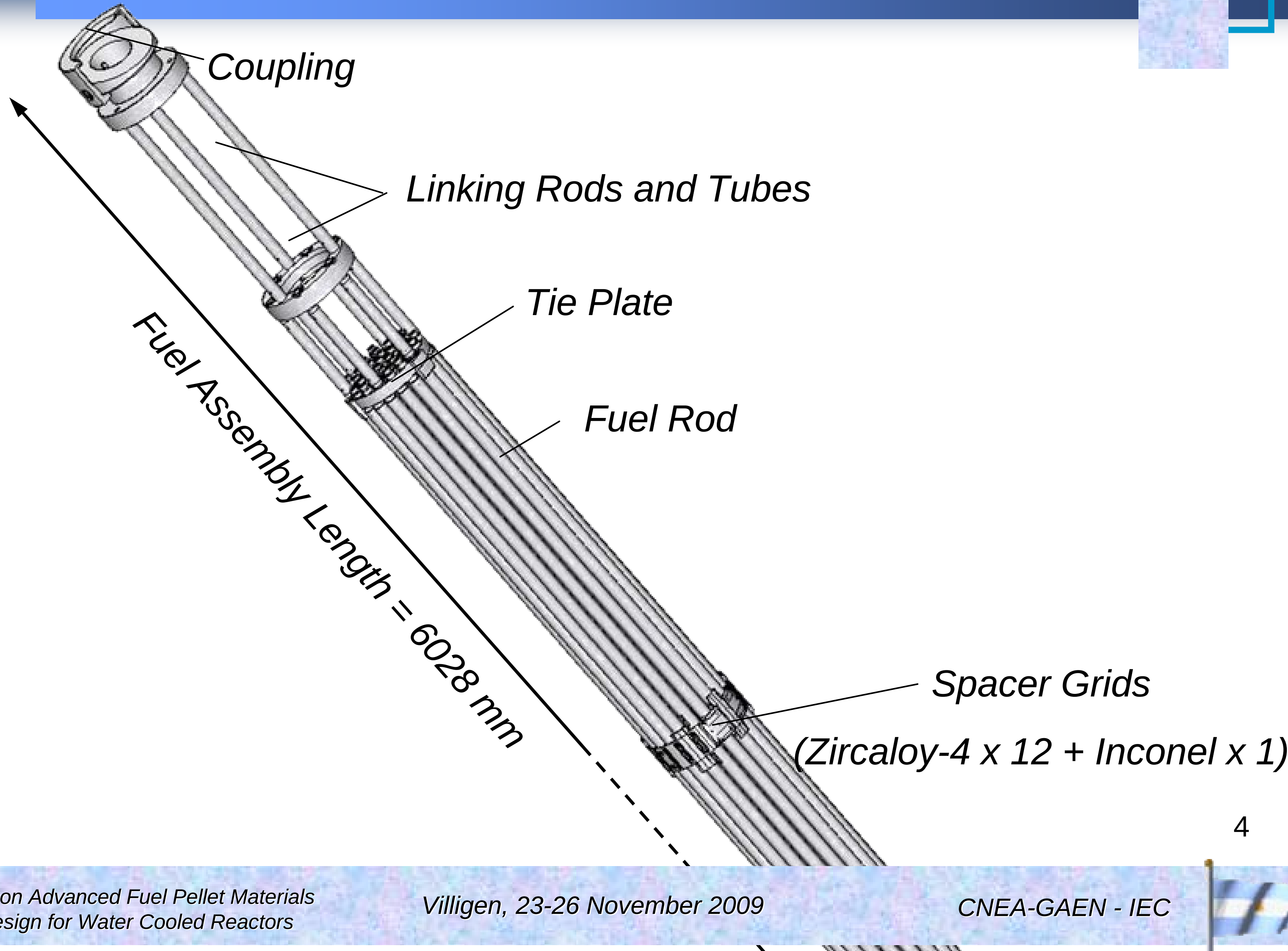
Atucha-2 Nuclear Power Plant



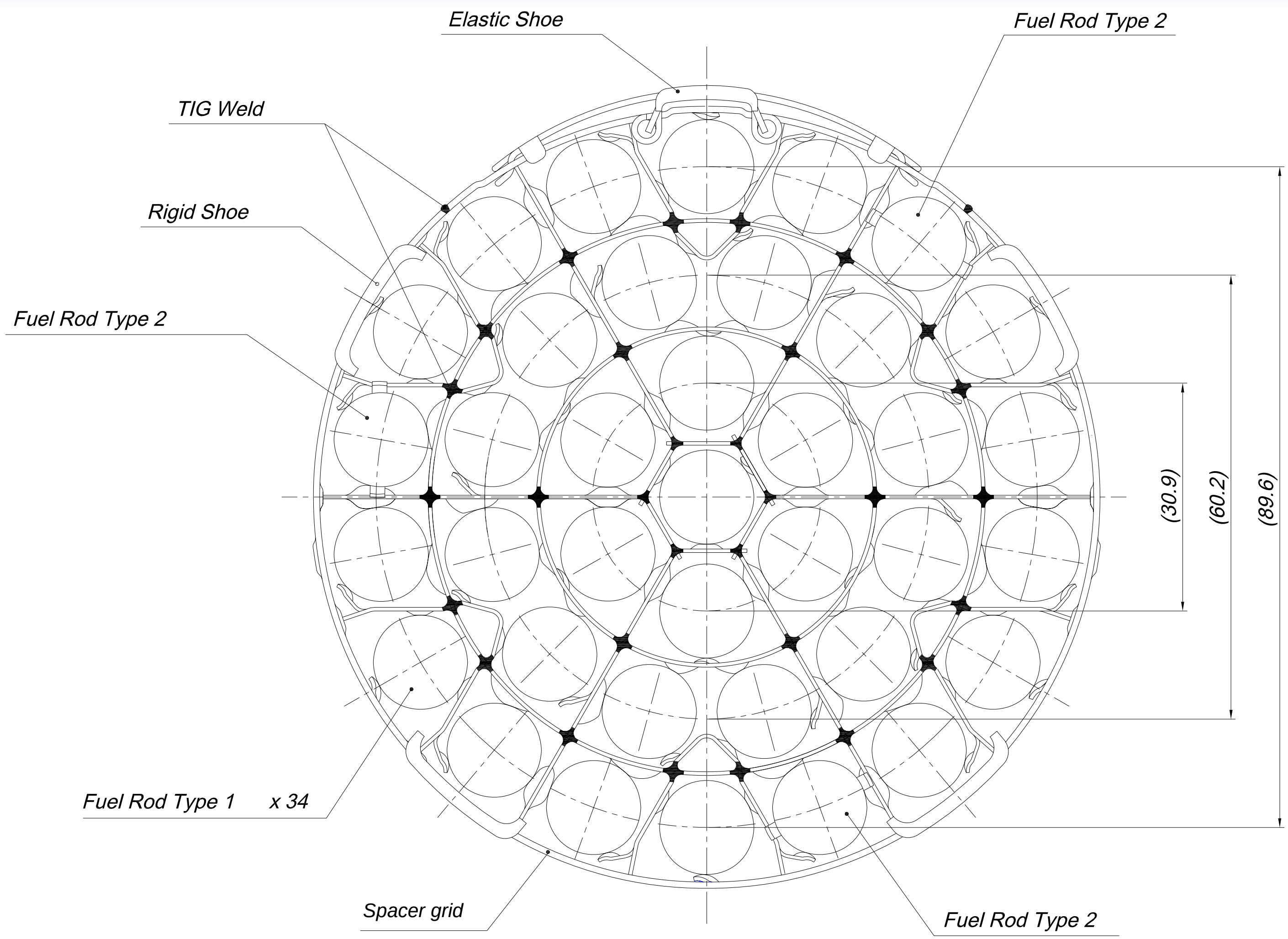
Outline

1. Fuel assembly & fuel rod description
2. Design study objectives
3. Calculation methodology
4. Results and conclusions

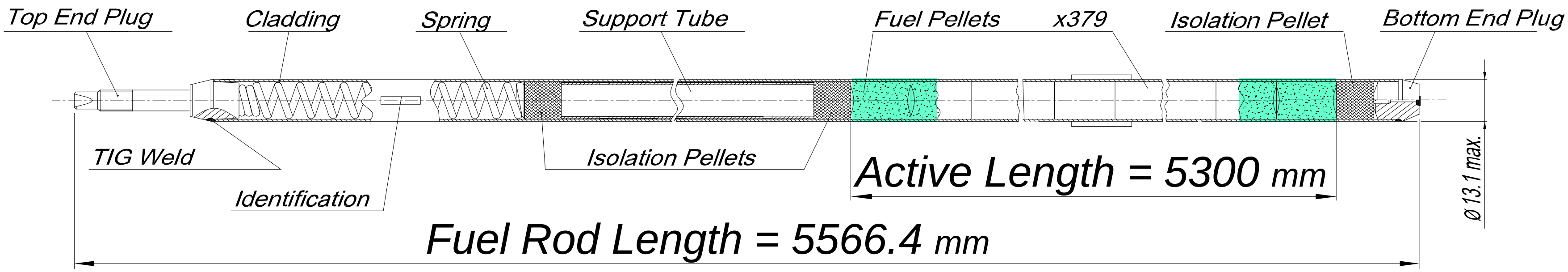
Atucha-2 Fuel Assembly



Atucha-2 Fuel Bundle Cross-Section



Atucha-2 Fuel Rod



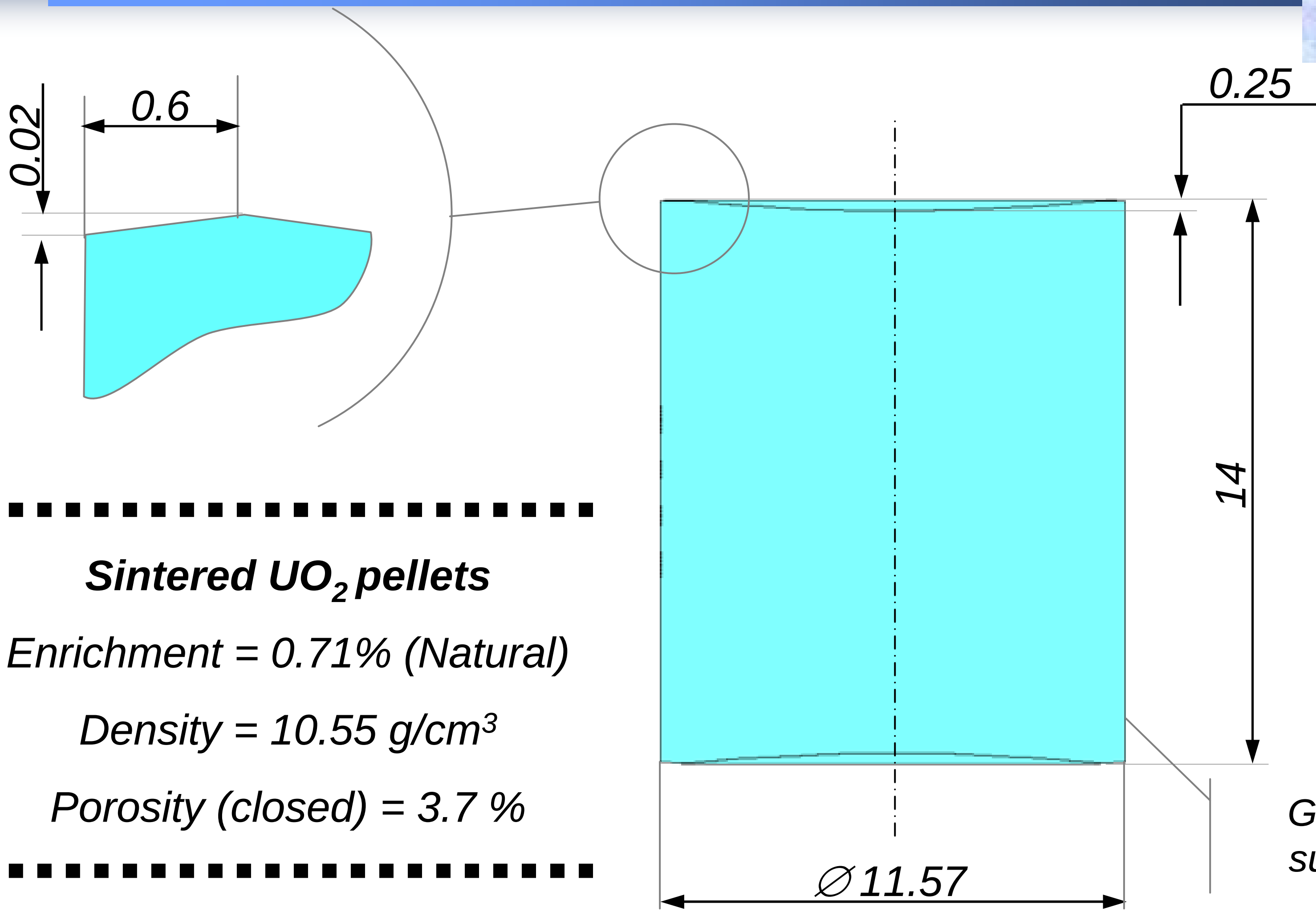
Zircaloy-4 cladding

Inner diameter = 11.81 mm

Thickness = 0.55 mm

Initial Pressurization = 22.5 bar

Atucha-2 Fuel Pellet



Sintered UO_2 pellets

Enrichment = 0.71% (Natural)

Density = 10.55 g/cm³

Porosity (closed) = 3.7 %

Design Parameters for Atucha's Fuel Rod

	Atucha-1	Atucha-1 (MASU)	Atucha-2
Pellet length (mm)	12	13	14
Pellet diameter (mm)	10.62	10.74	11.57
Pellet length/diameter ratio	1.13	1.21	1.21
Pellet density (g/cm^3)	10.55	10.60	10.55
Dishing depth (mm)	0.30	0.23	0.25
Cladding outer diameter (mm)	11.90	11.92	12.90
Cladding inner diameter (mm)	10.80	10.92	11.81
Minimum clad thickness (mm)	0.505	0.460	0.495
Pellet-cladding gap (mm)	0.18	0.18	0.24

Fuel Enginnering Department

Atucha-2 Fuel Design (KWU/Siemens-CNEA)

First Core
(Under Construction)

- Fuel Performance evaluation
- Reactor Commissioning
- Reactor Operation

Atucha-1 Experience

Atucha-2 Design Studies

Fuel Redesign

Future Atucha-2 Fuel (CNEA)

Atucha-1 & 2 Experience

- Neutronic & Thermohydraulic Studies
- Thermo-Mechanical Analysis
- Economic Analysis

Advanced Atucha-2 Fuel (CNEA)

Atucha-2 Fuel Assembly

Fuel Rod Design Studies

Studied fuel rod parameters:

1. **Fuel pellet density**
2. **Fuel pellet diameter**
3. **Fuel pellet length**
