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Testing of LWR Fuel Rods To Support Criticality Safety Analysis Of Transport Accident Conditions

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Abstract

For the transport of low enriched materials, criticality safety may be demonstrated by applying pessimistic modelling assumptions that bound any realistic case.

Where Light Water Reactor (LWR) fuel is being transported, enrichment levels are usually too high to permit this approach and more realistic data is needed. This requires a method by which the response of LWR fuel under impact accident conditions can be approximated or bounded.

In 2000, BNFL and COGEMA LOGISTICS jointly commenced the Fuel Integrity Project (FIP) whose objective was to develop such methods. COGEMA LOGISTICS were well advanced with a method for determining the impact response of unirradiated fuel, but required further test data before acceptance by the Transport Regulators.

The joint project team extensively discussed the required inputs to the FIP, from which it was agreed that BNFL would organise new tests on both unirradiated and irradiated fuel samples and COGEMA LOGISTICS would take major responsibility for evaluating the test results.

Tests on unirradiated fuel rod samples involved both dynamic and quasi-static loading on fuel samples. PWR fuel rods loaded with uranium pellets were dropped vertically from 9m onto a rigid target and this was repeated on BWR fuel rods, similar tests on empty fuel rods were also conducted. Quasi-static tests were conducted on 530 mm long PWR and BWR fuel specimens under axial loading.

Tests on irradiated fuel samples were conducted on high burn-up fuel rods of both PWR and BWR types. These were believed original to the FIP project and involved applying bending loads to simply supported pressurised rod specimens. In one test the fuel rod was heated to nearly 500°C during loading, all specimens were subject to axial impact before testing.

Considerable experience of fuel rod testing and new data was gained from this test programme.

Introduction

Demonstration of criticality safety under normal and accident conditions is essential for packages transporting fissile materials. In many cases, the quantity of such materials, allow very pessimistic assumptions to be applied to the criticality safety case. Because of the inherent high reactivity of Light Water Reactor (LWR) fuel, this approach is not normally acceptable and consequently specific fuel parameters must be assessed in conjunction with the fuel support system. In practice, the combined impact response of both support system and fuel must be understood before the criticality safety assessment can be completed. Impact responses of the fuel support system can be demonstrated by test and analysis but the behaviour of the fuel is more difficult to assess. However, understanding the response of fuel to impact became an increasing requirement of the Transport Regulators due to its influence on criticality safety. In order to respond to the Transport Regulators, the Fuel Integrity Project (FIP) was initiated and recognising common objectives became a joint BNFL and COGEMA LOGISTICS project. Both companies worked independently on this subject before deciding to work together, sharing knowledge and experience, then building from this to meet our common goal.

As the joint project developed, COGEMA LOGISTICS undertook the major responsibility for analysis whilst BNFL took responsibility for managing the agreed programme of new test work, as described in the following paper.

Background to Fuel Integrity Project

Criticality safety analysis for packages transporting both new and irradiated fuel assemblies must consider:

a. Fuel in new unirradiated condition ie original enrichment.
b. Damage and distortions from IAEA regulatory accident conditions.
c. Potential release of fissile material.

There are many designs of LWR fuel assemblies but in simple terms, most modern designs comprise of an array of zirconium alloy tubes (pins), each loaded with a stack of enriched uranium oxide pellets.

Fuel designers will decide on the diameter and spacing of the pins to achieve a level of reactivity but usually the array is designed to be 'under moderated' which means the reactivity could increase with an increase of the pitch between adjacent pins. Conversely, reactivity may actual fall as the pins move closer together and moderator is displaced.

Although, a uniform increase in pin pitch is an extremely unlikely result from an impact, this must be considered and evaluated.

A further significant consequence of an impact during transportation could be that one or more pins fail and fissile material is released from the break. Currently, some analysts allocate a percentage to the number of pins that fail in an array and consider all the fuel in these pins is released. It can be assumed this fissile material forms a 'sludge' of the most reactive density, which may settle in any part of the fuel array and thereby influence criticality safety.

Although the consequence of such scenarios may be evaluated by established criticality safety codes, such methods cannot determine the number of pins that fail or how much material is subsequently released. Bounding the number of failed pins and fissile material release was a key objective of the FIP.

