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ABSTRACT

The objective of this work is to evaluate the fuel behavior modeling code MARS against experimental data. Two cases were selected: an early comercial PWR rod (Maine Yankee rod) and an experimental rod from the Canadian BWR program (Canadian rod). The MARS predictions are compared with experimental data and predictions made by other fuel modeling codes. Improvements are suggested for some fuel behavior models. Mars results are satisfactory based on the data available.

I – INTRODCTION

The nuclear industry has an economic incentive for the current interest in fuel behavior modeling codes. Numerous computer codes exist for modeling fuel behavior. Unfortunately only a small amount of information is publicly available to justify the use of these codes in a practical manner.

MARS(4) is a FORTRAN-IV computer code designed to predict the in-pile performance of cylindrical light-water-reactor fuel elements. The code includes predictions of temperature distribution, thermoelastic and creep deformations of the fuel and the cladding, fuel restructuring, swelling due to fission products, fission gas release, fuel pellet cracking formation and crack healing, cladding plastic deformation, etc. Power is input as a function of time, allowing analysis of detailed power-time history.

MARS performs a one-dimensional, axisymmetric analysis with up to 21 axial nodes. The cladding is loaded externally by the coolant pressure. Either a gap or fuel-clad contact can be treated at the fuel-clad interface. The gap is allowed to open and close in response to the power time history. The formation of a central void is assumed not possible, neither by fabrication nor by operation.

In this work, results of 2 different cases calculated by MARS are benchmarked against experimental values and results of other codes evaluated by the Eletric Power Research Institute (EPRI).

II – CASE A – THE MAINE YANKEE PWR ROD

II.1 – Geometry and Experimental Conditions

This case analizes a Maine Yankee PWR Rod which was evaluated in the final fuel behavior modeling report of the EPRI project(1). The rod was similar to current commercial LWR fuel rods in terms of geometry and steady state operating characteristics. The rod contained UO_2 pellet fuel and the cladding was cold worked Zircaloy-4.

Although the rod was very similar to current commercial rods, some important differences did exist: current PWR rod is prepressurized to avoid dimensional instability while the Maine Yankee rod was not prepressurized.

The Maine Yankee PWR rod geometric data and experimental conditions are listed in Table II.1, Table II.2 and Figure 2.1 show the power time history used in this case.

Table II.1

General Characteristics of Maine Yankee PWR Rod.

Fuel – UO_2	
Fuel O. D.	9.639 mm
Active Fuel length	347.2 ± 0.635 mm
Fuel density	92.8% T. D.
Fuel enrichment	2.01% U^{235}
Clad - Zircaloy - 4	
Clad I. D.	9.868 mm
Clad thickness	0.66 mm
Clad length	373 mm
Initial fill gas – He	
Initial fill gas Pressure	0.10 MPa
Coolant – H_2O	
Coolant temperature	280°C
Coolant pressure	13.8 MPa

Table II.2

Maine Yankee Rod Power - Time History

Time x 10^{-6} (s)	Linear heat rating (KW/m)
1.18	16.9
1.84	16.8
3.08	0
12.6	17.6
15.2	16.0
17.9	14.0
20.9	0
24.6	7.25
25.8	20.5
29.7	19.6
28.9	2.07
34.2	0
34.7	21.6
35.1	22.5
38.4	20.7
42.1	22.5
44.0	24.3
50.4	20.4
50.5	0

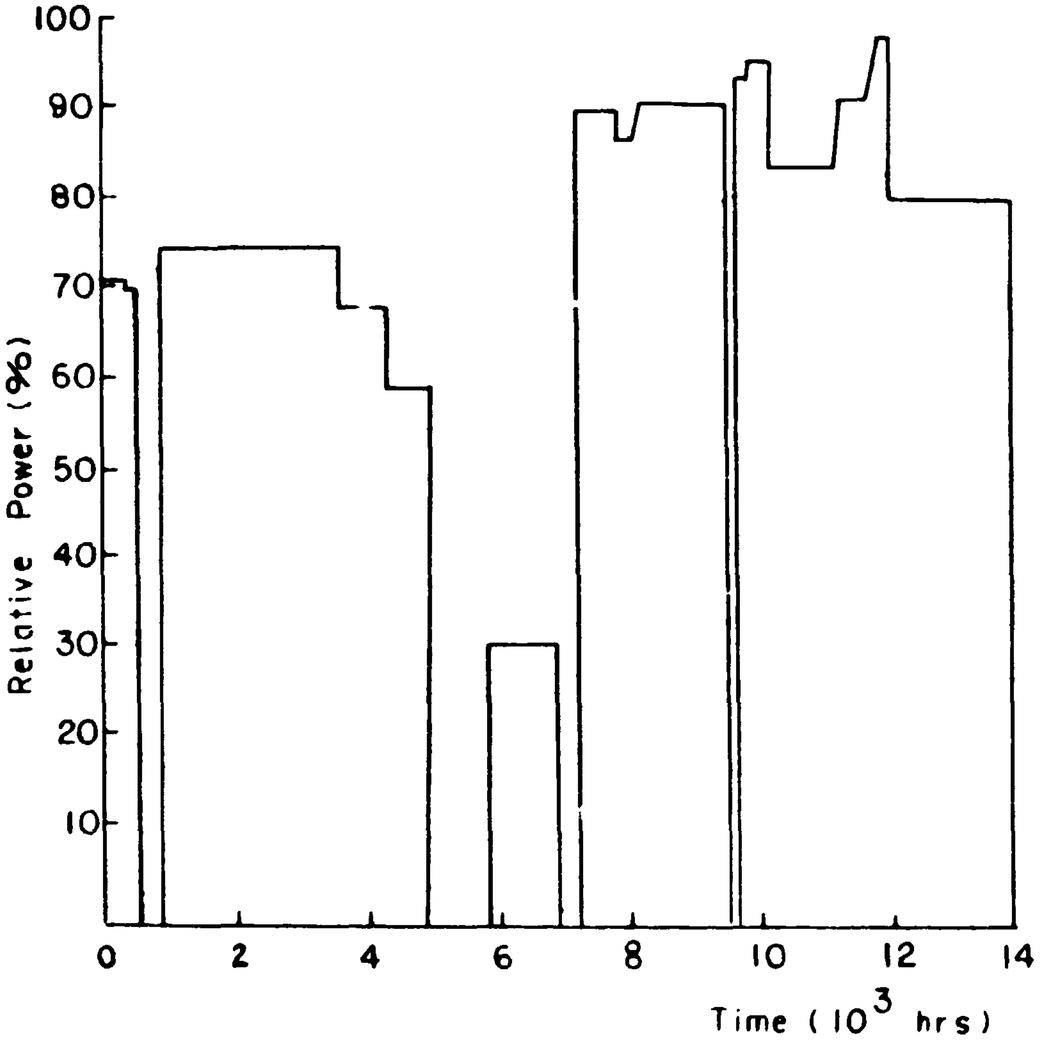

Figure 2.1 – Maine Yankee PWR Rod Power Time History.

