DESIGN CONSIDERATIONS FOR NUCLEAR FUEL ELEMENTS TO SUIT REACTOR OPERATING IN SMALL ELECTRICAL GRIDS

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SUMMARY

The 220 MWe Candu-PHW unit of the Rajasthan Atomic Power Station (RAPS) has experienced, to-date, over 130 reactor trips, shut downs or power cut-backs, as against a total of 100 planned and unplanned outages specified in the fuel design specification. Majority of these power cycles are ascribed to either class IV power failures or severe grid frequency swings. To overcome these problems, consideration is also being given for replacing existing turbine-follow-reactor philosophy by a modified reactor-follow-turbine control scheme. As such, in addition to power cycles associated with outages, the reactor is likely to experience daily cycling of some power level.

The objectives set out for the study were (i) to examine, whether or not, the current fuel of the wire-wrap design will survive power cycles (which may exceed 300 for the start-up charge) and (ii) to evolve fuel design modifications, so that power cycling does not become a performance limitation.

To begin with, relevant details of RAPS plant and fuel assembly are described to provide an understanding of the contributing factors and sequence of events in the life of fresh fuel entering the core. Because the cladding is not free-standing, it is assumed in the calculational model that the longitudinal ridge formed behaves like a hinge. The strain per cycle is based on the +2 sigma limit observed in actual sheath collapse test specimens. The fatigue characteristics are taken from the stress fatigue curves for irradiated zircaloy at 300°C published by O'Donnell and Langer corrected for variations in material ductility. These corrections were made using Langer's equation, which is a modification of Coffin's relationship of the plastic strain as a function of cycles to failure. To account for higher sheath ductility in the beginning of life, a two stage approach for unirradiated and irradiated zircaloy has been adopted in the calculational model. The factors of safety of 1.5 on plastic strain or 6 on number of cycles, have been used. The statistical incidence of actual diametral clearances as obtained during fuel fabrication are also presented to arrive at the probable failure rate of fuel elements due to power cycling.

It is found that the number of full power cycles to cause sheath failure at a longitudinal deformation varies from 100 for a diametral clearance of 0.14 mm to about 2500 for a lower limit of .07 mm diametral clearance.

It is also concluded that continued emphasis on sheath ductility would offer maximum advantage; as well as the nominal maximum diametral clearance, should be aimed at 0.11 mm instead of 0.14 mm. Further experimental work is needed to gain a better understanding of sheath instability and strain cycling during refuelling operation. A useful measure of RA % should also be evolved in tube burst tests. It is suggested that this may be determined from measurement of wall thickness at the point of initiation of fracture, and a RA % derived by comparison with the wall thickness prior to testing.

1. Introduction

The Rajasthan Atomic Power Station (RAPS) is the second atomic power station of India and consists of two heavy water moderated natural uranium fuelled reactors, each of 220 MW(e) capacity. Unit-1 achieved first criticality in August, 1972. Work on the second unit is nearing completion. The station is connected to the State electricity grid, whose peak load has been under 400 MW(e) during the past two years of reactor operation. Thus during operation of RAPS Unit-1, 60% to 80% of the total load is supplied by it. As a result, the station has experienced several reactor outages and consequent power cycles which have exceeded those in the original fuel design specifications.

In this paper, we have examined the capability of the RAPS-1 fuel of current design to survive larger than specified power cycles and to evolve fuel design modifications, as necessary, so that power cycling does not become a performance limitation. The relevant details of operation of RAPS-1 plant and the fuel bundles are also included to provide an understanding of the factors entering the design analysis.

The intent of the study is specific to RAPS-1, but the results obtained should find general application to other reactors as well.

2. Fuel Design And Performance

The fuel bundle as used in RAPS-1 is shown in Figure-1. It is a 19 element cluster, each element consisting of dished natural UO_2 pellets in collapsible zircaloy-2 sheathing. The salient fuel design parameters are given in Table-1.

As of date, over 120 fuel channels have been refuelled on-power. The fuel has to-date performed very satisfactorily without defecting and the establishing of on-power refuelling is a very important part of the success of the reactor.

3. Operational Data

The Rajasthan State Electricity grid to which RAPS-1 is connected serves the entire state of Rajasthan. Besides RAPS-1, there are three hydro-electric power stations feeding the grid.