The Fuel Integrity Project concerns the response of both unirradiated and irradiated LWR fuels during a transport impact accident. However, when analysing criticality safety for irradiated fuel payloads, new fuel parameters must be used, and no account of burn-up usually permitted.

Nevertheless, this only applies to the fissile parameters and the effects of irradiation on component material must be considered. For example, zirconium alloys typically experience a significant loss of ductility during irradiation in a reactor.

Objectives of Fuel Integrity Project

Soon after initiation, the joint BNFL and COGEMA LOGISTICS project team agreed the scope of the project, inputs from each party and the overall objectives.

a. The FIP was to focus on the impact response of both irradiated and unirradiated fuel during transport, but not the response of the fuel support frame.

b. Existing data on material properties and impact data were to be shared.

c. The FIP objective was to develop a method, based on test and analysis results, which would **bound** criticality safety case assumptions. **Precisely** determining geometry changes to LWR fuel elements under impact was not an objective, as this was considered highly problematical.

d. COGEMA LOGISTICS was to share its Simplified Impact Methodology (SIM) with BNFL.

e. BNFL were to project manage the agreed test programme and COGEMA LOGISTICS would take the lead in analysing the data obtained.

f. Criticality Analysis techniques were outside the scope of the collaboration.

Test Work

The principle objective of this paper is to outline the test work that provided the data necessary to support and progress the FIP. Essentially, test work was divided into two areas.

1. Unirradiated Specimens
2. Irradiated Specimens

In both cases, the specimens were either fuel rods, or lengths of fuel rod. No other fuel element components were tested within the FIP, although COGEMA LOGISTICS contributed their existing test data, previously conducted on simulant fuel assemblies and component parts. Correspondingly, BNFL contributed data from compression tests conducted on irradiated zirconium cladding hulls (Test Series 8). Such data was of particular relevance when determining the scope of FIP test work, in many cases the test objectives being to reinforce and extend existing test data.

Static Tests on Unirradiated Samples

A number of the tests on unirradiated samples were directly aimed at establishing parameters to be applied in the SIM.

Consequently, a series of quasi-static tests was devised to examine the individual and combined effects of the pellets and cladding under axial loading. In effect, to quantify the fraction of inertial loading which translates in to radial deflection of the specimen.

All 18 specimens provided for these tests were taken from full-length fuel rods manufactured by a qualified production process. The tests specimens were cut to an overall length of 530mm including the welded bottom end plug, nine were taken from BWR fuel rods and nine from PWR fuel rods, the cladding material being Zr-2 and Zr-4 respectively.
Outside diameter of the PWR cladding was 10.74 mm and the BWR cladding 12.54 mm. Three of each type were empty of fuel, whilst the remaining PWR and BWR test specimens were loaded with natural uranium (NU) and depleted uranium (DU) respectively. Choice of the pellet material for each specimen was purely arbitrary being determined by those installed in the fuel rods from which the specimens were taken. In both cases, pellets were manufactured to a qualified production process and ground to precise dimensions.

Figure 1 shows the schematic arrangement of the tests, effectively a series of compressive loads on strut configurations with pinned ends, allowing free rotation in one plane.

Initial tests were conducted on empty tubes whilst subsequent tests were on cladding tubes loaded with pellets, Table 1 gives the test schedule.

Test Series	Load N	No	Description
1	F1	3 PWR 3 BWR	Loads Applied On End Of Cladding Tube, No Pellets Fitted
2	F2	3 PWR 3 BWR	Loads Applied On End Of Cladding Tube, Pellets Fitted
3	F3	3 PWR 3 BWR	Load Applied On Top Of Pellet Stack