The rod was irradiated to a cumulative rod average burnup of roughly 13,350 MWD/MTU in about 14.000 hours at an approximate peak linear power rate of 29.1 kw/m.

II.2 – Results and Discussion

The MARS results are compared to several experimental values (fission gas release, enf-of-life (EOL) cold diameter gap and EOL cladding permanent tangential strain) and results of four other EPRI fuel modeling behavior codes (BEHAVE-4, COMETHE-III J, GAPCON-THERMAL-2 and LIFE-THERMAL) as shown in Table II.3.

Table II.3

Maine Yankee Rod – Experimental, Comparative and Predicted Data

Final Fission Gas Release

Experimental	13.4%
BEHAVE - 4	14.4%
COMETHE - III - J	2.2%
GAPCON - THERMAL 2	60.2%
LIFE - THERMAL - 1	5.1%
MARS	.52%

End - of - life Cold Diameter Gap, Microns

Axial location from inlet	**17 cm**	**91 cm**	**326.4 cm**
Experimental	130	120	110
BEHAVE	200	100	190
COMETHE - III - J	280	200	240
GAPCON - THERMAL - 2	300	290	300
LIFE - THERMAL - 1	110	61	89
MARS	96.9	78.5	93.8

End - of - life Cladding Permanent Tangential Strain

Axial Location from inlet	**17 cm**	**91 cm**	**326.4 cm**
Experimental	-0.23	-0.55	-0.34
BEHAVE - 4	-0.38	-0.59	-0.28
GAPCON - THERMAL - 2	0	0	0
COMETHE - III - J	-0.44	-1.06	-0.86
LIFE - THERMAL - 1	-0.39	-0.65	-0.67
MARS	-0.23	-0.31	-0.26

Figures 2.2, 2.4 and 2.6 show the results of MARS and the other codes for the fuel center line temperature, hot diameter gap and gap conductance, respectively, as a function of rod-average burnup at 17 cm from the coolant inlet end of the rod.

Figures 2.3, 2.5 and 2.7 illustrate the fuel center line temperature, hot diameter gap and hot gap conductance, respectively, as a function of burnup at 91 cm from the coolant inlet of the rod.

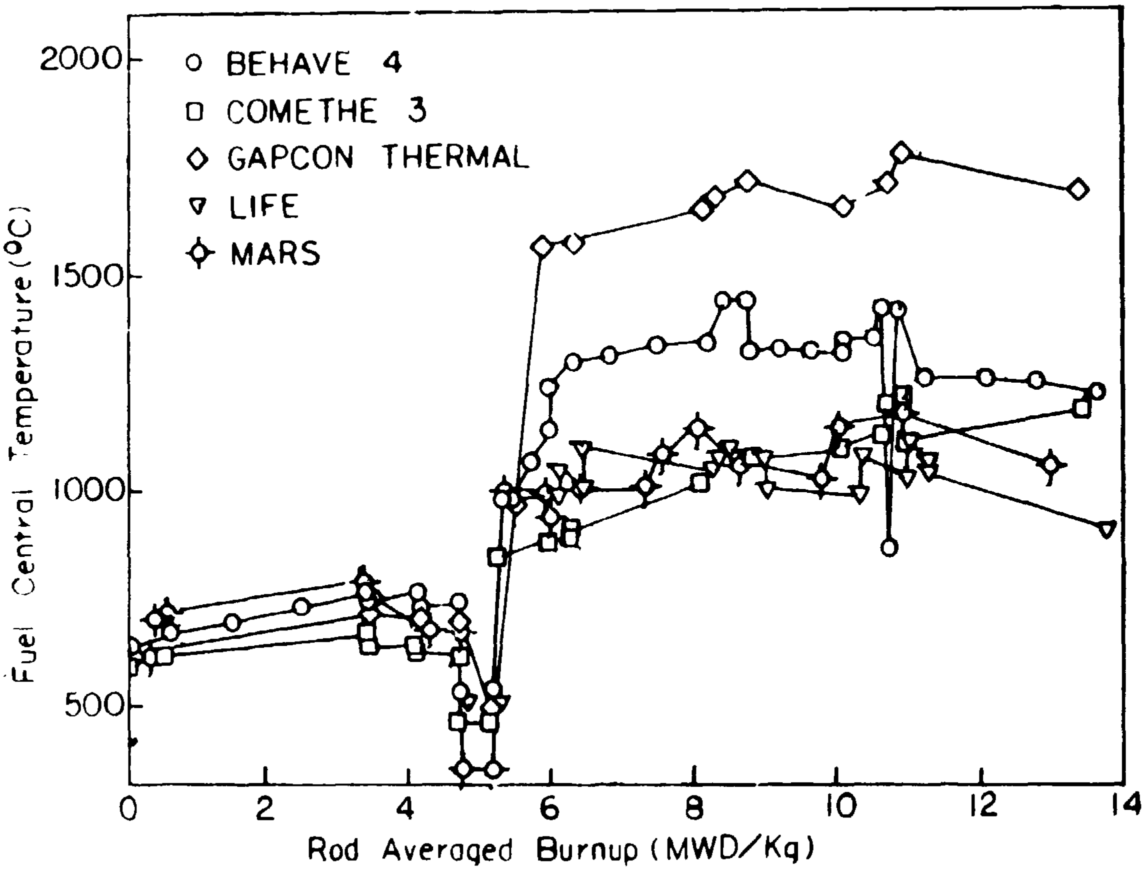

Figure 2.2 – Maine Yankee PWR Rod - Fuel Centerline Temperature vs Burnup at 17 cm from Inlet.

