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Performance Monitoring of Zircaloy-4 Square Fuel Channels at Taps - 1&2 / NPCIL

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Abstract

Tarapur Atomic Power Station is a twin unit Boiling Water Reactors. The rated initial capacity of each unit was for 210 MWe. Subsequently due to Secondary Steam Generator tube leak problem, the units were de-rated to 160 MWe in the year 1984-85. The station has completed 36 years of successful commercial operation. TAPS reactor fuel channels are made of Zircaloy -4, material. These are used along with 6x6 array nuclear fuel assemblies. The fuel channels need to be discharged once it reaches an optimum exposure limit and based on the surveillance programme, which monitors the channels performance. There are 284 fuel assemblies in each reactor. The fuel channel has a square cross section and it surrounds the fuel assembly. The channel is secured to the fuel assembly by means of channel fastener assembly. The fuel channel length is 158.625" and wall thickness is 0.060". NFC has indigenously developed fuel channels for TAPS and these are at various stages of exposure in both the reactor cores. The performance review of these channels was carried out by the expertise from TAPS-Site, NPCIL-ED and RED, BARC. The two major factors, which af1ect fuel channels performance, are (a) Bulge and (b) Bow. The phenomenon of longitudinal bow occurs due to the neutron flux gradient across the channels faces. Studies made on this subject by General Electric (GE) indicated that this channel def1ection occurs at a slow rate. Therefore, fuel channels surveillance programme is essential to check the irradiated fuel channels performance in order to replace the fuel channels once it reaches the optimum exposure limit. To estimate the useful life of irradiated fuel channels, channel def1ectionfbulge measurement inspection system and methodology was developed jointly by TAPS and Centre for Design and manufacture (CDM), BARC. This system was successfully deployed at TAPS. This paper briefly describes the developmental efforts made by Nuclear Fuel Complex (NFC), Hyderabad, NPCIL-Fuel Group, Engineering Directorate, RED/BARC, CDM/BARC.

Keywords: *Channel deflection, Channel fastener, Exposure, Bulge*

1. Introduction

In T APS- Boiling Water Reactors square fuel channels made of Zircaloy-4, material is used along with 6x6 array (7x7array) LEU fuel assemblies. Being reactor core component the fuel channel comes under critical nuclear core component category. The fuel channel has a square cross section and it surrounds the fuel assembly. The channel is secured to the fuel assembly by means of channel fastener assembly. Fig. l shows the general arrangement of fuel assemblies with channels & control blade. The fuel channels are exposed to neutron irradiation along with the fuel assembly. Therefore, the fuel channels need to be discharged once it reaches an optimum exposure limit, based on the surveillance programme, which monitors the channels growth/ change in critical dimensions.

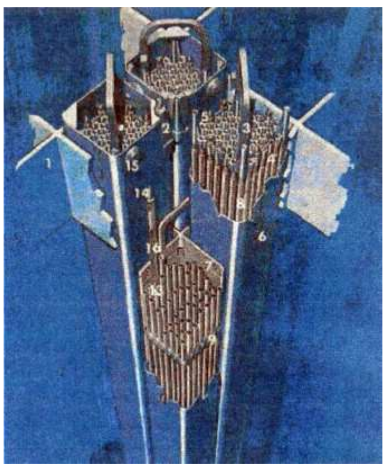

Fig. l: General arrangement of fuel I assembly channel & control blade

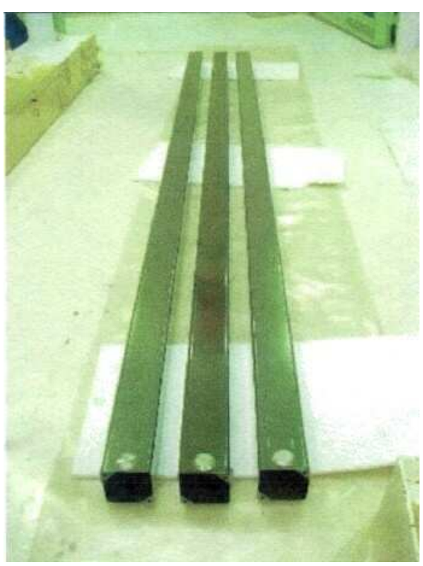

Fig. 2: TAPS square channels developed by NFC in seamless route

2. Functional Requirements

Each fuel assembly is contained in a Zircaloy-4 channel, which serves several functions. There are 284 fuel assemblies in each reactor core. The primary functions of fuel channel is (a) To direct the coolant to the fuel rods and to allow the leakage flow for control blade cooling (b) To maintain, in conjunction with the channel fastener assembly, the spacing between adjacent fuel assemblies (c) To provide guide surfaces for the control rods movement and (d) To provide the structural stability of the fuel assembly. The fuel channel is a square tube having 4.469"(1 13.5mm) outer width, length of 158.625" (4029mm) and wall thickness of O.060"(1.52mm). The channel is bolted to the fuel assembly upper tie plate by means of a channel fastener.

