EXPERIMENTAL INVESTIGATION OF COOLANT AND POISONED MODERATOR MIXING DUE TO A SIMULATED PRESSURE TUBE/CALANDRIA TUBE FISHMOUTH RUPTURE DURING AN OVERPOISONED GUARANTEED SHUTDOWN STATE

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1. INTRODUCTION

During a guaranteed shutdown state (GSS) in a CANDU reactor, there must be sufficient negative reactivity to ensure subcriticality in the event of a process failure. In one of the acceptable states, the reactor is kept subcritical by a high concentration of a neutron-absorbing chemical (the poison gadolinium nitrate) dissolved in the moderator (*i.e.*, the moderator is guaranteed overpoisoned). A postulated accident scenario which is considered as a part of reactor safety analysis is the rupture of a fuel channel (*i.e.*, a pressure tube/calandria tube break) when the reactor is in a GSS. If one of the channels in the core breaks (requiring a simultaneous failure of both the pressure tube and the surrounding calandria tube), coolant from the primary heat transport system will be discharged into the moderator, causing an associated displacement of fluid through relief ducts at the top of the calandria vessel. The incoming (unpoisoned) coolant may mix quickly with the moderator, or may mix slowly while displacing poisoned moderator through the relief ducts. The effectiveness of mixing generally depends on the break location, the coolant discharge rate and the moderator circulation. If an in-core loss of coolant accident occurred while the reactor is in this overpoisoned state, it must be guaranteed that even with the dilution of the poison by the incoming coolant the reactor will remain subcritical on both a local and global basis.

This paper presents an overview of an experimental program in progress at the Moderator Test Facility at Stern Laboratories to investigate coolant/poison mixing for a simulated in-core fishmouth pressure tube/calandria tube rupture. The nominal system conditions investigated are of a reactor in a GSS, with coolant in the primary heat transport system at the same temperature as the heavily poisoned moderator, *i.e.*, a depressurised 'cold' state. The results presented are those obtained during the commissioning of the modified Test Facility.

The contents of the paper are as follows. First, the objectives of the experimental program are summarised, and a description of the facility is given, with a discussion of the loop modifications required to perform the mixing study. Then a description of the conditions studied during commissioning in the Moderator Test Facility is given. Results obtained during the commissioning, both flow visualisation and measurements, are presented. Lastly, an overview of the tests to be performed during the remainder of the program is given.

2. OBJECTIVES OF EXPERIMENTAL INVESTIGATION

It is of interest to understand the nature of poison/coolant mixing which results when a discharge of unpoisoned fluid from a single ruptured channel enters a calandria geometry containing fluid of a different concentration. Aspects of interest are the factors which affect the evolution of the flow and concentration fields, the concentration variation throughout the vessel and poison displacement. The Moderator Test Facility is appropriate to simulate the mixing resulting from a fishmouth type rupture, due to its ability to provide the qualitative and quantitative information required for the geometry and conditions of interest.

The following are the primary objectives of the program:

- *Gain an understanding through flow visualisation of the roles of the calandria tubes, moderator inlet jets and the overall circulation pattern on the mixing of incoming fluid from a fishmouth break with that of the original fluid in the vessel.* The resistance to flow caused by the calandria tubes relative to that in the unobstructed reflector region may result in preferential flow outside the core. The effect of the inlet jets may be expected to vary according to the relative strength of the discharge, and the fuel channel location at which the break occurs. The overall circulation pattern is key in determining the long term dispersion characteristics.
- *Identify the effect of fuel channel location and the direction of the break discharge on the displacement of the original fluid in the vessel.* Breaks at the edge of the core, for example, directed towards the vessel wall may result in different flow fields than those occurring in the centre of the core.
- *Determine concentration throughout the vessel and at the top outlet at the simulated relief duct to assist in understanding the flow.* Measurements of fluid conductivity at the top outlet provide information on poison displacement and the amount of poison remaining in the vessel. The measurements throughout the vessel supplement the qualitative information gained through flow visualisation.
- *Obtain experimental data to assist in validating computational tools which may be used to simulate system characteristics.*

The investigation is performed in three stages. First, loop modifications were made to allow the conditions of interest to be simulated. These modifications were then assessed during a commissioning period, in which a break at only one channel location was investigated. The results obtained from this first stage are presented here. In the second stage, custom conductivity probes were designed, constructed and tested to allow for good coverage of the concentration field in the vessel. The program is now entering the third stage, in which breaks over a range of discharge rates at a number of fuel channel locations are being investigated.