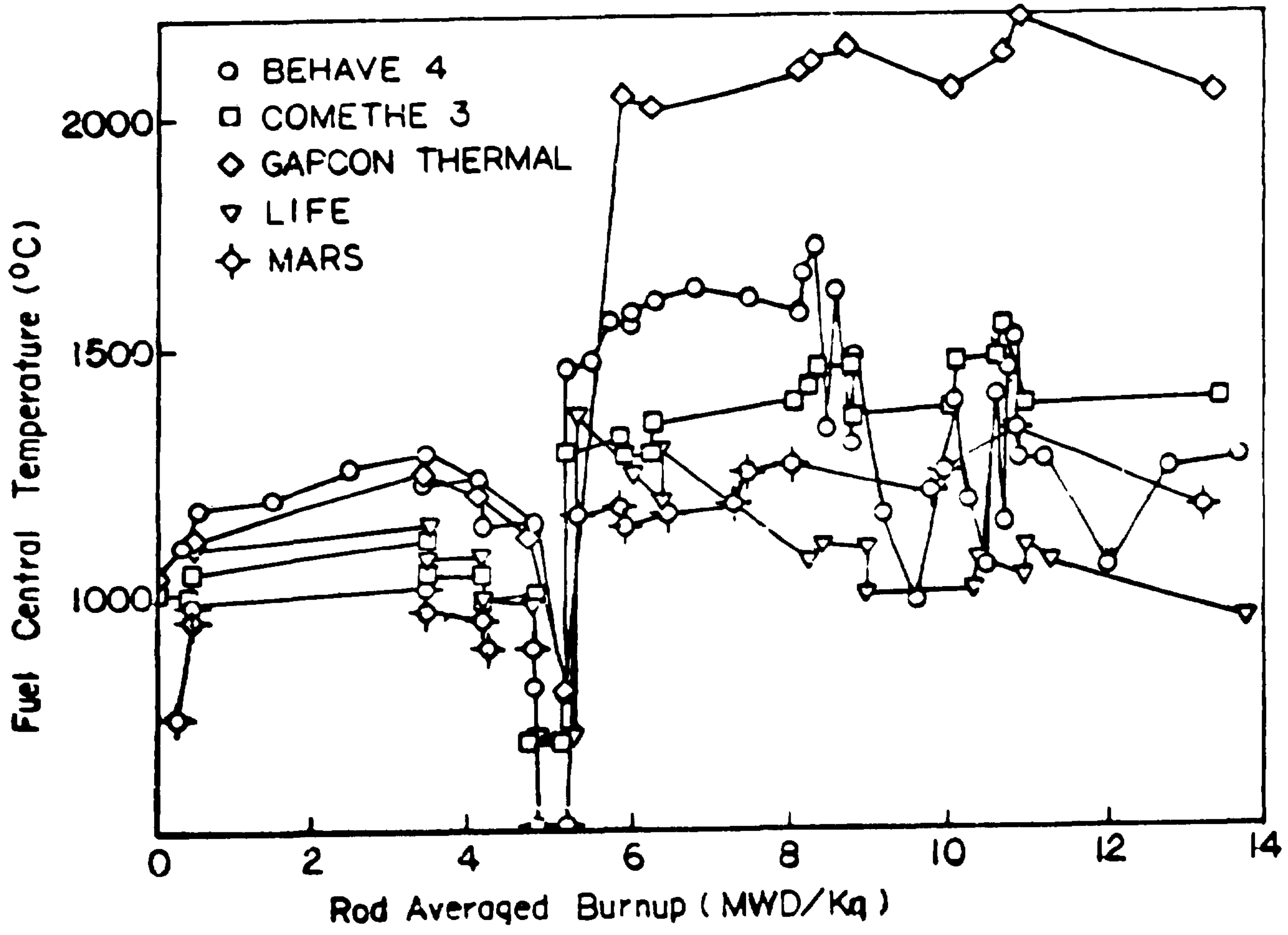

Figure 2.3 – Maine Yankee PWR Rod – Fuel Centerline Temperature vs. Burnup at 91 cm from Inlet.

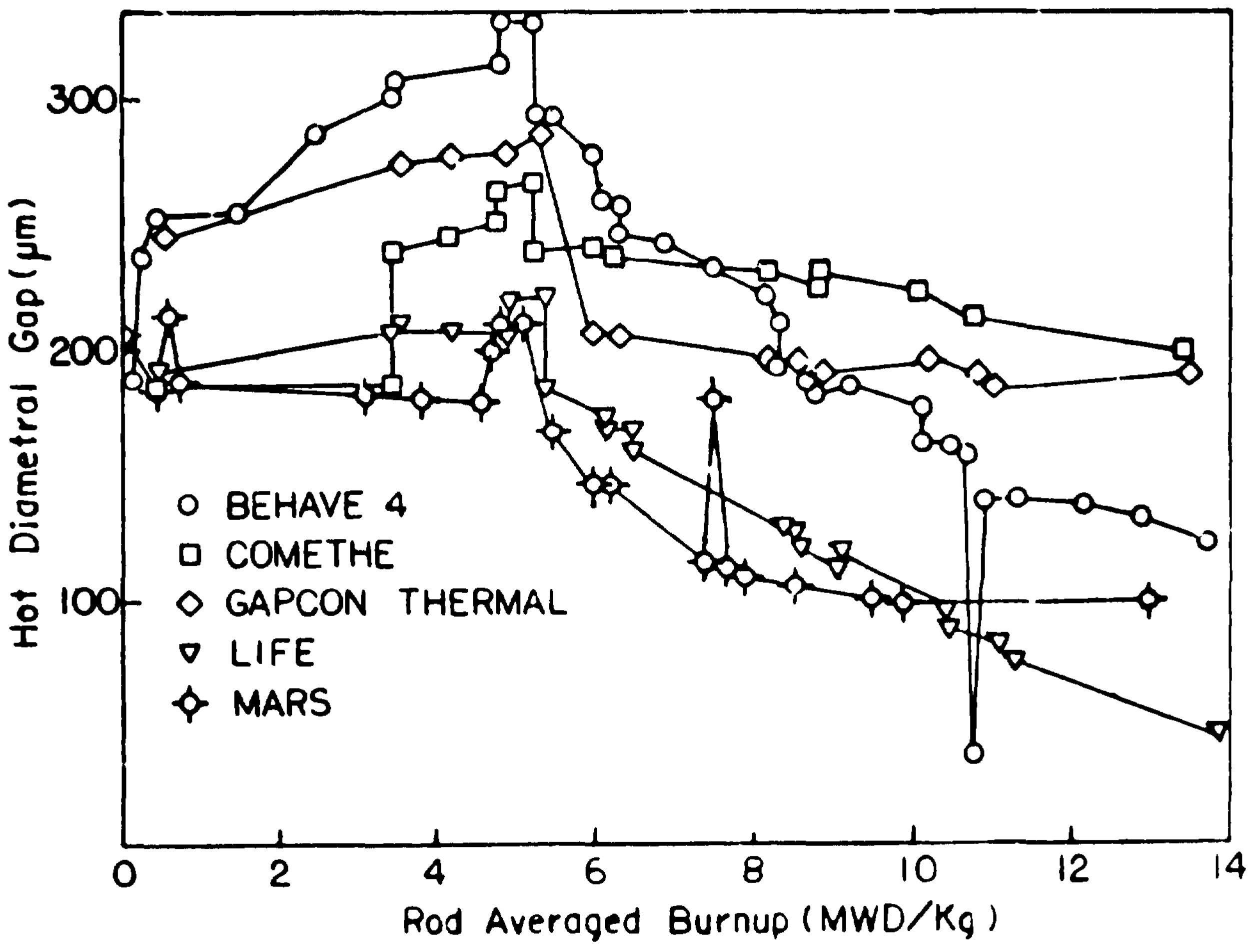

Figure 2.4 – Maine Yankee PWR Rod – Hot Diametral Gap vs. Burnup at 17 cm from Inlet.