4. **Initial pressurization of the fuel rod**

Motivations:

- **Evaluate operational constraints of the current fuel rod design**
- **Generate information to maintain the suitability and safety of future modifications**
- **Support the possible trends on design modifications**
  - ✓**Increase safety margins**
  - ✓**Uranium mass increase**
    - •Increase the residence time
    - •Reduce fuel consumption

Background:

MASU Program for Atucha-1: (Similar program applied to Embalse, a CANDU-6)

- Change in pellet length, dishing depth, pellet density, pellet diameter, cladding diameter and cladding thickness
- Nominal uranium mass increase of 6.7%

ULE Program for Atucha-1:

- Use of slightly enriched uranium (0.85%)
- Reduction on fuel consumption by almost duplicating resident time & burnup

Design and Safety Limits

A fuel rod performance code (Siemens/KWU) is used to predict the fuel rod behavior during irradiation

Calculations are perform to determine if any fuel-related design margins are exceeded in normal operational conditions.

The most important for this kind of reactors are:

1. Maximum fuel temperature: < UO_2 melting ~ 2800º C
2. Fuel-rod internal pressure: < coolant pressure = 115 bar
3. Strain of the clad due to pellet-cladding interaction: < 1%

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4. Maintain the structural design of the fuel assembly. Like cladding outer diameter or number of fuel rods

Fuel Rod Code (Siemens/KWU)

- **Input data:** Cladding geometry, pellet geometry, material properties, fuel characteristics, rod plenum volume, pellet stack length, parameters of the models, operation conditions.