3. Fuel Channels - Manufacturing & Loading History

The fuel channels can be manufactured either through Seam Welded route or Seamless route. Initially GE had supplied seam welded fuel channels that were loaded in both the reactors cores with the initial fuel charge. Subsequently, fuel channels were imported from various manufacturers. All these fuel channels were manufactured and supplied in seam - welded route only. As on date most of these fuel channels were discharged after achieving the exposure limit of about 45 GWd/ST. In reactor the channel undergoes dimensional changes due to differential pressures, fast neutron exposure and high temperature creep. The fuel channels are monitored for its dimensional changes under plant surveillance programme and discharged from the core at appropriate time.

4. Need for performance monitoring

The two major factors, which affect fuel channels in-core performance, are: (a) Bulge and (b) Bow. The permanent channel deflection/bulge is primarily a function of (a) Pressure differential across the channel wall face (b) neutron flux (greater than IMeV) (c) mechanical properties and (d) fabrication process. This phenomenon is valid for all the fuel channels irrespective of their location in the reactor core. The phenomenon of longitudinal bow occurs due to the neutron flux gradient across the channels faces.

The consequences of permanent deflection/bulge are (a) an increase in by-pass flow as a result of increase in the area between the channel & lower tie plate of fuel assembly and (b) decrease in the clearance between control rod & fuel channel resulting in an increase in control blade friction. This affects reactor performance and safety parameters and hence critical review is required about the performance of irradiated fuel channels after each cycle of neutron exposure. The exposure of fuel assemblies and channels are expressed as MWd/ST (or GWd/ST). Studies made on this subject by GE [1] indicated that this channel deflection gradually increases with channel exposure. Therefore, fuel channels surveillance programme facilitates to check the irradiated fuel channels performance in order to replace the fuel channels once it reaches the optimum exposure limit.

5. Development & Manufacturing of Fuel Channels by Nuclear Fuel Complex, Hyderabad

The requirement of fuel channels was envisaged in the year 1997 for continued operation of both the units, beyond 25-years of commercial operation. Due to embargo, efforts for importing the required channels for T APS-l &2 did not succeed. NFC took up on priority the developmental activities of fuel channel fabrication in the year 1994. The manufacturing of these channels was initially tried in seam-welded route and dimensional controls were studied and reviewed. Being a developmental activity various agencies were involved such as TAPS-site, NPCIL (Engg. Directorate) as well as BARC (RED) in reviewing the specifications of developed channels & their effects on fuel performance and other core thermal hydraulic parameters.

During fabrication care is taken to control its dimensions by following detailed Manufacturing Engineering Instructions (MEI), systematic Quality Assurance Plan (QAP) and Quality Control Instructions (QCI). NFC initially started manufacturing the channels in seam-welded route. To study the performance, two channels were loaded initially in the reactor core. The performance of these channels was verified and found to be satisfactory. It is worth mentioning that NFC produces seamless tubes of various sizes of zirconium material as well as stainless steel and other alloys. Therefore, manufacturing methodology has already been well established over the years. Due to vast experience in seamless manufacturing technology available with NFC, development of fuel channels in seamless route was taken up subsequently. Fig. 2 indicates the seamless channels developed by NFC.

To study the performance of both the manufacturing processes, the representative channels from both the routes were loaded in both the reactor cores. The performance of these channels were verified in the subsequent outages and found to be comparable.

6. Parameters that Effect Irradiated Fuel Channel Performance

6.1 Pressure Differential, High Temp Creep & Fast Neutron Fluence

GE has earlier developed an analytical model, which was used to estimate in-service deflection of fuel channels. This model includes consideration of elastic deflection resulting from relaxation of fabrication stresses and in-service channel creep [1]. From the analytical model, it observed that maximum deflection does not occur at the bottom of the channel where the pressure across the wall is maximum, but it occurs at a position further up where the combined effect of pressure and fast neutron flux is maximum. Therefore, the fuel channels used in BWRs are known to have undergone outward deflection or bulging due to creep caused by the intense irradiation, high temperature and the constant differential pressure [3].