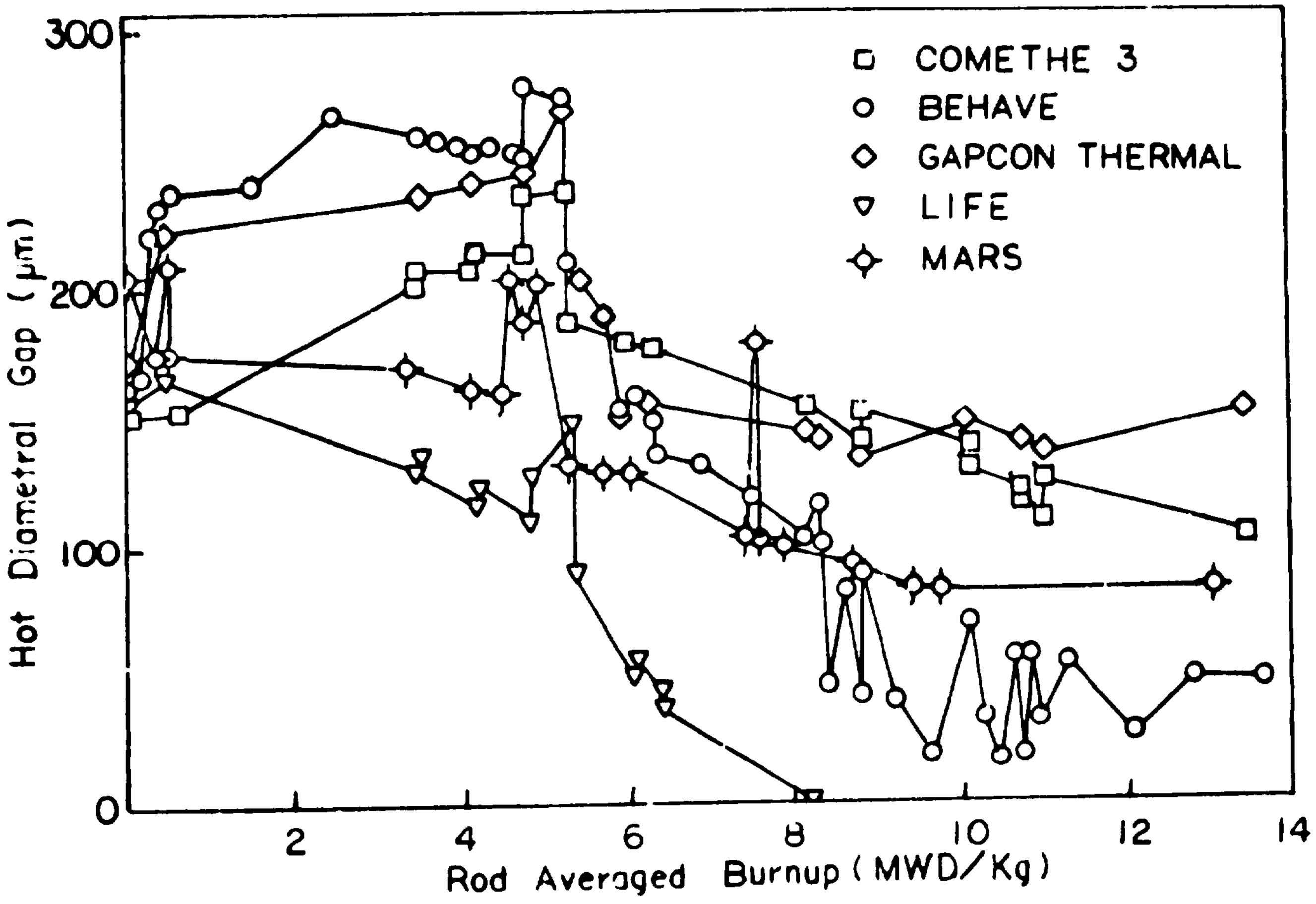

Figure 2.5 – Maine Yankee PWR Rod – Hot Diametral Gap vs. Burnup at 91 cm from Inlet.