3. EXPERIMENTAL FACILITY

3.1 Summary of existing features

The experimental facility, located at Stern Laboratories Inc., has been used for approximately ten years to enhance the understanding of flow phenomena occurring in the moderator fluid in the calandria of a CANDU reactor (1). In addition, it has provided experimental data to aid in the development and validation of thermalhydraulics codes (e.g., MODTURC_CLAS (2)) that calculate the velocity and temperature fields in this type of flow. Examples of experimental investigations completed at the Moderator Test Facility include: steady state and transient moderator temperature distribution tests for a wide range of conditions involving different ratios of inlet momentum to buoyancy forces; experiments to determine the pressure loss for flow through the calandria tube tank; and scaled moderator inlet nozzle flow distribution tests.

The test facility is a one quarter scale (2 m diameter) which reproduces the important characteristics of moderator circulation and heat transfer in a slice (0.2 m thickness) of the calandria vessel. Relevant conditions are derived through non-dimensionalization of the governing equations, and identifying and maintaining equivalence of key dimensionless quantities between the full scale calandria and the test facility. The test section walls have been fabricated from clear polycarbonate sheets to allow flow visualisation and Laser Doppler Anemometry. Flow visualisation is provided by injecting an acid or base into the circulation loop, which already contains a dissolved pH indicator. Four hundred and forty 1/4 scale electrical tube heaters (mounted in a square array with a lattice pitch of 71.4 mm) provide heating to the fluid if required. The heaters are designed so that all power connections can be made from one side to leave the other side free for instrumentation and flow visualisation. A circulating pump, heat exchanger and connecting pipe provide coolant circulation and heat removal. The working fluid is light water. The loop circulating pump can provide inlet flow rates up to 4 kg/s, distributed between the inlet ports which span the full thickness of the test section and are mounted on the side walls. The outlet port at the bottom of the test section covers the full thickness of the test section and is 16 mm wide. A schematic of the facility is given in Figure 1.

3.2 Loop Modifications

The present mixing investigation is a new application of the facility. A number of significant modifications to the loop were required for the present work. Firstly, a high pressure line was added to inject water (representing the coolant discharge) at a preset rate through a simulated calandria tube break. The injection line is instrumented with a thermocouple for temperature measurement and an orifice for flow measurement. An eductor is also provided in the injection line to allow for the addition of an acidic solution required for flow visualisation. A second modification was the construction of a simulated fishmouth break tube from which the coolant discharges (replacing the original heater tube at the fuel channel location at which the break occurs). This tube is connected to the high pressure line at one end. A slot spanning the length of the vessel is milled through the wall of the tube. The tube has a flexible inlet connection (to allow rotation), and provides a discharge at any angle without draining the test section.