Though the first synchronisation of RAPS-1 to the grid was in November, 1972, the unit could be taken to high power operation only in early 1974, when the desired degree of flux flattening had been achieved.

During the year 1973, there have been as many as 70 outages and in 1974, there were 55 outages. Many of the outages in the early operation have been traced to grid instability, and to-date on an average there have been one such outage per week. Figure-2 shows typical power cycling pattern of RAPS-1 for a month.

It would be appropriate to mention at this stage that efforts are being made to operate the grid in parallel with the Bhakra management system, which is a much bigger electrical grid and this has to some extent, helped in grid stabilization. For example, since the planned annual shut down of 1974 which ended in October 1974, there have been a definite reduction in the number of outages.

Further with a view to improve the station availability, a study has been initiated to assess the load following capability of RAPS units and to arrive at the modifications required in the control logic, the design of fuel and other reactor components. This would imply a larger number of power cycles, especially affecting the fuel, even though the reactor outages might be reduced with experience.

4. Statement of the Problem

As originally planned, it was estimated that there would be 12 planned and 12 unplanned outages per year totalling 50 to 80 in the life time of the fuel depending upon its position in the core. 100 full power cycles (100% F.P. to 0 power) were thus specified in the fuel design specifications. The reactor trips, shut downs or power set backs experienced by the station have, however, already exceeded 100. Although refuelling has been started, the initial fuel load in the reactor will reside for another year and a half and it is expected that certain fuel bundles may see more than 200 power cycles towards the end of their life.

To better appreciate how power cycling affects in-reactor fuel behaviour, one needs to follow the sequence of events in the life of fresh fuel entering the core. Prior to generating any significant amount of power, the fuel is exposed to relatively high external pressures and temperatures. Because the sheath is not free standing, the high external pressure will collapse it on to the pellet and depending on its strength and diametral clearance, it may either assume a stable elliptical shape, else a longitudinal ridge may be formed.

If conditions are such that longitudinal ridge is not formed, then it could be shown that the strain of the sheath is relatively small and no deleterious effects are envisaged during the life of the fuel. If on the other hand, a longitudinal ridge is formed, it causes permanent i.e. plastic deformation in the sheath. This permanent deformation acts like a hinge and when cycled due to power fluctuations, indications are that plastic strain cycling occurs which can lead to low cycle fatigue failure of the sheath. Whether or not a fuel bundle will survive this power cycling depends upon a number of factors, such as:

- Yield strength of the cladding
- Wall thickness of the cladding
- Diametral clearance between pellet and cladding
- Percent Reduction of Area (% RA) i.e. ability to withstand local deformation
- Number of power cycles
- External coolant pressure and temperature
- Fuel heat rating

In the section following, the input data used in the analysis, are presented. The mathematical model for low cycle fatigue analysis and determination of probable fuel failure rate are also described.

5. Input Data

5.1 Fuel Performance

This is included in Table-I.

5.2 Sheath Properties

Table-I gives mechanical properties of zircaloy-2 cold-worked and stress relieved sheathing as used in the reactor.

5.3 Collapse Strain

The sheath collapse strain resulting in formation of longitudinal ridges is an important parameter to be factored into the low cycle fatigue analysis. Out-reactor collapse tests are underway to determine sheath deformation as a function of time, temperature and pressure. From limited data available, it has been possible to estimate the upper limit ($+ 2\sigma$) of sheath strain coincident with minimum sheath thickness and maximum diametral clearance. Figure-3 shows the deformed sheath profile and a mathematical formulation of collapse strain behaviour. The derived values of plastic collapse strain are:

Diametral Clearance, δ mm	Plastic Collapse Strain, %
.051	.15
.076	.19
.102	.30
.130	.45

5.4 Burst Test Data and RA%

The ductility requirements of the sheath in terms of Total Circumferential Elongation (TCE) are specified by closed end burst test at room temperature conditions and at 300°C which is the operating sheath temperature in the reactor. In low cycle fatigue analysis it is, however, required to determine the percent Reduction of Area (RA%). As uni-axial test values usually reported in literature (See Table-II) do not properly represent the bi-axial stress distribution of the sheath, a usefuel measure of RA% must be evolved from tube burst tests only. It is suggested that this can be determined from measurement of wall thickness at the point of initiation of fracture and RA% derived from comparison with wall thickness prior to testing. Data for 50 unirradiated burst test samples of RAPS sheath were correlated to obtain a relationship between TCE and RA% [1] . For various sheath lots used in the reactor, RA% at room temperature condition is observed to fall in the range of 14 to 27%. The corresponding residual RA% at the end of life is estimated to be in the range 10 to 20%. The changes in ductility arising from radiation and temperature effects are taken from Ref. [2] .

