

ANÁLISE DE DESEMPENHO DO COMBUSTÍVEL NUCLEAR

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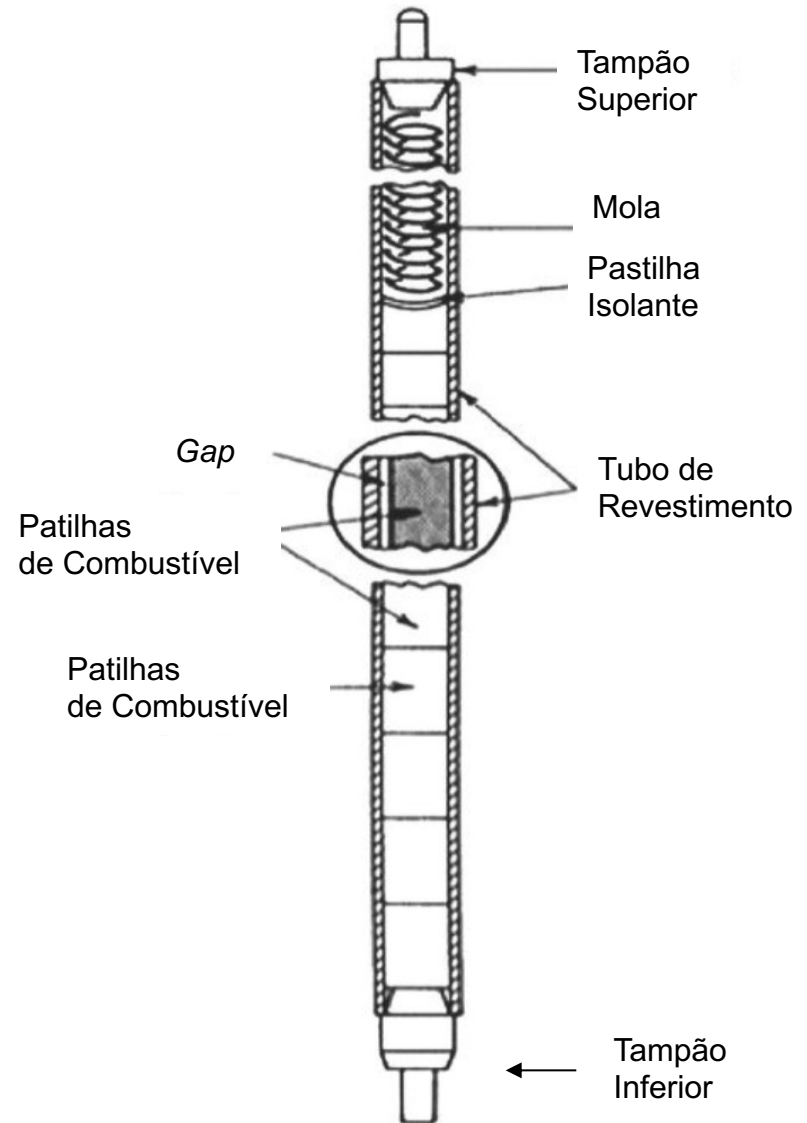
Novembro 2023

