2.1.

RISØ

August-1989

SPECIAL PIE TECHNIQUES AT RISØ

by C. Bagger, M.Mogensen and P. Knudsen

Metallurgy Department
RISØ National Laboratory
DK-4000 Roskilde Denmark

To be presented at the plenary meeting of the CEC Working Group "Hot Laboratories and Remote Handling" on 27-28 September 1989 , Karlsruhe.

SPECIAL PIE TECHNIQUES AT RISØ.

Three large internationally sponsored fuel projects have been launched by RISØ during the period 1980-1989 to investigate the behaviour of high burnup fuel in power transients. Directly related to the projects, techniques have been developed for refabricating short lengths of irradiated power reactor fuel pins for further irradiation in test reactors, instrumenting the test fuel rodlets with pressure transducers and -in the Third RISØ Fission Gas Project - additionally with fuel centerline thermocouples. New hot cell techniques, such as on-line pore analysis and x-ray fluorescence analysis of Xe[1], have been established and used with existing methods to provide radial or diametral distributions of porosity, volatile fission product concentrations, grain boundary gas[2] and average grain size.

The present paper describes first the refabrication technique used for inserting fuel centerline thermocouples in spent fuel and secondly the on-line image analysis system.

1. REFABRICATION WITH THERMOCOUPLES

In a typical RISØ experiment, a short, instrumented length of an irradiated power reactor pin is submitted to a programmed change of fuel power in the DR3 reactor, while the fuel temperature and the internal gas pressure are monitored.

The general requirements to the refabrication from the Third RISØ Fission Gas Project were:

1) Use fuel that has accumulated significant burnup in commercial power reactors.

2) Use fresh termocouples for the measurement of fuel temperature to avoid decalibration problems. Temperatures should be measured up to 2000 °C if possible.

3) Place the thermocouple hot junction in the fuel axis in a depth of about 4 pellet heights (40-45 mm) from the top end.

4) Maintain the original pellet fragment configuration in the irradiated fuel throughout the refabrication procedure.

5) Avoid contamination of pellet cracks and fuel-cladding gap with particles from the refabrication.

6) Avoid heat induced restructuring of fuel and avoid redistribution/release of volatile fission products.

7) Backfill the refabricated test fuel pin with any desired fill gas composition and pressure.

Requirement 6) points to a cryogenic drilling technique and terminated otherwise successfull experiments with laser drilling. 4) and 5) suggest utilization of an impregnating material, which can fill out all voids during drilling, "gluing" pellet fracments together, and which can be completely removed after production of the center hole. No chemical interaction between fuel and impregnating material is of course allowed. Early experiments with fluorocarbons were terminated because of the risk of introducing stress corrosion enhancing

elements. CO_2 was selected in favour of Kr and Xe because it can be handled as a liquid at room temperature and 60 bar while it is gaseous at 1 bar. At the relevant temperatures no interaction with fuel components is suspected.

The disintegrated pellet structure in high burnup fuel necessitates a reinforcement of the inner wall of the thermocouple hole to avoid collapse, when the impregnation material is removed,. Molybdenum was chosen to clad the walls of the fuel center hole, because it resists chemical attack from the hot fuel. Molybdenum is usually used as thermocouple sheath for high temperature measurement in UO_2 but is too brittle to allow handling of the thermocouple by master slave manipulators. Introduction of molybdenum as a separating layer between hot fuel and the thermocouple gave larger freedom in selecting the sheath material for the W/Re thermocouple. Tantalum was chosen because of ductility and commercial availability.