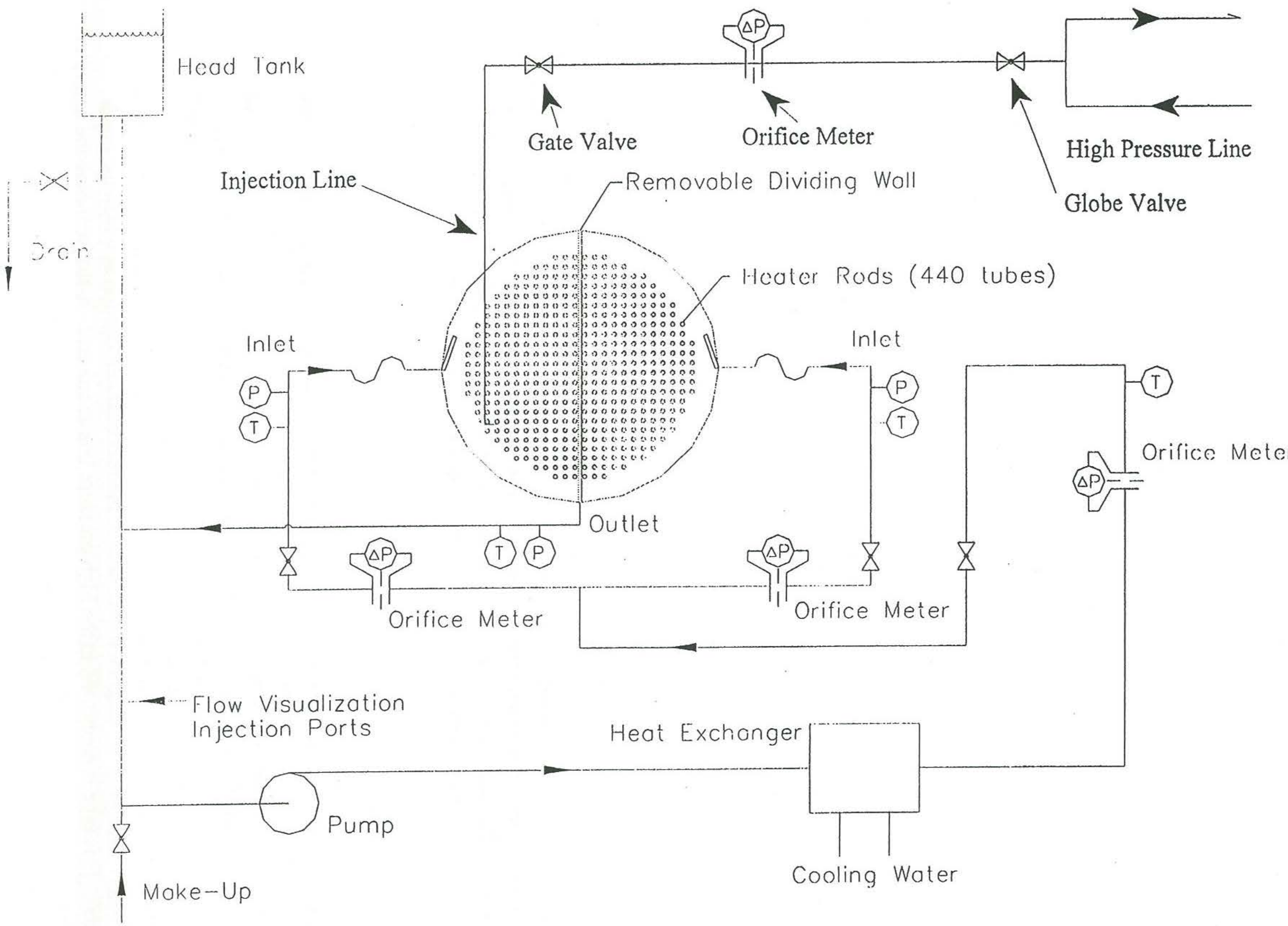


Figure 1 Schematic of test loop

The simulated relief duct is located at the top of the test rig. It consists of a rectangular perforated plate section, 286 mm wide by 200 mm depth, with a pyramidal shaped channel fastened to it. The channel converges to a 2 inch diameter pipe which discharges to a catch tank. A conductivity probe is installed in the converging channel/pipe to monitor the conductivity of the discharged coolant.

During the initial commissioning, conductivity was measured only at the relief duct. Subsequently, custom conductivity probes were constructed to allow for measurement throughout the vessel. These probes may be placed at any of 54 locations throughout the core and reflector regions (at the original 40 thermocouple locations and 14 new locations). Additional probe locations include a point upstream of the discharging inlet (providing inlet concentrations), and downstream of the bottom outlet (in the piping immediately below the vessel, to provide outlet concentrations).

4. TEST CONDITIONS

Details of the original design and scaling of this experimental facility are given in Reference (3). That work describes the derivation of the nominal operating conditions at the facility representative of full power operation of a typical CANDU reactor. In that document, a detailed similarity analysis of the governing mass, momentum and energy conservation equations was performed which specified the dimensions and operating conditions of the test facility so as to achieve (as closely as possible) thermalhydraulic similarity in the flow pattern and temperature field within a typical CANDU calandria. Due to the significantly different conditions between full power and GSS operation and associated governing phenomena determining the flow field in the vessel, the nominal operating conditions relevant to the present GSS analysis will be different from those derived in Reference (3). In this section, the Moderator Test Facility conditions used to simulate the cold GSS scenario will be presented.

4.1 Nominal system conditions for cold GSS

For the GSS conditions of interest in a typical CANDU reactor calandria vessel, moderator fluid is drawn from the calandria outlets by an auxiliary moderator pump (reducing the flow by an order of magnitude from that under normal operation). Because the moderator and primary heat transport fluids are at 30°C, no thermal phenomena are involved and the temperature remains constant in both the pre- and post-break stages. Experimental conditions for the Moderator Test Facility are chosen by seeking fluid dynamic similarity with the operating parameters of a typical CANDU calandria vessel. If the fluid is to behave in a dynamically similar fashion in the prototype (the CANDU vessel) and the model (the Moderator Test Facility), then the governing conservation equations, boundary conditions and geometry in both systems should be equivalent. The conventional manner to derive the parameters which provide this similarity is to recast the conservation equations and boundary conditions into non-dimensional form. By introducing reference system parameters and appropriate non-dimensional variables into the equations and boundary conditions, the dimensionless coefficients which result completely determine the quantities which must be the same to ensure similarity.

The governing equations describing the prebreak flow are conservation of mass and momentum. Non-dimensionalizing the equations, the dimensionless group which describes the system is the vessel Reynolds number, based on the inlet nozzle velocity and vessel diameter. The Reynolds number for flow in the reactor calandria is 2.1×10^6, corresponding to an average inlet velocity of approximately 0.24 m/s. The Moderator Test Facility nozzle inlet velocity calculated by equating the Reynolds numbers for the two vessels is 0.84 m/s, corresponding to a total inlet mass flowrate of 2 kg/s. It should be noted that one constraint imposed in deriving the nominal model GSS conditions is that the present Moderator Test Facility geometry (*e.g.*, inlet slot jet width and flow area) will not change.

