INSTRUMENTATION METHODS FOR INTERCHANNEL
COOLANT MIXING STUDIES IN WIRE-WRAP
SPACED NUCLEAR FUEL ASSEMBLIES

by

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ABSTRACT

A wire-wrap spaced, rhombus shaped, 25-pin experimental rod array was constructed with parameters typical of LMFBR's: $D=0.25$ in., $P/D=1.25$, Lead=12 in. Instrumentation design for coolant mixing experiments was discussed in detail. Salt (NaCl) solution tracers offered inherent advantages in detection. Experiments revealed no influence of salt type or injection solution concentration on results. Transverse injection caused more flow perturbation than a hypodermic tube mounted at 20° from the tube centerline. Injection velocity influenced the flow perturbations; for this work, injection at the average subchannel velocity was used with water for the flow media.

Using an injector moving over the upper thirty inches of the rod array, tracer dispersion was detected at the outlet. The instrumentation was evaluated by comparing the tracer injected to that detected. Inherent loss of tracer due to concentration inhomogeneities occurred over the last four inches of injector-detector separation with no serious effects. An unexpected loss of mass occurred at separations greater than twelve inches due to mechanical difficulties in the design.

The axial behavior of interchannel coolant mixing with tracer injection into an interior and a peripheral subchannel was established for both turbulent and laminar flow and required more than four data points per inch for its complete determination. With interior subchannel injection, the tracer dispersion pattern was dominated by flow sweeping effects with separations less than twelve inches; at greater separations, natural turbulent interchange dominated the dispersion. In laminar flow, the results were similar; however, the amount of tracer transferred by flow sweeping was markedly increased, apparently due to the change in wire-wrap drag coefficient and the absence of turbulence. The laminar flow signal fluctuated due to wire-wrap vortex shedding or injection instabilities.

Peripheral injection, mixing results were similar except the results were dominated by flow sweeping over the entire injector travel. A swirl flow around the bundle periphery was determined to be $4.9^\circ \pm 1.4^\circ$ using salt tracer data and $5.5^\circ \pm 1.0^\circ$ via flow visualization. The swirl flow remained away from the rod gaps and did not mix with adjacent interior subchannels in either flow regime.

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†MITMIX Listing not included - appears only in T.Eaton, Engineer's Thesis, MIT, June 1974.

* Not included - appears only in T. Eaton Engineer's Thesis, MIT, June 1974.

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Chapter 1

INTRODUCTION

1.1 Mixing in Nuclear Fuel Assemblies

Many nuclear power reactor cores are made up of fuel assemblies composed of an array of fuel bearing tubes called fuel rods. The fuel rods are arranged into an array and are held in the lattice arrangement by a spacer device, e.g., spacer grids or wire-wraps. The spacer devices serve primarily to maintain the coolant flow passages and to prevent fuel rod vibrations. The fuel rod array may be contained within a box structure to provide support for the rods and to contain the coolant within the array. The rod array is constructed so as to provide for transverse communication of the coolant as it passes axially through the fuel assembly. The transverse exchange or transfer of coolant and energy within the fuel assembly is the subject of interchannel coolant and energy mixing. The word interchannel is introduced in rod array or rod bundle thermal-hydraulic analysis where the coolant flow passages are divided into unit flow areas called subchannels.

Transverse coolant and energy transfer or mixing occurs via natural or inherent mechanisms and by forced or mechanical (design) mechanisms. Fluid transfer or coolant mixing inherently gives rise to energy mixing as well; however, thermal conduction within fuel assembly materials and radiation (with gaseous coolants) transfers energy without coolant transfer. The design option of using extended surfaces (fins) to promote energy transfer can be considered a mechanical mechanism to promote energy mixing. The natural coolant and energy mixing effects are turbulent interchange and diversion cross flow while the forced or mechanical coolant (and energy) mixing mechanisms are turbulence promotion (flow scattering) and flow sweeping. These mechanisms of coolant and energy mixing are summarized in Table 1.1. Additional discussion of mixing effects may be found in Rogers and Todreas (1.1), Todreas and Turi (1.2) and Brodkey (1.3).

1.2 Natural Mixing Effects

The primary natural mixing effect is turbulent interchange (resulting from transverse eddy transport) of coolant and energy within the gaps between fuel rods where the fluid flowing axially in the rod array communicates transversely (across the artificial subchannel boundaries); turbulent interchange does not involve a

Table 1.1

A Summary of Mechanisms for Interchannel Coolant and Energy Mixing Effects
Within Nuclear Fuel Assemblies⁺

	NATURAL	FORCED or MECHANICAL
FLUID AND ENERGY MIXING EFFECTS	TURBULENT INTERCHANGE DIVERSION CROSS FLOW*	TURBULENCE PROMOTION (Flow Scattering) FLOW SWEEPING*
ENERGY MIXING EFFECTS ONLY	THERMAL CONDUCTION RADIATIVE TRANSFER	THERMAL CONDUCTION IN EXTENDED SURFACES (FINS)

⁺Adapted from Rogers and Todreas (1.1)

*Directional Coolant Mixing Effects

net fluid transfer but can result in net energy transfer from one flow region to another. Diversion cross flow is a directional inherent mixing mechanism which results from changes in the differences of hydraulic resistance between flow subchannels. An excellent example of diversion cross flow is the flow development in rod arrays enclosed within a fuel assembly box or can. The flow normally enters the rod array from a plenum with a uniform velocity and is redistributed as hydraulic flow development occurs due to differences in the hydraulic resistances of the various subchannels. That is, because the local hydraulic resistance adjacent to the wall is less, coolant is diverted from the rod array interior toward the array sides in the flow development region (the effect is directional in nature). Another example of diversion cross flow arises when a gaseous coolant is used in a fuel assembly subjected to radial power gradients; density decreases in higher powered regions result in a transverse or diversion cross flow to the cooler side of the fuel assembly.

Secondary flow occurs naturally whenever the wetted perimeter (hydraulic resistance) is not distributed uniformly around the flow area. These non-circular flow geometries give rise to transverse pressure gradients which generate secondary flows (superimposed on the main axial flow). Although secondary flows are not

responsible for the transfer of coolant from one sub-channel to another, such internal subchannel flows can be expected to have a significant influence on the transfer of coolant and energy in the vicinity of the subchannel gaps.

1.3 Forced Mixing Effects

Forced mixing results from coolant flow interaction with mechanical components within the assembly. Several types of forced mixing effects are possible - turbulence promotion, which includes flow scattering, and flow sweeping. Turbulence promotion is a non-directional mechanical method of increasing the level of background or natural turbulence; this forced mixing effect is introduced into the fuel assembly by using roughened surfaces of various types. Turbulence promotion (which is used to improve the convective heat transfer coefficient) is desirable only in the active fuel region of the assembly and thus gives rise to diversion cross flow at the start (and termination) of roughening. This is because only the heated surfaces are roughened, and the increase in hydraulic resistance is greater within the rod array than along the smooth edges of the assembly. Flow scattering is a non-directional type of turbulence promotion which results from mechanical protuberances in the flow field, e.g., spacer grids.

