



**Summary –
Fuel Assembly Design Modification to
Incorporate a Stopper – E0083**

**Prepared By
Australian Nuclear Science and Technology Organisation**

19 December 2007

Page 1 of 11

1	INTRODUCTION	3
2	APPROVAL REQUESTS.....	3
3	THE EVENT AND SUBSEQUENT WORK PROGRAM	4
	3.1 Fuel Fault Event	4
	3.2 Work Program	4
4	DESIGN OF THE STOPPER AND THE FUEL ASSEMBLY.....	6
	4.1 Design Features	6
	4.2 Flow Loop Tests.....	7
	4.2.1 Standard design tests	7
	4.2.2 Modified design tests	7
	4.3 Design Review & Risk Assessments	8
5	KEY FACTORS CONSIDERED IN ESTABLISHING THE ROOT CAUSE.....	8
	5.1 Approach	8
	5.2 Operations	8
	5.3 Other Environmental Conditions in the Reactor	9
	5.3.1 Fuel Assembly Clamps	9
	5.3.2 Vibration	9
	5.3.3 Oxide layer thickness and fuel plate heating	10
	5.4 Fuel Assembly Design.....	10
	5.5 ROLL-SWAGING.....	10
	5.6 Summary of Considerations	10
6	LESSONS LEARNT AND PROCESS IMPROVEMENTS.....	11
7	CONCLUSION	11

1 INTRODUCTION

This document provides an assessment and summary of a large work program that encompassed investigations into the OPAL research reactor fuel fault and a modification of the fuel design to prevent recurrence of the fault.

The submission to ARPANSA, “*Fuel Assembly Design Modification to Incorporate a Stopper*”, requests approval for use of a modified fuel design and operation of the OPAL reactor using fuel that incorporates that design.

Due to the size and complexity of the work program, this document presents, necessarily in a summarised form, a description of the various work projects that were undertaken.

This document discusses and explains:

- The process undertaken during the work program to investigate the abnormal fuel event and to prepare a design modification that will eliminate recurrence of the event;
- The main outcomes from the projects undertaken by ANSTO and the design authority INVAP;
- A summary of the design of the stopper, key findings from the design review, the testing undertaken to verify the design and the consequences of postulated abnormal conditions for the stopper and the fuel assembly;
- A summary of the event investigations and the root cause; and
- Lessons learnt and the incorporation of process improvements for operation.

2 APPROVAL REQUESTS

Approval is sought from the Chief Executive Officer (CEO) of ARPANSA to:

1. Modify the OPAL fuel design and,
2. Operate the OPAL reactor using fuel manufactured or modified to that design.

The submission “*Fuel Assembly Design Modification to Incorporate a Stopper*” (E0083) contains information that supports this request. The reason a modification to the fuel design is being requested is due to the identified fuel fault event at the OPAL reactor.

If the approval is granted, the nuclear fuel to be loaded and used for subsequent operating cycles will incorporate “stoppers” specifically designed to limit longitudinal movement of fuel plates within the fuel assemblies. The stoppers provide a defence-in-depth feature that prevents significant fuel-plate displacements from fuel assemblies.

The proposed design has been thoroughly tested and evaluated, including flow-loop tests that exceeded conditions that would be experienced in the reactor. Design reviews, risk assessments and technical analyses have been undertaken to support the safety of the design modification.

If approval is given, operation of OPAL would recommence using a replicate of core number 1, using 13 special fuel assemblies with lower uranium mass in conjunction with three standard fuel assemblies. All these fuel assemblies incorporate stoppers and meet the more stringent requirements on manufacturing testing and inspection identified in the E0083 submission.

3 THE EVENT AND SUBSEQUENT WORK PROGRAM

3.1 FUEL FAULT EVENT

During a routine inspection of the shutdown reactor core on 24th July 2007, fuel assembly (FA) ARS 013 was found to have one individual fuel plate projecting above, but still attached to, the fuel assembly. Immediate action was undertaken to ensure safety of the reactor, including the fuel, personnel and the environment. The situation was assessed by a group of ANSTO and INVAP specialists and reported to ARPANSA. The reactor has remained shutdown since that time.

