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Quality Assurance of Post-Irradiation
Examination Measurements from
Nuclear Fuel Elements Examined at
Windscale Nuclear Power Development
Laboratories

by T. Davis

WINDSCALE NUCLEAR POWER DEVELOPMENT LABORATORIES

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For many years methods have been available to enable a manufacturer to guarantee that his products are being made within certain definable limits which are of interest to himself or to the buyer of the product. These 'Quality Control' techniques have been particularly useful in revealing peculiarities or abnormalities in sets of measurements of parts from repetitive operations in the engineering industry or in tests from the operation of continuous plant.

The providers of experimental and scientific data are also required to demonstrate that the quality of the data meets specified standards of accuracy and reproducibility. As an example in the UK it is proposed that post-irradiation measurements on fuel elements from two laboratories should be combined in a single data bank and each laboratory needs to be satisfied that the two sets of data are of comparable quality. Eventually data from the combined data bank will be used in a number of ways, eg in the definition of irradiation limits which in turn requires some qualifying statement of accuracy.

The provision of quality assurance data can be time-consuming. In this paper methods relating to post-irradiation examination of fuel elements are described which aim to minimise the amount of work required and indicate how the results are being used.

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1. INTRODUCTION

The accurate, reproducible and consistent measurement of the principal dimensions of irradiated uranium bars, is an essential part of the post-irradiation examination of uranium-Magnox fuel elements. (Appendix 1 defines the terms "accurate, reproducible and consistent").

Since 1956, measurement at the Windscale Nuclear Power Development Laboratories has been carried out by radiographing fuel elements, measuring the radiographic images of the bars using simple optical aids and applying a factor to the results to obtain an estimate of the true dimensions. Measurements of the radiographic image are now being made automatically using a Radiograph Measuring Machine and at the same time, new X-radiography equipment has been brought into operation, replacing obsolete equipment which was at the end of its useful life.

This document sets out the steps being taken to ensure that the required standards of accuracy, reproducibility and consistency are maintained, with the new system in operation.

2. BACKGROUND

Measurement of irradiated uranium bars by the radiograph technique involves four main stages. These are:

- (i) making the radiographic exposure,
- (ii) processing the exposed film,
- (iii) measuring the image on the film,
- (iv) estimating the bar dimensions from these measurements.

At present it has not been established how reproducibility and consistency are dependent upon film exposure conditions or upon the manner in which the film is processed, so, for the time being at least, these conditions have been optimised to provide acceptable radiographs and then held constant. The confidence in the system's overall ability to produce reproducible and consistent results depends upon the clear demonstration that the image on the film can be adequately measured and that a firm basis exists for estimating the bar dimensions from these measurements.

In principle, the method is straightforward. The dimensions of the image on the radiographic film are related by simple geometry to the dimensions of the actual uranium bar. However, the most satisfactory way of obtaining consistent results is not by calculation from first principles but by calibration against radiographs of bars of known dimensions.

The way in which these calibration and quality control methods are carried out will now be detailed keeping in mind that they will be required to:-

- (i) provide a factor which will relate the dimensions taken from the radiograph to a real dimension of the uranium bar - the calibration factor.
- (ii) show how this factor varies with time - the stability of the system,
- (iii) show that the variability of the measurements is within acceptable and stable limits.

3. CALIBRATION METHODS - THE MAINTENANCE OF STANDARDS

The results of measurements on standard measured bars can most usefully be presented in the form of quality control charts which allow for the values of calibration factor or other parameters to be displayed and assessed on a continuing basis. By allowing trends to be examined it becomes possible to take corrective action at the earliest possible moment.

A control chart consists of a central line and two pairs of limit lines spaced above and below the central line and usually referred to as the Inner Limits and the Outer Limits. Some prior knowledge is required to allow these lines to be drawn - it is necessary, for example, to have sufficient data available to allow a well defined estimate of the population mean and variability to be calculated which will become the basis for subsequent comparison with similar estimates based on smaller samples of data. If necessary the original control lines can be modified as more data become available.

Two likely kinds of variation in the control parameter may arise. The first will be shown as either long or short term changes of a systematic nature to which some actual cause can be assigned and some action taken to correct. The second relates to chance causes which may be many in number but which contribute to the total variation; they are inherent in the system and are difficult to estimate but nevertheless must be assessed to make sure that no marked change arises.