Flow sweeping is a directional forced mixing effect which is caused by such mechanical devices as wire-wrap or spacer turning vanes that are oriented with an angle to the axially flowing coolant. Swirl flow is a cumulative flow sweeping effect that is discussed next.

It is important to note that no interchannel coolant mixing effect has the capability to transfer coolant over length scales larger than those typical of the fuel rod pitch. It may be speculated that wire-wrap spaced fuel assemblies induce a bulk swirl component, i.e., a large length scale secondary or swirl flow superimposed on the main axial flow. This swirl flow is speculated to occur because all flow sweeping in wire-wrap spaced fuel assemblies is in the same angular direction at a given axial plane (all wire-wraps are at the same angular orientation on each rod at a given axial location). In the rod array interior the wire-wraps from the three contiguous rods traverse the subchannel in such a manner that over one axial pitch of the wire-wrap, the coolant flowing axially in the subchannel experiences no net flow sweeping. However, as the coolant flows axially in the peripheral subchannels between the outside rods and the channel walls, the wire-wrap spacers always enter and traverse the subchannel with the same rotational direction. Thus, a net flow sweep is experienced in the peripheral subchannels of wire-

wrap spaced rod arrays, and a peripheral swirl flow might be expected. Such swirl flow has the capability of producing transverse coolant transfer over length scales typical of several rod pitches or perhaps more. Further experimental investigation is required before swirl flow can be assessed quantitatively.

1.4 The Significance of Mixing

Interchannel coolant and energy mixing are important in the thermal-hydraulic and thermal-mechanical design of nuclear fuel assemblies because its mechanisms influence the coolant temperature profile and reduce hot spot temperatures. These considerations of temperature profile are particularly important in fast breeder reactors where coolant and structural temperatures are higher and where structural materials undergo volumetric swelling in a strongly temperature dependent manner. The length scale typical of mixing mechanisms limits the ability of mixing to reduce temperature gradients over lengths greater than a few rod pitches, e.g., the radial assembly temperature tilt occurring in fuel assemblies subjected to steep radial power gradients. Mixing effects can be very effective in reducing local temperature differences in fuel assemblies but cannot be effective in reducing temperature differences across the entire assembly. Figure 1.1 shows typical results of

FIGURE 1.1 - INFLUENCE OF INTERCHANNEL COOLANT AND ENERGY MIXING ON THE TRANSVERSE BUNDLE TEMPERATURE PROFILE ARISING FROM RADIAL POWER GRADIENTS*

* Adopted from Markoczy (1.4)

increasing mixing levels on the temperature tilt across a wire-wrap spaced nuclear fuel assembly characteristic of Liquid Metal-Cooled Fast Breeder Reactors, LMFBR's. The steep temperature gradients near the array sides in Figure 1.1 are due to a by-pass flow that over-cools the near-wall region. The by-pass flow results from the mechanical design of the wire-wrapped fuel assembly which has a lower flow resistance at the array edge than in the array interior.

1.5 Work Scope

The objective of this investigation is to discuss, compare and develop techniques for instrumenting experimental facilities for determining interchannel coolant mixing in nuclear fuel assemblies and to assimilate experimental mixing data with continuous axial resolution. This information will be used to aid in the development of breeder reactor fuel assemblies. To date, several experimental methods have been used to assess mixing in fuel assemblies; however, little effort has been devoted to discussing and comparing the instrumentation methods of coolant mixing experiments. Also, few of the experiments reported thus far have had the capability to provide axially detailed information (1.1, 1.2).

The balance of this work includes a discussion of mixing experiment instrumentation methods, a description

of the experiments conducted as part of this work, a presentation of experimental results, and recommendations for further experimental work on interchannel coolant mixing. The experiments mentioned are directed toward rod arrays with geometries typical of the LMFBR with wire-wrap spacers, i.e., a rod diameter $D = 1/4$ inches arranged with a rod-to-rod pitch $P = 5/16$ inches ($P/D = 1.25$) in an equilateral, triangular lattice rod array. Figure 1.2 shows a true-size cross-section of a 217 pin (rod), hexagonal, LMFBR fuel assembly with these characteristic rod array parameters. Note that the rod-to-wall gap is set by the wire-wrap diameter on the outer row of fuel rods; designs using the same wire diameters on all rods, e.g., the LMFBR, have the inherent by-pass flow near the assembly walls noted earlier.

TRUE SIZE

ROD DIAMETER = 0.250 IN.

ROD-TO-ROD PITCH = 0.3125 IN.

PITCH/DIAMETER = 1.25

ROD-TO-WALL GAP = 0.0625 IN.

TRIANGULAR LATTICE ARRAY

WIRE-WRAP NOT SHOWN

FIGURE 1.2 - A CROSS SECTION VIEW OF A 217 PIN,
HEXAGONAL FUEL ASSEMBLY CHARACTERISTIC
OF LMFBR'S

Chapter 2

INSTRUMENTING COOLANT MIXING EXPERIMENTS

2.1 Tracer Instrumentation Techniques

The purpose of a coolant mixing experiment is to observe transverse fluid motions within the flow passages of a fuel assembly. This may be done by inserting or injecting a small amount of tracer into the fluid flowing axially through the rod bundle geometry of interest. The tracer then travels with this main flow and is dispersed by the various fluid mixing mechanisms discussed in Chapter 1. Detection instruments are mounted downstream of the injector. A primary requirement for the experiment is that the injection and detection activities (and apparatus) not interfere with the mixing phenomenon being observed. This requirement is of most concern in the injection activities because the wake from this operation is within the flow region being monitored. Because flow disturbances upstream of a protuberance are small compared to the wake behind, cf. a ship on calm water, the detection activities would appear to be of less concern with respect to main flow perturbations.

The tracer injection technique for coolant mixing experiments has three major areas of concern: (1) tracer

selection, (2) injection system design and (3) detector system design. The tracer used strongly influences the detection system; whereas the injection system is relatively independent of both tracer and detection systems. The design options arising during experiment design are tabulated in Table 2.1.

Key factors in tracer selection are the diffusivity of the tracer and the influence on detection system design. Key factors in design of the injection system are the location, mobility and geometry of the tracer injection device. Key factors in design of the detection system are the type and design of the measuring instruments and the instrument location relative to the geometry of interest (inside or outside the experimental rod array).

2.2 Tracers for Coolant Mixing Experiments

Obviously there are numerous tracers which could be used for mixing experiments. Electrolytic solutions, photoluminescent liquids, radioactive solutions, dye solutions and hot water are examples of the fluid injection type tracers. Also, a heated rod might be included in the experimental array such that heat could be added to the main flow as a tracer.