This submission will show that the fuel roll-swaging process used for the manufacture of the faulted fuel is the primary cause attributed to the movement of fuel plates. It has been demonstrated in testing that longitudinal (vertical) strength in the swaging of the fuel plates in the reactor at the time of the event is significantly less than the strength in the lateral (horizontal) direction. It is also demonstrated that there is variability in swaging strength of these fuel plates. These factors when combined with the action of the coolant flow, vibrations and heating inherent in the reactor resulted in movement of some fuel plates. The OPAL fuel design did not incorporate a secondary mechanism to limit the longitudinal movement of fuel plates.

Following the event a detailed root cause analysis was conducted and demonstrated the need for a design change to the fuel.

3.2 WORK PROGRAM

A work program was immediately initiated under the control of ANSTO (Reactor Operations) management. Safety of personnel, the reactor facility and the surrounding environment were paramount in the planning process for the recovery and were factored into actions that were subsequently undertaken. A guiding team, which included ANSTO and INVAP staff, was formed to oversee and manage the day-to-day process of investigations. The “STAR” (Stop, Think, Act, Review) principle was reinforced by the guiding team as multiple actions were initiated and executed throughout the program. Appropriate resources in terms of equipment and personnel have been utilised throughout the program. Independent experts have been consulted on key issues or engaged as reviewers for the program. These factors lend confidence to the results from the investigations, tests, analyses and to the conclusions reached.

Following the event and initial evaluation, response and reporting, the guiding team planned work which is represented by the following “projects”:

- Core recovery operations;
- Investigations into reactor conditions;
- Investigations into fuel conditions; and
- Root cause investigations.

As those projects were undertaken, a framework for submission E0083 was developed. A summary of the main outcomes from each project is reproduced with additional explanatory comment in the following table.

Project chain	Main outcome	Comment
Core recovery operations	Fuel was safely removed from the core and is safely stored in the service pool.	A subsequent submission has been developed to enable a longer term storage solution for the two fuel assemblies with the largest fuel plate displacements.
Investigations into reactor	Other than displaced fuel	The behaviour of the reactor

Project chain	Main outcome	Comment
conditions	plates in 7 fuel assemblies, there were no abnormalities identified in operation of the reactor in cycle 5 that may have contributed to the fault.	(excluding the displacement of fuel plates) has been assessed as lying within the boundary of the Safety Analysis Report (SAR). Review of video footage of previous cycle reactor cores indicates it is highly probable that one fuel plate in FA ARS 008 was displaced by a small amount (some mm) during operation in cycle 4. That displacement had no effect upon reactor safety or performance.
Investigations into fuel conditions		
<ul style="list-style-type: none"> • <i>Design</i> 	The modified design of the fuel assembly is considered to be acceptable. Flow-loop tests under simulated normal and abnormal (116% of nominal reactor flow-rate) reactor conditions with a dummy fuel assembly with only 7 out of 21 fuel plates fully swaged was used to support the design assessment.	It is noted that the design modification proposed eliminates the possibility of the fuel fault identified in July 2007 recurring.
<ul style="list-style-type: none"> • <i>Manufacture</i> 	The control of the roll-swaging process is critical in determining the strength of the fuel plate and side frame joint.	ANSTO has purchased OPAL fuel from two different suppliers. An evaluation of both manufacturing methods has been undertaken.
<ul style="list-style-type: none"> • <i>Behaviour in reactor</i> 	<p>The conditions in the reactor are considered to be normal and similar to those experienced in other high-power research reactors.</p> <p>Testing of clamping force on FAs established the fuel assemblies are tightly secured under normal, transient and abnormal conditions</p> <p>Extensive reactor vibration testing established vibrations measured at the FA clamps are of high-frequency and very low amplitude</p> <p>Oxide-layer measurements demonstrate no abnormalities</p>	<p>Advice received from independent experts was that high-frequency low-amplitude vibrations are known not to cause structural damage to components and have been observed in other reactors.</p> <p>A comparison measurement of vibration on the control rod guide box fastener (CRGBF) established that the vibration characteristic was very similar to the benchmark measurement of June 2006.</p>