- **Geometrical subdivision of fuel rod:** Axial segments of equal length.

- **Geometrical subdivision of fuel pellet:** Concentrical annular element of equal mass.

- **Time subdivision of power and fast neutron flux:** Variable time step lengths for a best representation of changes in fuel condition.

- **Conservatism:** Proper selection of input data (tolerances, model parameters, operative conditions) to obtain conservative results.

Simulation of Rod Behavior

Normal Operating Conditions

- Primary system pressure (Coolant) = 115 bar
- Coolant channel inlet temperature = 277.8º C
- Mean coolant channel outlet temperature = 314.6º C

Power History

- Ramp on fresh fuel to the maximum LHGR **(Hot Channel)**
- Simulated power histories (most demanding) with extended burnup **(End of Life)**

Fuel Rod Model

- Selection of geometrical tolerances
- Selection of model parameters

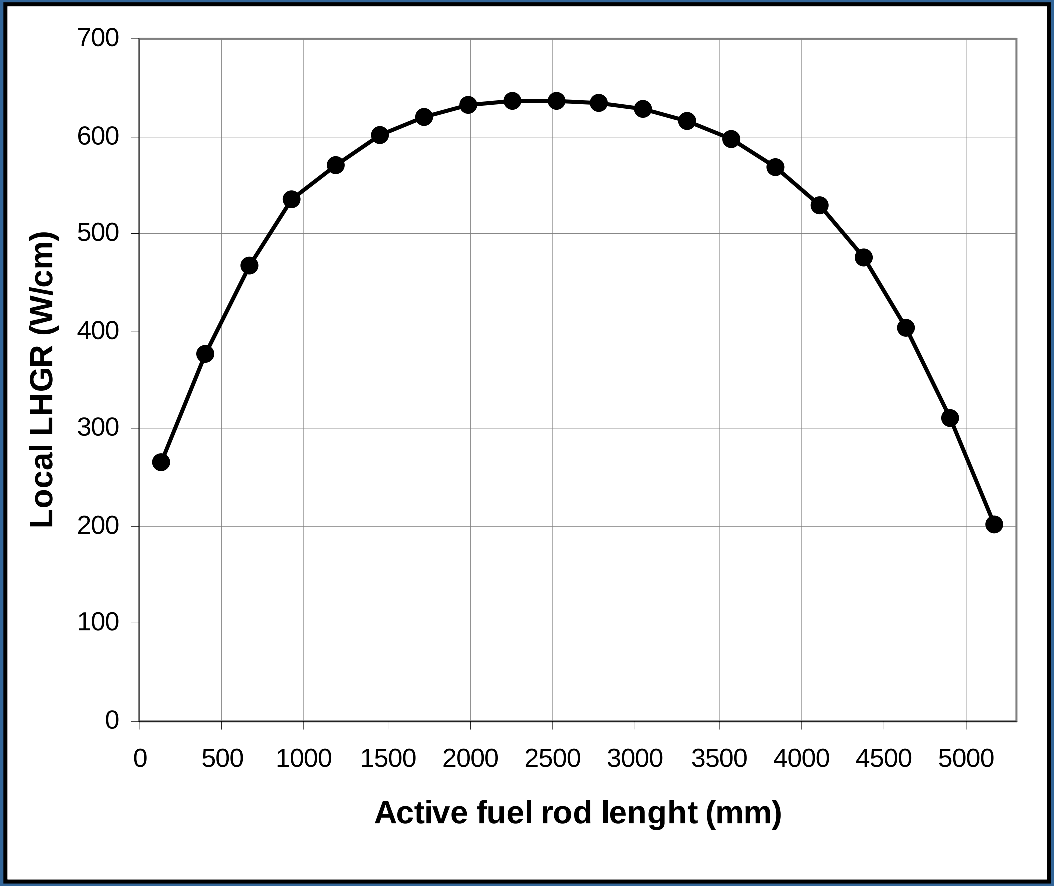
Time Dependent Fuel Rod Thermo-Mechanical Behavior

Hot Channel Calculations

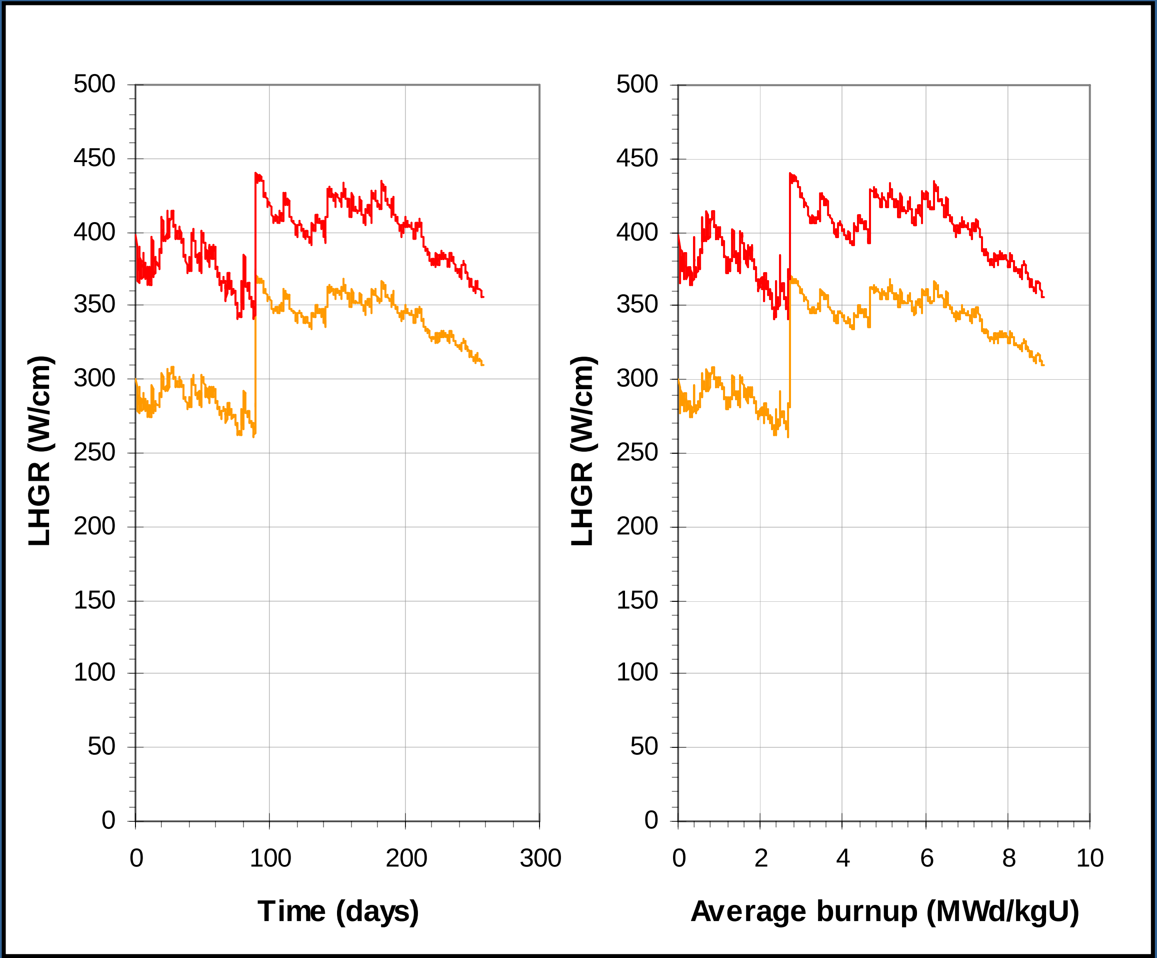
Design Maximum LHGR
640 W/cm

Maximum LHGR
468.7 W/cm

Average core LHGR
237.7 W/cm



End of Life Calculations



Selected power history, most demanding in:

- **Average LHRG**
- **Dwell time**
- **Burnup**

Extended 160 days to reach 15 MWd/kgU.