MÓDULO 6

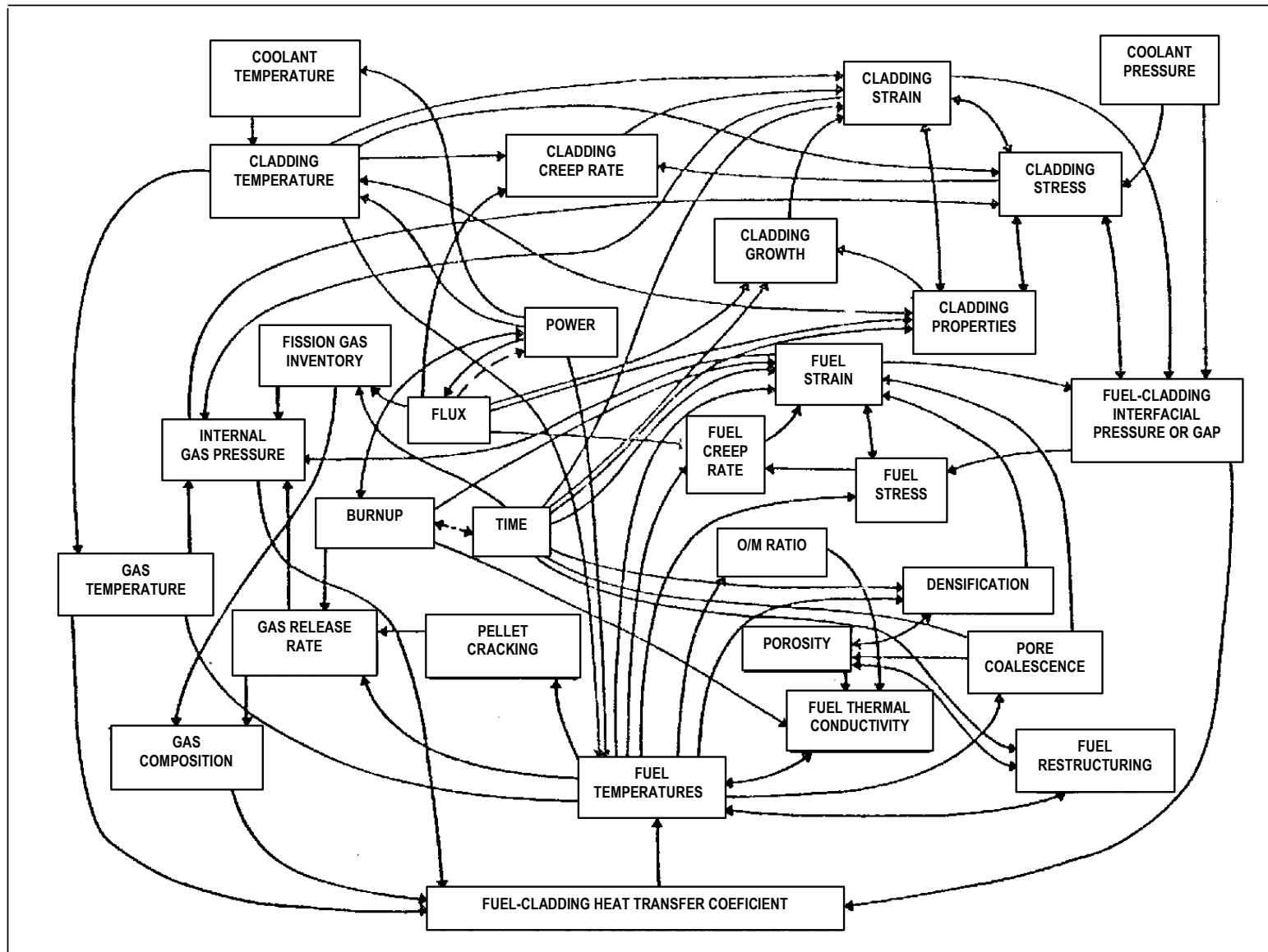
FERRAMENTAS COMPUTACIONAIS PARA ANÁLISE DE DESEMPENHO DE VARETAS DE COMBUSTÍVEL

MÓDULO 6

TRANSURANUS

VARETA DE COMBUSTÍVEL**COMPONENTES:**

- Tubo de Revestimento
- Tampões de Extremidades (Superior e Inferior)
- Pastilhas Isolantes (Al_2O_3)
- Pastilhas de Combustível (UO_2)
- Mola
- Gás de enchimento



TRANSURANUS

- ✓ Programa computacional para a análise do comportamento termo-mecânico de varetas de combustível em reatores nucleares
- ✓ Código programado em FORTRAN 95
- ✓ Ferramenta computacional desenvolvida no Instituto para Elementos Transurânicos (ITU)



- ✓ **Pode ser aplicado a diferentes condições: regime estacionário, transientes operacionais e acidentes**
- ✓ **A escala de tempo a ser estudada pode variar de milisegundos a anos**
- ✓ Pode ser aplicado na análise de varetas refabricadas

TRANSURANUS - Verificação

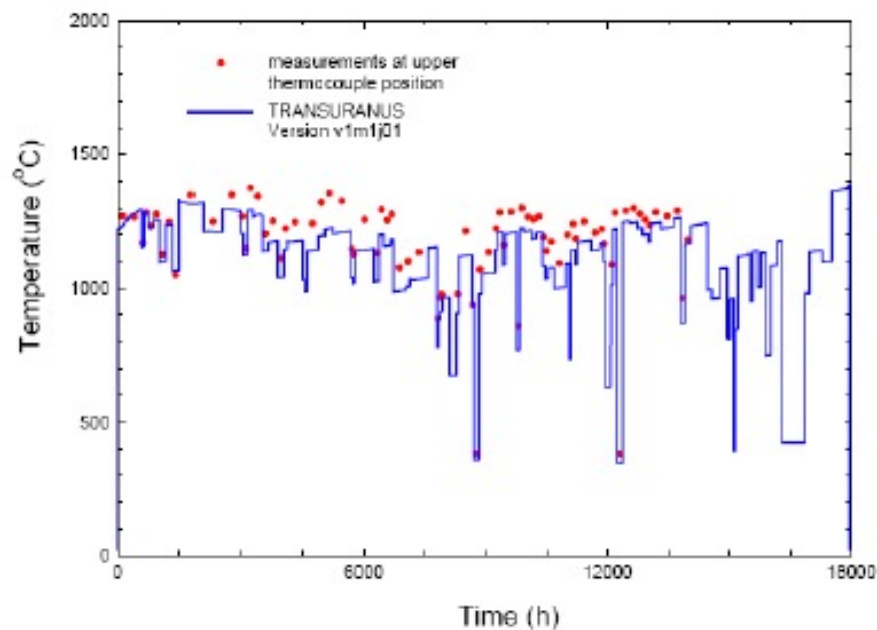
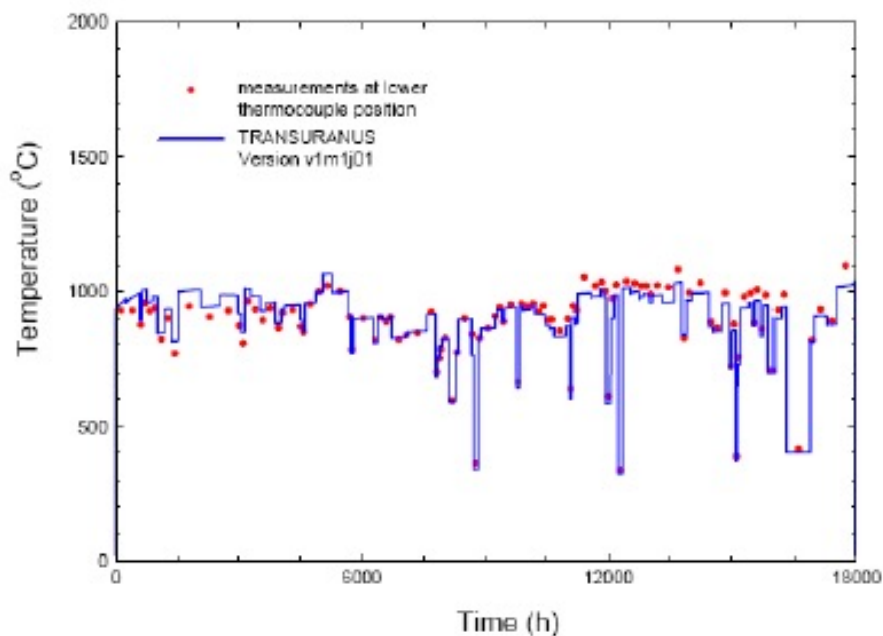
Etapas aplicadas no processo de verificação do código:

- ✓ Verificação por meio da comparação com cálculos analíticos
- ✓ Verificação extensiva de modelos
- ✓ Verificação por meio de comparações com diferentes códigos
- ✓ Verificação por meio de comparações com dados experimentais

TRANSURANUS - Verificação

Experimento de Irradiação (OECD-HRP):

- ✓ Comparação da temperatura central do combustível medida em experimento da OECD-HRP (IFA-432, vareta 30 com a temperatura calculada pelo código TRANSURANUS

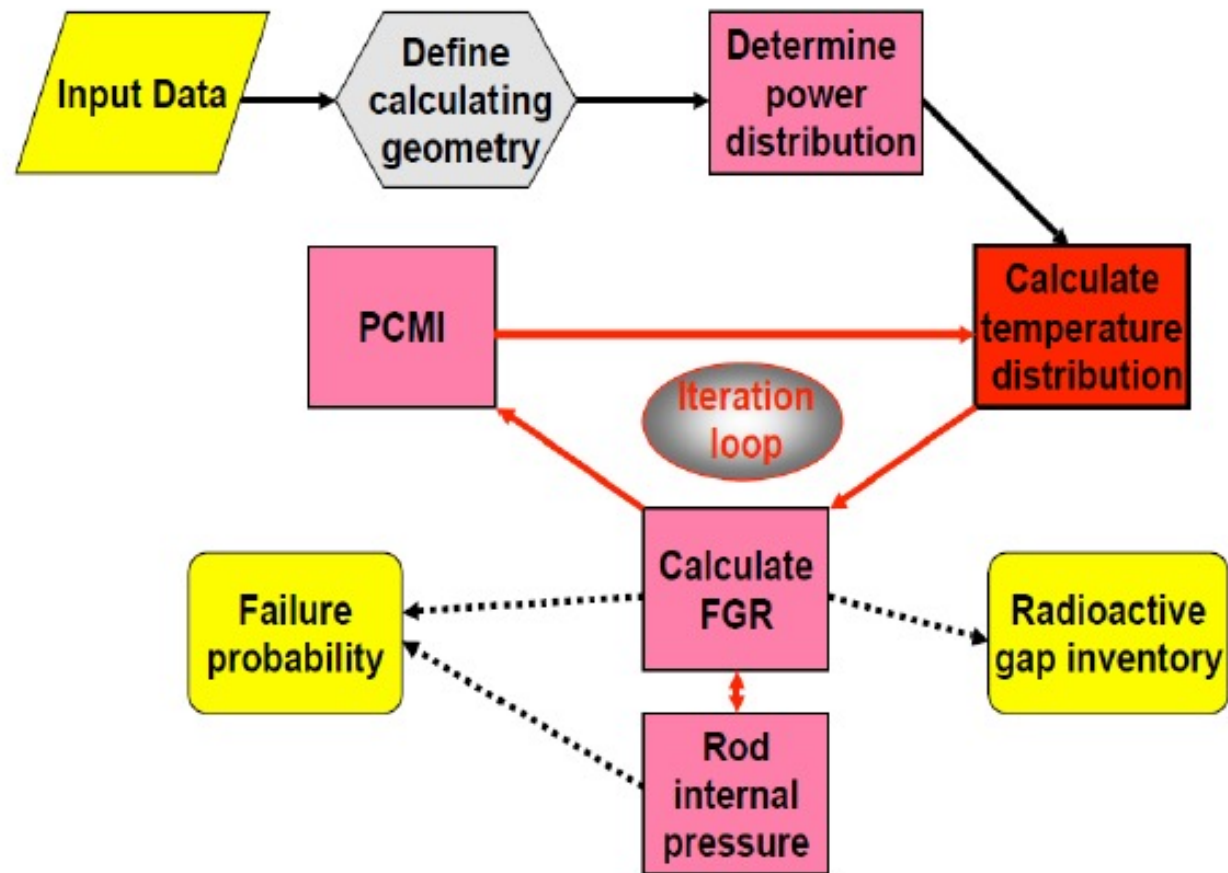


TRANSURANUS – Dados de Entrada

Dados de entrada: estado inicial + histórico de potência

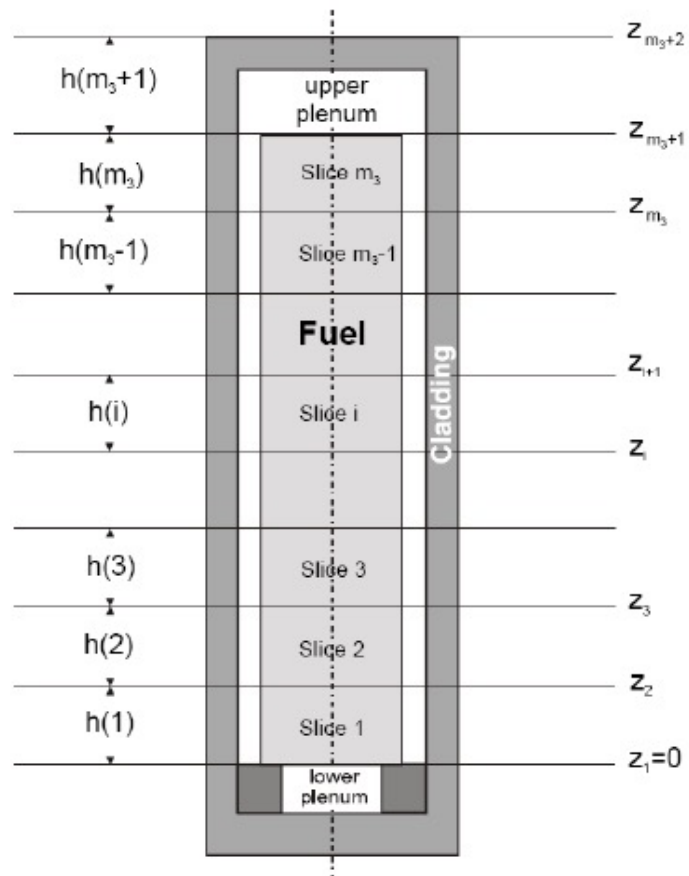
- ✓ Dados geométricos da vareta de combustível
- ✓ Opções do código para as propriedades dos materiais (combustível, revestimento)
- ✓ Opções do código para os modelos incorporados (densificação, corrosão etc)
- ✓ Dados de entrada variáveis com o tempo (potência linear da vareta, temperatura de entrada do refrigerante etc)

TRANSURANUS – Estrutura do Código

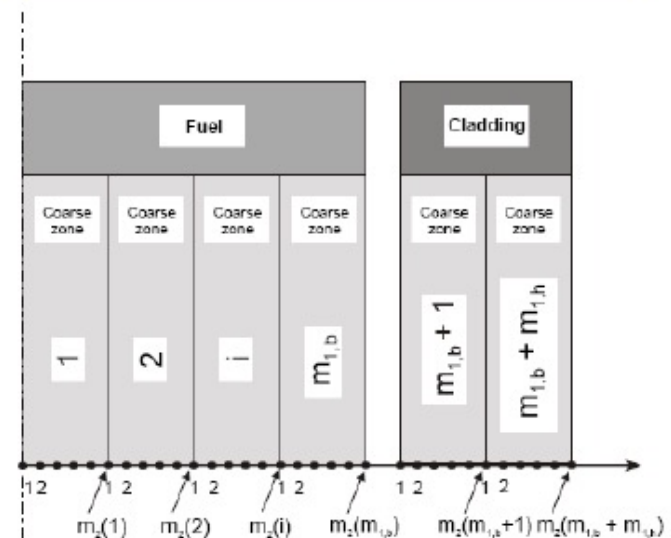


TRANSURANUS – Nodalização

Axial discretization of the fuel rod



Radial discretization of the fuel rod
(coarse zones)



TRANSURANUS – Dados de Entrada

```

INPUT FORMAT
*****
*  m3      fgrmod    ixmode  ModProp    istati    ibmech    izenka    ioxire
*      itheoc    ikuehl    iDifSolv  ModAx      idensi    ialpha    insta    kplot
*---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
*   9     2     4     1     0     0     4     0     0     2     0     2     0     2     0     1
*---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
*****

```

M3	= 9	Number of axial slices
ITHEOC	= 2	Second order mechanical theory in cladding
fgrmod	= 4	Fission gas release model : K. Lassmann, URGAS-model for LWR; Diffusion coefficient according to Matzke and Lassmann-White
IKUEHL	= 1	The coolant temperature is prescribed; see MACRO variable WERT(9)
IXMODE	= 0	Local no-slip condition in case of radial contact
iDifSolv	= 0	The diffusion equation for calculating the intragranular fission gas release is solved by the URGAS algorithm
ModProp	= 4	The general choice of material properties is modified for fuel and cladding
ModAx	= 0	Modification of the general choice of material properties applies for all sections or slices
ISTATI	= 0	Deterministic analysis (no statistical treatment)
IALPHA	= 2	Heat transfer coefficient between coolant and fuel pin is set to infinity
IZENKA	= 0	The formation of a central void is not accounted for
INSTA	= 2	Steady-state thermal analysis for base irradiation and transient analysis for time T grater then TTRANS
IOXIRE	= 0	Oxygen redistribution is not considered
KPLOT	= 1	Plot data is written to the Micro- Macro- and plot information data set