4.2 Calculation of Fishmouth Break Characteristics

In order to completely specify the problem, the following information must be specified: the geometry of the break (length and opening width) and its location relative to it surroundings, the inlet mass flow rate of the discharge, and the concentration.

4.2.1 CANDU Characteristics

First, the geometry of the break will be considered. For the present experimental design, a rupture length of 2.5 m (consistent with rupture lengths considered in previous analyses (4)) is chosen. The rupture is assumed to be diamond-shaped, with the greatest opening occurring at the centre. The rupture is assumed to be fully open upon the initiation of the transient. Lastly, the total cross-sectional flow area is taken to be equal to twice the available flow area in the fuel channel (based on the flow area for a 37 element bundle associated with fluid in the fuel channel approaching the rupture from either side). The maximum opening is 0.0055 m, corresponding to a circumferential opening of approximately 5°. Rupture characteristics in the CANDU vessel over the central 0.8 m must be derived in order to calculate similar conditions over the 0.2 m wide Moderator Test Facility. The flow area over the central 0.8 m is approximated as a uniform crack height of 0.0046 m, which corresponds to an opening angle of 4°.

The rupture flow conditions required to obtain similarity between the CANDU scenario and that for the Moderator Test Facility are obtained by requiring the non-dimensionalized velocity boundary conditions to be equal. At the inlet nozzles the dimensionless velocity U^* equals 1, obtained by dividing the inlet velocity U_i by a reference velocity $U_{ref} = U_i$. The dimensionless velocity condition over the rupture, U^*, may then be calculated for a given discharge flow rate.

From non-dimensionalization of the concentration equation, similarity is maintained if: i) the Schmidt numbers (ratio of momentum to mass diffusivities) are equivalent; and ii) the non-dimensional concentration boundary conditions are equivalent at the inlet nozzle and the location of the break.

4.2.2 Moderator Test Facility Characteristics

Due to the existing geometrical characteristics of the rig, two degrees of freedom remain to specify the rupture geometry and flow conditions: the size of the rupture and the discharge flowrate. These are derived by applying similarity for the geometry and velocity boundary conditions respectively. This geometrical similarity is desired in order for the surrounding tubes to have an equivalent impact on the development characteristics of the jet issuing from the rupture, *i.e.*, the size of the opening relative to the tube pitch must be equivalent for both. Because the design of the Moderator Test Facility is to 1/4 scale, the appropriate opening should be (0.25x0.0046 m) = 0.00115 m. Maintaining this geometrical similarity also results in an equivalent opening angle.

By ensuring equivalent dimensionless velocity boundary conditions, the relationship between the discharge flowrate in the two facilities is derived. For the conditions used in commissioning, the 1.7 kg/s discharge rate corresponds to approximately 17 kg/s in the calandria. The equivalence of concentration boundary conditions at the inlet nozzles will only strictly be valid at the initiation of the break, for beyond this time the inlet concentration differs somewhat with time as a result of the relative difference in the transit times of the vessel fluid leaving the bottom outlet of the vessels and re-entering the vessel at the inlet nozzles.

4.2.3 Commissioning Test Conditions

Commissioning of the rig was performed by focusing on a break at one fuel channel location (the U5 channel, located at the bottom outer edge of the core) and three different discharge directions (6, 9, and 12 o'clock). These conditions were chosen for a number of reasons, with a major consideration being the investigation of the relative flow resistance for fluid in the reflector versus the core region. The focus was on flow visualisation and monitoring the concentration of fluid leaving the vessel at the top outlet. For the nominal conditions investigated, the flowrate through each of the two inlet nozzles on the sides of the vessel was 1 kg/s for a total of 2 kg/s. The break discharge rate was 1.7 kg/s.

5. COMMISSIONING RESULTS

5.1 Procedure

The simulated break tube was placed at the U5 channel location. For each of the three discharge directions investigated, two types of tests were performed:

- Flow visualisation tests (denoted FV) in which a high concentration HCl solution (exact concentration unknown) was injected into a basic solution in which the indicator bromothymol blue was dissolved. The initial solution in the tank was blue (pH greater than 7.6); colour change to yellow occurs at a pH of approximately 6.0.
- Transient outlet conductivity measurement tests (denoted TRC) in which de-ionized water (conductivity approximately 1 μmho/cm) is injected into fluid of conductivity of approximately 100 μmho/cm.

Prior to any discharge experiments, a FV test was conducted to qualify the pre-test conditions. In all tests, flowrates (discharge, inlet nozzles), temperatures (discharge, circulating loop) and conductivity (at the top relief duct) were measured at a frequency of 10 Hz. The flow visualisation tests were videotaped and photographed with a 35 mm camera (every five seconds). After approximately five minutes for the TRC tests or when the total colour change has occurred for the FV tests, the discharge was stopped and data acquisition was terminated.