Table 1 – Schedule of Static Tests

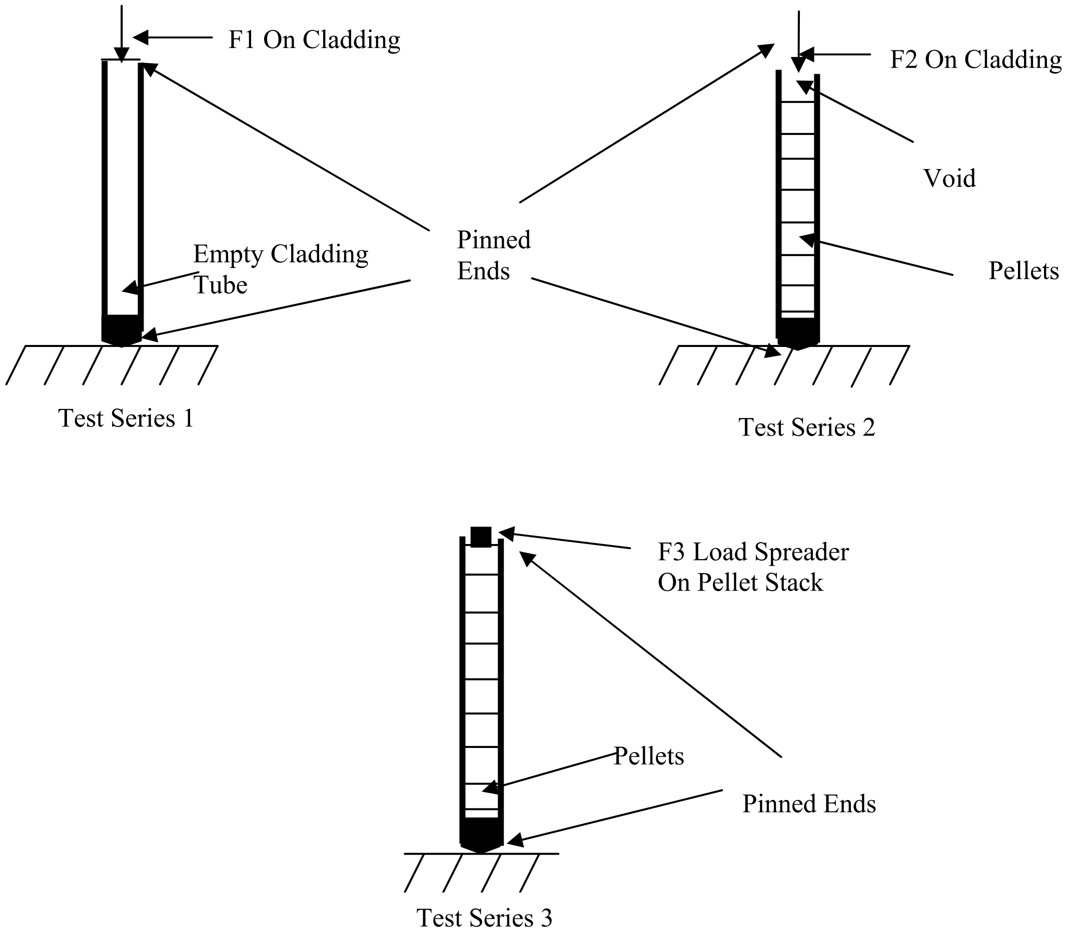

Figure 1 - Loading Arrangements - PWR and BWR Specimens – Not to Scale

Each specimen type was tested three times during which the loads and resulting deflections were recorded throughout the test. Test series 1 and 2 were fitted with strain gauges positioned to measure in the plane of maximum deflection. Testing was deemed complete when the total deflection (bow) reached 120mm and 80mm for the PWR and BWR specimens respectively. Upon reaching the specified deflection, the load was gradually reduced leaving residual deflections of approximately 75mm and 45mm for PWR and BWR specimens respectively.

Test series 1, 2 and 3 were successfully completed, yielding consistent results.

Dynamic Tests on Unirradiated Specimens

Dynamic tests were an essential part of the FIP as these would confirm SIM parameters, in addition to directly providing the following impact response data:

a. Length to which distortion will extend along the rod in a severe axial impact

b. Potential for cladding/weld/plug failure in a severe axial impact

Test specimens were from the same batch of fuel rods from which the specimens for the static tests were taken. As before, the BWR fuel rods were loaded with DU pellets and the PWR rods with NU pellets except for specimens that were tested without any pellets installed. Full-length fuel rods were used for all the dynamic tests and were loaded with pellets, pressurised to 20 and 5.5 bar, for PWR and BWR respectively.