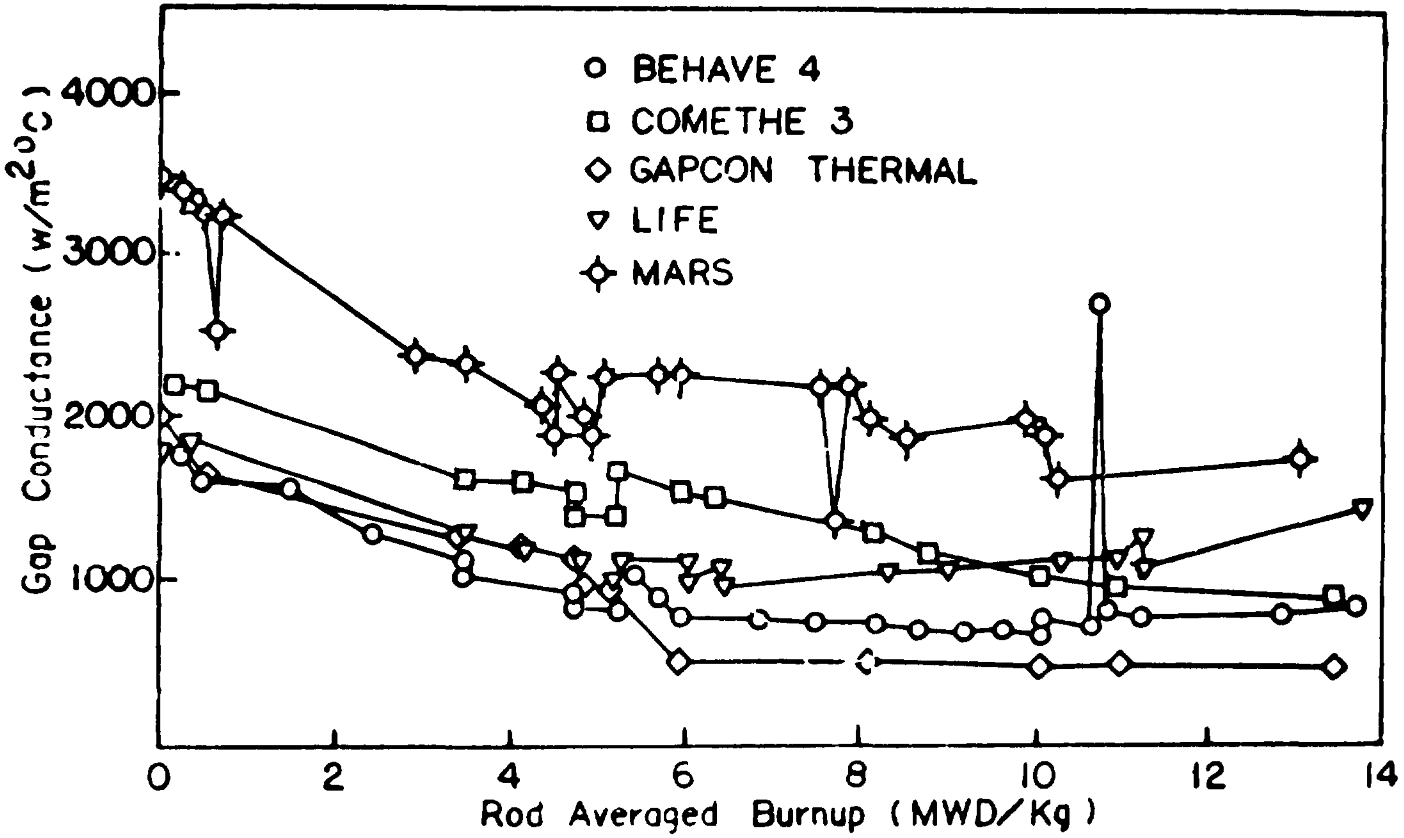

Figure 2.6 – Maine Yankee PWR Rod – Gap Conductance vs. Burnup at 17 cm from Inlet.

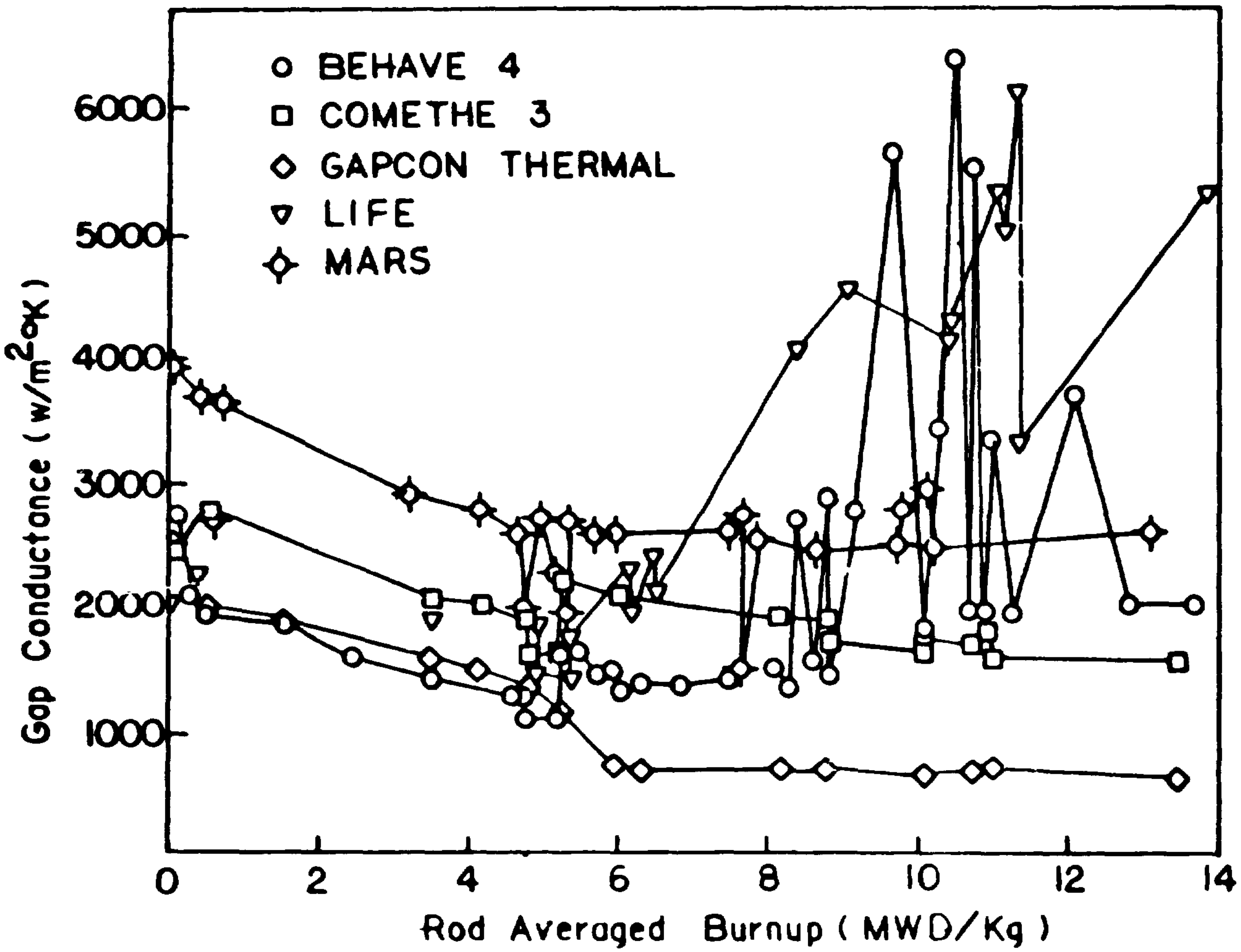

Figure 2.7 — Maine Yankee PWR Rod — Gap Conductance vs. Burnup at 91 cm from Inlet.

Table II.3 reveals that MARS underpredicts the fission gas release, compared to experimental data and the results from the other codes. It underpredicts the EOL cold diameter gap and EOL cladding permanent tangential strain compared with the experimental data. This table also shows that MARS predicted a small diametral gap though the clad creepdown is relatively low. The probable explanation resides on the excess fuel swelling due to the low fission gas release which seems to more than compensate for the low clad creepdown.

Figures 2.2 and 2.3 show that the fuel center line temperature compares favorably with the results from other codes. With the exception of BEHAVE – 4, all codes predict that the fuel centerline temperature peaks when power is maximum, i.e., after 12000 hours of operation. Unfortunately no experimental result is available.