As the fuel channel undergoes creep deformation because of the pressure and radiation effect, the clearance between the fuel channel and the control blade decreases. The deformation is a very slow process and presents no significant problem during the useful life of the fuel channels. Fuel channel bulge, which is a result of fuel channel creep, if allowed to proceed unchecked could eventually create interference between the control rod & the fuel channels. This interference initially occurs at the axial location point of maximum channel deformation (about 48" from the bottom of channel), however, as creep continues, the distance over which interference occurs also increases. This interference is checked by CRD scram tests.

6.1.1 Recommendations of GE

GE indicated that the estimated incremental mid-span (across width) creep deflection of a Tarapur channels during one cycle of operation is 0.035 inches [2]. This incremental deflection would occur at the location of maximum deflection on the channel approximately 30 to 50 inches from the bottom of the channel. The cycle length used to estimate this value was core average bum up of 7GWd/ST. The incremental deflection for cycles of different length is approximately proportional to the change in the cycle accumulated exposures. Since the creep deformation is non- linear for the initial period of channel life, the incremental deflection during the first cycle is not considered for estimating the accumulated total channel deflection. GE recommended periodic inspections of channel deflection as an aid to prediction of future channel replacement requirements [4].

6.2 Channel Bowing Due to Differential Neutron Flux [5][6][7][8] - Phenomenon Other Than the Above

Longitudinal channel bowing results when fuel channels are irradiated in a region of the core having a sharp gradient in fast (> I MeV) neutron flux. This condition primarily exists in the core periphery where the fast neutron flux level on one side of a channel is significantly greater than the fast neutron flux on the opposite side of channel over an extended period of time. Under this condition a difference in channel side elongation occurs from irradiation growth and results in "Bowing" of the channel mid-span. Whereas cumulative exposure of channel affects its by-pass flow, the channel bowing due to unequal exposure along its faces affects movement of control blade. The bow associated with this peripheral effect is significant, and the magnitude is roughly the same, in the outer three rows (approximately 18") from the edge of the core. A method of measurement need to be developed and established to check the longitudinal bow of the channels, which occurs due to the phenomenon as explained above. This is again a developmental activity, which needs to be taken up subsequently with the various agencies such as CDM, DRH~ RED/BARC, NFC and NPCIL (Engg. Directorate).

7. Inspection Methodology Followed at TAPS

TAPS is monitoring the control blade "in & out" movement as well as SCRAM timings of each blade/control rod drive during the refueling outages. As per the recommendation of GE, TAPS has developed an inspection and testing techniques in the year 1978 to check the usability of the irradiated channels at the pre-determined exposures.

This method includes (a) under water visual examination and (b) dimensional stability check using fixed gauge (Go-No-Go gauge). Procedure-cum-guide lines were developed and are in use for the past 3-decades. The useful life of the irradiated channels is determined with respect to their dimensional stability. The fuel assembly exposure is considered as channel exposure. The design burn up of the fuel assembly is about 21GWd/ST and each fuel assembly would reside in the core for approximately three cycles, depending upon the core location and exposure. The channel also would be exposed to the same level of exposure i.e., 21GWd/ST and thereafter it is channeled on the next fuel assembly for further exposure. The performance of irradiated fuel channels is being monitored at regular intervals. The limits for discharge of exposed channels have been arrived at based on the guide lines provided by GE and as well as the experience gained by TAPS for the past three decades on fuel management. Since it is not possible to perform these inspections in the reactor core, the channels of interest along with the fuel assemblies are brought to the fuel storage pools. The fuel channel inspection is carried out by an approved procedure using remote handling systems to minimize the station man-rem consumption.

7.1 Visual Examination

In visual examination the channel surfaces are checked for any mechanical damage such as scratches and deficiency in channel fastener mounting etc (Fig. 3), In case of any major abnormality observed on channel outer surface, the respective channel is inspected by illuminating the inner surface with under water lights and keeping the outer surface under dark background (Fig. 4) . If the channel is acceptable, then the channel along with the fuel is put back in the core location based on the fuel management programme, provided that the channel cumulative exposure is within the limit.