1. Study of Fuel Pellet Density

- Current fuel Pellet density 10.55 g/cm^3
- Possible fuel pellet density 10.60 g/cm^3 (Used in Atucha-1)
- Current fabrication tolerances

Hot Channel Calculations

- Cladding strain due to pellet-cladding interaction
- Maximum pellet temperature & fuel rod pressure

End of Life Calculations

- Cladding strain
- End of life fuel rod pressure

No significant impact up to the studied burnup

2. Study of Fuel Pellet Diameter

- Pellet diameter from 11.56 mm to 11.73 mm
- Pellet cladding gap from 0.24 mm to 0.08 mm
- Current fabrication tolerances

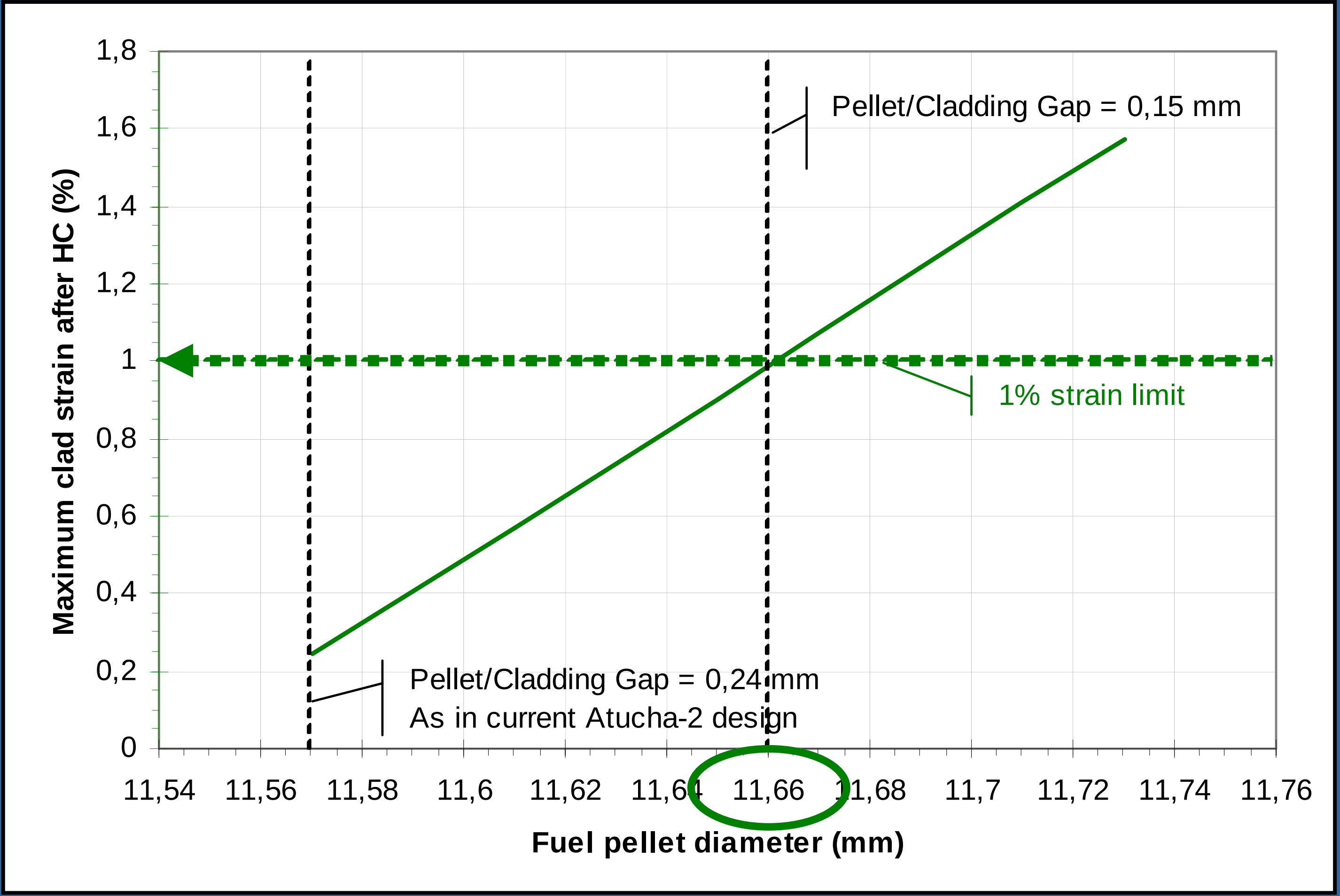
Hot Channel Calculations

- Cladding strain due to pellet-cladding interaction
- Power to reach hard contact
- Maximum pellet temperature & rod pressure