The procedure is as follows. A standard measured unirradiated bar in a can with appropriate end fittings is introduced to the radiograph machine in a 'normal' manner and X-rayed. The element is rotated twice through 60° and re-radiographed each time. The element is then removed completely from the radiograph machine. The radiographs are processed and the dimensions of the bar measured on the reading machine.

The above procedure is repeated, removing the element after each set of 3 X-ray shots and re-introducing it for the following group of shots until, initially, 15 sets of radiographs are available for assessment. If the radiographs are acceptable, a value for the diameter of the uranium bar image is produced approximately every 2.5 cm along the bar as well as a measurement of overall length. The actual dimensions of the measured bar are known to a high degree of accuracy and do not vary significantly along the depth of the bar, so the readings from the radiographs can readily be used to provide calibration factors which allow the real dimensions of irradiated bars to be determined in further work.

As a result of these preliminary procedures, about 40 measurements of bar diameter are available on a fuel element; there are 45 (ie 15 x 3) sets of data covering variability associated with placing the element in the chucks of the radiograph machine and with rotating the element, as well as the ability of the radiograph reader to make reproducible readings.

When irradiated elements are being measured the average bar diameter taken over the three angular rotations is used as a parameter to define the condition of the bar at each axial position along the bar. It seems appropriate therefore that this should also be used as a parameter for quality control purposes and therefore we have 15 such values - one for each set of 3 radiographs - for every axial position on the bar.

The 15 sets of measurements as read from the radiograph are subject to variation and a mean value (\bar{x}) and standard deviation (σ) based on these 15 readings can be calculated. (Each 'reading' being the average obtained from 3 rotations). The values of \bar{x} and σ are our best estimate of the population values and are used to calculate limit lines on the assumption that a normal routine sample of data will contain less than 15 readings.

It can be shown that if individual observations are distributed around a population average \bar{x} with a standard deviation σ then the averages of samples each containing n individuals drawn from the population at random are distributed around \bar{x} with a standard deviation of σ/\sqrt{n} . Even if n is as low as 5 the distribution of sample averages can be assumed to be closely normal and this allows the probabilities associated with the Normal Distribution to be used. Thus only 1 sample mean in 20 is likely to be outside the limits $\bar{x} \pm 2.13 \sigma/\sqrt{n}$; again only 1 in 500 will be outside the limits $\bar{x} \pm 3.73 \sigma/\sqrt{n}$. (The values of the constants 2.13 and 3.73 are related to the size of the batch of data used to assess \bar{x} and in this case 15).

A similar presentation can be made for sample standard deviations or ranges. Here the best estimate of the population standard deviation is obtained from 15 values and this provides the central value. The upper and lower control limits are obtained by multiplying the central value by constants depending on the value of n and the levels of control chosen. For $n = 5$, only one sample standard deviation in 20 should lie outside the limits 0.85σ and 4.20σ and 1 sample standard deviation in 500 should lie outside the limits 0.37σ and 5.48σ . A set of typical data is given in Appendix 3.

4. CALIBRATION PROCEDURES

Calibration shots should be taken before each investigation, and at the end of one investigation if another investigation is not to follow immediately, using the standard measured bar.

It would clearly be desirable to be able to carry out calibration measurements in the middle of an investigation but here difficulties arise because the chucks holding the element in the radiograph equipment are specific to each element design. To use the standard bar referred to above, in most cases, would require chucks to be changed which is not desirable. It is therefore proposed that an element of the same type as involved in the particular investigation should be

available and checked at least once per week or every 20 experimental elements as an intermediate sub-standard. The readings made on the standard bar before and after a full investigation will remain the main basis for continued quality control.

The standard bars against which calibrations will be checked are in elements obtained from BNFL Springfields and are described in Appendix 2.

A permanent record of all calibration results will be maintained and will include presentation of the appropriate data in the form of quality control charts and also statements, as required, of any changes which may be made to operational procedures and equipment.

5. DISCUSSION

An appreciable amount of effort will be required to collect and present the quality assurance data as described above. It may be possible with experience to reduce the number of shots below the 15 proposed but only if it can be demonstrated that one or more of the sources of variability assumed to contribute to the total variability is small.

The most likely sources of variability which can be identified are the ability of the radiograph reader to take a particular reading, the effect of rotating the element when being radiographed and the effect of actually placing the element in the chucks of the radiograph equipment. There can be up to 40 readings along the length of a standard bar and it can be assumed, for the time being at any rate, that the bar diameters do not vary along its length. There are only three levels of element rotation and the 5 re-insertions of the element are just about the minimum acceptable if this source of variability is to be identified.