Several years of development fulfilled all requirements by the below procedure:

a) Cut a short segment from a longer, irradiated power reactor fuel pin. The long fuel pin has been characterized as far as possible.

b) Remove fuel from both ends to provide volumes for insulator pellets, plenum and end plugs.

c) Remove cladding oxides (inner and outer) at positions for subsequent welding.

d) Mount and weld a lower end plug, shaped as a mini valve for later evacuation and backfilling with gas.

e) Mount a special spring sleeve in the new plenum which will guide a hollow core drill at a later stage.

f) Mount and weld an upper end plug, shaped as a thick walled tube.

g) Check fuel stack homogeneity by gamma scanning.

h) Impregnate the fuel rod with liquid CO_2 at room temperature (pressure app. 60 bar).

i) Cool down the impregnated fuel pin to liq. N_2 temperature and keep the pin at low temperature during the following operations j-k.

j) Drill a 2.5 mm dia. hole 40-45 mm into the fuel stack with a hollow core diamond drill, through the center of which is passed liquid N_2. Centering of the drill at the top end of the fuel stack is accomplished by the spring sleeve (e).

k) Mount a 2.5 mm OD molybdenum tube in the fuel hole. The tube is closed at the bottom.

l) Allow the pin to return to room temperature in a pressurized system, melting the dry ice.

m) Slowly leak off the CO_2 which evaporates at pressures below 60 bar.

n) Check fuel stack homogeneity and hole depth by gamma scanning, carry out profilometry if required.

o) Bake out remnants of CO_2 in vacuum, 300 ^{o}C, 72h.

p) Assemble the fuel pin with an instrumentation section, which acts as an extra top plug. The instrumented section carries a pressure transducer and a Ta-clad W/Re thermocouple, the latter protruding from the bottom end. During the assembling the thermocouple slides into the Mo-tube inserted in the fuel and the instrumented section seats on the upper end plug.

q) Weld the instrumentation section to the fuel pin.

r) Evacuate the fuel pin through the bottom plug valve, refill with gas of selected composition at elevated pressure several times with intermittent evacuations. Finally fill to selected pressure.

s) Close the bottom plug valve and seal weld it.

t) Check function of the instrumentation.

u) Ship for reirradiation.

The refabrication procedure outlined has by now been used succesfully for 12 tests, 10 of which are included in the Third RISØ Fission Gas Project. Generally a refabrication lasts between 20 and 30 calendar days in the hot cells, to which should be added the time necessary to produce and test the instrumentation section (p-q) in a cold laboratory. A significant part of the time is waiting time; end plugs cannot be completed to measure until the refabricated pin has reached a stage where the necessary measurements can be taken; preparation for drilling lasts half a day, the drilling itself may last 10 minutes, while return to room temperature lasts the rest of that day plus the following night; bakeout lasts 3 days; the length of the instrumentation section has to be precisely adapted to the depth of the hole drilled, etc.

Fig. 1 shows a longitudinal section of the first test fuel pin refabricated along the above guidelines. The test fuel pin (46 GWd/tU) was transient tested, including a 24h hold at 37 kW/m. During this hold the fuel temperature was about 1550 °C. Fig. 2 shows a longitudinal fuel section sampled close to the refabricated fuel length after base irradiation. Comparison of Fig. 1 and 2 shows that refabrication did not disturb the cracking pattern and the relative positions of fuel fragments significantly.

The irradiation performance of the refabricated tests has been satisfactory for short term reirradiation, typical overpower tests lasting up to 6 days. No experience exists with long term reirradiation. Fuel temperatures in excess of 1900 °C have been measured but led to failure of the thermocouple after some time because of mechanical damage caused by fuel interaction (heavy deformation of Mo tube and thermocouple sheath). Fuel temperatures up to 1600-1700 °C are considered to be "safe" for the thermocouple in relation to the power ramps experienced. Slower power changes might extend the operational temperature range. Insertion of the thermocouple from the bottom end of the fuel stack would minimize differential axial movement between thermocouple and fuel and would so be expected to extend the operational temperature range of the thermocouple as well. This was not possible in the present case because of the design of the irradiation facility.

Fig. 3 gives an impression of results obtained from reirradiation of a test fuel pin, refabricated with a pressure transducer and a fuel centerline thermocouple. The gas release curve shown was derived from the hot pressure curve.