TRANSURANUS – Dados de Saída

Overview-table on TRANSURANUS-results						
=====						
Time T = 0.499690D+05 Hours = 2082 Days + 1 H + 0 Min + 0.07584 Sec						
Time-step No 2001 - 0.966348D-09 H Run No 1						
No. of section or slice		1	2	3	4	5
Axial coordinate	(mm)	29.89	89.67	149.45	209.23	269.01
Relative position	(%)	5.56	16.67	27.78	38.89	50.00
Linear rating	(kW/m)	7041.93	7905.43	8591.94	9070.46	9245.20
Fuel centre temperature	(C)	383.79	396.11	406.24	413.18	415.71
Fuel surface temperature	(C)	389.24	402.05	412.05	419.04	421.62
Clad inner temperature	(C)	333.98	340.54	345.80	349.46	350.82
Clad outer temperature	(C)	282.24	280.50	282.85	283.10	283.19
Clad surface temperature	(C)	280.24	280.29	280.32	280.34	280.35
Melt fraction fuel	(%)	0.00	0.00	0.00	0.00	0.00
Melt fraction clad	(%)	0.00	0.00	0.00	0.00	0.00
Fuel inner radius	(mm)	0.000	0.000	0.000	0.000	0.000
Fuel outer radius	(mm)	4.203	4.203	4.203	4.204	4.203
Thickness HBS, transition	(mm)	4.203	4.203	4.203	4.204	4.203
Thickness HBS, fully develop.	(mm)	0.891	0.911	0.885	0.876	0.847
Clad inner radius	(mm)	4.203	4.203	4.203	4.204	4.203
Clad outer radius	(mm)	4.747	4.745	4.745	4.743	4.742
Total clad outer radius	(mm)	4.785	4.785	4.787	4.786	4.787
Outer clad corrosion layer	(um)	38.32	39.82	41.26	42.88	44.47
Relative radial clad deformation:						
inner radius	(%)	0.58	0.60	0.60	0.60	0.59
outer radius	(%)	0.46	0.48	0.48	0.48	0.48
Average strains in cladding:						
effective creep strain	(%)	0.74	0.76	0.75	0.75	0.74
effective plastic strain	(%)	0.00	0.00	0.00	0.00	0.00
permanent tangent.strain	(%)	0.41	0.42	0.41	0.42	0.41
Cavity pressure	(MPa)	5.48	5.48	5.48	5.48	5.48
Clad inner loading	(MPa)	8.51	8.92	9.76	10.12	10.33

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REGULAR ARTICLE

OPEN ACCESS

Assessment of stainless steel 348 fuel rod performance against literature available data using TRANSURANUS code

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TRANSURANUS – Modificação do código

“The comparison of the main properties for non-irradiated annealed AISI 304, 316 and 348 shows that the properties for AISI 316 and AISI 348 are very close which enable to expect a similar performance for both materials under irradiation.

Based on the literature research, the following properties related to the annealed AISI 348 were introduced in the TRANSURANUS code to obtain the adapted version: elasticity constant, Poisson’s ratio, strain due to swelling, thermal strain, thermal conductivity, creep strain (thermal and irradiation creep rate), yield stress, rupture strain, burst stress, specific heat, density and melting temperature.”

TRANSURANUS – Modificação do código

Table 1. Austenitic stainless steel series 300 properties at room temperature [7–9].

Property	AISI 304	AISI 316	AISI 348
Density (10^3 kg/m^3)	8.0	8.0	7.9
Rockwell-B hardness	70	79	80
Ultimate strength (MPa)	505	580	605
Tensile strength at yield (MPa)	215	290	220
Maximum elongation (%)	70	50	40
Elastic modulus (GPa)	200	193	200
Poisson's ratio	0.290	0.295	0.283
Specific heat ($\text{J/g}^\circ\text{C}$)	0.5	0.5	0.5
Thermal conductivity (W/mK)	16.2	16.3	16.4
Thermal expansion coefficient ($10^{-6}/\text{K}$)	17	17	17
Melting point ($^\circ\text{C}$)	1450	1427	1400

TRANSURANUS – Modificação do código

“It was assumed that correlations already programmed in TRANSURANUS for the AISI 316 are acceptable and validated enough being the TRANSUNARUS originally developed to deal with fast breeder reactor fuel and considering its validation program [6]. In addition, the new correlations related to the AISI 348 properties somewhat reflect the same structure of the equivalent formula already programmed for the AISI 316. These correlations similarities should (at least partially) ensure that code numerical stability issue is not to be expected.

The AISI 348 behavior predicted by the modified code version has been compared against AISI 316 behavior which is part of the original (hence validated) code version. In general, the two steels present, as expected, similar trends. AISI 316 has shown a bit more conservative results in respect to AISI 348.”

YANKEE ROWE NPP

“The Yankee Rowe PWR has been owned and operated since startup in 1960 by the Yankee Atomic Electric Co. at Rowe, Massachusetts. The reactor and its initial core and stainless steel reloads were designed and built by Westinghouse. Yankee Rowe was the first fully commercial PWR of 250 MWe, which started up in 1960 and operated to 1992 [10]. Yankee Rowe produced 44 billion kilowatt-hours of electricity from 1961–1992 when it was permanently shutdown for economic reasons. The plant was successfully decommissioned between 1992–2007 with structures removed and the site restored to stringent federal and state remediation standards [11].