5.5 Power Cycles

A power cycle for RAPS fuel has been defined as one which causes a gross power change in the fuel from 100% F.P. to 70% F.P. or lower. The reason is that although the cold pellet/sheath gap is fully taken up at peak rating at 100% F.P., it is not taken up at all positions and more over a definite gap can exist at all positions when power is below 70% F.P. A detailed study of the station operation over the past 2 years has revealed that over 130 events could be categorised as power cycles and out of them, 75 had occurred before the sheath had seen neutron fluence of 2×10^{20} n/cm^2, $E > 1$ Mev. (Note. it is assumed that sheath is in irradiated state and suffers radiation damage above 2×10^{20} n/cm^2 fluence). To account for higher sheath ductility in the beginning of life, a two stage approach for unirradiated and irradiated zircaloy has been adopted. The "normalised" power cycles for the start-up fuel and reload fuel are estimated to be 200 and 175 respectively. For a load following reactor there will be additional cycling of some power level. From reactor dynamic simulation studies, it was estimated that the maximum grid frequency fluctuation, as recorded during station operation produces a power swing of 100% F.P. to 65% F.P., which is likely to occur once per day. While full load following capability would certainly mean a very severe operating condition of the fuel, it was suggested that the feasibility of limited load following capability, say 100% F.P. to 80% or 90% power level should be examined.

5.6 Dimensional Data

Five representative RAPS fuel elements were selected and detailed measurements on pellet O.D., sheath I.D. and wall thickness were carried out [3]. The data gathered was analysed by a computer programme and the percentage incidences obtained are as follows:

A. **Diametral Clearances** (Nominal maximum : 0.13 mm)

Diametral Clearance, δ mm	Percent Incidence, %
$0 < \delta \leqslant 0.050$	11
$0.050 < \delta \leqslant 0.076$	46
$0.076 < \delta \leqslant 0.102$	40
$0.102 < \delta \leqslant 0.130$	3

B. **Wall Thickness**

16% of measurements of wall thickness fell in the lower range of 0.38 mm to 0.40 mm.

5.7 Zircaloy Fatigue Data

For strain cycling of aluminium and steel, Manson had found that a relation exists between plastic strain range and the number of cycles to failure [4].

$$\Delta e_p = M N_f^{z} \tag{1}$$

Where

$M = \frac{e_f}{2}$

e_f = Fracture ductility = $l_n \left(\frac{100}{100-RA} \right)$

RA = Reduction of area in a tensile test

N_f = Number of cycles to failure

z = - 0.5 (as found out by Coffin) [5]

$$\text{i.e.} \Delta e_p = \frac{1}{2\sqrt{N_f}} \quad l_n \left[\frac{100}{100-RA} \right] \tag{2}$$

O'Donnel and Langer used the following modified S-N_f relationships as a mathematical model to plot the best fit curve for zircaloy-2 experimental data at 600°F [6] .

$$S = \frac{E}{4\sqrt{N_f}} \ln\left(\frac{100}{100-RA}\right) + Se \qquad (3)$$

Where

E = Elastic Modulus, 81×10^4 kg/cm^2

S = $\frac{1}{2}$ E e_t, pseudo-stress amplitude to cause failure in N_f cycles

e_t = Strain range (Peak to peak excursion)

S_e = Endurance limit, 1740 kg/cm^2

Hosbons conducted experiments to study 300°C low cycle fatigue behaviour of zircaloy-2 in various metallurgical conditions [7] . The following general correlation was derived representing annealed zircaloy-2.

$$\triangle e_p = 0.57\, N_f^{-0.48} \qquad (4)$$

From his studies, it is established that reduction in area as measured in tension tests is a good parameter determining fatigue life. Also, iodine atmosphere appears to reduce fatigue life of zircaloy, which is quite relevant to the fuel sheathing analysis. An important deduction from Hosbons measurements is that the uncertainty factor in predicting cycles to failure is only 5. Based on plastic strain, this uncertainty or the safety factor works out to 1.3.