Photoluminescent, radioactive chemical and dye solutions would be expected to mix in a manner similar to a salt solution; they were not considered for this

Table 2.1

Interchannel Coolant Mixing Experiment Design Options Using Tracer Techniques

TRACER

- Salt Solution
- Heated Fluid
- Heat Addition (Heated Rod)
- Photoluminescent Solution
- Radioactive Chemical Solution
- Dye Solution

INJECTION SYSTEM

- Location Within Rod Array

- Axial

- Fixed Inside Array
 - Fixed At Array Inlet
 - Movable Within Array

- Radial

- Interior Subchannel
 - Peripheral Subchannel
 - Corner Subchannel

- Injection Geometry

- Needle (Jet)

- Needle With Diffuser

- Transverse (through a hole in the array rod)

- Withdrawl

- Withdraw a flow equal to that injected

- Do not withdraw

- Isolated Subchannel

DETECTION SYSTEM

- Location

- Internal-Inside Array

- Instrumentation Mounting Technique

- Mounted on or Inside Array Rods

- Mounted on Externally Supported Probes

- External-Outside Array

- Withdrawal Technique

- Withdraw Transversely through Array Rods

- Withdraw Sample Axially through an

- Externally Supported Tube

- Withdraw Entire Subchannel Flow through

- Flow Splitter and Tube Arrangement

Table 2.1 (Concluded)

INSTRUMENTATION TYPE
(Set by Tracer)

Instrumentation Design

Response Time

Physical Size

Flow Diversion arising from Detection Activities

work due to instrumentation complications. Local heat additions (either by using heated rods or heated rod sections) has the noteworthy advantage of not disturbing the main flow field as do the injection tracers; however, such devices were dismissed because of hardware complications.

Salt solutions and hot water were the tracers considered best suited for the work at hand. Each of these tracers has inherent advantages and disadvantages; a detailed comparison of these tracer types will be presented after discussion of the injection and detection systems.

2.3 Injection System Design

The purpose of the injection system is to insert a tracer into the main flow of the experimental test section with a minimum disturbance to the main flow. This minimum disturbance criterion is important because the wake of the injection stream is inside the region being monitored by the detection system. The level of main flow perturbation due to injection is mainly a function of injector design and injection flow rate.

The location and mobility of the injection device are of primary concern and strongly influence the geometry of the injector, see Table 2.1. Injection

can be done at the array inlet or inside the array and can be either stationary or mobile. Stationary injection often involves detection and/or injection at several axial levels so as to provide additional information on mixing behavior. Fixing the detectors at one axial level and moving the injector within the rod array provides the ability to perform mixing experiments with detailed axial resolution of the coolant mixing phenomenon. The same capability of axial resolution may be obtained by moving the detection devices; however, the detection system with its numerous instruments is much more difficult, if not impossible, to move inside the experimental array.

It should be noted that moving the injector while holding the detectors stationary gives data with notable differences from that which would be expected using a fixed injector with moving detectors. This is a consequence of the difference between wire-wrap orientation with respect to the injector for the alternative methods (2.1).

The axially movable, rod-mounted, injection device appears the better option for satisfying the flexible requirements of coolant mixing experiments. (Changing the position and/or mounting angle of the injection rod provides for radial mobility within the experimental array.) The moving injector consists of two concentric

tubes; the outer tube is slotted, and the inner tube moves axially inside the outer tube. The injector device is mounted to the inside tube through the slot in the outside tube. The geometry of this injection device could be expected to significantly influence flow perturbations due to tracer injection. Although numerous designs are conceivable, the simplest design has the tracer injected into the main flow through a hole drilled transversely through the inner rod. Alternately, a needle could be inserted into a hole drilled at an angle to the axis of the injector tube, say 15° - 20° . This injector needle arrangement would reduce the tracer insertion flow perturbation.

With needle injection there is the question, "How much tracer fluid to inject?" Two criteria come to mind; inject with a velocity equal to the average velocity in the subchannel or inject such that the entire flow of the subchannel is displaced. Injecting at flows greater than required for the equal velocity criterion will result in a turbulent jet (and "jet pump," flow induction effects) in the injection region. The influence of injection flow perturbations on experimental coolant mixing results may be readily assessed by running a series of experiments varying only the injection flow rate. In the case where it is desirable to inject a flow equal to the entire subchannel flow, a diffuser

should be mounted on the needle so that the turbulent jet is decelerated to reduce jet mixing not characteristic of the rod array. The diffused jet flow rate should be based on the discharge area of the diffuser and should give a discharge velocity approximately equal to the average velocity characteristic of the subchannel. The detailed design of the injector will be discussed in Chapter 4.

Inserting the tracer into the main flow field unavoidably causes main flow perturbations. In the case of the needle, the wake from the needle, the slot in the outer tube, and the diversion cross flow arising from the injection flow, all serve to perturb the normal flow in the test array. With the diffuser type injector, all the effects are increased; there is more diversion cross flow from injection and a larger wake from the diffuser. Also, with the diffuser it may be necessary to break the wire-wrap across the slot to allow passage of the diffuser (when an axially moving injector is used). The advantage of the diffused jet is that the subchannel starts with a uniformly mixed tracer in the injection subchannel (as does an isolated subchannel). For the needle, the tracer must mix with the subchannel flow before such a uniform concentration can be achieved. In order to achieve a uniform, injection subchannel, tracer concentration,

it is also possible to isolate the subchannel with real boundaries (e.g., fins) in the injection region. This isolated injection region prevents interchannel mixing until the tracer injected has been mixed with the main flow in the injection subchannel. Nevertheless, the isolated subchannel also causes flow perturbations and is not a flexible technique.

Injecting the tracer flow into the injection subchannel causes a diversion cross flow away from the injection region. This flow diversion can be avoided by withdrawing an amount of fluid equal to the injection flow just upstream of the injector. This localized source-sink would reduce the diversion flow perturbation; however, the complications associated with design, construction and operation of a withdrawal device more than offset any advantages of reducing the diversion cross flow. Furthermore, the effect of injection-induced flow diversion can be assessed by varying the injection flow rate holding other experimental parameters constant.

2.4 Detection System Design

The primary consideration in detection system design is the tracer used. The tracer determines what type of instrumentation is required, see Table 2.1. Given the tracer, the concern of the detection system design becomes the location of the detectors with

respect to the experimental array, i.e., inside the array or outside the array - internal or external detection, respectively. The detection system, whether internal or external, is most conveniently located near the outlet of the test bundle.

Internal instrumentation is preferred if the detectors are amenable to measurements in the main flow field, because the overall detection system is simplified. With internal detectors the major difficulty is locating the instrumentation within the limited space available inside the experimental rod array. The instruments or detectors may be supported either from the rods of the array or from externally supported probes which penetrate into the rod array subchannels axially from the outlet plenum. Internal instruments are also subjected to the turbulent flow field inside the experimental array. Because the properties of a turbulent flow fluctuate rapidly, internal instruments must be capable of dealing with these fluctuations.

With external detectors, the major difficulty is withdrawing the fluid samples from the main flow field. A sample may be withdrawn transversely through passages in the array rods or axially through an externally supported, probe tube. Another sample withdrawal option is to mount sharp-edged, flow separators at the exit of the subchannels of interest and withdraw the entire subchannel flow.

Perturbing the main flow is a consideration in detection system design regardless of the instrument location. Placing the instrumentation inside of the array changes the hydraulic resistance in the region of the detectors, but a withdrawal apparatus has a similar effect. The perturbation of the main flow by the instrumentation is important only if the perturbations propagate upstream into the region where mixing behavior is being monitored. The changes in hydraulic resistance arising from detection apparatus can be regulated (by varying the probe size) and distributed (by using dummy probes) over the array outlet so as to minimize diversion cross flows due to detection activities.