Starting from its 7th cycle of operation, the reactor began to change to zircaloy cladding, the transition was completed with cycle 12. The stainless steel clad reactor core consisted of 76 assemblies and 24 cruciform control rods. A typical stainless steel assembly was made up of 9 subassemblies each arranged in a 6x6 array, to make up an 18x18 fuel rod array. The subassemblies were tied together along their length to form a complete integral fuel assembly.”

YANKEE ROWE NPP

“The clad material was both seamless and welded annealed AISI 348 and represents the only large scale fuel experience with this steel in a PWR. The chemical composition of the adopted AISI 348 is identical to the niobium stabilized AISI 347, with the exception of a 0.10% limit on tantalum to reduce the neutron absorption cross-section. The fuel rod was also unique in that 6 physically separated fuel stacks spaced by equally spaced stainless steel discs. Each segment contains about 25 pellets. The objective of such design was to minimize differential thermal expansion between fuel and clad. There were no reported stainless steel clad fuel failures. The average fuel rod heat generation rate was 114 W cm^{-1} , the design rate was 353 W cm^{-1} (with a peak as high as 410 W cm^{-1}). The maximum cladding surface temperature was 343°C . A total of 16 assemblies were examined, all the assemblies were in excellent conditions with a minor amount of crud deposited [1].”

YANKEE ROWE NPP

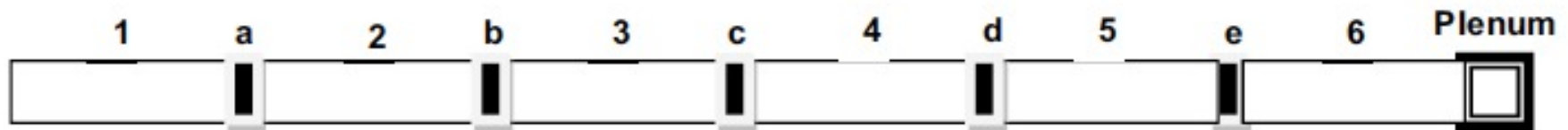
Table 2. Yankee Rowe general data and assumptions.

Parameter	Value	Remark
Rod outside diameter (cm)	0.864	[1,12]
Cladding thickness (cm)	0.053	[1,12]
Gap size (diametral) (cm)	0.011	[1,12]
Fuel rod pitch (cm)	1.153	[1,12]
Fuel pellet diameter (cm)	0.747	[1,12]
Fuel pellet density (%)	93	[1]
Fill gas internal rod pressure (MPa)	0.1	The fuel rod is not pressurized [1]
Active fuel length (cm)	229.9	[12]
Concentration of the gas components at the beginning of the calculation	0.8 N ₂ 0.2 O ₂	The fuel rod is not pressurized, then it was considered the air composition [1]
U235 enrichment degree (%)	3.4	[1,12]
Free volume in the upper plenum available for filling gas and fission gas (cm ³)	4.359	The plenum height assumption considered a conservative value taking into account the fuel stack height
Coolant flow rate (g h ⁻¹)	7.86×10^5	[12]
Coolant temperature (°C)	252	[1,12]
Coolant pressure (MPa)	14	[1,12]
Average LHGR (kW m ⁻¹)	11.4	Average rod power given in the literature for the Yankee Rowe fuel rods [1,12]
Design LHGR (kW m ⁻¹)	35.3	Design rod power given in the literature for the Yankee Rowe fuel rods [1,12]
Maximum cladding temperature surface (°C)	343	[1,12]
Average burnup (MWd tU ⁻¹)	31000	[1,12]
Neutron flux (cm ⁻² s ⁻¹)	6.3×10^{13}	Average assumed value to achieve the final fluence level and burnup [1,12]
Final fluence level (n cm ⁻²)	6×10^{21}	[1,12]

YANKEE ROWE NPP

“The clad material was both seamless and welded annealed AISI 348 and represents the only large scale fuel experience with this steel in a PWR. The chemical composition of the adopted AISI 348 is identical to the niobium stabilized AISI 347, with the exception of a 0.10% limit on tantalum to reduce the neutron absorption cross-section. The fuel rod was also unique in that 6 physically separated fuel stacks spaced by equally spaced stainless steel discs. Each segment contains about 25 pellets. The objective of such design was to minimize differential thermal expansion between fuel and clad. There were no reported stainless steel clad fuel failures. The average fuel rod heat generation rate was 114 W cm^{-1} , the design rate was 353 W cm^{-1} (with a peak as high as 410 W cm^{-1}). The maximum cladding surface temperature was 343°C . A total of 16 assemblies were examined, all the assemblies were in excellent conditions with a minor amount of crud deposited [1].”

YANKEE ROWE NPP



1, 2, 3, 4, 5, 6: 36.5 cm (25 fuel pellets) divided in 4 segments each one of 91 mm (apart the first two meshes of 85 mm); a, b, c, d, e: 40 mm (stainless steel disk); Plenum: 140 mm

Fig. 1. Yankee Rowe fuel rod assumed discretization based on the literature data [1].

“In order to prepare this model, it was considered the following information: the fuel rod had six physically separated fuel stacks with a perforated stainless steel disk between them localized at equally spaced axial locations, each segment contains about 25 UO_2 pellets, the active fuel length is 229.9 cm and the height of the fuel pellet is 1.46 cm.”