A decision was made to ensure the dynamic tests were severe and consequently the specimens were to be dropped from a height of nine metres on to a rigid target.

In order to accurately replicate the support provided by spacer grids, the fuel rods were installed inside a module, which was then dropped with the rod inside. Using this method, radial supports for the fuel rod were provided at axial locations corresponding to the grid positions.

The module was guided on to the rigid target without shock absorption but a load cell was positioned between the bottom end plug of the fuel rod and the solid steel impact cone, fixed at the centre of the module end plate.

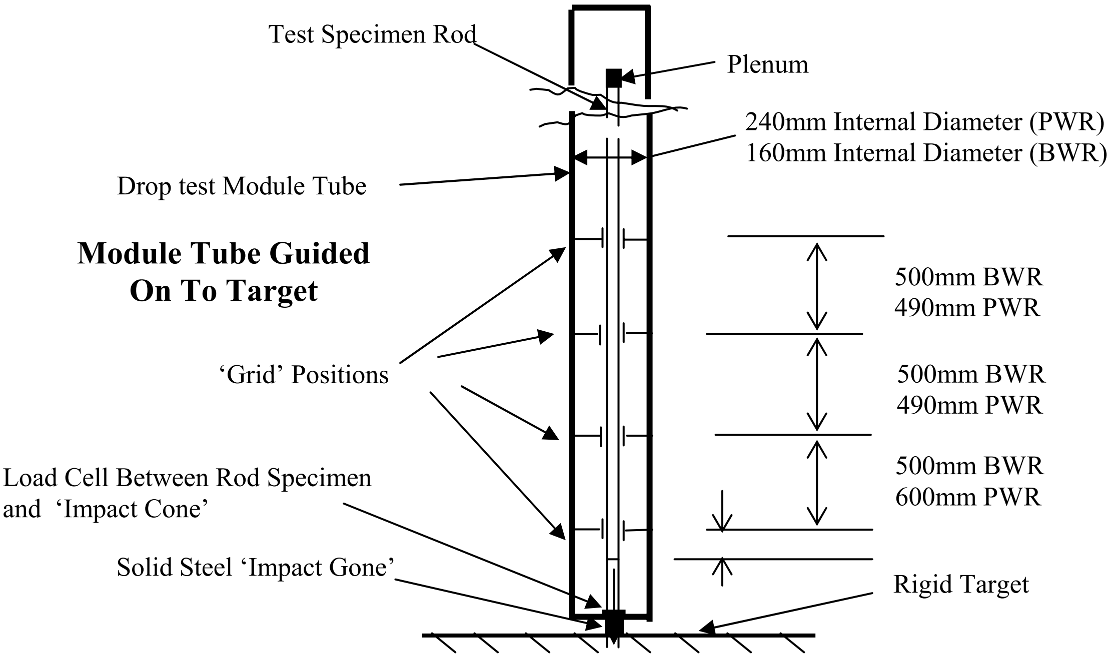

Figure 2 - Arrangement of Dynamic Drop Test Module – Not to Scale

Figure 2 shows the schematic arrangement of the test module and fuel rods during the dynamic tests. In all dynamic tests, the module was dropped from a height of nine metres, measured from the lowest point of the impact cone and the target. Two diameters of modules were used, set to represent the potential lateral deflection limit of PWR and BWR fuel rods in their respective compartments during transport. A single load cell was used to record the time/load relationship during the impact event.

The following table gives the schedule of tests in the order they were carried out;

Test No	Specimen Type	Description
6.1	PWR (Nat U)	9m drop - rigid target
6.2	PWR (Nat U)	9m drop - rigid target
6.3	PWR (Nat U)	9m drop - rigid target
7.1	PWR (empty)	9m drop - rigid target
6.5	BWR (Dep U)	9m drop - rigid target

Table 2 – Schedule of Dynamic Tests

Tests were designated as series 6 or series 7 for loaded and empty fuel rods respectively.