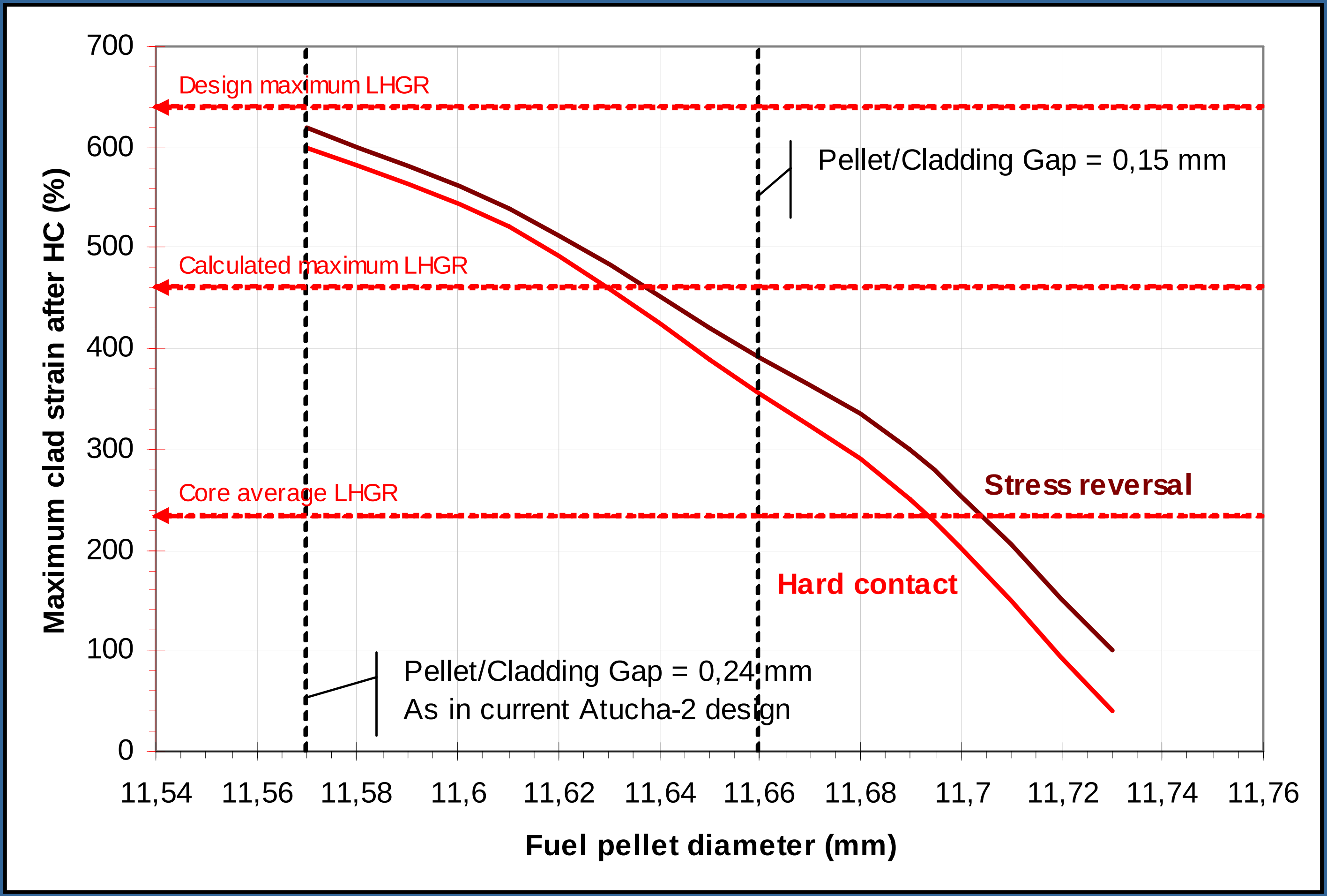
End of Life Calculations

- Cladding strain
- End of life pressure

Study of Fuel Pellet Diameter



Study of Fuel Pellet Diameter



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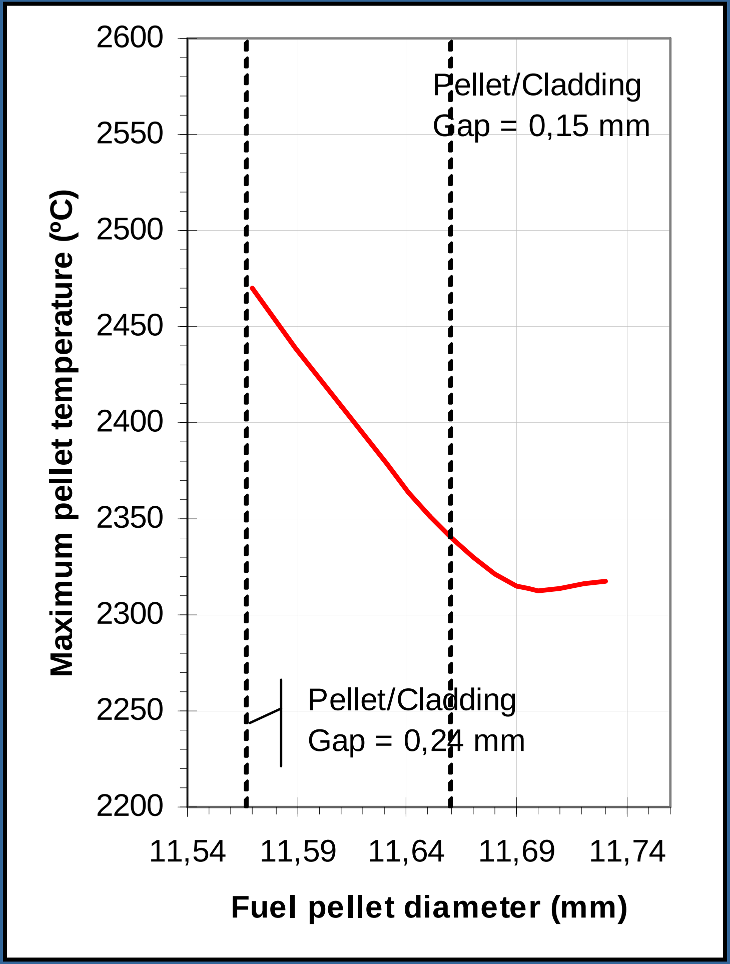
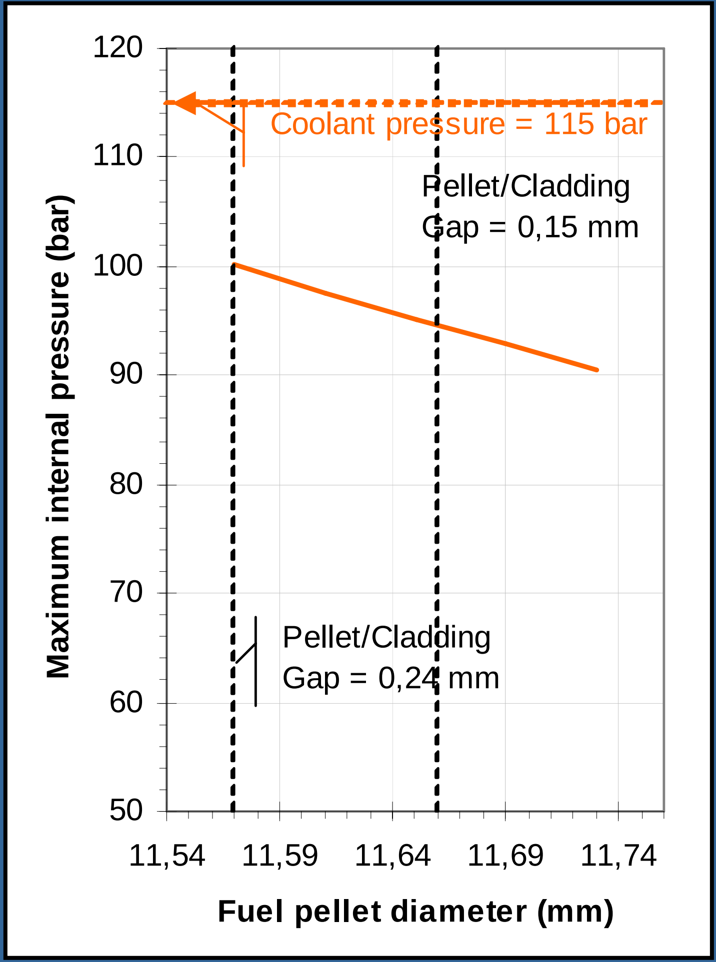
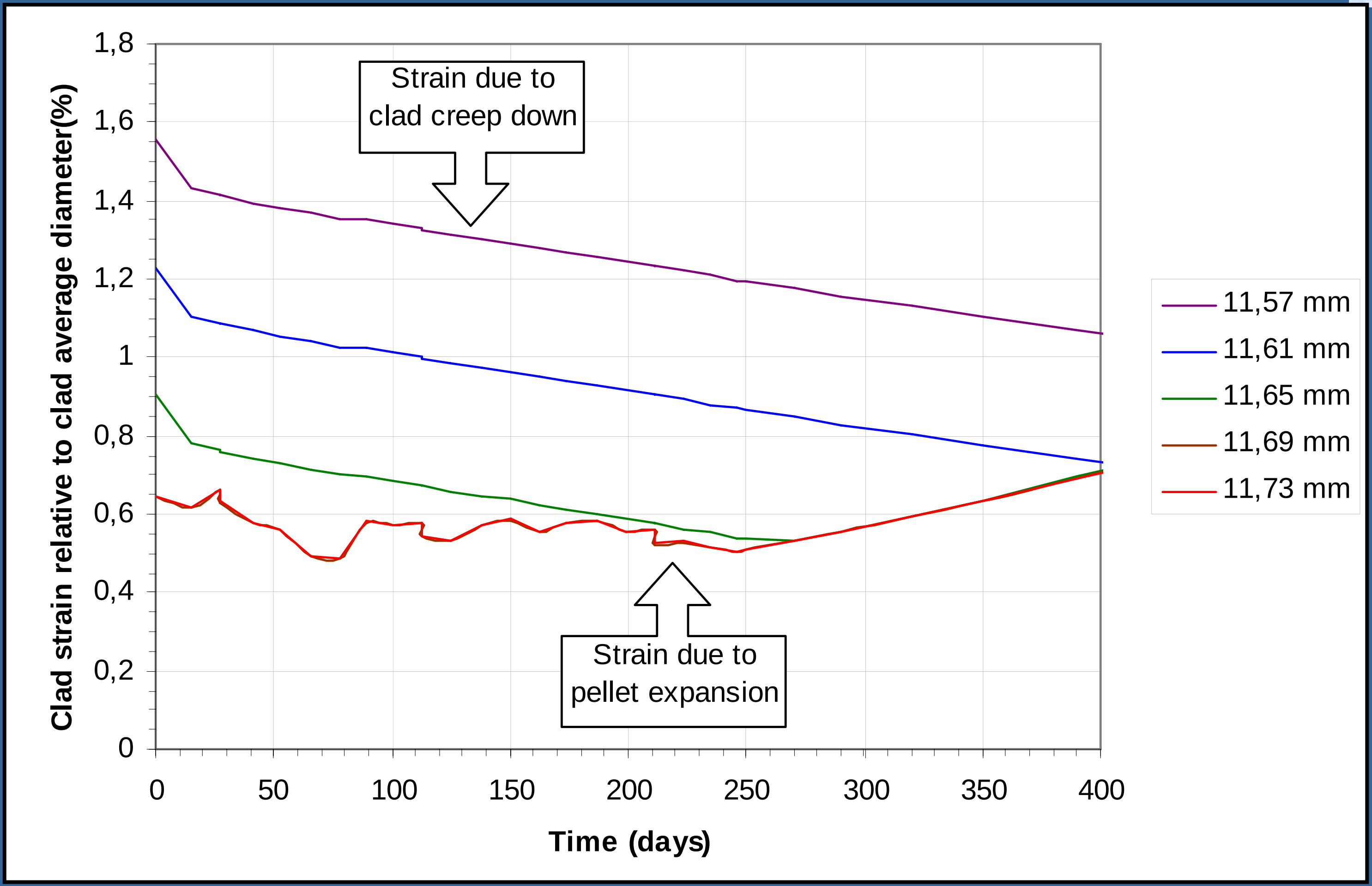