YANKEE ROWE NPP

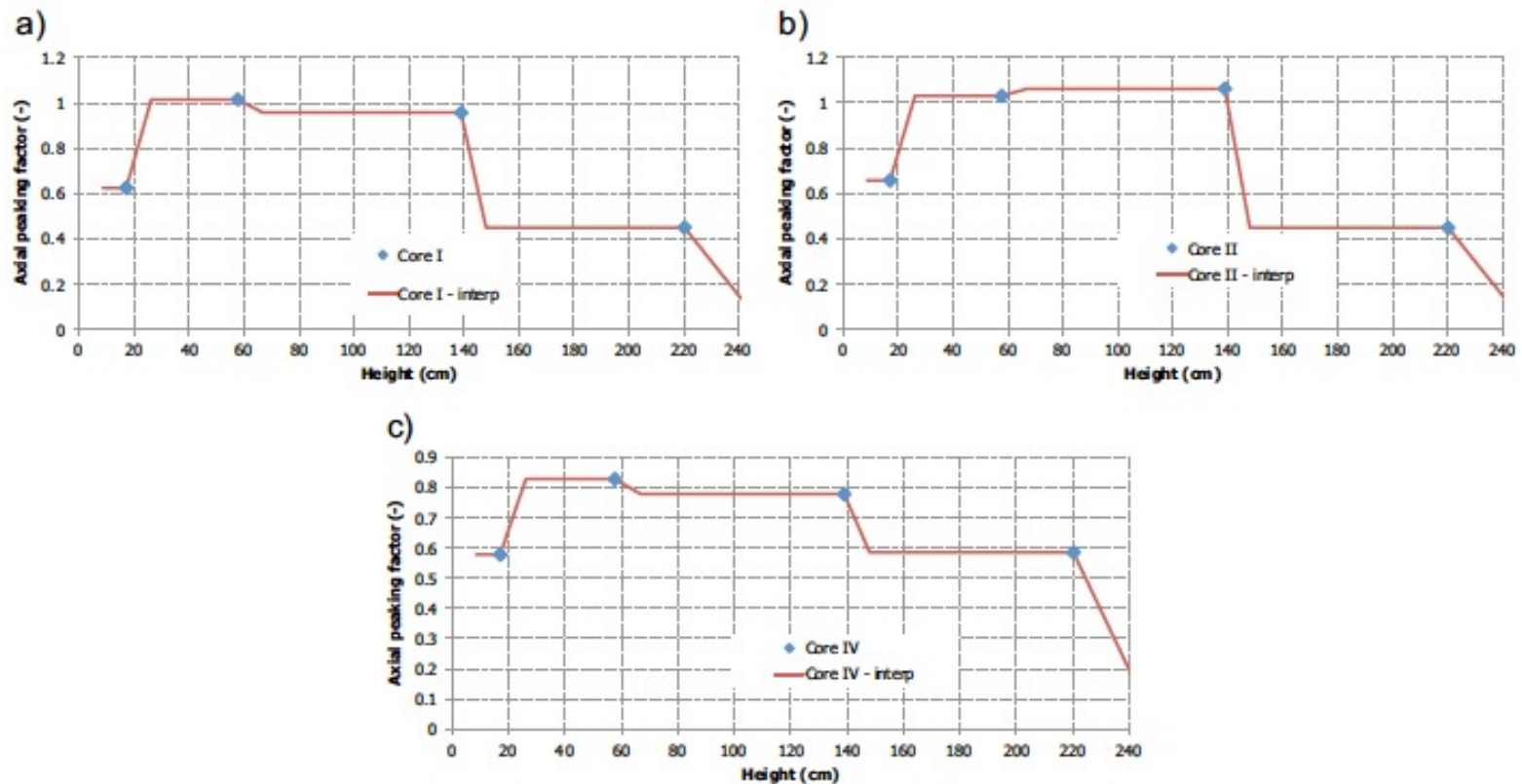


Fig. 2. E6-C-f6 fuel rod axial peaking factor for Core I (a), Core II (b) and Core IV (c), available data (blue dots [12]) and related interpolation (red curve).

RESULTADOS

“The parameters attaining to the Core I cycle are reasonably reproduced by the TRANSURANUS code (Tab. 3), noticeably the burnup matches fairly good in all four locations.

Regarding the fuel temperature calculated by the code, centerline and surface values are provided since for the reference data no specification about the radial position is provided. It can be seen that reference fuel temperature is within the code prediction for all the four axial positions.

The same considerations apply for the clad temperature (apart for the top position which is slightly underpredicted due to the underestimation of the coolant temperature) in relation with both reference data radial position and calculated values.

Additional calculated data are provided in Table 3 regarding fission gas release which remains very low; fuel and clad axial elongation, both are lower than 0.5%; maximum fluence value and plenum pressure which is double of its starting value.”

Table 3. Yankee Rowe E6-C-f6: comparison between reference and calculated data at the end of Core I cycle.