2. ON-LINE POROSITY ANALYSIS

A computer based image analysis system has been established in direct connection to the shielded microscope. The main objectives of the system are to extend porosity analysis to 100% of the fuel diameters being examined ceramographically, to decrease the cost of photography for pore analysis and to produce results, while the sample in examination is still on the microscope stage.

Previously a number of radial fuel positions (typically 5-7) were photographed at magnifications x100 and x400. From enlarged copies the perimeter of each pore was traced manually, recorded and treated electronically to give local porosities and porosity size distributions. The procedure was labour demanding with a considerable time elapsing between preparation of sample and feedback of information necessary for further examination and photographic documentation. Consequently samples often had to be reprepared and large numbers of photographs were actually wasted by documenting fuel structures of little interest. Furthermore it was often felt that important pore size variations in a sample could be missed as a result of the small number of porosity analyses in more or less fixed radial positions with relatively large intervals.

In order to improve this examination field so important for fission gas release studies, a relatively inexpensive (20.000 ECU) analysis system has been developed and attached directly to the shielded microscope. Porosity is now analyzed by a personal computer operating on sample images, acquired from the microscope with a solid state television camera and a frame grabber. The frame grabber (print card in the PC) transforms the analogue camera image into a digital bitmapped image of 512x512 elements (pixels), which is displayed on an attached colour monitor; each pixel is represented by a gray scale value in the range 0(black)- 255(white). The contrast of the image can be adjusted during the conversion. The digital gray-scale image is transformed into a binary image (pixel value 0 or 1) after interactive selection of the gray scale threshold which separates objects (pores) and background (fuel matrix). The binary image may easily be edited. Small fuel cracks and other objects not to be included in the analysis (e.g. grain pullout) are deleted and separating lines between agglomerated pores may be inserted. Computer software tracks the circumference of each pore and calculates the pore area by planimetry. The area is converted to equivalent pore diameter and classified in 17 logarithmically increasing pore size intervals from 0.5-127μm. Results in the form of pore size frequency histograms may be shown on the monitor and compared to "standard" distributions (e.g. pore size frequency histograms from base irradiated fuel) after each point analysis and gives an instantaneous tool for acceptance/rejection of the individual analysis.

The typical operator time invested per point of analysis is between 1 and 2 minutes. The analysis sequence is repeated up to 120 times along a fuel diameter, depending upon magnification and fuel dimensions. Images are generally taken adjacent to each other, omitting only cracks occupying more than 10% of the image area. Typical image parameters are given in Table 1. The location of an image on a sample radius is automatically read from the microscope stage control. The area position on the sample, given as the

fractional radial position, and other basic text information such as sample name, date of analysis and file name is overlaid the microscope image on the monitor. This composite image may be transferred to high resolution video tape (Super-VHS) for cheap storage.

Pore analysis of a complete fuel diameter lasts between two and four hours and gives instantaneous feedback to further examination and documentation work. Diameters are usually examined at two magnifications (Table 1), the low magnification analyses improving the statistics for larger pores (20μm). Upon completion of the measurements the data acquired with the two magnifications are merged and the resulting 2D size distribution is converted to a 3D volume fraction distribution. The output of the calculations is formatted to be fed to standard spredsheet programs for further analysis and plotting.

Fig. 4 shows an example of porosity analysis along a transient tested fuel radius, giving the radial distribution of porosity in the pore interval 0.7-2 μm and of total porosity. In Fig. 5 local measurements of relative fission product release (^{137}Cs from micro gamma scanning and Xe from X-ray fluorescence measurements) are shown together with the distribution of small porosity in the same radial interval (Fig. 4). The porosity curve has been normalized to minimum and maximum values for ^{137}Cs release.

As can be seen there is proportionality between fission product release and swelling in the actual pore size interval, a correlation which would not have been evident without the mass accumulation of porosity data in the narrow radial band shown.

REFERENCES

1. M.Mogensen, J.Als-Nielsen and N.H.Andersen, Determination of Fission Products in Irradiated Fuel by X-ray Fluorescence, RISØ- M-2599, RISØ National Laboratory, 1986.