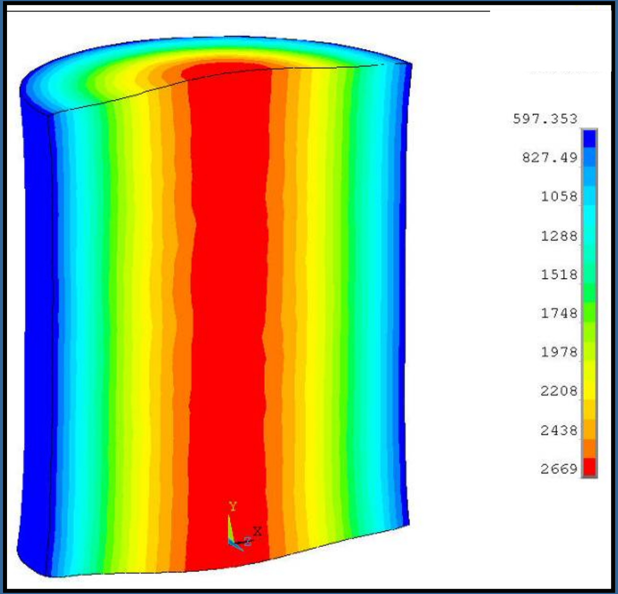
Study of Fuel Pellet Diameter



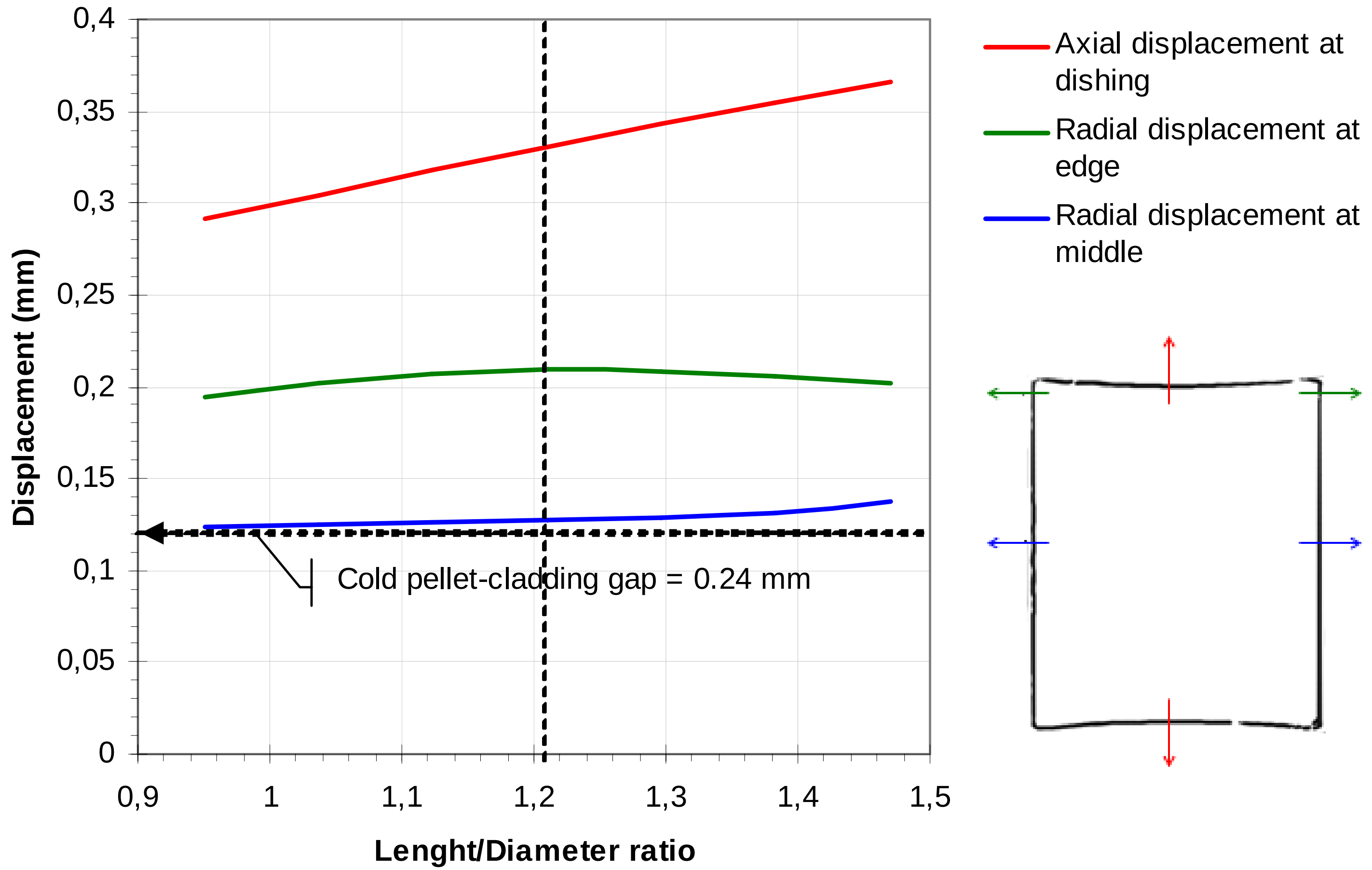
3. Study of Fuel Pellet Length

- Length/diameter ratio from 0.95 to 1.40
- Current fabrication tolerances

- Use fuel radial temperature profile (fuel rod output) at maximum power (hot channel) to calculate pellet thermal expansion by a 3D finite element model of the pellet



Study of Fuel Pellet Length



4. Study of Rod Initial Pressurization

- Rod initial pressurization from 10 bar to 35 bar
- Current fabrication tolerances