Figures 2.4 and 2.5 illustrate that MARS obtained a lower hot diameter gap throughout life, at 17 cm from inlet which results on higher gap conductance compared to the results of the four other codes as shown in Figures 2.4 and 2.6. At 91 cm from inlet, the hot diameter gap and gap conductance compare well with the other codes.

III – CASE B – CANADIAN BWR ROD

III.1 – Geometry and Experimental Conditions[2,3]

In recent years, increasing amount of attention has been focused on the response of fuel rods subjected to strong power ramps The attention is derived from observations in which a relatively high incidence of rod failure occurs as a result of power changes as compared to failure rates during steady state operation.

This case investigates the performance of the MARS code in predicting the response of fuel rods to relatively high power ramps. The rod undergoes extensive plastic deformation during the ramp due to hard fuel-clad contact. If the code performs well for high power ramps, a certain amount of confidence in this code is implied for the treatment of lower power ramps.

In Phase II of EPRI fuel behavior modeling program, two Canadian experimental rods were analyzed. The X-264 rod was selected for this study.

The X-264 rod is a relatively short, Zircaloy-2 clad rod fueled with highly dense, dished (one side only) UO_2 pellets of low enrichment. The rod is of greater diameter than typical commercial BWR pins. Minimum axial clearance exists between fuel and clad, in order to minimize fuel axial relocation. Circumferential strain gauges were fixed at pellet interface and midplanes on the clad outside to determine any relative differences in behavior at those locations.

The purpose of the Canadian experiments was to measure the axial and circumferential strains during element power cycles under nominal CANDU-BLW (Boiling Light Water) reactor conditions. Detailed data on the response of the rod with hard fuel-clad contact while ramped to 66-69 Kw/in a matter of hours is available.

X-264 rod ran through one power cycle before the rod failed due to a leaking pressure seal. The internal fill gas pressure was maintained at one atmosphere during the power cycling by means of a stainless steel vent tube connected to out of reactor apparatus.

The general characteristics of the X-264 rod are presented in Table III.1. Table III.2 shows the power time history.

Table III.1

General Characteristics of the Canadian Rod

Fuel – UO_2	
Fuel O. D.	18.55 mm
Active Fuel length	382.0 mm
Fuel density	96.3% T. D
Fuel enrichment	1.59% U^{235}
Clad - Zircaloy - 2	
Clad I. D.	18.66 mm
Clad thickness	0.546 mm
Plenum length	99 mm
Initial fill gas - He	
Fill gas pressure	0.10 MPa
Coolant – H_2O	
Coolant temperature	220°C
Coolant pressure	8.00 MPa

Table III.2

Canadian Rod Power - Time History

Time (x 10^{-3}), (s)	Linear heat rating (KW/m)
0	0
8.218	68-9
9.601	68-9
16.32	0

The rod is so short that a uniform axial power profile has been assumed. The EPRI code evaluation program report suggests a coolant– cladding heat transfer coefficient of 3.50×10^4 W/m^2°K.

III.2 – Results and Discussion

The predictions from MARS and other codes evaluated by EPRI are compared to the experimental data in Table III.3 and Figures 3.1 through 3.3.

Table III.3

Canadian Rod Experimental, Comparative and Predicted Data.

Peak Fuel Center Line Temperature (°C)	
Experimental	2166
BEHAVE - 4	2015
COMETHE - III - H	2044
CYGRO - 3	2216
FMODEL	1904
GAPCON - THERMAL - 1	2181
LIFE - THERMAL - 1	2181
MARS	2073

Cladding Tangential Strain (% Δ D/D)

	Peak Power	Cold EOL
Experimental	0.34	0.43
BEHAVE - 4	0.34	0
COMETHE III - H	0.61	-0.05
CYGRO - 3	0.64	0.05
FMODEL	-0.64	0
GARCON - THERMAL - 1	0.04	–
LIFE - THERMAL - 1	0.68	0
MARS	0.99	0.80

Table III.3 contains the experimental, comparative and predicted peak fuel center line temperature and cladding tangential strains at peak power and the end of life. Figures 3.1, 3.2 and 3.3 exhibit the behavior of MARS and the codes in predicting the cladding tangential strain, fuel-clad contact pressure and the clad hoop stress respectively during the power cycle.