Project chain	Main outcome	Comment
	in oxide layer thickness on selected fuel assemblies	
<ul style="list-style-type: none"> <i>Irradiated and fresh fuel investigations and analysis</i> 	Assessment of the displaced fuel plates raised issues on the manufacturing process used for that fuel.	The two suppliers of fuel for OPAL use different manufacturing methods to roll-swage fuel plates.
Root Cause Investigations	<p>The fuel manufacturing process is considered as a major contributory cause to the movement of fuel plates.</p> <p>The process of roll-swaging used on the faulted fuel is shown to have inherent variability in strength between the lateral and longitudinal directions. Fuel from a separate manufacturer shows consistency in strength between the longitudinal and lateral directions</p> <p>The root cause analysis identified a design deficiency as the underlying cause of the fuel fault event.</p> <p>The combination of inadequate design, inherent variability of the joint strength due to detailed roll-swaging methodology employed during manufacture and normal reactor conditions is the explanation of the fuel fault event.</p>	<p>A secondary method of mechanically limiting the longitudinal movement of fuel plates should have been a feature of the original design.</p> <p>There was no indication of any systemic failure of the design review processes employed by ANSTO and INVAP.</p>

4 DESIGN OF THE STOPPER AND THE FUEL ASSEMBLY

4.1 DESIGN FEATURES

After the fuel plate displacement event was detected, ANSTO raised a formal Notification for Rectification of a Defect (NRD) to the design authority INVAP. INVAP worked with the Argentine fuel manufacturer CNEA, to design a modification that would be safe, minimise any consequential effects to the OPAL safety case, and limit the longitudinal movement of fuel plates to prevent recurrence of the fuel fault. The main features of the proposed mechanical “stopper” design resulting from that process are:

- Robustness – each stopper is a 4mm thick plate of aluminium fixed by two screws to a side-frame of the fuel assembly (FA), and held in position by the screws and the FA handling pin. The screws fixing the stopper to the side-frame are peened.

- Redundancy – there are two stoppers per FA and two screws per stopper.
- Safety – there will be minimal effect on coolant flow as the stoppers are positioned at the exit of the fuel plate coolant channels and are fixed directly to the side-frame of the FA. The reactivity effect of the stoppers is small. The stoppers do not mechanically interact with un-displaced fuel plates. The material used for the stopper mechanism (Aluminium Al-6061) is the same as that used for the frame, and comb of the FA. The design function of the stopper (to limit longitudinal movement of fuel plates within the FA) can and will be visually verified.

4.2 FLOW LOOP TESTS

The stopper design was thoroughly tested in a flow-loop which simulates flow conditions experienced in OPAL. Flow-loop tests were also conducted on a standard dummy FA. The two dummy FAs were manufactured to the same specifications and using the same methods as fuel used in the reactor. Natural uranium was used as the fuel meat for both test dummy FAs, to ensure that the tests were representative of the actual fuel.

4.2.1 Standard design tests

The tests on the standard dummy FA were conducted to verify the dynamic response of the FA to different FA clamping forces and different flow conditions, and to investigate possible impact between the FA and the grid to which the FA is clamped. The tests also served as a repeat of the qualification benchmark for fuel. There was no indication of longitudinal movement of fuel plates in the latest tests, which was the same outcome as the earlier testing. Other observations in the latest tests with the standard dummy FA, were that:

- high-frequency low-amplitude vibration induced by turbulent coolant flow was present at the FA clamp. Similar types of vibration were identified in ANSTO tests at the FA clamps in the reactor. Checks undertaken on the dummy FA after loop-testing did not reveal excessive wear or buckling that may indicate that undue stresses were imparted to the FA by vibration;
- lower frequency vibrations were measured on the outer fuel plate and the fuel assembly side-frame, and the amplitudes (displacements) due to those vibrations were also low (< 20µm). Those lower frequency vibrations are an expected consequence of flow through the fuel assembly and were considered and accounted for in the original design;
- there was no evidence of excessive impact between the FA and the grid surrounding the FA.