5.2 Results

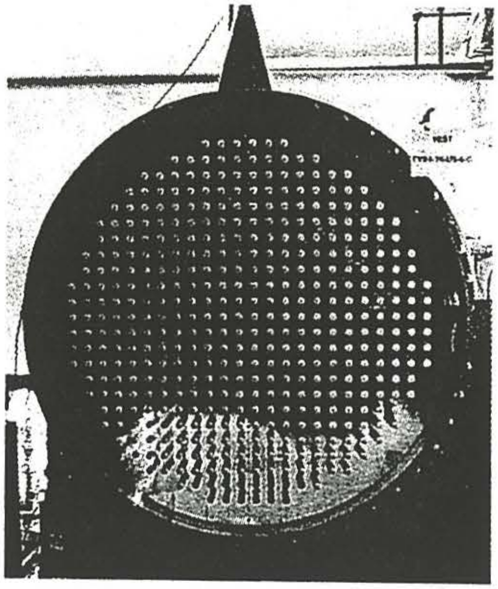
Results from the flow visualisation tests are discussed first. For these tests, it is estimated that the duration of the acid injection is approximately 15 seconds. This quantity of acid injected is sufficient to cause a complete colour change. In interpretation of the flow visualisation results, care must be taken in inferring concentration levels at the interface of the colour change. Fluid of colour yellow does not necessarily denote a very low concentration; relative to the high injected acid concentration, the differences in concentration corresponding to the pH values at which the colour changes (of 6.0 and 7.6) may be negligible.

Although not shown, the pre-test visualisation (*i.e.,* without discharge) shows a symmetric flow pattern where the inlet nozzle jets merge at the top of the test section and the combined jet is re-directed downward. Photographs taken with approximate elapsed time, from start of injection, are shown in Figures 2 and 3 for discharges in the 6 and 12 o'clock directions. The flow patterns for all injection tests are asymmetric. For the 6 o'clock discharge (Figure 2) the jet travels counter clockwise, primarily around the periphery of the test section (*i.e*, in the reflector region), and merges with the right hand side inlet nozzle jet. Due to the greater strength of the combined injection/nozzle jet relative to that issuing from the left hand side nozzle jet, the jet stagnation point moves to approximately the 10:30 position (from the 12 o'clock position under no injection conditions). This scenario clearly shows the preferential flow through the reflector region.

For the 12 o'clock discharge case (Figure 3), the injection jet merges with the left hand side inlet nozzle jet to form a clockwise dominant flow pattern. As observed for the 6 o'clock case, the jet stagnation point also shifts from the 12 o'clock position. Relative to the other discharges, there is a greater amount of fluid discharged towards the core during the initial part of the transient.

5.3 Analysis

In order to quantify the transient mixing characteristics, the vessel-average concentration throughout the experiment may be derived from the measured outlet conductivity at the relief duct and the total volume of the test section (loop piping, vessel and relief duct nozzle to the probe location). The derived average concentration may then be compared to that calculated by assuming uniform mixing in the vessel. This analysis was performed for all TRC tests.



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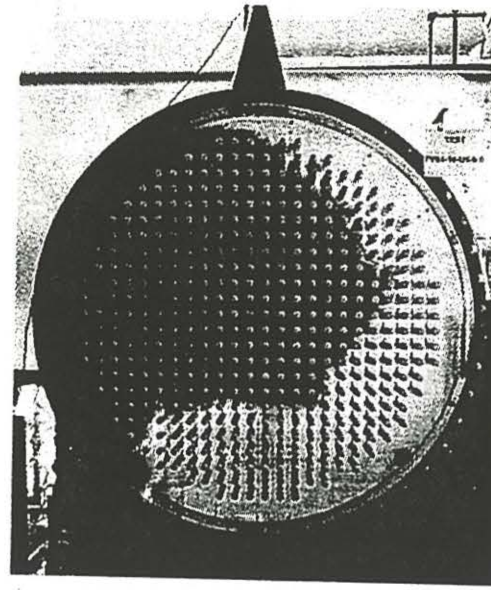

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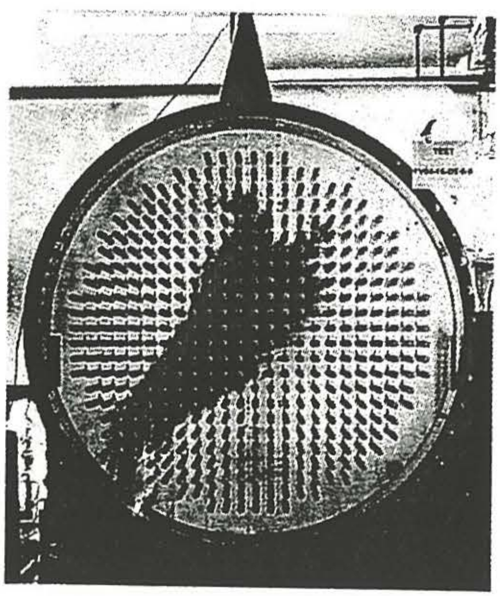