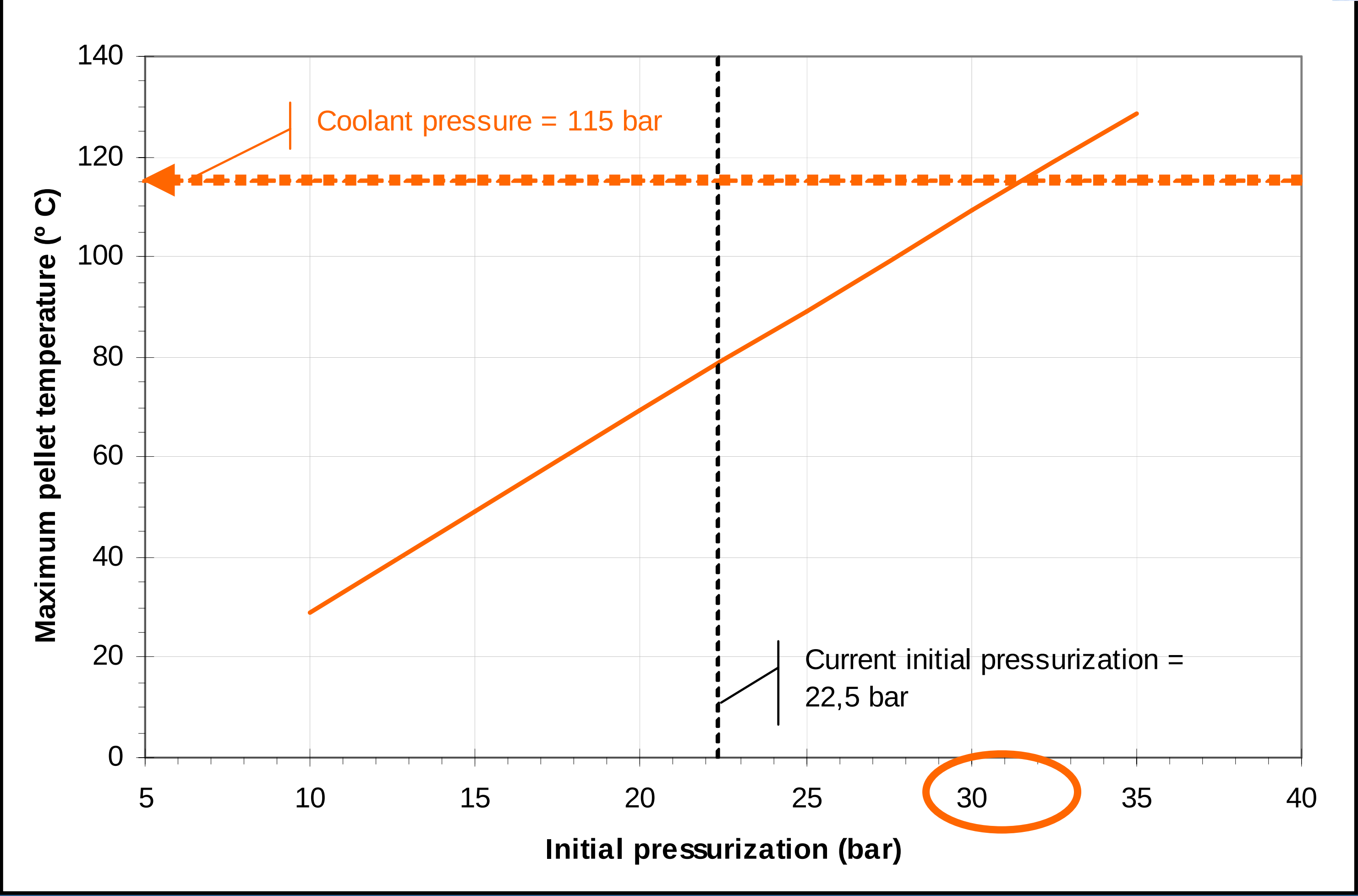
Hot Channel Calculations

- Maximum temperature & pressure

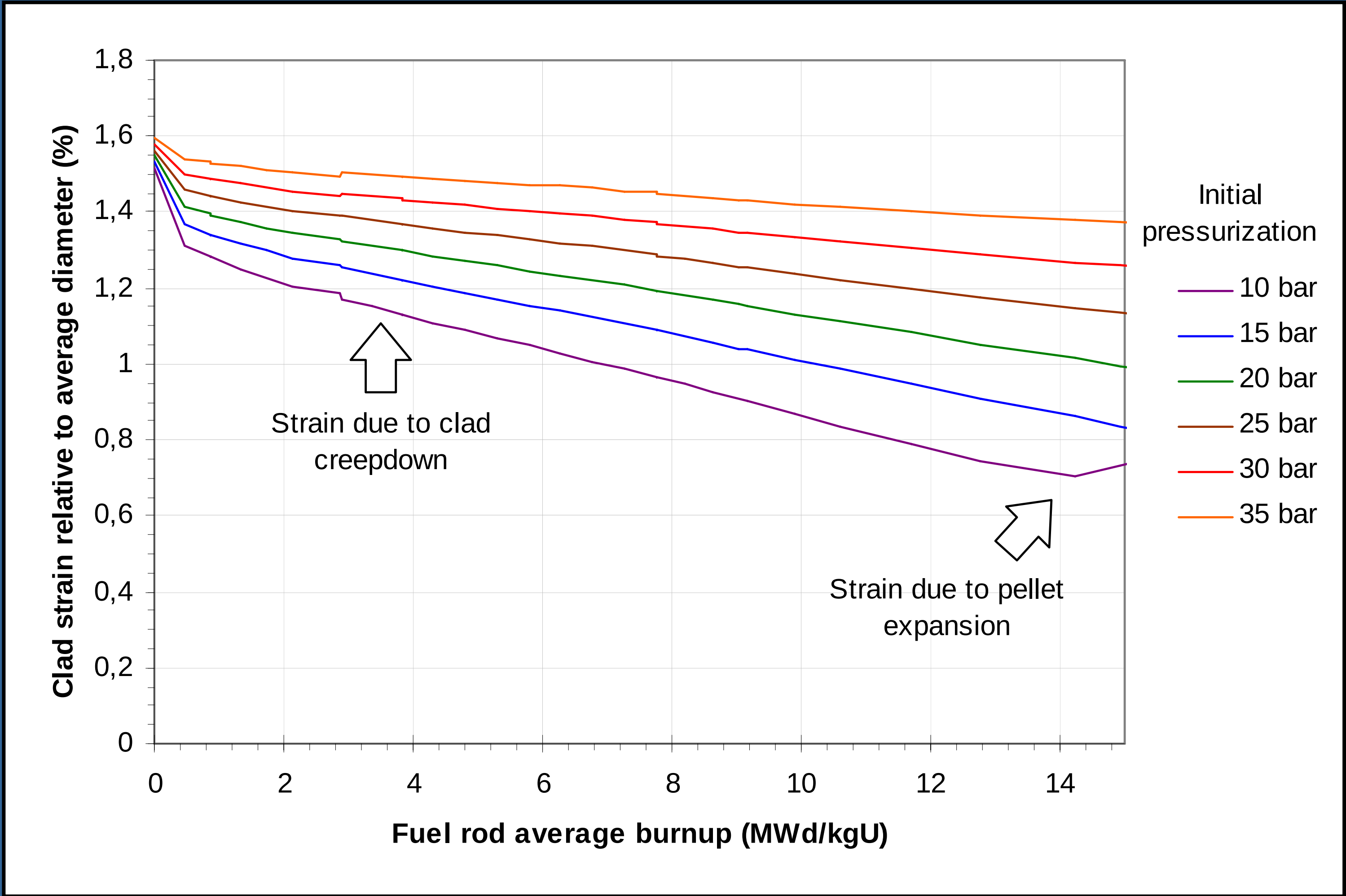
End of Life Calculations

- Cladding strain
- End of life pressure

Study of Rod Initial Pressurization



Study of Rod Initial Pressurization



Summary

- **Fuel rod performance for a nominal pellet density of 10.60 g/cm^3 for hot channel and end of life**
- **Minimum pellet-cladding gap to reach the strain limit at hot channel (0.15 mm)**
  Safety margins for a range of pellet-cladding gap size
- **Pellet thermal expansion characterized for a range of pellet length/diameter ratio**
- **Maximum initial pressurization to reach coolant pressure at hot channel (30 bar)**
  Safety margins for a range of initial pressurization

Conclusions

- Various margins for design improvement has been identified

- Important information for future development of Atucha-2 fuel was obtained

- Conservative models and operative conditions were used in the calculations

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- Next Steps
  - Calculation with other fuel rod codes to compare results
  - Studies on more design parameters

Atucha-2 Project

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Thank You for Your Attention!!!