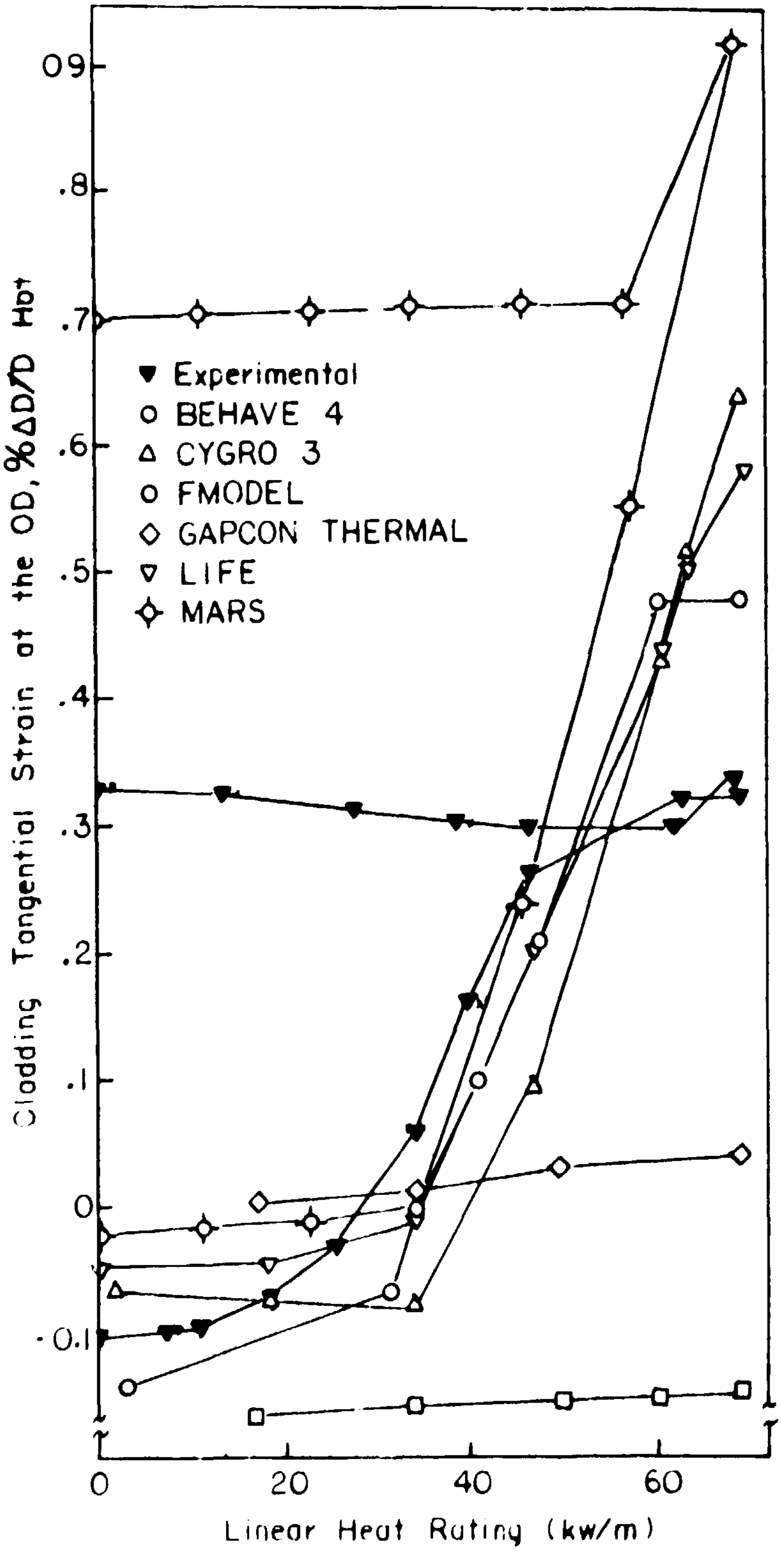

Figure 3.1 – Canadian Rod - Cladding Hoop Strain vs. Linear Rate.

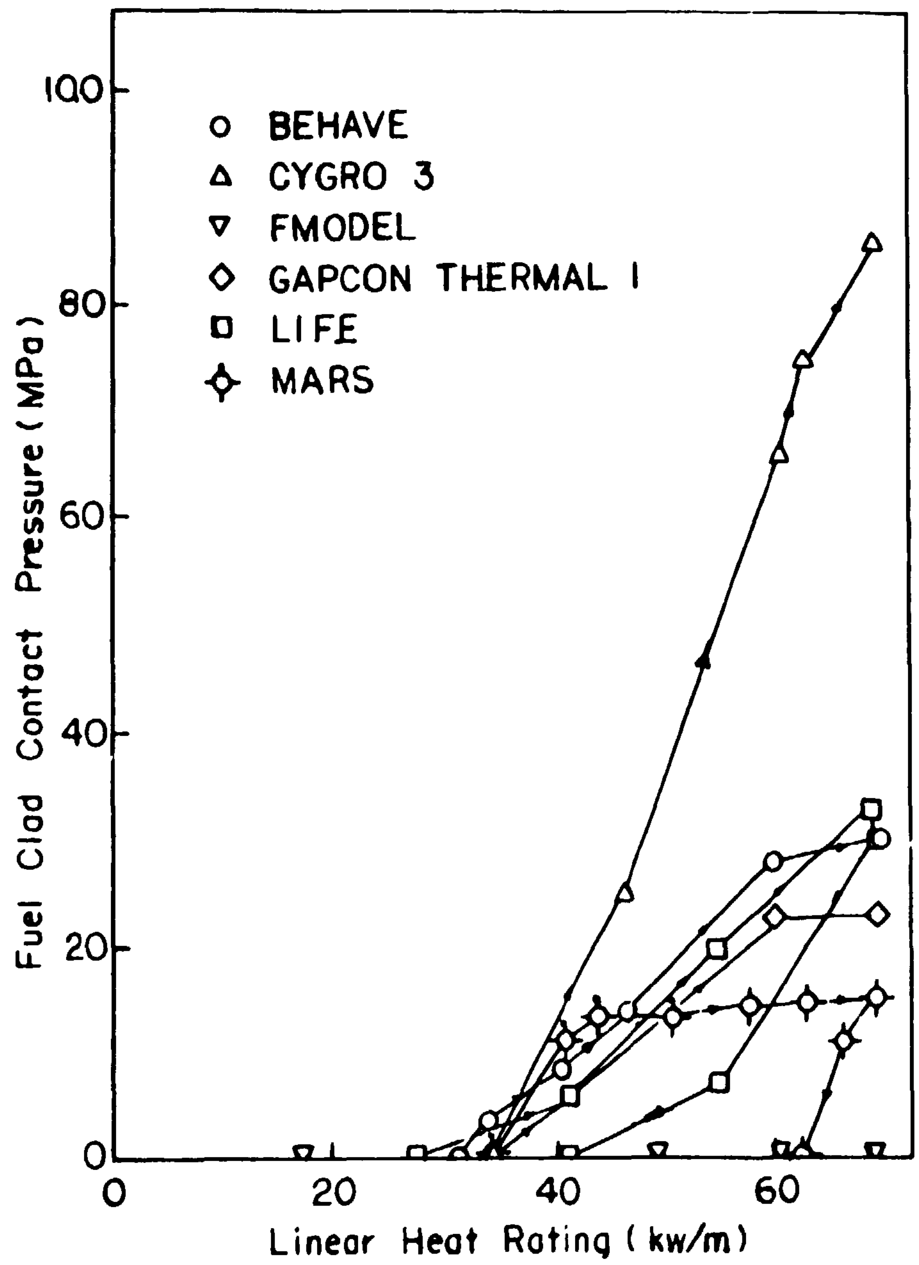

Figure 3.2 – Canadian Rod Fuel Clad Contact Pressure vs. Linear Heat Rate.