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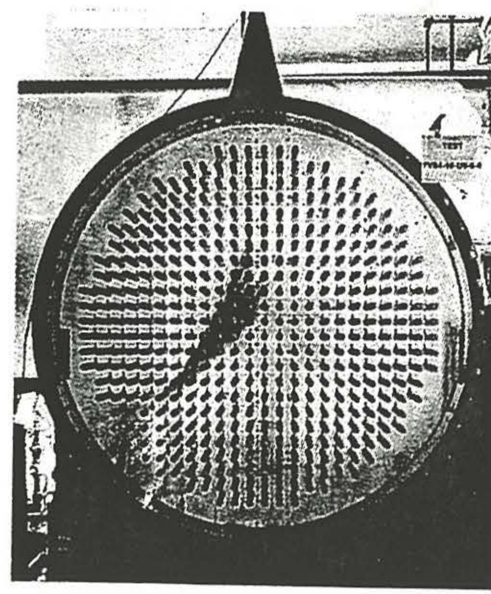

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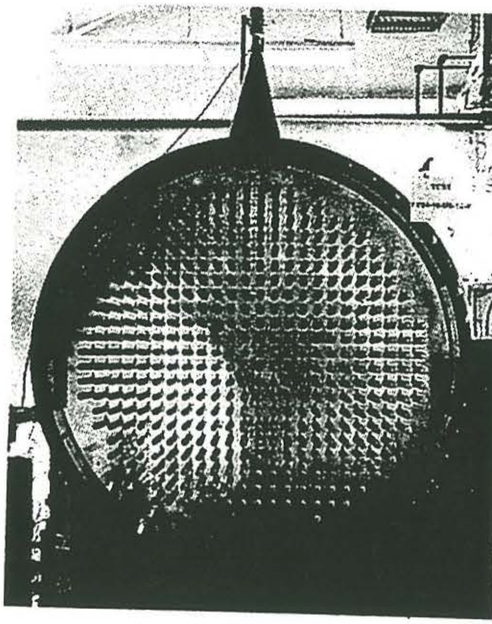
Figure 2 Flow visualisation results for discharge in 6 o'clock direction



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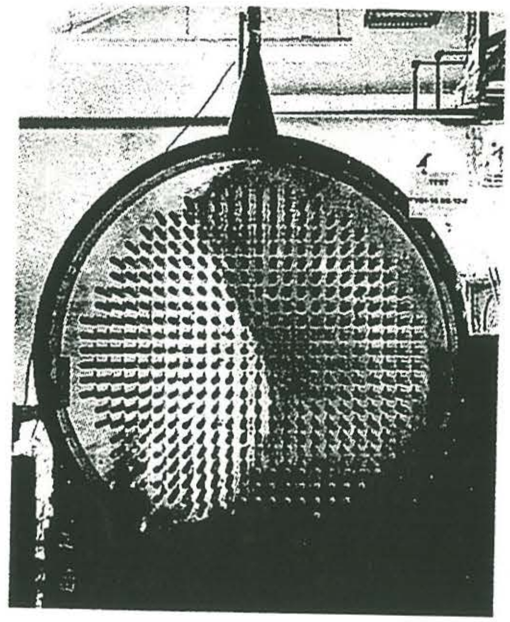

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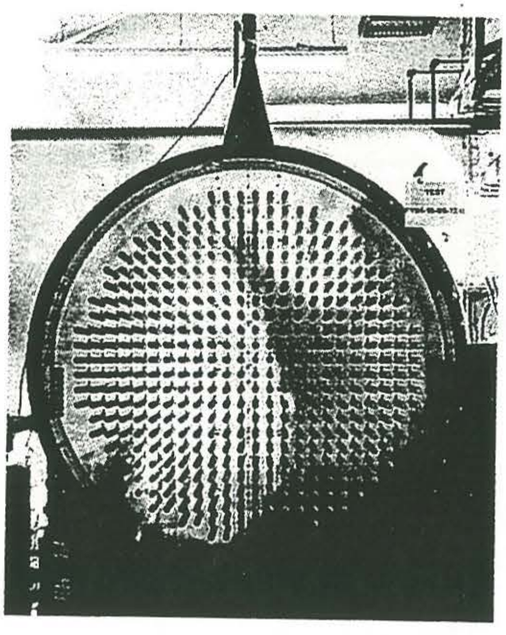