For the present study, we have used a safety factor of 1.5 and the following fatigue correlation:

$$S = \frac{E}{4\, N_f^{0.48}} \ln\left[\frac{100}{100-RA}\right] + Se \qquad (5)$$

5.8 Failure Probability

The probability of fuel surviving the expected number of power cycles is related to:

(i) position of the fuel in the core, as it determines the actual pseudo-stress amplitude for individual fuel bundles with respect to that of the highest rated bundle.

(ii) the statistical distribution of various sheath properties such as ductility, yield strength, wall thickness and diametral clearances, as they determine the percentage incidences of actual applicable input values with respect to certain base data used in the general solution.

The method used is to determine the combination of optimum fuel design parameters from Figure-4, and then from the statistical distribution of these parameters, the failure probability can be calculated.

6. Discussion

6.1 Results of the study are presented in Figure-4. It gives the number of cycles to failure in the maximum rated channel as a function of percent reduction of area for diametral clearances of 0.076 mm, 0.10 mm and 0.13 mm and safety margins of 1.0, 1.5 and 2.0. The number of cycles to failure are the normalised power cycles accumulated during residence in the highest rated channel and does not include power cycling due to load following.

6.2 The method of analysis shows that for RAPS sheath with an end of life reduction of area of 10%:

(i) The maximum number of normalised power cycles to cause failure at an longitudinal deformation varies from 700 for a diametral clearance of 0.13 mm to about 10,000 for a diametral clearance of 0.076 mm.

(ii) The factor of safety of 2.0 on predicted strain as recommended by ASME Code [8] gives less than 100 power cycles to cause fuel failure. This was considered over-pessimistic, as by now several fuel failures would have been caused. Accordingly, a safety margin of 1.5, as discussed in the text, has been adopted for the fuel design evaluation. It may also be noted that the results on Figure-4 are applicable for a minimum wall thickness of 0.38 mm. However, as discussed in section 5.6 only 16% of wall thickness measurements fall in the 0.38 - 0.40 mm range. In other words, 84% of sheath used in the reactor has a wall thickness of 0.40 mm to 0.46 mm. The additional safety margins with increased wall thickness also have been calculated. For 0.41 mm, 0.43 mm and 0.46 mm thickness, the factor of safety on collapse strain are 1.22, 1.47 and 1.72 respectively.

6.3 For 200 normalised power cycles in the life of start-up fuel the following local ductilities are required:

Diametral Clearance, δ mm	RA%
0.076	5
0.102	9
0.130	14

The estimates of local ductilities made in bi-axial burst test samples are such that it is considered likely that adequate reduction of area is possibly achieved for majority of fuel elements. However, it is necessary to closely watch the performance of fuel bundles presently loaded in the reactor to ascertain the number of power cycles this fuel is able to withstand. It will be then possible to correlate the data with regard to cold diametral clearance and associated fuel failure rate.

6.4 The analysis also shows that increase in the sheath ductility, increase in wall thickness and reduction in diametral clearance are helpful in improving the fatigue life of fuel.

6.5 Should the effects of load following be taken into consideration, it will be required to plan for not only higher sheath ductility but also increase in wall thickness and/or reduce the normal maximum diametral clearance as achieved during fuel fabrication. These aspects will however, be finalised after more operational experience with the current fuel is available.

7. Conclusions

7.1 RAPS-1 fuel has so far experienced 130 power cycles, which exceed those in the fuel design specifications. Because of collapsible sheathing and 200 normalised power cycles expected to be seen by the fuel during its residence time, the problem of low cycle fatigue becomes important to RAPS fuel.

7.2 Reduction of Area is the most important parameter affecting low cycle fatigue behaviour. A method is suggested for obtaining this parameter from tube burst tests, which closely simulates the biaxial stress distribution in an operating fuel element.

7.3 The safety factor of 2 on strain or 20 on number of cycles, as recommended by ASME Pressure Vessel Research Committee is found to be over-pessimistic and a safety factor of 1.5 on strain has been taken for the present design study.