2.5 The Significance of Tracer Diffusivity

In coolant mixing experiments, several factors must be considered in evaluating the observed dispersion of a tracer. Molecular diffusion (with a mass tracer) or thermal conduction (with a heat tracer) does not represent mixing of the fluid; tracer diffusion due to these molecular transport mechanisms occurs simultaneously with tracer motion due to any existing coolant (fluid) mixing phenomenon. Tracer diffusion does promote homogenization of the tracer concentration or temperature as the tracer is dispersed within an experimental rod array by fluid mixing mechanisms. Concentration measurement techniques work well for uniformly dispersed tracers. The occurrence of tracer concentration or temperature inhomogeneities can make accurate measurements difficult when utilizing internal detectors.

To quantify the significance of tracer diffusivity, consider the dimensionless groups given below with a description of their meaning (2.18):

$$Le = \text{Lewis Number} = \frac{\rho_p C_D}{k} = \frac{Pr}{Sc} = \frac{\text{Mass Diffusivity}}{\text{Thermal Diffusivity}} \quad (2.1a)$$

$$Pe_h = \text{Peclet Number (heat transfer)} = \frac{\rho_p V d_e}{k} = \frac{\text{Heat Convection}}{\text{Heat Conduction}} \quad (2.1b)$$

$$Pe_m = \text{Peclet Number (mass transfer)} = \frac{d_e V}{C_D} = \frac{\text{Bulk Mass Transfer}}{\text{Diffusive Mass Transfer}} \quad (2.1c)$$

$$Pr = \text{Prandtl Number} = \frac{\mu_p}{k} = \frac{\text{Momentum Diffusivity}}{\text{Thermal Diffusivity}} \quad (2.1d)$$

$$Re = \text{Reynolds Number} = \frac{\rho V d_e}{\mu} = \frac{\text{Inertia Force}}{\text{Viscous Force}} \quad (2.1e)$$

$$Sc = \text{Schmidt Number} = \frac{\mu}{\rho C_D} = \frac{\text{Momentum Diffusivity}}{\text{Mass Diffusivity}} \quad (2.1f)$$

For comparing tracer diffusivities of aqueous, sodium chloride solutions and heated water, the following values of the dimensionless variables are established for the temperature range of experimental interest and for dilute NaCl solutions (2.16, 2.17):

$T (^{\circ}\text{F})$	=	50	-	100
$T (^{\circ}\text{C})$	=	20	-	40
Le	=	0.012	-	0.015
Pr	=	10	-	5
Sc	=	750	-	300

Note that the Lewis number is low, i.e., the thermal diffusivity is 65 to 85 times the mass diffusivity. For the salt tracer the Schmidt numbers are of the order 500 - 1000 (2.16); this indicates that momentum transport

mechanisms are over two orders of magnitude greater than mass diffusion. When only fluid motions (coolant mixing other than the integrated effects of fluid and energy mixing) are of interest, salt solutions are better suited for mixing experiment tracers than heated fluids.

Further discussion of tracer and coolant diffusivity will be given in Chapter 6.

2.6 The Advantages of Salt Solution Tracers

Salt solution tracers, in addition to low mass diffusivity, enjoy another marked advantage over hot water tracers. With salt solutions, the tracer concentration can be much greater than background concentration thus giving a wider range of tracer dilution during the experiment and reducing experimental error due to instrument sensitivity. The equivalent conductivity of tap water at 140F is of the order of 150 ppm of NaCl; tracers can be injected at concentrations of 50,000 ppm or more; this gives a tracer-to-background ratio of 300:1. For water at atmospheric pressure and say 60F, the enthalpy is 28 Btu/lbm, and the practical limit of tracer enthalpy (212F) is 180 Btu/lbm - a tracer-to-background ratio of about 7:1. Without pressurization of the system or cooling the main flow (and increasing pumping power to keep the same Reynolds number), the tracer-to-background enthalpy ratio is limited. Further,

using high tracer enthalpies leads to significant changes in fluid physical properties, particularly viscosity, in the experimental array. Table 2.2 gives a comparison of salt solution versus hot water tracers for inter-channel coolant mixing experiments.

Because the tracer may become highly diluted before being monitored by the detectors, weak signals are common in mixing experiments. Salt solution conductance measuring equipment is very sensitive to weak signals while temperature measuring equipment is not sensitive. This gives salt solutions another advantage over heated water tracers (more instrumentation details in Chapter 3).

For hot water tracers, internal thermocouples are not seriously affected by small inhomogeneties in the fluid temperature field but are affected by conduction within rod array materials. Thermocouples act as integrators and respond to average temperature changes with a characteristic time constant (of the order of seconds). With external temperature measurements, errors are introduced due to heat transfer in the withdrawal apparatus. Hot water tracers are amenable to internal detection only.

Salt solution tracers may or may not be desirable for internal measurements. A primary objective of this report is to experimentally establish the compatability,

Table 2.2

A Comparison of Salt Solution and Hot Water Tracers

<u>Salt Solution Tracer</u>	<u>Hot Water Tracer</u>
++High injection-to-Background concentration ratio	*Low injection-to-background ratio (high instrument accuracy required)
+Low mass diffusivity	*High thermal diffusivity
+Nonlinear relation between conductivity and solution concentration results in instruments sensitive to weak signals	*Linear relationship between enthalpy and temperature requires sensitive instruments to monitor weak signals
*Rapidly fluctuating measurements <u>may</u> be difficult to interpret with internal measurements	+Time integrated signal results with internal instrumentation
No storage or diffusion of tracer between injection and detection (except within coolant)	Materials within the test section conduct and store heat (the detected tracer)
External detection eliminates internal measurement difficulties without interference	External detection suffers from heat conduction interference
**Internal detection <u>may</u> be inherently impossible due to inhomogeneous solution concentrations within the conductance cells	High temperature injection influences the fluid viscosity and, therefore interferes slightly with the flow field
+Primary Advantage	
*Primary Disadvantage	

feasibility, and reliability of internal measurements of electrolytic conductance. The main concern is the level of inhomogeneity of salt solution concentration in the vicinity of the conductance cell used to measure solution concentration. How variations of solution strength and resistance (in a complex, three dimensional, time-dependent manner) in the region of the conductance cell influences the measurements is not clear. If the solute mass balance criterion is met, i.e., if the salt detected equals the salt injected (discussed in detail in Chapter 3), this inhomogeneity or unmixed solution consideration will not be of concern. If homogeneous concentrations are serious enough to generate difficulties with internal measurements, the difficulties should reduce with mixing, i.e., as the injector is moved away from the detector and the tracer solution mixes more with the main flow. Nevertheless, inhomogeneous solution problems can be eliminated by using an external detection system, if necessary.

2.7 A Review of Instrumentation Methods Used in Other Interchannel Coolant Mixing Experiments

This section shall discuss the instrumentation methods used in experiments on interchannel coolant mixing in triangular lattice, wire-wrap spaced fuel assemblies. A review of mixing experiment results is given in Rogers and Todreas (1.3) and in Todreas and

Turi (1.1). The literature cited in these papers may be consulted for instrumentation details of the investigations not discussed here.