All dynamic drop tests on the PWR fuel rods were successfully carried out with no failure of the bottom end plug, cladding or weld, as demonstrated by helium detection systems. In all cases, the permanent lateral deflection of the fuel was less than 20mm, with no plastic deformation evident anywhere on the rod, except near to the lower end.
The one corresponding test on the BWR fuel rod specimen (Test 6.5) gave similar results.

Note;-

Test Series 4;- Variations on the described static tests but not actually carried out, being considered unnecessary due to the consistent data obtained from test series 1, 2 and 3.

Test Series 5:- Simple tests to measure the coefficient of friction between unirradiated pellets and cladding are not discussed in this paper.

Test Series 8;- Compression loading tests on irradiated cladding – see paper presented by COGEMA LOGISTICS

Tests on Irradiated Specimens

Determining the optimum test programme on irradiated specimens was a difficult process because of the need to balance the limited specimen availability and the substantial testing costs against the value of the data obtained.
It was totally impractical to obtain specimens to meet pre-specified parameters and so the FIP had to make use of what was available. Fortunately, BNFL owned a number of complete and undamaged PWR and BWR zircalloy clad fuel rods of typical European and US design, these being destined for reprocessing but became available to the FIP. All specimens were approximately 50GWd/t burn-up from four operating cycles and a minimum of 20 years cooled.
Owing to the size of hot cell facility where the tests were to be conducted, full-length rods could not be used, hence test specimens were cut to approximately 600mm and fitted with the appropriate adapters and plugs. All specimens, except for Test Series 12, were taken from the central, hence, highest burn-up, section of the fuel rod.
After much discussion and consultation by the project group it was agreed that the most efficient use of resources would be from static tests because high speed tests, although feasible, were considered technically complex and may only result in limited data.
As a compromise, it was decided to subject a number of the test specimens to an axial impact before being statically loaded, this being called pre-conditioning.

Pre-Conditioning Irradiated Specimens

Experience from Post Irradiation Examination (PIE) work had consistently shown that fuel pellets became bonded to the cladding during irradiation and despite cracking, the pellets, were difficult to remove, even using power tools. Despite this, the FIP decided that the test programme should include a means of shock loading some specimens to investigate the consequence to material release, in effect would the pellet material become loosened or break up?

The pre-conditioned operation would provide shock loading by means of an axial impact into a stiff target at a speed of approximately 10 m/s, this being the maximum speed the specimen could be accelerated in the cell.

Out of cell calibration tests were undertaken on a range of wood samples to determine the one most appropriate to be the shock absorber. A dummy specimen fitted with accelerometers and of representative mass was being dropped from 5m on the samples to determine the relationship between wood properties and acceleration. Consequently a hardwood sample was selected giving an indentation of around 2mm and a corresponding average acceleration value of around 2500g. Shock absorbers were made from the same hardwood stock sample and fitted in to a device shown in Figure 3.

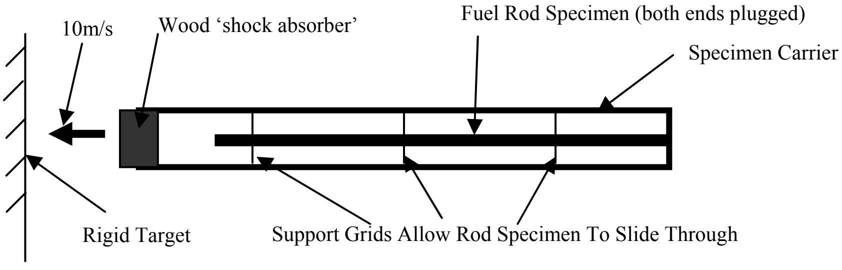

Figure 3 – Schematic Arrangement of In-Cell Pre-Conditioning System

The specimen carrier is accelerated to 10m/s, then released in ‘free flight’ on to the rigid target causing the rod specimen to impact into the wood shock absorber. It was not practical to eliminate the use of a shock absorber as a rigid impact may have damaged the end of the specimen rendering it unfit for further use.

Overview of Tests on Irradiated Specimens

These tests were conducted by AEAT in their facility at Sellafield using an Instron calibrated loading machine in a hot cell. AEAT were consulted on all aspects of the test programme, providing essential advice on the feasibility of testing proposals.