4.2.2 Modified design tests

The tests with the dummy FA with stoppers contained two conservative measures. Firstly, coolant flow-rates were up to 116% of the nominal flow-rate in the reactor. Secondly, only 7 of the 21 fuel plates were fully roll-swaged. This test, which was run in stages for a total operational test period of 33 days, demonstrated that the modified design was safe and restricted longitudinal movement of fuel plates from the FA. After the tests, there was only slight damage to the leading edge of the stoppers and the trailing edge of the loose unswaged fuel plates. The damage was caused by the action of coolant flow pushing the loose plates onto the stoppers' leading edges. The integrity of the cladding on the fuel plates was not compromised. There was no evidence of the stoppers being displaced by the impact of the loose fuel plates.

Pressure drop across the dummy FA with stoppers fitted was approximately 5% less than that measured for a dummy FA without stoppers. This effect has been attributed to the more gradual change in flow area at the end of the fuel box caused by the stoppers, and/or a reduction in friction due to the partial covering of the FA side-frame grooves by the stoppers. The ANSTO design reviewers judged this effect will be negligible in the reactor as the pressure drop in the reactor is measured between the inlet plenum and the reactor pool, not directly across the inlet and outlet of the fuel assemblies as done in the flow-loop tests. To check the effect of the design modification

on pressure drop in the reactor, a data gathering program will be instituted at OPAL to analyse pressure drop data using modified fuel assemblies and comparing this to data from previous operating cycles. The initial test will be done at zero power, prior to start-up.

4.3 DESIGN REVIEW & RISK ASSESSMENTS

The design review conducted by ANSTO provides an analysis of the proposed design modification. The effects of the design change are considered to be benign in the normal state. A risk assessment in the form of a Failure Modes and Effects Analysis (FMEA) for the stopper was conducted and this analysis concluded that the stopper mechanism would fulfil its primary function of remaining in place and limiting longitudinal movement of fuel plates. Core cooling would not be affected by the design, even in the case where a fuel plate is displaced longitudinally and limited to further movement by the stoppers. A beyond design basis scenario was also considered as an event of interest. In that scenario, the screws on the stopper were assumed not to be present when the stopper was subjected to a force induced by coolant flow. Under conservative assumptions, it was concluded that the stopper would not deform sufficiently to present a potential blockage at the outlet of the FA.

An additional risk assessment was undertaken to evaluate the integrated FA design with incorporation of the stopper. The effect of the design change on the SAR was also considered. In the beyond design basis scenario of the stoppers failing to perform their design function and considering that a fuel plate had dislodged from the fuel assembly and broken, the resulting fission product release from broken fuel plates would be bounded by the SAR beyond design basis accident where complete melting of three fuel plates is assumed. Therefore, the design modification does not introduce any additional effect not considered previously on the safety of the reactor.

5 KEY FACTORS CONSIDERED IN ESTABLISHING THE ROOT CAUSE

5.1 APPROACH

A systematic methodology was applied throughout the investigations on the event. Detailed investigations were undertaken with the intent of either eliminating a potential contributing factor to the event, or identifying an area for further consideration. A guiding team that was formed concentrated on operational issues, investigations and planning for other work. A brainstorming session was held with representatives from ANSTO and INVAP having wide-ranging technical areas of competence, providing input to the possible causes of the event, investigations required and possible design issues. From this session a number of work initiatives were considered, assessed and if appropriate were acted upon. An independent root cause investigation was requested by the General Manager, Reactor Operations.

5.2 OPERATIONS

The pump combination used in cycle 5 is judged not to be a contributory factor to the event, on the basis of:

- Analysis of operational records for cycle 5 by both ANSTO and INVAP demonstrated no anomaly in any recorded parameter that could be attributed to the fuel fault event. While various transients were experienced (e.g. power cycling for neutron guide measurements, reactor trips), the reactor operated and responded as per the design.
- Maintenance activities that had been undertaken during cycle 5 were reviewed and it was noted that cycle 5 was the first operational cycle where Primary Cooling System (PCS) pump combination was changed. Accordingly, examinations were done to ascertain if this pump combination contributed to the cause of the event. Investigations with dummy fuel assemblies established that specific pump combinations did not lead to discernible

differences in reactor conditions. Furthermore, the results demonstrated that there is a lack of correlation between the observed FA clamp vibrations, flow variations, or clamping forces and the core positions of FAs with displaced fuel plates.