7.4 Applying a factor of safety of 1.5 to the predicted collapse strain, the minimum number of power cycles to cause failure vary from 100 for a diametral clearance of 0.13 mm to 2500 for a diametral clearance of 0.076 mm.

7.5 It is possible to improve the low cycle fatigue behaviour of fuel elements by a combination of factors such as use of fully annealed sheath, increased wall thickness and reduced diametral clearances.

7.6 It is required to closely watch the future performance of RAPS fuel to obtain further data in this regard and also to support the theoretical results for the design modification, if any.

7.7 More precise data on initial collapse strain and subsequent on-power thermal expansion strain as a function of power cycling is required to be generated in out-reactor tests.

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TABLE I

RAPS FUEL DESIGN AND OPERATIONAL DATA

Bundle	
Fissionable Material	Sintered UO_2 pellets
Structural Material	Zircaloy-2
Length of bundle	495 mm
Diameter of bundle	81 mm
Weight of bundle	16.7 Kg
Number in Reactor	3672
Sheath	
Outside diameter	15.2 mm
Wall thickness	0.38 + 0.08 mm - 0 mm
End Plug	
Plug to sheath closure	Resistance weld
Thickness - minimum	4.6 mm
End Plates	
Diameter	68.5 mm
Thickness	1.53 mm
Element Assembly	
Pellet to sheath diametral clearance	0.051 - 0.127 mm
Concentrated axial clearance	1.83 mm
Fuel Performance	
Normal rating for outer element,	40 w/cm
Normal bundle power output	420 KW
Bundle maximum residence time	4 years
Average fuel burn-up	7000 MWD/TeU
Coolant	
Mass flow	4.54×10^4 kg/hr
Outlet pressure	94.2 kg/cm^2
Outlet temperature	293°C
Velocity	8.25 meters/sec

TABLE II

RAPS SHEATH MECHANICAL PROPERTIES

Longitudinal Tensile Properties	
Ultimate Tensile Strength	4920 Kg/cm^2
0.2% Yield Strength ($\bar{x} - 3\sigma$)	4000 Kg/cm^2
Elongation in 50 mm	20%
Closed-End Burst Properties	
Ultimate Hoop Stress	6310 Kg/cm^2
Total Circumferential Elongation ($\bar{x} - 2\sigma$)	15%