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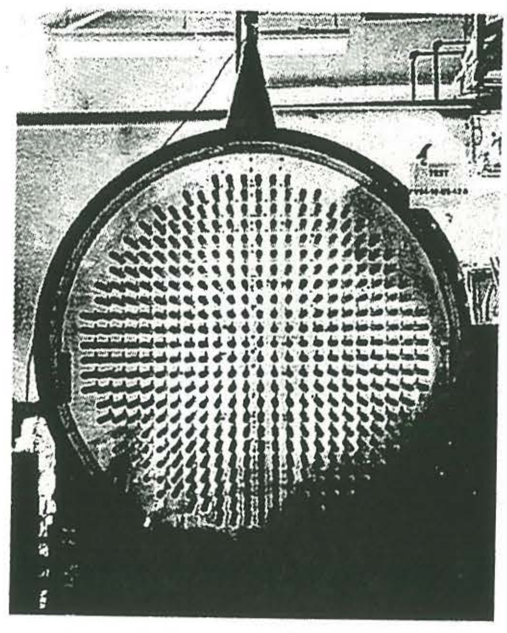

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Figure 3 Flow visualisation results for discharge in 12 o'clock direction

5.3.1 Derivation of vessel-average concentration from measured conductivity

The interest is in the ratio of the average concentration in the vessel at any time to the initial concentration, defined as the average concentration ratio and denoted as $N_a(t)$. This quantity may be obtained by considering the molarity of the solute, and a mass balance on the system:

$$N_a(t) = \frac{N_o V + Q_i \int_0^T (N_{inj} - N_{out})dt}{N_o V} \qquad (1)$$

where N_o is the initial vessel-average concentration, V is the total volume, Q_i is the volumetric break injection flowrate, N_{inj} is the concentration of the injected solution, and N_{out} is the concentration of fluid displaced through the relief duct. The total volume used in the calculation is that in the test section, the piping associated with the pump (between the bottom outlet and the inlet nozzles on the side of the vessel), and the portion of the simulated relief duct below the conductivity probe location). With the conductivity, K, proportional to the concentration, N, the vessel-average concentration ratio may be expressed as:

$$N_a(t) = \frac{K_o V + Q_i \int_0^T (K_{inj} - K_{out})dt}{K_o V} \qquad (2)$$

where K_o is the initial test section conductivity, K_{inj} is the conductivity of the injected solution ($1\,\mu$mho/cm), and K_{out} is measured conductivity of the solution displaced through the relief duct. Equation (2) may therefore be used to determine the average concentration ratio of the test section.

5.3.2 Calculation of average concentration for a uniformly mixed solution

A uniformly mixed solution is one in which all fluid in the vessel is at a uniform concentration, and equal to the concentration of the fluid displaced through the top outlet. The concentration ratio for a uniform mixture, denoted as $N_{a,T}$, is derived from equation (2):

$$N_{a,T} = e^{-\frac{Q}{V}t} + \frac{K_{inj}}{K_o}(1 - e^{-\frac{Q}{V}t}) \qquad (3)$$

5.3.3 Evaluation of mixing

For each of the TRC tests performed, the calculated vessel-average concentration (equation (2)) was compared to that which results from uniform mixing (equation (3)). A typical result is shown in Figure 4 for the discharge in the 9 o'clock direction. The three curves shown are the derived vessel-average concentration evaluated using equation (2) (denoted as Average in the figure), that would result form uniform mixing evaluated using equation (3) (denoted as Theoretical), and the ratio of the measured relief duct outlet to the initial concentration (denoted as Outlet). A value of time equalling zero seconds corresponds to the time at which the injection valve was opened.

Over the initial period of approximately 10 seconds, the displaced fluid concentration is close to the initial value. Subsequently, it drops below that resulting from uniform mixing until