- Detailed examination of video recordings from previous cycle core loadings prior to operation, indicated that it is highly probable that one fuel plate was partially displaced, by only a few millimetres, during cycle 4. It is noted that the objective of those recordings was to check fuel assembly orientation and positions and not to check for fuel plate displacement. The small displacement is not a prominent feature on the recordings, and given that the focus of the operational personnel was on checking as per established procedure, and the images are not of high definition, it is reasonable that the minor displacement went unnoticed. The fuel assembly was ARS 008, plate number 14, in core position D4.

5.3 OTHER ENVIRONMENTAL CONDITIONS IN THE REACTOR

Investigations into other environmental conditions in the reactor, and in particular those experienced in the core were undertaken. It was considered after the event that the most likely motive force that could move fuel plates upwards longitudinally was the PCS flow. Since operational records showed no abnormalities in PCS conditions, deeper investigations were undertaken to ascertain other factors that may have contributed to the fault.

5.3.1 Fuel Assembly Clamps

Incorrect tightening of the nuts on the fuel assembly clamps is not considered to be a contributory factor to the event on the basis of:

- The positions of the nuts were examined immediately following the discovery of the fuel fault and found to be normal.
- The performance of the fuel assembly clamps was investigated. Investigations into the positioning of the nuts securing the fuel assembly clamps showed that the fuel clamps adequately secure the fuel assembly clamp stems and thus the fuel assemblies to the core grid, even when the nuts are not tightened correctly.

5.3.2 Vibration

Vibration characteristics at the fuel assembly clamps and the control rod guide box fastener were studied. It was hypothesised that vibration, probably induced by coolant flow could be a significant contributory factor to the event. Under this hypothesis, even though the fuel assemblies were secured to the core grid, primary coolant flow combined with vibration would provide sufficient force to move fuel plates.

Analysis of measurements undertaken on the fuel assembly clamps established that RMS (root mean square) displacements of $1\mu\text{m}$ were typical, with accompanying vibration frequencies measured in vertical and horizontal directions ranging between 500 – 1500 Hz. Expert advisors consider those high frequency low-displacement amplitude vibrations experienced at the OPAL fuel clamps were likely to be transmitted through the system (i.e. experienced at the fuel assemblies), but are not sufficient to affect the structural integrity of the fuel and are consistent with conditions in other higher powered research reactors. Further evidence that high frequency low-displacement amplitude vibration alone did not play a significant role in the event was gained from the measurements done on a standard fuel assembly in the test flow-loop

Vibration is not considered to be a major factor in the event on the basis of:

- the large number of tests done with dummy FAs without any evidence of plate movement in the reactor;
- the tests done in the flow-loop with dummy FAs without any evidence of plate movement;
- several operational cycles without any evidence of fuel plate displacement; and

- there was no correlation established between core positions where fuel plate displacements were identified and a range of tested reactor conditions.

5.3.3 Oxide layer thickness and fuel plate heating

Abnormal fuel plate heating is not considered to be a major factor in the event on the basis of:

- Measurements of oxide layer thickness on fuel assemblies which showed that oxide layer thickness was consistent with values considered in the SAR. The measurements undertaken on outer fuel plates are generally conservative, as neutron flux and therefore temperature tends to be higher in outer plates. It is noted that oxide-layer measurements could not be done on the two fuel plates that were displaced to the greatest extent, as the technique requires a resistant surface to obtain an accurate measurement.
- Power peaking factor (PPF) measurements conducted in cycles 1 and 2 showed good comparison with calculated PPF values, establishing confidence that calculated PPF values are acceptable. Neutronic calculations for cycle 5 showed that PPF values were well within the Operational Limits & Conditions (OLC) value for PPF.
- A calculational analysis of fuel plate temperatures in cycle 5 showed that those temperatures were within the design basis.