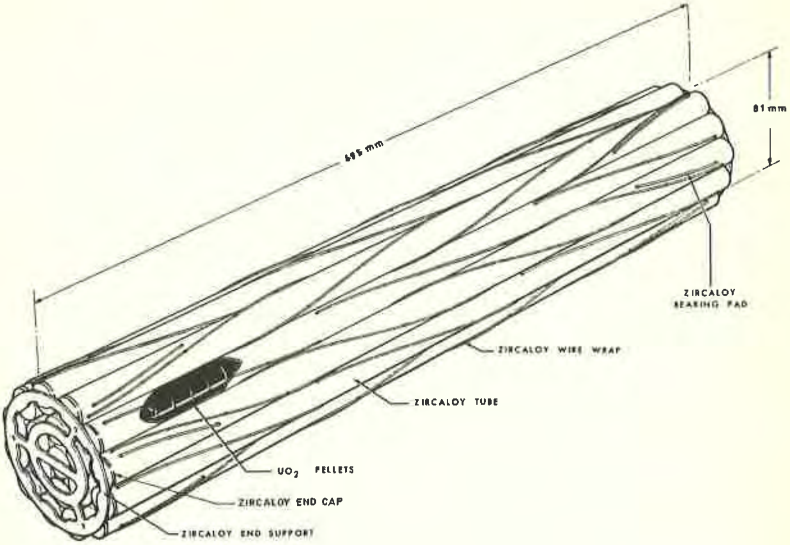


FIGURE 1 RAJASTHAN POWER PROJECT - FUEL BUNDLE

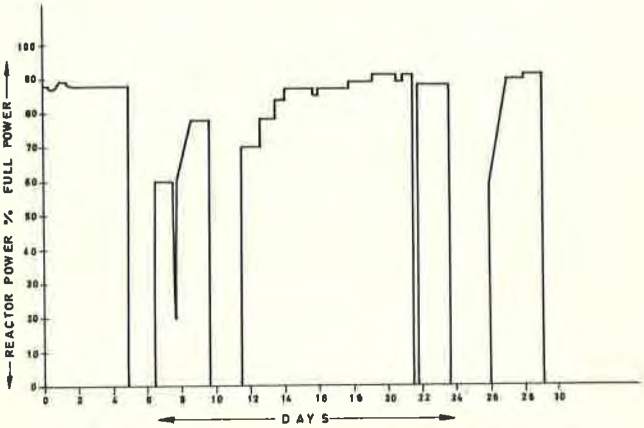
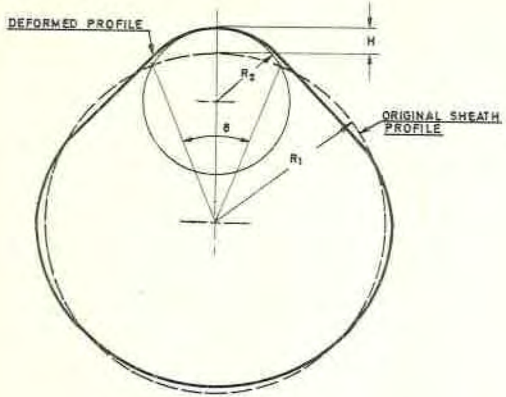


FIG: 2. REACTOR POWER VARIATION SHOWING TYPICAL POWER CYCLES FOR JUNE 1974.



$$e = \frac{t}{2}\left[\frac{1}{R_2} - \frac{1}{R_1}\right]$$

Where:

$$R_2 = \frac{(R_1 \sin \theta/2)^2}{2B} + \frac{B}{2}$$

$$B = H + R_1\left(1 - \cos\frac{\theta}{2}\right)$$

e = maximum sheath strain at deformation

t = sheath thickness

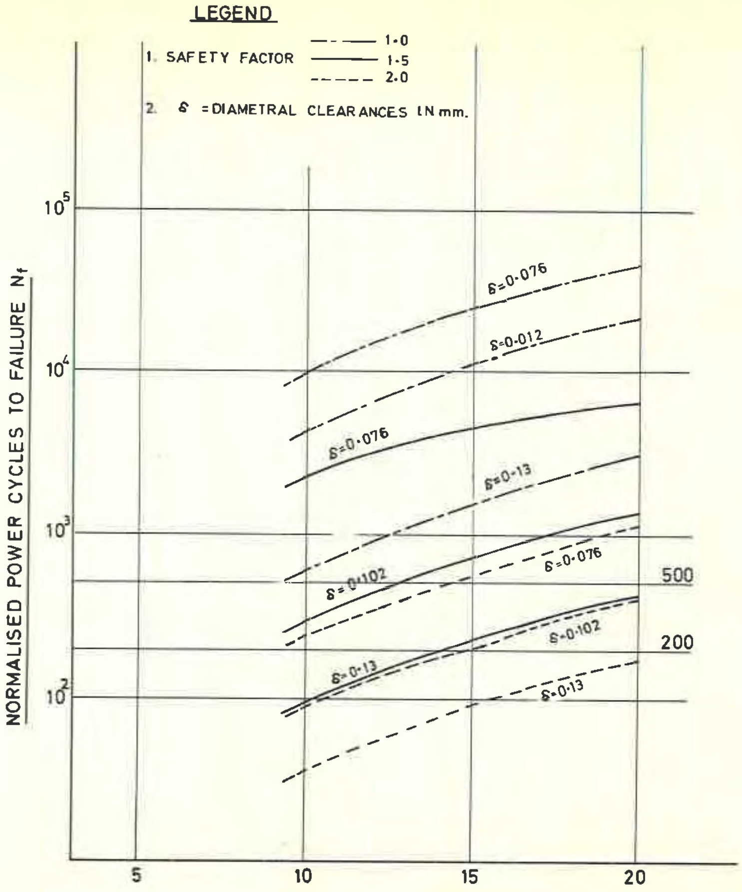
R_1 = original radius of curvature of undeformed sheath

R_2 = minimum radius of curvature at deformation

θ = angle subtended by deformation

H = height of deformation

FIG. 3. FORMULATION OF SHEATH COLLAPSE STRAIN



REDUCTION IN AREA RA%

FIG. 4-FATIGUE CHARACTERISTICS OF RAPS FUEL