Interchannel coolant mixing is currently of interest in light water reactors, gas-cooled reactors and particularly fast breeder reactors. In light water and gas-cooled thermal reactors, mixing is of interest because a better understanding of the mixing phenomenon can lead to improvements in reactor thermal performance. During thermal reactor development, conservatism in thermal design permitted demonstration reactors to safely compensate for lack of thermal-hydraulic development work. In fast breeder reactors, mixing is an important part of core thermal-mechanical as well as thermal-hydraulic design; thus for fast breeder reactors, the mixing phenomenon must be understood during reactor development, because it strongly influences core design.

The bulk of recent experimental activities in interchannel coolant mixing have been devoted to wire-wrap spaced fuel assemblies with geometries characteristic of LMFBR design. Table 2.3 summarizes details regarding the instrumentation methods used in wire-wrap spaced, rod array, coolant mixing experiments. Table 2.4 gives the geometrical parameters for these experimental rod arrays while Table 2.5 summarizes the operating parameters of the experiments.

Table 2.3

Instrumentation Methods Used in Wire - Wrap Spaced Coolant Mixing Experiments

Group	Exper. No.	Main Flow	Tracer	Injection Technique	Detection Technique	Ref. No.
ANL CT	1-3	Water	Salt (NaCl)	Axial, Low Velocity into Peripheral Channel	External, Full Subchannel Flow Withdrawal	[2.2] [2.3]
ANL CT	Planned	Water	Salt (NaCl)	Axial, Low Velocity into Peripheral Channel	External, Full Subchannel Flow Withdrawal	[2.4]
ANL RAS	4	Water	Heated Water	Transverse Low Velocity	Thermocouples Inside Pins, 4 Contiguous Subchannels, Numerous Axial Locations	[2.5]
ANL RAS	Planned	Water	Heated Water	Transverse Low Velocity	Transversing Thermocouples	[2.3] [2.6]
		Water	Salt (NaNO_3)	Axially through Tube, Equal Velocity	Internal, Flush, Rod-Mounted Electrodes	[2.7]
GE	5-6	Water	Heated Water	Axially into Six Interior Subchannels, Six Inches Above Inlet	Internal, Moving Thermocouple Probes Inside Array Rods.	[2.8]

Table 2.3 (Continued)

HEDL	7	Water	Salt (NaNO_3)	Needle, Isolated Subchannel with	Internal, Nickle Plated Copper Wire Flush with Rod	[2.9]
MIT (Eaton)	8	Water	Salt (NaCl)	Needle, Axially Moving	Probe Mounted, Platinized Conductivity Cells	-
MIT (Hanson)	Planned	Water	Salt (NaCl)	Needle, Axially Moving	Probes Mounted, Platinized Conductivity Cells	[2.10]
ORNL	9	Sodium	Heat Addition	Any Rod or Combination of Rods may be Heated Over 21 Inches Length	Thermocouples Mounted at Various Loca- tions within the Array Rods	[2.10]
France (Skok)	10-14	Water	Heated Rod	Traveling In- jector with Subchannel Isolation	Thermocouple Probes in Isolated Sub- channels at the Outlet	[2.11]
Germany (Baumann)	15-17	Sodium	Heat Addition	Central Array Rod Heated over First 39.4 Inches	Thermocouples at Subchannel Outlets	[2.12]

Table 2.3 (Concluded)

Japan (Okamoto)	18	Water	Salt (NaCl)	Injection Axially through a Tube at the Inlet	Conductance [2.13] Measuring Probes [2.14] in the Center of the Subchannel at the Bundle Outlet
Japan (Okamoto)	19	Water	Salt (NaCl)	Inection Trans- versely through Numerous Holes Around the Cir- cumference of an Array Rod	Conductance [2.13] Measuring Probes [2.14] in the Center of the Subchannel at the Bundle Outlet

*See Table 2.4 for Experimental Rod Array Geometrical Details and
Table 2.5 for Experimental Operating Parameter Details

Table 2.4*

Geometrical Parameters of Wire Wrap Spaced Rod Arrays
Used for Coolant Mixing Experiments

Group	Exper. No.	No. of Pins	Bundle Geometry	P/D	D	ℓ
ANL CT	1	7	Hexagon	1.20	0.25	6
	2			1.20	0.25	12
	3			1.20	0.25	18
ANL RAS	4	19	Hexagon	1.21	0.25	12
GE	5	127	Hexagon	1.20	0.25	12
	6			1.28	0.25	6
HEDL	7	217	Hexagon	1.24	0.23	11.9
MIT (Eaton)	8	25	Rhombus	1.25	0.25	12
ORNL	9	19	Hexagon	1.24	0.23	12
France (Skok)	10	7	Hexagon	1.36	0.67	17.7
	11			1.14	0.83	11.8
	12			1.14	0.83	17.7
	13			1.14	0.83	23.6
	14			1.07	0.91	17.7
Germany (Baumann)	15	61	Hexagon	1.32	0.24	3.94
	16					7.87
	17					11.8
Japan (Okamoto)	18	91	Hexagon	1.19	0.25	10.6
	19	19	Hexagon	1.08	0.59	11.8

* See Table 2.5 for Experimental Operating Parameter Details

Table 2.5

Operating Parameters for Wire-Wrap Spaced Rod Array,
Coolant Mixing Experiments

Group	Exper. No.	Re	Tracer	Tracer Cond.	Tracer Inject. Rate	Bkrd.	No. SC Monit.	No. Inj. Arr.	Axial Resol. (in.)
ANL CT	1	*	Salt (NaCl)				12		
	2		Salt (NaCl)				12		
	3		Salt (NaCl)				12		
ANL RAS	4		Heated Water						
GE	5	39,000	Heated Water	161 F	6.8 GPM	100 F	15	1	6
	6	54,900	Heated Water	161 F	8.8 GPM	100 F	38	1	1
HEDL	7	10,000- 30,000	Salt (NaNO ₃)	4145 ppm 2165 ppm	1.81, 0.95 lbm/hr	City Water	1/6 Bundle Sector	3	6
MIT (Eaton)	8	15,000 1,500	Salt (NaCl)	2.0 gr/lb 1.0 gr/lb 3.0 gr/lb		City Water	27 20	2	Continuous; Exit
ORNL	9		Heat Addition					Any Rod	

Table 2.5 (Concluded).

France (Skok)	10	42,000	Heated Water	60-70 C	Full SC Flow	20 C	12	3	2
	11	25,000- 55,000	Heated Water	60-70 C	Full SC Flow	20 C	12	2	1, 1/2
	12	42,000	Heated Water	60-70 C	Full SC Flow	20 C	12	3	2
	13	42,000	Heated Water	60-70 C	Full Sc Flow	20 C	12	3	3
	14	42,000	Heated Water	60-70 C		20 C	12	3	2
Germany (Baumann)	15	8,000- 70,000	Heat Addition	*	3-15 Kw, Center Rod	300- 500C	50	1	Exit
	16	8,000- 70,000	Heat Addition			300- 500C	50	1	Exit
	17	8,000 70,000	Heat Addition			300- 500C	50	1	Exit
Japan (Okamoto)	18		Salt (NaCl)					1	Exit
	19		Salt (NaCl)					1	

*Information deleted was not reported

Some experiments have used sodium, the LMFBR coolant, for the main flow, and others have used water to model sodium. Sodium (at LMFBR operating conditions) is hydraulically quite similar to water, so that water is a good fluid for modeling sodium flow (using the equal Reynolds number criterion). Sodium flow experiments have used heated rods for tracer insertion (heat addition) and internal thermocouple detectors. Water flow experiments have used both heated water (from injection and heat addition) and electrolytic solution injection and have had both internal and external detection systems. No effort has compared techniques of injection and detection, but instead, each experiment has used one injection design and one detector design. In the literature to date, discussion of the methods and design of coolant mixing experiment instrumentation has been poor.