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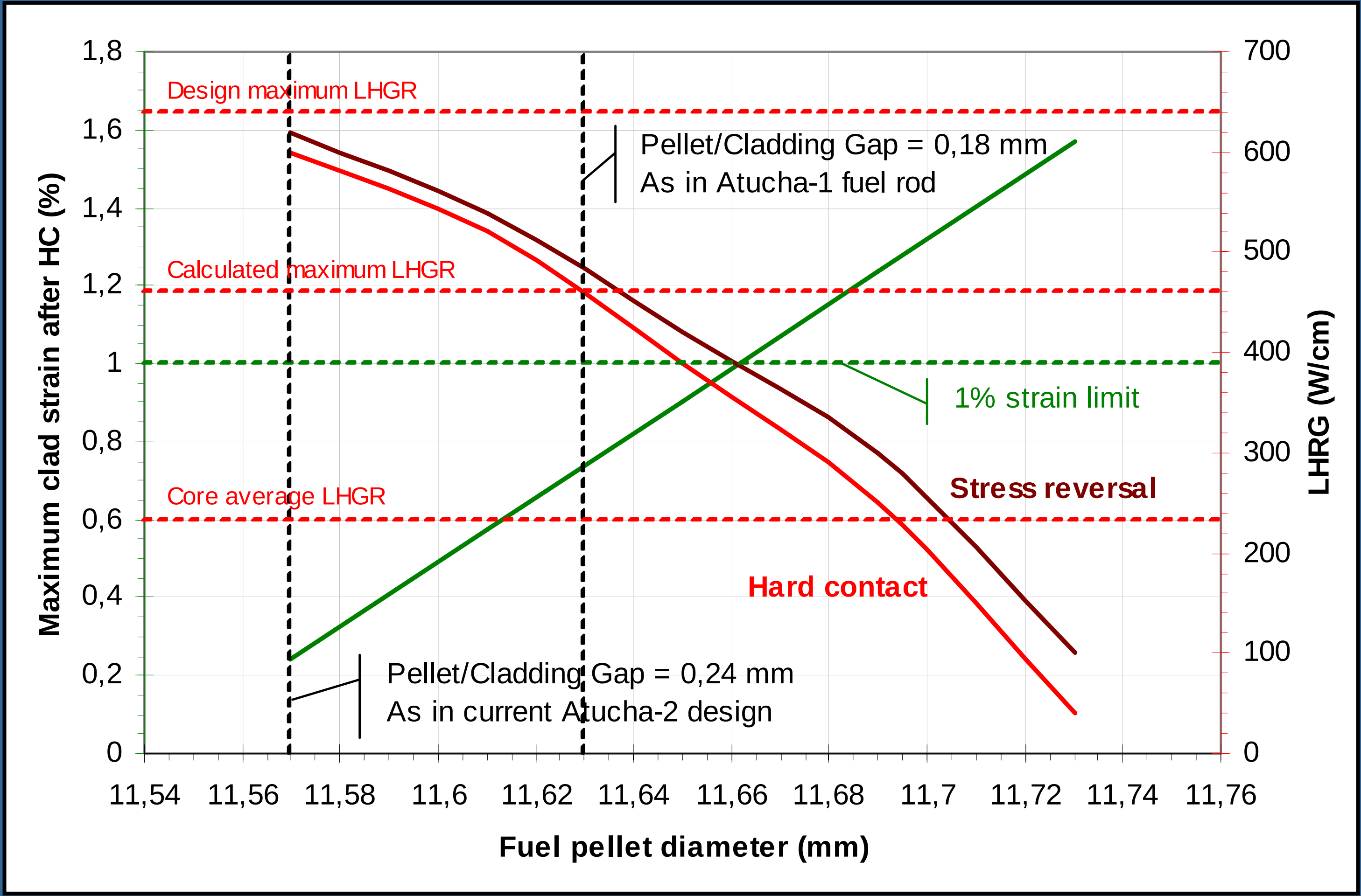
Study of Fuel Pellet Diameter



Fuel Rod Code (Siemens/KWU)

- Temperatures
- Thermal expansion and elastic deformation
- Thermal and irradiation creep
- Growth induced by irradiation
- Corrosion
- Absorption of hydrogen (deuterium)

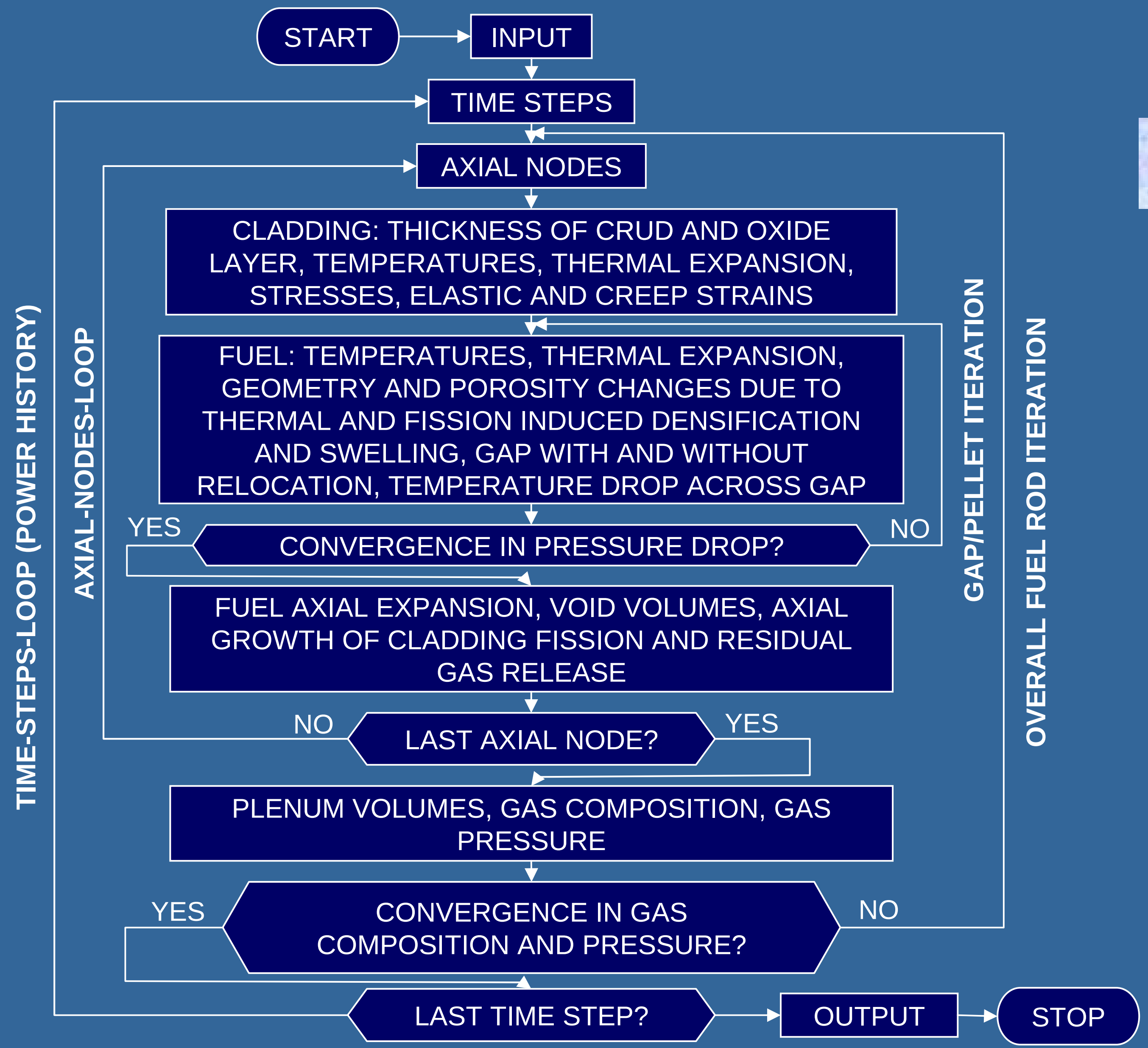
Cladding

- Temperatures
- Thermal expansion
- Cracking, radial and axial relocation
- Densification and irradiation swelling
- Restructuring
- Release of fission gas
- Release of residual gases
- Absorption of helium

Pellet

- Pressure
- Temperature and volume of the plenum
- Composition of the internal atmosphere

Rod


START
INPUT
TIME STEPS
AXIAL NODES
CLADDING: THICKNESS OF CRUD AND OXIDE LAYER, TEMPERATURES, THERMAL EXPANSION, STRESSES, ELASTIC AND CREEP STRAINS
FUEL: TEMPERATURES, THERMAL EXPANSION, GEOMETRY AND POROSITY CHANGES DUE TO THERMAL AND FISSION INDUCED DENSIFICATION AND SWELLING, GAP WITH AND WITHOUT RELOCATION, TEMPERATURE DROP ACROSS GAP
YES
CONVERGENCE IN PRESSURE DROP?
NO
FUEL AXIAL EXPANSION, VOID VOLUMES, AXIAL GROWTH OF CLADDING FISSION AND RESIDUAL GAS RELEASE
NO
LAST AXIAL NODE?
YES
PLENUM VOLUMES, GAS COMPOSITION, GAS PRESSURE
YES
CONVERGENCE IN GAS COMPOSITION AND PRESSURE?
NO
LAST TIME STEP?
OUTPUT
STOP
TIME-STEPS-LOOP (POWER HISTORY)
AXIAL-NODES-LOOP
GAP/PELLET ITERATION
OVERALL FUEL ROD ITERATION