It is noted that small longitudinal displacement of fuel plates caused by thermal expansion during operation is an expected phenomenon for roll-swaged fuel plates, and therefore it cannot be ruled out that normal heating of fuel plates was a contributory factor to the event. However, it is judged not to be a major contributor, as several operational cycles were conducted prior to any fuel plate displacements were recorded and there was no correlation between those plates which moved and the length of time they had been in the core.

5.4 FUEL ASSEMBLY DESIGN

Information obtained from research reactor fuel manufacturers and other research reactor operators showed that many, but not all, research reactors use fuel that has mechanical restraining mechanisms for movement of fuel plates. Such a restraint was provided for in the OPAL design to prevent coolant channel restrictions due to flow-induced vibration at the leading edge of fuel plates. However, no secondary restraining device was incorporated on the trailing edge of the fuel plates to prevent abnormal longitudinal movement of the plates. This design deficiency is the major root cause of the event. A risk assessment in the form of an FMEA has been done for the modified FA design.

5.5 ROLL-SWAGING

The analysis of the roll-swaging process for the fuel in question indicated that the roll-swaging procedure for the fuel in question included a corrective step when swaging fuel plate 14. This was required due to a compounding error incurred in the placement of the swage wheel relative to the fuel plate. Most of the displaced plates are in this position or adjacent to it (excluding channels without Cadmium wire).

On the basis of this evidence, it was concluded that fabrication was a major contributory factor in the displaced fuel plates observed in OPAL fuel. The concerns on the roll-swaging process were supported by an assessment conducted by independent reviewers.

5.6 SUMMARY OF CONSIDERATIONS

The evidence from the projects undertaken to investigate the cause of the event strongly indicates that a combination of factors was required to enable the displacement of fuel plates in fuel assemblies. The most significant factors were:

- the roll-swaging process employed in manufacturing fuel; and
- the lack of a secondary mechanism to limit the longitudinal movement of fuel plates.

If a stopper had been employed in the original design, fuel plate displacements may have occurred, but the displacements would have been acceptably limited. It is known that vibration and heating of the fuel plates occurs during operation in all reactors. Therefore, it is judged that the fuel plate displacement in fuel assemblies in OPAL was caused by the variability of swaging strength introduced by the roll-swaging process, in combination with normal operational factors of upward coolant flow, flow-induced vibration and heating of the fuel plates.

6 LESSONS LEARNT AND PROCESS IMPROVEMENTS

The modification proposed for the fuel assembly will improve the defence-in-depth provisions on the current fuel design.

Surveillance of fuel assemblies will be improved. In-core video inspections will now be performed before and after fuel change operations. Specific inspection criteria will be used to assess the state of both in-core fuel assemblies and assemblies that are discharged from the core.

Fuel inspections will be improved. For all future fuel assemblies to be manufactured or modified and intended for use in OPAL, ANSTO will conduct detailed inspections for those fuel batches at the point of manufacture (or modification). The process to be used will be consistent with inspection methods currently used by other leading research reactors.

The OPAL fuel specification will be modified so that individual fuel plate pull tests are conducted similar to those conducted for other leading research reactors. For the OPAL tests, 7 of the 21 plates in a test sample will be pulled from the side-frame in the lateral direction to determine those individual fuel plates' swaging strength.

The pressure drop across the core will be measured with a full core of modified FAs. The results will be compared with previous operational data. The purpose of those measurements will be to monitor any possible effects on core pressure drop introduced by the fuel assembly design modification.

To check that no other nuclear safety significant items require risk assessments, a review of Safety Category 1 structures, systems and components will be undertaken as part of the safety case update program. A revision to the schedule of work will be issued for the Safety Case update program.

7 CONCLUSION

An assessment and summary of a proposed modification of the fuel design to limit longitudinal movement of fuel plates has been presented. The submission documents show the design to be robust and safe, and that it will perform the intended design function. Risk assessments have been performed to assist with demonstrating the safety of the design.