The Argonne National Laboratory (ANL) has two coolant mixing investigations underway. Lorenz and Ginsberg (2.2, 2.3) of the Components Technology (CT) Division have run experiments with a 7-pin, hexagonal rod bundle with a pitch-to-diameter P/D ratio of 1.20 and 0.25 inch diameter rods. The experiments used water for the main flow and salt (NaCl) solution as the tracer. The solution was injected into a peripheral subchannel and in the axial direction through a hole

drilled into a tube penetrating transversely into the subchannel through the flow channel wall. The detection system used a full subchannel flow withdrawal technique with an external conductivity cell. The subchannels were monitored individually giving averaged, outlet, subchannel tracer concentrations. This technique has been expanded into a 91-pin, hexagonal array (2.4).

J. van Erp and T. Chawla (2.5, 2.6) of the ANL Reactor Analysis and Safety Division have conducted experiments with a 91-pin hexagonal rod bundle with 0.25 inch diameter rods ($P/D = 1.21$). These experiments used water for the main flow and heated water as the tracer. The tracer was injected at low velocity transversely through a hole in one of the array rods. The detection system used thermocouples mounted inside the array rods at numerous axial locations. Only four contiguous subchannels were monitored in these experiments. The work has also been extended to a 91-pin, hexagonal geometry (2.3, 2.7).

At General Electric, Marian and Hines (2.8) have run a 127-pin bundle with two rod arrays, $P/D = 1.20$ and 1.28 , $l = 12$ inches and 6 inches, respectively, and $D = 0.25$ inches. A heated water tracer was used and temperatures were measured with transversing thermocouples inside the rod array tubes. The heated water was injected near the inlet into the six interior

subchannels surrounding the central array rod.

Salt (NaNO_3) tracer experiments have been run with internal conductivity cell instrumentation at the Hanford Engineering Development Laboratory (HEDL) by Collingham, et al. (2.9). The experimental test section is the only published full-scale 217-pin, hexagonal array used for mixing studies. The tracer was injected through a stationary needle into a subchannel confined by fins in the injection region; a flow equal to the injection flow rate was withdrawn from near the injector. Nickle plated (not platinized) copper electrodes flush with the rod surface were mounted in several axial detection locations.

The details of the MIT 25-pin rhombus experiments by Eaton and Todreas are discussed within this report. Briefly, a salt solution tracer was injected from a continuously moving injection device. The tracer dispersion in the wire-wrapped rod array ($l = 12$ inches, $P/D = 1.25$, $D = 0.25$ inches) was monitored by internal conductivity-measuring probes near the bundle outlet. The details of the experimental design shall be discussed in Chapter 4.

Hanson and Todreas (2.10) shall be using methods developed as part of this work to do a series of investigations of 61-pin, hexagonal wire-wrapped rod arrays. The objective of this work shall be to examine the

influence of geometrical parameters, e.g., pitch-to-diameter ratio, rod diameter, and lead length on inter-channel coolant mixing in rod bundles of typical LMFBR geometries.

A 19-pin, hexagonal bundle has been used for coolant mixing studies at the Oak Ridge National Laboratory ORNL (2.10). The main flow for this work was sodium and heat addition was used as a tracer. Any one of the array rods could be heated individually (or in any combination) over a 21 inch (approximate) length. Thermocouples were mounted at various locations within the rod array and in the flow channel walls to monitor temperatures.

Foreign interchannel coolant mixing studies have been reported in France, Germany and Japan. Skok (2.11) in France has run a series of 5 different rod bundles in a 7-pin, hexagonal geometry. The rod size was about 3 times (3X) nominal size ($D = 0.83$ in), and the effect of lead length on mixing behavior was examined. The experiments used water for the main flow and heated water injection for the tracer. The tracer was injected at variable levels into subchannels isolated by fins in the gaps between the rods (in the axial region near the injection point). Fluid temperatures were detected by thermocouples in the subchannels near the bundle outlet.

Baumann and Hoffmann in Germany (2.12) have done coolant mixing experiments in a 61-pin, hexagonal assembly ($D = 0.24$ in., $P/D = 1.32$) using a sodium flow. A heated central rod was used for tracer insertion, and temperatures were measured internally with thermocouples mounted in the subchannels near the array outlet. Included as part of these experiments was a parametric study of the influence of lead length l on interchannel coolant mixing.

In Japan, Okamoto, et al. (2.13, 2.14) have run experiments in a 91-pin, hexagonal assembly typical of LMFBR's, and also, an experiment was run with a 19-pin, hexagonal rod bundle typical of a LMFBR blanket assembly. Both experiments used water for the main flow with internal, probe-type (externally supported) conductivity cells mounted in the center of the flow subchannels and located at the outlet of the bundle. The salt (NaCl) solution tracer was injected into the inlet of the injection subchannel through a tube in the case of the 91-pin experiment. In the 19-pin experiment, the tracer was injected transversely around the periphery of the circumference of the injection rod.

Davidson (2.15) has reported results of salt tracer instrumentation development work in a single (unwrapped) subchannel. This work was done to assess

the influence of boundary layers on conductivity cell detectors mounted flush against an array rod (internal detection). Because the tracer (NaNO_3) was injected into the center of the subchannel, it was found that a 4 to 6 inch development length was required for the tracer to penetrate to the rod surface, i.e., to be properly detected. For this work, the conductivity detectors were located directly in the flow of the subchannel so that these results may not be applicable.

Chapter 3

SALT SOLUTION TRACER EXPERIMENTS

3.1 Water Solutions and Electrolytic Conductance

When electrolytic salts are dissolved in water, the dissolved salt disassociates (to a certain degree) into ions. These dissociated ions serve as electrical charge carriers within the solution and thus decrease the resistance to the flow of electrical charge below that resistance characterized by the pure solvent. The conductance, the inverse of electrical resistance, of an electrolytic solution depends quite strongly on solution strength; as solution concentration is increased, the electrolytic conductance rapidly rises. It then saturates quickly and approaches a limit monotonically as the solution strength approaches saturation. A solution resistance versus salt concentration curve is given in Figure 3.1, and well illustrates this conductance behavior in the case of sodium chloride dissolved in 140F distilled water. Notice the resistance drops from well over 300,000 Ohms-cm for the pure water to around 500 Ohms-cm for a NaCl solution of 113 ppm (parts per million) but has dropped to only 100 Ohms-cm when the solution concentration is further increased six-fold.