Position* (cm)	Parameter	Reference [12] CORE I	TRANSURANUS	Note
17.02	Cumulative burnup (MWd tU ⁻¹)	8.19	8.2	
57.66		13.29	13.32	
138.94		12.53	12.55	
220.22		5.9	5.91	
17.02	Fuel temperature (°C)	515	654.6	Centerline
			496.2	Surface
57.66		612	887.7	Centerline
			589.3	Surface
138.94		621	866.6	Centerline
			588.8	Surface
220.22		482	575.9	Centerline
			468.9	Surface
17.02	Clad temperature (°C)	267	270.4	Inner
			262.0	Outer
57.66		278	285.4	Inner
			271.9	Outer
138.94		287	292.0	Inner
			279.4	Outer
220.22		285	282.2	Inner
			276.2	Outer
17.02	Coolant temperature (°C)	254	252.9	
57.66		258	257.2	
138.94		268	265.6	
220.22		275	269.8	
	Fission gas release (%)	-	0.07	
	Fuel axial elongation (%)	-	0.39	
	Clad axial elongation (%)	-	0.43	
	Gap size (μm)	-	26.8/41.02	Min/Max value
	Fluence (n/cm ²)	-	2.4e21	Max value
	Plenum pressure (MPa)	-	0.22	

* Position from the bottom to the top of the fuel rod.

RESULTADOS

“Table 4 compares reference and calculated data related with the Core II cycle. Also for this irradiation step the code gives reasonable results, showing the same (as in Core I) good compliance regarding the burnup data.

Calculated values of fuel and clad temperature include the corresponding reference data. Notwithstanding the accumulation of the burnup, the fission gas release is still low (0.12%); fuel and clad axial elongation do not change so much from the previous cycle (both slightly increased); the gap is reducing but still open; the plenum pressure is slightly increased from the previous cycle.”

Table 4. Yankee Rowe E6-C-f6: comparison between reference and calculated data at the end of Core II cycle.

Position* (cm)	Parameter	Reference [12] CORE II	TRANSURANUS	Note
17.02	Cumulative burnup (MWd tU ⁻¹)	14.54	14.57	
57.66		23.24	23.31	
138.94		22.78	22.85	
220.22		10.23	10.25	
17.02	Fuel temperature (°C)	523	662.6	Centerline
			486.8	Surface
57.66			856.9	Centerline
			540.4	Surface
138.94		642	882.9	Centerline
			553.3	Surface
220.22			575.1	Centerline
			464.8	Surface
17.02	Clad temperature (°C)	267	275.2	Inner
			266.4	Outer
57.66			289.8	Inner
			276.2	Outer
138.94		290	299.6	Inner
			285.7	Outer
220.22			286.9	Inner
			281.0	Outer
17.02	Coolant temperature (°C)	254	256.9	
57.66			261.2	
138.94			270.5	
220.22			274.6	
	Fission gas release (%)	-	0.12	
	Fuel axial elongation (%)	-	0.52	
	Clad axial elongation (%)	-	0.44	
	Gap size (μm)	-	19.8/37.6	Min/Max value
	Fluence (n/cm ²)	-	4.4e21	Max value
	Plenum pressure (MPa)	-	0.25	

* Position from the bottom to the top of the fuel rod.

RESULTADOS

“Table 5 reports the comparison discussed above but at the end of the Core IV cycle. Also at this stage of the simulation, the code shows the same capabilities in relation with the burnup, fuel and clad temperature. Coolant temperature is also reasonably predicted as well.

At the end of the whole simulation, the fission gas release is below 0.2%; fuel and clad elongation are well below 1%; the gap kept open with a minimum value of about 16 mm (about 1/4 of its initial value) and the plenum pressure is less than the triple of its initial value.

In relation with the fuel and clad relative elongation it can be seen that the code is able to reproduce one of the objective of the particular Yankee Rowe rod design, namely to minimize the differential thermal expansion between fuel and clad.”

Table 5. Yankee Rowe E6-C-5: comparison between reference and calculated data at the end of Core IV cycle.

Position* (cm)	Parameter	Reference [12] CORE IV	TRANSURANUS	Note
17.02	Cumulative burnup (MWd tU ⁻¹)	20.19	20.25	
57.66		31.33	31.45	
138.94		30.39	30.50	
220.22		15.95	15.99	
17.02	Fuel temperature (°C)	504	606.4	Centerline
			449.2	Surface
57.66			716.7	Centerline
			462.8	Surface
138.94		575	702.3	Centerline
			466.0	Surface
220.22			641.6	Centerline
			484.5	Surface
17.02	Clad temperature (°C)	270	272.4	Inner
			264.7	Outer
57.66			282.4	Inner
			271.4	Outer
138.94		284	287.3	Inner
			277.0	Outer
220.22			286.8	Inner
			279.0	Outer
17.02	Coolant temperature (°C)	258	256.7	
57.66			260.0	
138.94			266.3	
220.22			271.1	
	Fission gas release (%)	-	0.17	
	Fuel axial elongation (%)	-	0.58	
	Clad axial elongation (%)	-	0.43	
	Gap size (μm)	-	16.4/32.6	Min/Max value
	Fluence (n/cm ²)	-	5.9e21	Max value
	Plenum pressure (MPa)	-	0.26	

* Position from the bottom to the top of the fuel rod.

CONCLUSÃO

“In general, the TRANSURANUS code performed reasonably well even facing with a rod design which is quite far from the typical (current) PWR technology (e.g. clad material, filling gas type, lack of gap pressurization, presence of different segments within the fuel rod). Any predicted parameters for the simulated fuel rod are of no concern regarding their corresponding design data.

The carried out calculations show reasonably agreement with available data confirming the modified code capabilities. This constitutes an indication of the modified TRANSURANUS code capabilities to perform fuel rod investigation of fuel rod manufactured with AISI 348 cladding material.”