2. M.Mogensen, P.Knudsen and C.T Walker, "Fission Gas Release Mechanisms Operating in Water Reactor Fuel Power Transients" in Improvements in Water Reactor Fuel Technology and Utilization, Proc. IAEA Symposium, Stockholm, September 15-19, 1986, pp.291- 303, Vienna, 1987.

TABLE 1

Image Parameters for the On-Line Porosity Analysis System

Standard True Optical Magnification	63	252
Image Magnification on Monitor	630	2520
Sample Frame Length, μm	400	100
Pixel Dimension, μm x μm	1.3 x 0.9	0.3 x 0.2
Lower Pore Area Size Limit, μm^2	8	0.7

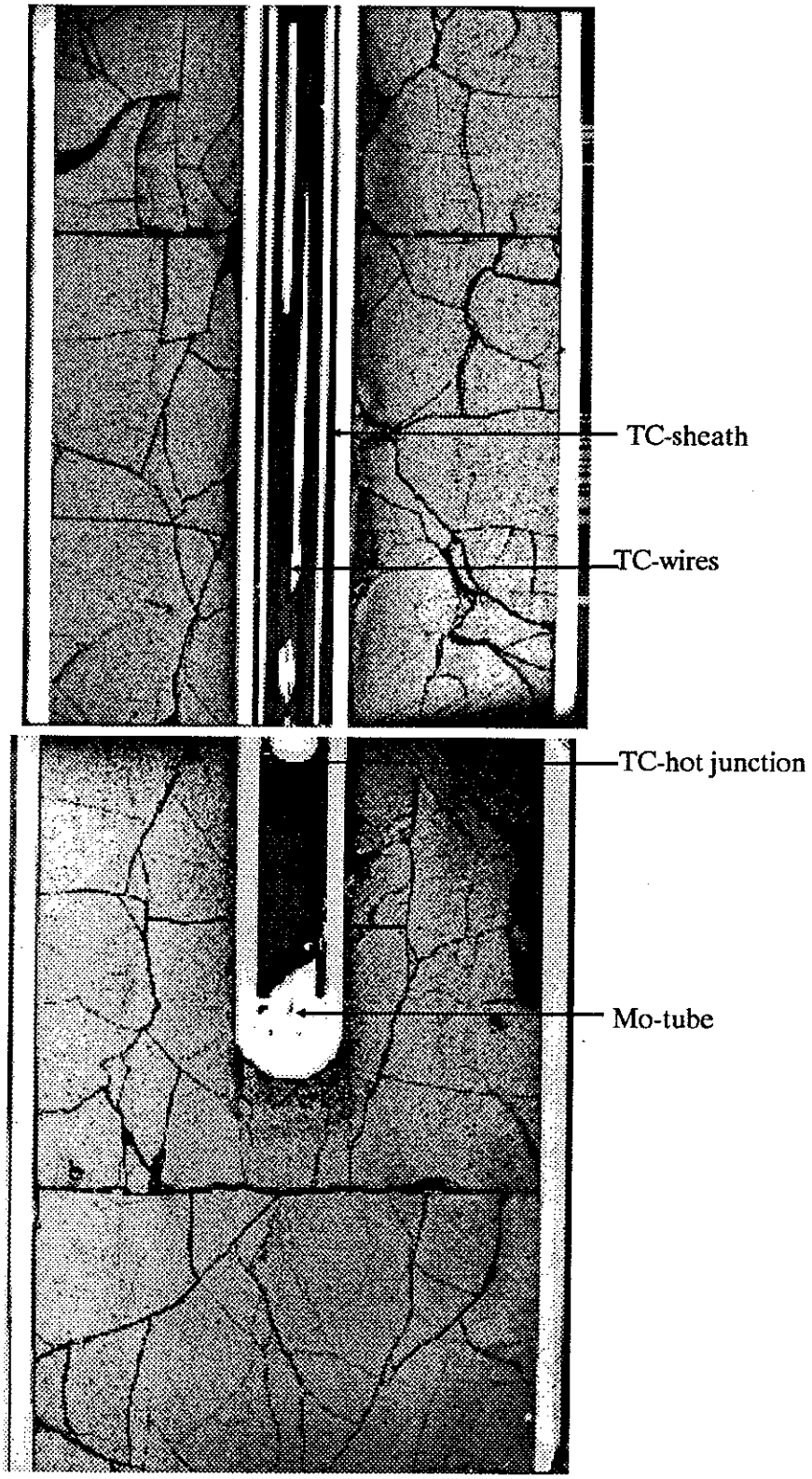

Fig. 1. Longitudinal sections at inserted thermocouple in prototype test fuel pin. Burnup 46 GWd/tU, transient tested to 37 kW/m, 1550°C.

Fig. 2. Longitudinal fuel section taken close to that of Fig. 1 after base irradiation to 46 GWd/tU.

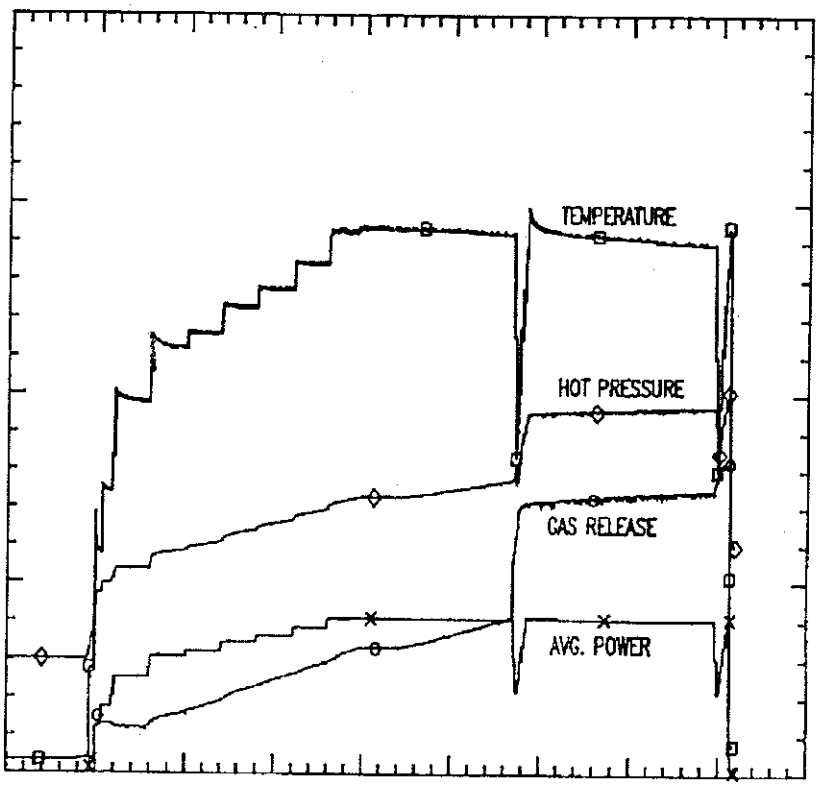

Fig. 3. Example of in-pile measurements obtained with a refabricated pin. The gas release curve was calculated from the hot pressure measured.