Some familiar water solutions include saltwater which is greater than 15,000 ppm dissolved solids by

FIGURE 3.1 - SPECIFIC RESISTANCE vs. CONCENTRATION OF SODIUM CHLORIDE DISSOLVED IN DISTILLED H₂O AT 140F

weight, seawater which is about 35,000 ppm, and brackish which is from 1,000 to 15,000 ppm. Municipal water supplies are usually less than 500 ppm. Good tasting drinking water contains about 300 ppm dissolved solids; water for irrigation should be less than 200 ppm; and supercritical pressure, steam generators operate with less than 0.1 ppm (3.1). Note, 1 ppm equals 0.0022 grams per pound.

The complex topics of electrolytic solutions and electrolytic conductance measurements are well discussed in standard electrochemistry books (3.2, 3.3). The interested reader is referred to such texts for detailed discussion of the topics of this chapter. In order to describe salt tracer experiments, an abbreviated discussion of electrolytic solutions and the measurement of electrolytic conductance is presented below.

3.2 Electrolytic Conductance Mechanisms

The ability of a salt solution to conduct electricity is explained by two phenomenon: (1) ionic velocity or mobility and (2) ionic dissociation. The strong dependence of solution resistance on the concentration of dissolved solids results because at higher concentrations interionic interactions increase and ionic dissociation decreases. At "infinite dilution," where only a minute trace of solute is present, ionic dissociation of the solute is

complete and the ions move through the solution unhindered by interactions with other charge carriers. As solution strength is increased, the presence of other ions in the solution reduces the fraction of the solute dissociated and therefore available to transport charge; the other ions also slow the velocity of ionic movement due to electrical interactions between oppositely charged ions.

The complex nature of electrical conduction in electrolytic solutions obviously depends on the specific electrolyte and solvent involved. The presence of other solutes within a solution can alter the electrolytic conductance behavior of the solute of interest. Most importantly, however, the electrical conductance of solutions is strongly dependent on temperature. The conductance of aqueous solutions is strongly temperature dependent and changes about 1% per degree Fahrenheit (3.3). Accurate solution temperature control is a must for reliable conductance measurements.

3.3 Electrolytic Solutions as Tracers

With the conductance behavior of electrolytic solutions briefly explained, the discussion shall now turn to the utilization of salt solution tracers for mixing experiments. It is necessary only to remember that the salt solution is introduced into the experimental array at some distance upstream of the detectors. Items

relating to conductance measurements which have a fundamental influence on this experimental method include: (1) molecular diffusion of salts due to concentration gradients, (2) general behavior of solution resistance versus concentration and (3) the concentration of the tracer compared to the concentration equivalent of the main flow.

The low mass diffusivity of salt solution tracers introduces a fundamental difficulty in coolant mixing experiments with internal detectors. A stream of salt solution injected into a flow field will be dispersed in part by large scale turbulent eddies thus generating inhomogeneities of solution concentration (turbulent fluctuations), particularly in regions near the injector, but electrical conductance measuring devices, conductivity cells, require a homogeneous solution in order to provide reliable measurements. An inhomogeneous solution within a conductance cell will indicate a different resistance than would be indicated by a homogeneous solution involving the same quantity of electrolyte (salt). Specifically, the measured resistance is difficult to interpret because of the nonlinear relationship between conductance and solution concentration. The concentration of solute in parts of the solution being measured changes the overall resistance more than the dilution of solute in other

parts of the solution offsets it. This three dimensional, solution inhomogeneity problem is a complex question that is difficult to assess. However, if the conductance is monitored in all subchannels within the flow channel, the instrumentation should detect the same total amount of salt going past an axial plane located downstream of the injector as is known to be injected. This monitoring criterion is referred to as the salt "Mass Balance" and is an effective measure for assessing the inherent accuracy of the conductivity instrumentation. Because stripping, the failure to meet the mass balance criterion, is characterized in part by specific flow conditions within the experiment, a mass balance should be an integral check of any salt tracer experiment.

The electrical resistance versus solution concentration, R vs. C , curve in Figure 3.1 shows that salt injection instrumentation methods can be expected to have good resolving power (the ability to monitor weak signals) because the resistance of the solution is strongly dependent on solution strength at low concentrations. The nonlinear behavior of R vs. C gives flexibility to the experimenter with regard to the results sought. The nonlinear character also influences the accuracy of the technique when low salt concentrations must be detected; the salt injection technique is very capable of monitoring weak signals common to a coolant

mixing experiment. This is a marked advantage over the linear temperature versus enthalpy relationship characteristic of hot water tracers.

3.4 Conductance Measurement Networks

The measurement of the electrical conductance of an electrolytic solution consists of using the solution to complete an electrical circuit. The circuit itself is a combination of electrical equipment to measure an unknown electrical resistance. Several methods of measuring and recording the unknown resistance can be used. The primary requirements of the method used are that the resistance be reliably and rapidly measured. A preliminary consideration in selecting measuring equipment is the option of using either direct current DC or alternating current AC circuitry. AC measurements are preferred over DC for reasons discussed below.

The use of an AC conductance measuring circuit instead of a DC circuit significantly influences the accuracy of conductance measurements. A tabulation of the characteristics of each technique is given in Table 3.1. Briefly, the major reason for using the AC circuit is the ability of this method to overcome polarization errors inherent to the DC technique (discussed later); the major disadvantage of the AC circuit is the introduction of inherent reactance effects within the

Table 3.1

Characteristics of AC and DC Conductance Measuring Circuits*

<u>Alternating Current</u>	<u>Direct Current</u>
Polarization can be greatly reduced and eliminated for practical purposes	No reactance effects that are inherent to AC
More accurate measurements with standard equipment	Simple Electrical Network
No stray DC influence on measurements	Thermoelectric and contact potentials may interfere with measurements
Amplification simple and inexpensive	High sensitivity equipment is more expensive and less common
Reactance effects complicate measurements	

*References (3.2, 3.3, 3.4)

circuitry. Accurate AC equipment is readily available; also stray DC currents, contact potentials and thermoelectric effects, do not interfere with AC measurements. Details concerning electrical conductance measuring equipment and methods used for this work are given in Appendix 2.

3.5 The Conductivity Cell

The apparatus that uses the electrolytic solution to complete the electrical measuring circuit is the conductivity cell. The solution acts as an electrical conductor between the cell's two exposed electrodes when they are submerged into the solution. With this cell, the conductance of the solution may be determined and used as a measure of the concentration of dissolved salt in the solution. The resistance measured between the electrodes or within the cell is determined by the cell's design as well as by the solution.

The electrical network equivalent of a conductance cell (3.5) is shown in Figure 3.2(A). The solution acts as a resistance R between the two electrodes; it is this component of the electrical network shown that is of interest. The capacitance C is the result of the dielectric action of the solution between the electrodes and of the capacitive effects in the lead wires connecting the cell to the measurement equipment.