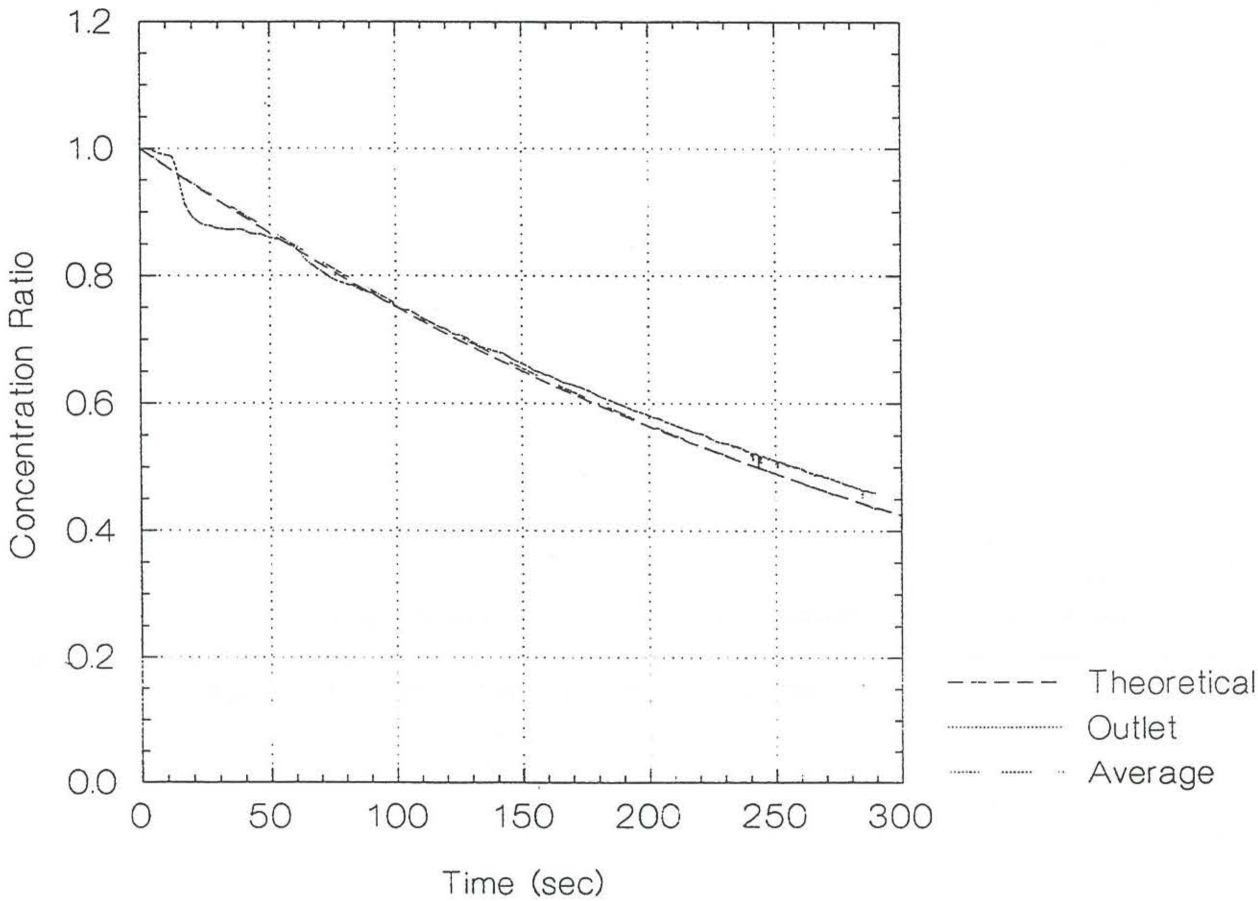

Figure 4 Concentration ratios for discharge in 9 o'clock direction

approximately 50 seconds. After this time, it is clearly shown that the Average and Theoretical curves are very similar, a result observed for all three discharge directions. This comparison indicates that the average mixture concentration in the test section is very well described by a uniform mixing model.

6. CONTINUATION OF EXPERIMENTAL PROGRAM

The commissioning results with the modified loop have demonstrated the viability of the design. Subsequently, custom conductivity probes have been constructed and tested. These probes will allow for determining the concentration field throughout the vessel.

In the next phase of the experimental program, the following aspects will be considered:

- investigate breaks at a number of channel locations and discharge directions (including repeating the U5 tests),
- introduce a range of discharge flowrates, between approximately 0.2 and 3 kg/s,
- perform experiments with and without forced circulation, to understand the effect of the inlet jets on poison displacement,
- perform velocity measurements using Laser Doppler Anemometry for certain experiments to better understand the development of the discharging jets, and
- measure conductivity (and hence derive concentration) at approximately 15 locations throughout the vessel.

Consideration will also be given to a limited number of tests in which the discharge is a flashing jet.

The end product from the program will be a data base (concentration and velocity measurements) and flow visualisation records to provide an understanding of mixing characteristics for use in the validation of tools used in the analysis of coolant/poison mixing.

7. CLOSURE

This paper has presented an overview of the experimental program in progress at the Moderator Test Facility to better understand simulated coolant/poison mixing due to a pressure tube/calandria tube fishmouth rupture during an overpoisoned guaranteed shutdown state. A number of modifications to the facility were required to perform the experiments, primarily associated with introducing a discharge of fluid from an arbitrary fuel channel location in the vessel. Conditions of interest were derived through maintaining equivalence of relevant dimensionless groups, boundary conditions and geometry. Commissioning of the loop modifications proved the viability of the design. Flow visualisation indicated the impact of different resistance to flow in the reflector versus the core region. Analysis of conductivity measurements at the top of the vessel demonstrated that for the conditions investigated the vessel-average concentration was well described as being uniformly mixed. The next phase of the program includes testing for a wide range of fuel channel break locations and discharge rates, and conductivity measurements throughout the vessel .

ACKNOWLEDGEMENTS

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