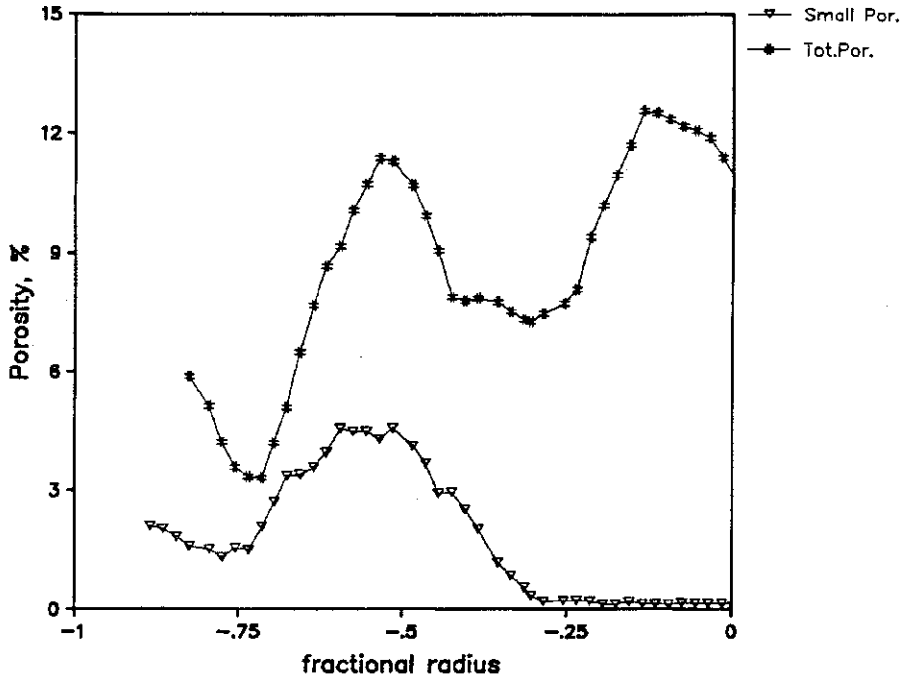

Fig. 4. Radial distribution of small porosity (pore size interval 0.7-2μm) and total porosity after transient testing, measured by the on-line analysis system.

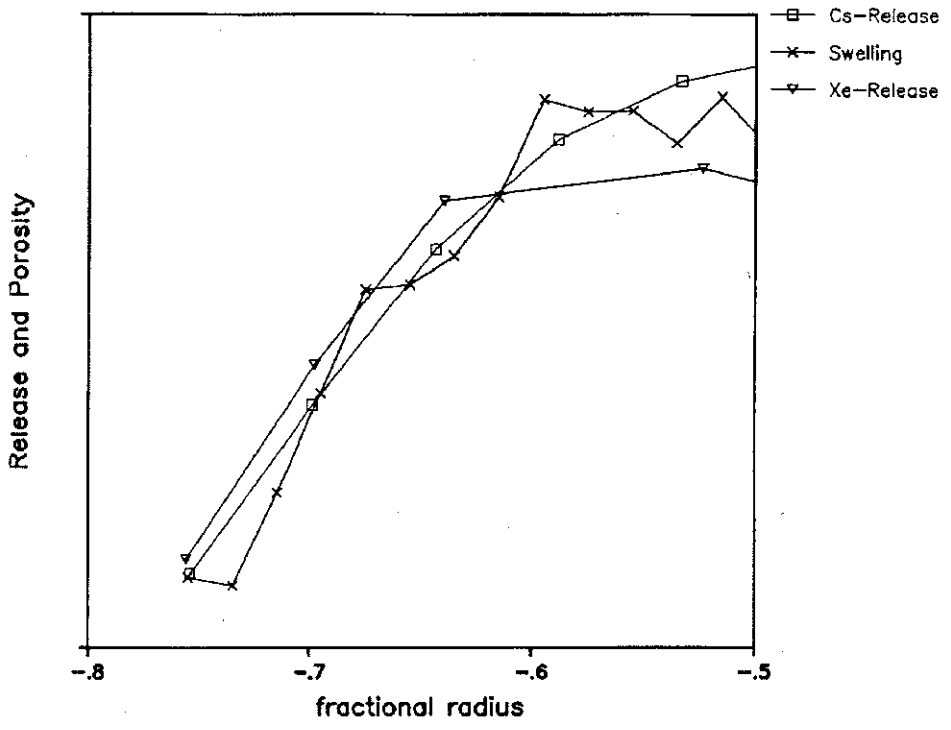

Fig. 5. Part of radial distribution of relative fission product release (Xe by X-ray fluorescence, ^{137}Cs by micro gamma scanning) and small porosity (Fig. 4) . The porosity curve has been scaled to the minimum and maximum ^{137}Cs release values.