Fortunately techniques are readily available which allow the questions raised above to be examined and a decision to be made either to reduce the total amount of effort involved or to suggest a different balance of effort between the number of levels of 'rotation' compared with the number of levels 'replacement' (see reference to paper by Wilkie).

CONCLUSIONS

The measurements being made to provide calibration factors and quality control with radiography equipment recently commissioned at the Windscale Nuclear Power Development Laboratories have been described. This required that a standard bar should be radiographed 15 times before each investigation and occasionally in the middle of a particular investigation. It is suggested that data arising as part of this exercise should be regularly monitored to ensure that effort is being efficiently used.

Reference

WILKIE D. A method of mixed level factorial experiments Appl. Statistics, 1962, vol. 11, no. 3, p 184.

APPENDIX 1

Some Definitions

Certain terms in this document are used in the senses defined by Davies* as follows:

Accuracy: correctness or truth, ie closeness of agreement between the experimental value and the true value. (It is usually impossible to ascertain the true value).

Reproducibility: A method of high reproducibility is one capable of yielding closely concordant results in replicate analyses. These results, while showing a small variation among themselves, do not necessarily vary about the true value, so that a method may be reproducible without being accurate.

Error: A divergence from the truth which arises from causes inherent in the analytical method eg from the fact that a burette can be read, at best, correct to one-fifth of a division.

Mistake: A divergence arising from an unintentional departure from the usual procedure, eg a misreading of a burette, a copying mistake, etc.

Random error: An error which individually is unpredictable but whose average tends to zero in the long run. If a length is measured to the nearest scale division on a ruler graduated in millimetres, the error on one occasion may be anything between + 0.5 and - 0.5 mm, but the average of a long series of such measurements will be virtually correct.

Bias, or systematic error: An error which persists during a series of the same or similar measurements or analytical determinations and which is therefore not eliminated by any process or averaging. The total error of any measurement may contain both a bias and a random component; averaging several measurements reduces the random component, but does not affect the bias.

In addition, the term consistency has been used to mean that several sets of results on different samples, each set showing high reproducibility although not necessarily high accuracy, would stand in the same quantitative relationship to one another if those sets of measurements were repeated.

The term precision has been avoided as being superfluous and potentially ambiguous.

(* Davies O L et al. "The design and analysis of industrial experiments". P104. Published by Oliver & Boyd, London and Edinburgh 1956).

APPENDIX 2

Standard fuel elements and measured bars

Fuel elements incorporating measured bars have been made up for most reactors to act as standards for establishing magnification factors and maintaining quality control. The bars were measured at BNFL Springfields using a micrometer calibrated with gauge blocks certified by the Standards Laboratory at SNL and results on each bar are available at 7 axial positions with 3 readings at 60° at each axial position. Bars were chosen to cover the range of bar diameters and lengths that exist but the different end fitting designs were also taken into account.

The bars were inserted in the appropriate cans after measuring and the end fittings attached but not welded. The elements were not heat treated or pressurised. If it is necessary, at some future date to check the measurements on the rods using the same bench techniques the elements can be dismantled and the uranium bars removed.

APPENDIX 3

Typical set of quality assurance data

In the Table a set of typical reading machine values is quoted. These are actual readings from the machine and a reading of about 850 corresponds to the real bar diameter of 1.1025 in. (2.300 cms). The readings refer to a particular axial position.

REPEAT	ROTATION			Mean	Group of 5 x, σ	Overall group of 15, x, σ
	1	2	3			
1	848	848	848	848.8	$x = 848.93$ $\sigma = \pm 0.596$	$x = 848.22$ $\sigma = \pm 1.12$
2	850	848	850	849.3		
3	848	850	850	849.3		
4	850	850	848	849.3		
5	848	848	850	848.7		
6	848	846	850	848	$x = 848.67$ $\sigma = \pm 0.943$	
7	846	848	848	847.3		
8	848	850	850	849.3		
9	850	850	848	849.3		
10	850	850	848	849.3		
11	848	846	846	846.7	$x = 847.07$ $\sigma = \pm 0.76$	
12	850	846	848	848		
13	846	850	846	847.3		
14	848	846	848	847.3		
15	846	846	846	846		

Inner and Outer Limits

Mean	Inner	847.2 and 849.3
	Outer	846.4 and 850.1
Std. deviation	Inner	0.95 - 4.69
	Outer	0.41 - 6.12

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