Consequently a test programme was developed making the most efficient use of resources whilst providing the maximum range of data for subsequent analysis purposes. Test results, together with data from the FIP material property data-base, would be used to develop analytical model to cover a broader scope of deformation scenarios.

The initial series of tests devised was designated Test Series 10, and involved the axial loading of sections of irradiated fuel rod cladding. Each section being cut to the length of one pellet after the position of the pellet interfaces had been located using gamma spectroscopic scans. Axial loads were applied through a hardened adapter ensuring the load was distributed over the cladding circumference, see Figure 4.

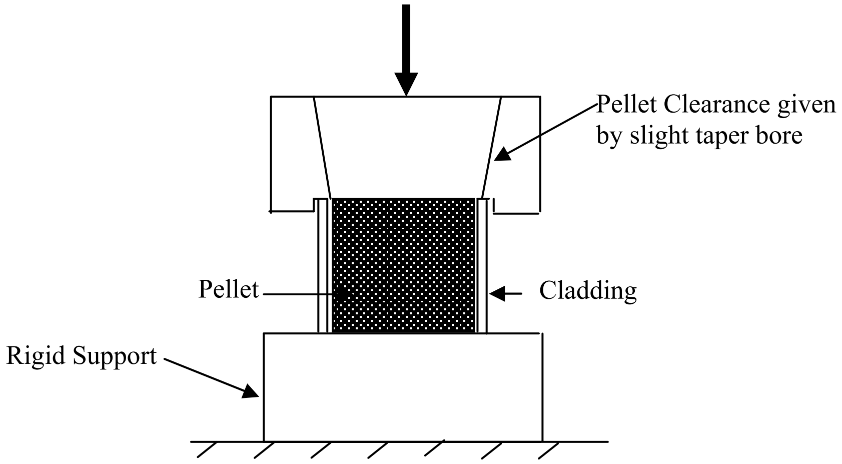

Figure 4 – Test Series 10 - Schematic Arrangement

Further tests, designated Test Series 11, were a series of bend tests on specimens in a beam configuration with a span of 479 mm. At each end, the rod was rigidly supported by a built-in arrangement that prevented rotation but allowed the ends to slide during deflection.

A single point load was applied incrementally at mid span until the specimen broke into two pieces. Loads and displacements were continually monitored and the mass of released material was recorded, see Figure 5 (considerable simplified !).

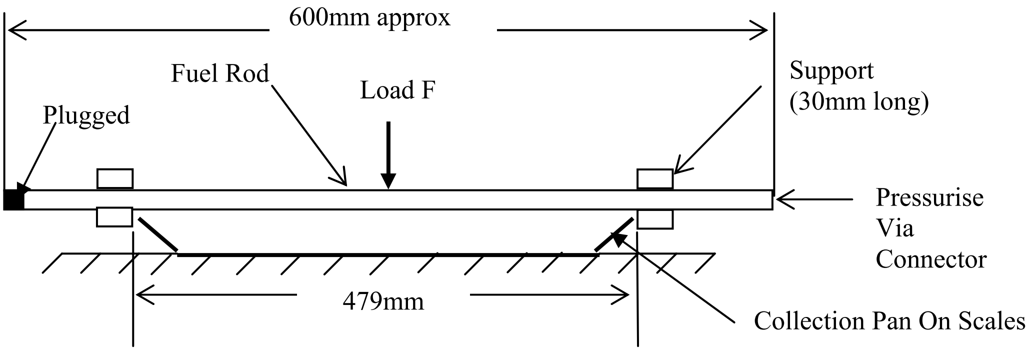

Figure 5 - Schematic Arrangement of Test Series 11

Test series 11 comprised of six separate tests involving both PWR and BWR specimens under a range of pressures.