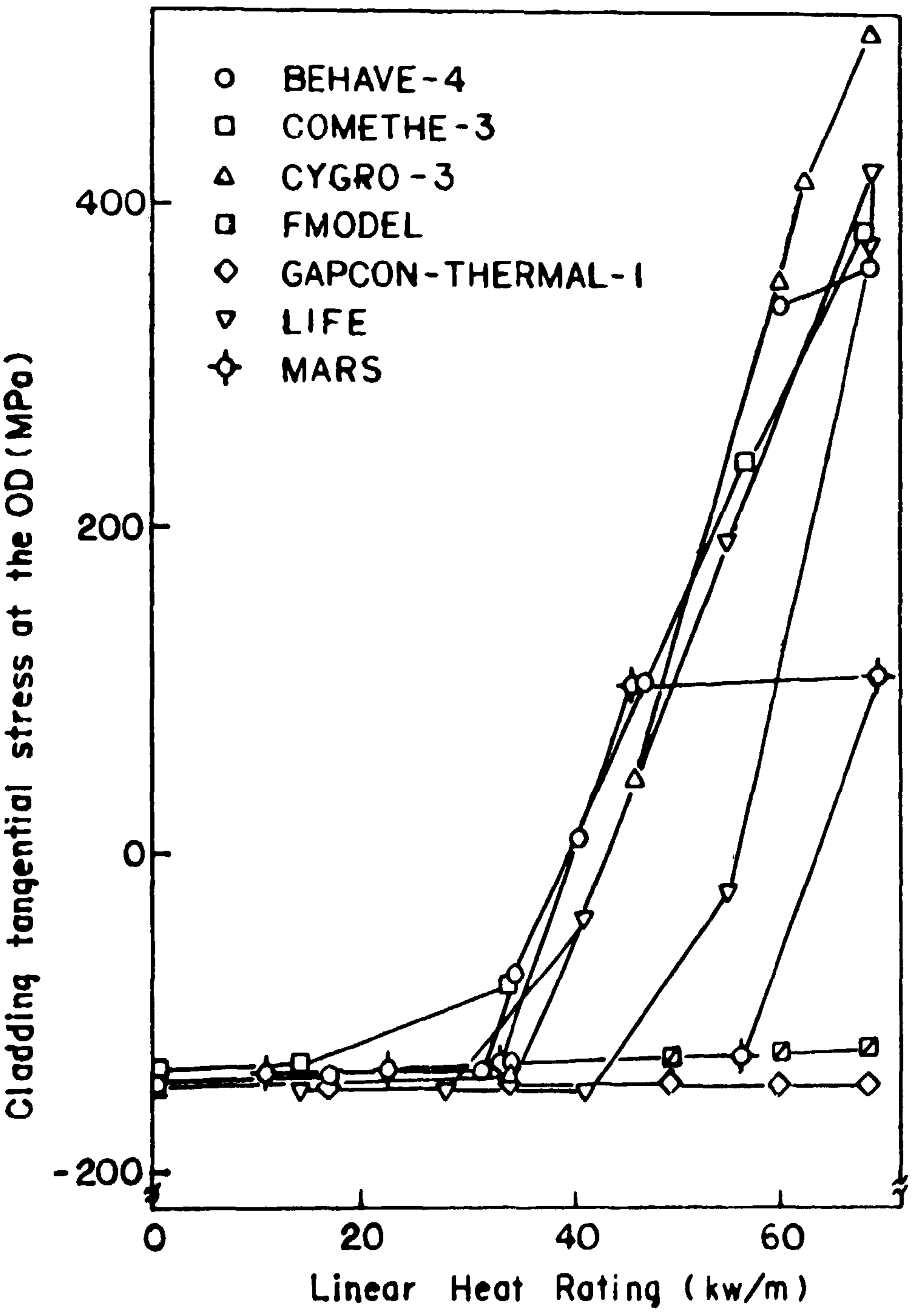

Figure 3.3 – Canadian Rod – Cladding Hoop Stress vs. Linear Rating.

Table III.3 shows that the fuel center temperature predicted by MARS compares quite well with the experimental data. Relative to the values obtained by other codes MARS best estimates the fuel center line temperature after GAPCON-THERMAL II. The same table shows that MARS prediction of clad tangential strain at peak power and cold EOL permanent tangential strain is substantially higher than the experimental result.

Fuel-clad contact takes place at about 55% full power during the rising power ramp for MARS. The fuel and clad came out of contact at about 90% full power during the descending power ramp. This is clearly illustrated in Figures 3.1 to 3.3.

Figure 3.1 shows that the experimental clad hoop strain although more negative at the begining, exceeds the MARS clad hoop strain prediction after the fuel-clad contact occurs on the ascending power ramp. As the power is further increased, the clad tangential strain predicted by MARS exceeds the experimentally determined strain by about 100%. MARS maximum cladding strain reached during the power cycle exceeds all results of the 6 codes evaluated by EPRI.

The MARS response for cladding tangential strain, stress and contact pressure illustrated in Figures 3.1 to 3.3 are explained as follows. The negative strain and stresses at the initial of lifes is due to the external coolant pressure. The fuel-cladding contact pressure does not exist because of the initial gap between them.

As the rod power rises, the fuel cracks in the radial and axial directions on the outer periphery of the fuel. After the fuel and clad come into contact, the cladding strain increases while the fuel expands. The fuel-cladding contact pressure rises rapidly, so does the cladding stress, while going from compression to tension. When the cladding reaches its yield point, plastic flow occurs so that the cladding stress and the fuel-cladding contact pressure remain practically constant. During the peak power, as pellet cracks are being healed, the cladding strain remains constant.

As the power goes down, the cladding strain, stress and contact pressure decrease while the fuel pellets contract until the fuel and cladding come out of contact. The contact pressure is again zero and the cladding stress becomes again compressive due to the coolant pressure. From then on the cladding strain remains practically constant.

IV – CONCLUSIONS

In the light of the experimental data and predictions from other fuel modeling codes the following conclusions can be made with respect to the results obtained with MARS:

a) MARS predictions of fuel centerline temperature are in good agreement with the experimental data from the Canadian rod experiment. As for the Maine Yankee case MARS follows closely the results from other codes. In short, MARS is apparently doing a good job in predicting fuel temperature distribution.

b) MARS predictions of fission gas release for commercial PWR rod are well under the experimental data and results from other codes. Improvements on the fission gas release model are recommended.

c) In case of hard fuel-cladding contact, MARS overpredicts the cladding permanent tangential strain. In this respect MARS is conservative. This result is probably associated with the underprediction of fission gas release mentioned in b.

d) In case of fuel-cladding contact MARS underpredicts both the measured EOL cold diametral gap and EOL cladding permanent tangential strain by a small amount. However, MARS predictions are better than those of other codes.

Finally, it must be said that the available experimental data on fuel rod behavior is very limeted and only a few parameters are measured. Therefore, any attempt to sophisticate the mathematical models is not justified unless it is supported by a sound experimental program. Of course these experiments involve a great investmentneed of a operative materials test reactor, miniscule instrumentation, etc. Therefore, it is obvious that a research program in this area calls for cooperation with other countries already committed with this kind of investigation.

RESUMO

O objetivo deste trabalho é avaliar o programa de computador MARS desenvolvido para simulação do comportamento da barra de combustível, com resultadados experimentais. Dois casos foram selecionados: uma barra de combustível de um PWR comercial (Maine Yankee) e uma barra de combustível experimental do programa Canadense de BWR. As previsões do programa MARS são comparadas com resultados experimentais e, também, com resultados de outros programas de computador. Sugere-se que alguns modelos físicos sejam melhorados para melhor desempenho do programa. Com base nos resultados disponíveis pode-se afirmar que os resultados de MARS são satisfatórios.

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