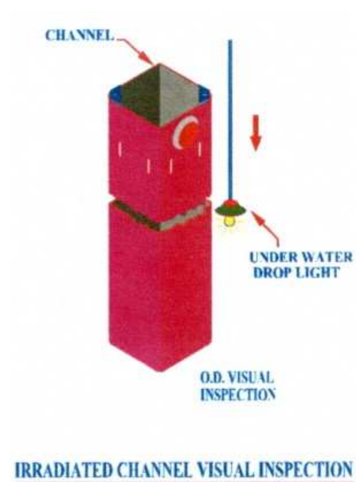

Fig. 3: Visual Examination of OD surface

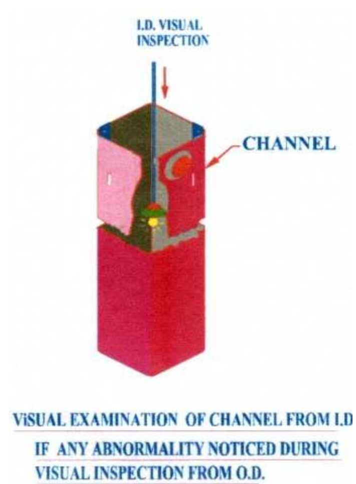

Fig. 4: Visual Examination of ID surface

7.2 Dimensional Stability Test

If channel exposure exceeds 20GW d/ST level, dimensional stability needs to be confirmed by passing the irradiated channels through a gauge. The go-no-go gauge developed by TAPS based on GE recommendations is shown in Fig. 5. In order to check the dimensional stability, the channel needs to be removed from the fuel assembly after removing the channel fastener and it is passed through the gauge. Fig. 6 & 6-1 shows the irradiated channel passing through go-no-go gauge. All these operations are performed under water using remote handling tools to minimize the man-rem consumption.

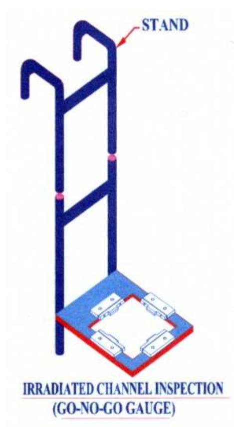

Fig. 5: General arrangement of go- no-go gauge

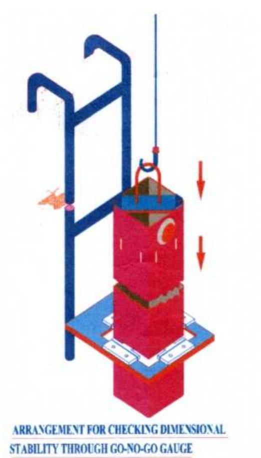

Fig. 6: Irradiated fuel channel testing in the gauge

Fig. 6-1: Dimensional stability) check of irradiated fuel channel in progress (Underwater)

However, this method only indicates that the channel's deflection is less than the gauge dimension and does not provide any information about the actual deflection with respect to the exposure levels. Therefore, it was necessary to develop a method for measuring the actual channel deflection/growth at different locations, which would be further useful in determining of "Channel Useful Life".

8. Co-relation Between Channel Exposure Vs Channel Deflection

It is necessary to establish the relation between the channel outer dimensions with respect to irradiation exposure levels. Presently, the inspection methodology followed at TAPS would not give the actual deflection of the irradiated fuel channel. It only gives that the channel deflection did not exceed the specified limit for further reactor use. Therefore, the irradiated channels in the range of 5 to 35GWd/ST are to be selected to establish the deflection pattern. Due to the limitation with the above method of checking, it was felt necessary to develop a non-contact ultrasonic inspection system, which measures accurately the channel dimensions, so that deflections can be compared with the predicted values. Also base I ine data will be generated and relation between channel deflection versus channel exposure can be obtained. It is also possible to extrapolate the channel deflections once this relation is established from the representative NFC channels.

9. Design of Ultrasonic Inspection System for Def1ection/Bulge Measurement

Considering the above requirements, an idea of under water inspection system with very high accuracy was conceived for measuring the external dimensions as well as wall thickness of the irradiated fuel channels. Subsequently, deflection-measuring device based on ultrasonic immersion technique was designed and developed by CDM, BARC. It is a non-contact, remotely operated device mainly consisting of ultrasonic probe holder assembly and channel guide roller mounting frame. There are total five UT probes fixed on the probe holder assembly and are located at the centre of the assembly. Fig. 7 & 8 shows the mounting arrangement ofUT probes on the assembly.

Fig. 7: UT probes (4) mounted on probe holder

Fig. 8: Probe holder mounted on column assembly

As the dimensions are to be measured under water having different water temperatures, an additional probe was installed to compensate the velocity changes. In order to compare the estimated channel deflections, a unirradiated test channel manufactured by NFC was used. Step thickness block was machined and installed on faces of the calibration sample to demonstrate the deflection ranges anticipated during the measurement. Fig. 9 shows the system calibration set-up prior to actual in-situ measurement.