A connection at one end enables the rod to be pressurised with helium gas up to 130 bar where required. The schedule of Series 11 tests is given in Table 3;

Test No	Pressure Bar	Temp °C	Pre- Conditioned	Description
11.1	0	24	No	Initial development trial on simplified test rig
11.2	50	24	No	PWR specimen
11.3	50	24	Yes	PWR Specimen
11.4	130	27	Yes	PWR Specimen – Strain gauged
11.5	130	500	Yes	PWR Specimen
11.6	50	25	Yes	BWR Specimen

Table 3 – Schedule of Series 11 Tests

The final tests on irradiated specimens were designated Series 12 involving two tests. Both were conducted on BWR specimens with identical test parameters except one rod had been pre-conditioned with an impact directly on the bottom end plug, the second specimen had not been pre-conditioned. These test were devised to examine the influence of bending loads being transmitted via the bottom end plug during the collapse on a BWR fuel assembly under axial impact. Such a consequence had been demonstrated by tests and analysis conducted by COGEMA LOGISTICS. A significant feature of these tests was to study the behaviour and characteristics of the cladding and pellets at the lowest burn-up region on the fuel rod.

Incremental loads were applied directly to the plug in an upward direction to ensure the fracture would occur on the underside and released material would fall on to the collection tray. Loads were applied until the plug was completely detached from the cladding.

A schematic arrangement of test series 12 is given in Figure 6.

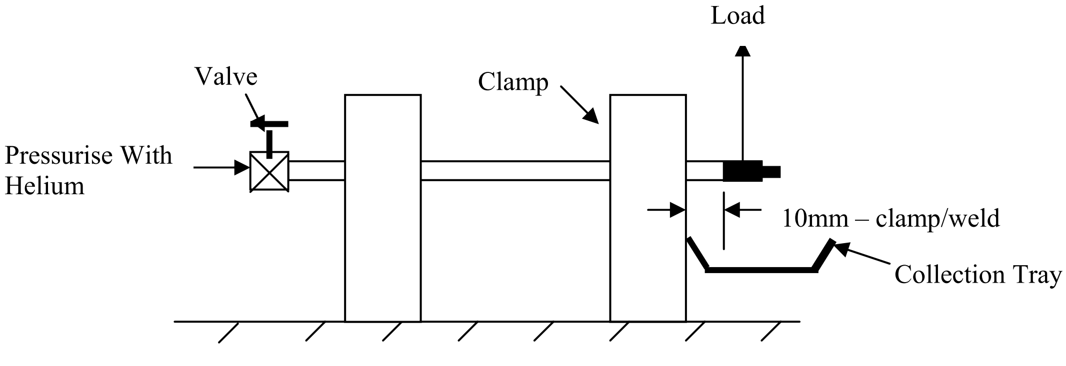

Figure 6 – Schematic Arrangement of Test Series 12

The schedule of Series 12 tests are given below in Table 4;

Test No	Pressure Bar	Temp C	Pre-Conditioned	Description
12.1	100	25	No	BWR Specimen, 10mm overhang
12.2	100	24	Yes	BWR Specimen 10mm overhang

Table 4 - Schedule of Series 12 Tests

Tests on Irradiated Specimens – General Observations

The test work outlined above yielded substantial data for analytical model validation.

No test result gave cause for concern and correlated well with predictions.

Results from test series 11 proved to be consistent in respect of load/displacement characteristics and showed that the pre-conditioning procedure had no discernible effect on the mass of released material.

Pressure in the specimens also had no apparent influence on the load/displacement characteristics nor on the quantity of released material.

Strain gauge data from test 11.4 initially gave useful data but as the specimen neared failure the gauge adhesion was lost. This was probable due to the highly brittle oxide coating on the specimen surface which tended to fail before the cladding. This was very evident from the test series 10 where under load, the oxide coating was observed to craze and fall away as the loads increased.

Very little plastic deformation was evident from any of the tests, except for Test 11.5. Here the specimen was heated to 500°C and approximately 50% more deformation at failure was witnessed compared with cell temperature tests. Load at failure was about 20% lower than the tests conducted at cell temperature and considerable residual plastic deformation was evident.

Test series 12 showed more deformation at failure than test series 11 and release of fissile material was noticeable greater, this being as predicted.

Releases of fissile material from both test series 11 and 12 were very low giving substantial margins over previous assumptions applied to criticality safety analysis.

Conclusion

A very successful programme of tests resulting in valuable new data to support the analytical phase of the FIP.

Most significantly, the test work revealed no surprises and no reason for fresh concerns over the current assumptions concerning fuel responses under impact.