10. In-situ Measurement of Irradiated Fuel Channels [10]

Some of irradiated (NFC make) fuel channels were selected for deflection/growth measurement having exposures ranging from 5000MWd/ST to 19000MWd/ST. A mock up facility was made for calibration of the inspection system prior to actual testing. The aim of measuring the channel deflection data is to predict the channel deflection after certain exposures~ say at an interval of 5,000; 10,000; 20,000MWd/ST so that the deflections can be extrapolated for cumulative exposures beyond says 35,000MWd/ST. Once this data is obtained, the useful life of NFC channels can be predicted and accordingly the replacement criteria can be formulated in the future. The measurements were made from channel bottom. Total 10 nodes were made and each node was separated by 6", therefore 4.5ft length of channel was covered during this measurement. Fig. 10 shows the irradiated channel that is being passed through the system. Fig. 11 shows the UT measuring instrument showing the water path. All the selected channels were inspected and channel outer width & wall thickness were measured. The measured values were evaluated and found to be within the expected limits of deflection/growth. There was no appreciable change in the wall thickness of irradiated channels.

Fig. 9: Mock-up facility used during calibration at site

Fig. 10:Dimension measurement of irradiated channel

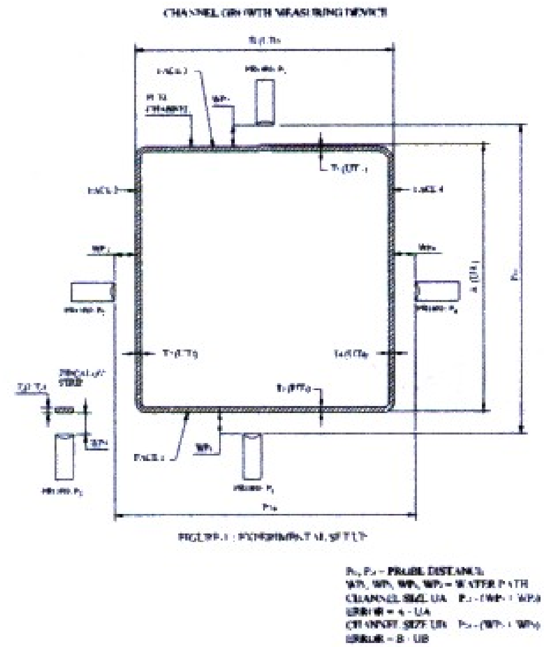

Fig. 11: Shows the general arrangement of probes (water path) & irradiated fuel channel

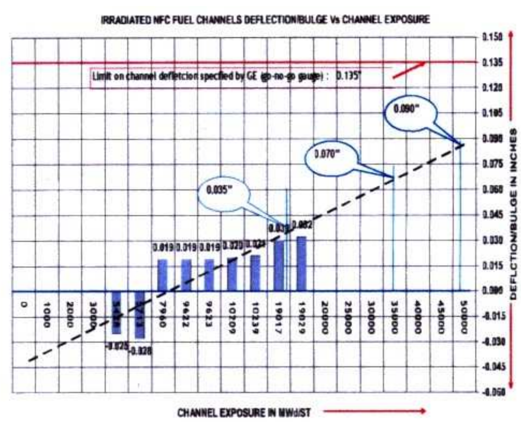

Fig. 12: Shows the relation between fuel channel exposures Vs deflection

The maximum deflection observed is about 0.032". Based on the data a graph was plotted between Deflection Vs Channel exposures. The estimated channel deflection at the end of 36GWd/ST exposure would be about 0.070'. GE specified the channel use should be limited up to a deflection limit of 0.150". Based on the projected values this limit would not be crossed by the channels manufactured by NFC even at an exposure level of

45GWd/ST (Fig. 12). This can be verified after checking the above selected channels after at the end of 36GWd/ST exposures. This is necessary to validate these data, which will be obtained later during the deflection measurements in the years to come.

11. Conclusions

Based on the limited inspection results obtained on the representative irradiated fuel channels, the performance of Zircaloy-4 fuel channels manufactured by NFC channels as measured by channel deflection measurements is found to be satisfactory. The channels behavior will be monitored during the subsequent exposures. The data is collected for different channels at the different exposures. Single fuel channel deflection data at different exposures will be available in the subsequent units operation, which will provide better information about the behavior of Zircaloy-4 fuel channels.

Further studies needs to be taken up before drawing firm conclusions. The measurements have been carried out only on NFC made channels. The measurements on channels manufactured by other manufacturers (GE, KOBE STEELS, MAN & HITACHI) are also needed for comparison. This is needed since we do not have full idea of the metallurgical state of Zircaloy-4, which controls all the properties.

12. Acknowledgements

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