(A)

CONDUCTIVITY CELL WITH BRIGHT PLATINUM ELECTRODES

(B)

CONDUCTIVITY CELL WITH PLATINIZED PLATINUM ELECTRODES

FIGURE 3.2 - ELECTRICAL NETWORK EQUIVALENT OF A
CONDUCTIVITY CELL USING AC MEASURING
TECHNIQUES (From 3.5)

R_s , W_s and C_s are effects at the electrode surfaces. These surface effects are consequences of the change of the electrical conduction mechanism from that of a solid wire to that of an electrolytic solution. Because ionic velocities are slow, a double layer of ions is generated at the electrode surfaces in the process of AC charge transport; the layer acts as a capacitance C_s in series with the solution resistance. Electrolysis at the electrode surfaces is represented in the network equivalent by R_s and W_s ; these surface phenomenon are in parallel with C_s . R_s is a representation of the resistance to charge flow generated by the electrolysis process, and W_s is a "Warburg Impedance" which may be considered a resistance in series with a capacitor. For further details the reader is referred to Robinson and Stokes (3.5).

The electrolysis process occurring at the surfaces of the electrodes, referred to as polarization, interferes significantly with AC conductance measurements. "Kohlrausch (3.6) discovered that errors due to polarization in the measurement of conductance can be minimized by covering the electrodes by a deposit of finely divided black platinum." (3.7) Jones and Bollinger (3.7) have studied platinization in more detail. Platinizing the electrodes of a conductance cell proceeds by cleaning the cell surfaces in a

solution of isopropyl alcohol, ethyl ether and hydrochloric acid (see Equipment List, Appendix 4). Platinum black is next electroplated on the electrodes from a platinizing solution made of 3% platinum chloride dissolved in a 0.025% lead acetate solution. With the cell electrodes platinized, the conductance measurements become considerably simpler as evidenced by the network electrical equivalent of the platinized conductivity cell shown in Figure 3.2(B). The electrolysis effects represented by R_s and W_s are for all practical purposes, eliminated from the network equivalent by platinization.

The effectiveness of platinization can be readily evaluated by making conductance measurements at several frequencies, say 60, 100 and 10,000 Hertz. Polarization effects are frequency dependent and decrease with increasing frequency. Audio range frequencies (less than 15,000 Hertz) only are of interest here because other reactive elements in the measurement circuit become overbearing at higher frequencies. The deviation of measured resistance of a given solution with changes in frequency (in the audio frequency range) should be at most a few per cent if the cell has been platinized properly. The cell user is cautioned that, in order to prevent gas entrainment onto the platinized surfaces, a conductivity cell should be

stored in a salt solution when not in use (say 0.1N NaCl). Only when storage is for more than a month should the platinized surfaces be allowed to dry in air.

As was mentioned previously, the resistance measured across the leads of a conductivity cell immersed in a solution is determined by the solution's concentration and by the design of the conductivity cell itself. The ratio of electrode separation distance l_e to exposed electrode area A_e is the cell constant and is a function of cell design only:

$$K_c = l_e / A_e \quad (\text{cm}^{-1}) \quad (3.1)$$

This standard definition is really oversimplified; it assumes that the exposed area of each electrode is parallel and that the exposed electrode surface is constant along its length. The cell constant is the geometric characteristic which relates measured resistance R_m to the specific resistance r_s (or to the specific conductance k_s) of the solution:

$$r_s = R_m / K_c \quad (\text{Ohm-cm}) \quad (3.2a)$$

$$k_s = K_c / R_m \quad (\text{mho/cm}) \quad (3.2b)$$

A conductivity cell constant may be either calculated with this simple geometry method or calibrated with a solution of known conductance. Calibration, the more reliable technique, may be accomplished by either the reference solution method or the reference cell method (3.8). In the reference solution calibration technique,

a solution of known conductance is used to determine K_c with the measured resistance known. Table 3.2 gives the specific conductance of several standard solutions of potassium chloride dissolved in distilled water and exposed to air; the strong temperature dependence and range of cell constants should be noted. The cell constant range is required so that the measured resistance will be within a high accuracy range on the Wheatstone bridge as discussed in Appendix 2. With the reference cell method, the cell to be calibrated and a reference cell of known cell constant, e.g., a commercial cell, are submerged in a common solution. The reference cell is used to measure the solution specific resistance, and the calibration procedure becomes identical to the reference solution method.

It is easily established that the unknown cell constant K_{cu} is related to the unknown measured resistance R_{mu} , the reference cell constant K_{cr} and the reference measured resistance R_{mr} by:

$$K_{cu} = K_{cr} R_{mu} / R_{mr}. \quad (3.3)$$

3.6 Accurate Conductance Measurements

The accurate measurement of the specific conductance or specific resistance of an electrolytic solution requires the following major conditions (3.5):

- (1) accurate electrical measurements,

Table 3.2
Standard Reference Solutions*

Normality	Definition	Temp. (°C)	Specific Conductance (micromhos)	Cell Constant Range
1.0 N	71.1352g KCl/1000g Solution	0	65,176	50 - 10
		18	97,838	
		25	111,342	
0.1 N	7.41913g KCl/1000g Solution	0	7,137.9	1.0
		18	11,166.7	
		25	12,856.0	
0.01	0.74526g KCl/1000g Solution	0	773.64	0.05 - 0.5
		18	1,220.52	
		25	1,408.77	

*From (3.8)

- (2) avoidance of polarization errors,
- (3) accurate control of solution temperature and,
- (4) in the case of standard techniques, a solution of homogeneous concentration.

For this work, sodium chloride NaCl dissolved in city water (1.0 - 3.0 grams - NaCl / lbm - city water) was used as the salt solution tracer. City water with a specific conductance ranging from 2500 - 4000 Ohm-cm was used for the main flow fluid. AC measurements with heavily platinized, platinum electrode, conductivity cells were used to provide accurate measurements of solution conductance. Temperature control was achieved by making all measurements under isothermal, room temperature conditions.

It cannot be overemphasized that electrolytic conductance measurements are complicated in nature and susceptible to error in numerous ways. Although the operational procedures are straightforward and simple, the measurer should always be on the lookout for indications that something is wrong. Unfortunately, reliable conductance measurements are subject to a myriad of errors which are often subtle in nature. Erroneous signals do, however, offer signals to a judicious investigator.

Chapter 4

EXPERIMENT DESIGN AND CONSTRUCTION

4.1 Experiment Design Criteria

The experimental investigation of interchannel coolant mixing is the main objective of this work. The design and construction of the Mixing Instrumentation Test Facility MITF shall be discussed in this chapter.

The experimental MITF was designed and constructed based on the following criteria:

- (1) axially detailed, experimental coolant mixing results,
- (2) a salt solution tracer,
- (3) internal detection instruments,
- (4) a partial bundle section geometry (rhombus), and
- (5) a plexiglas flow channel.

Prior to June 1972, the project was handicapped by limited financial support which retarded the initial activities of the experimental program. After June 1972, external support of the project was received from the USAEC, and the experimental facility was completely redesigned and reconstructed by the author.

4.2 Experimental Objectives

The objectives of the experimental efforts regarding interchannel coolant mixing follow:

- (1) to evaluate the compatability of internal instrumentation for salt solution tracer experiments and
- (2) to assimilate interchannel coolant mixing data with continuous axial resolution.

4.3 The History of MITF, the Mixing Instrumentation Test Facility

MITF has had a long history of difficulties during construction and operation. The problems have been in three general areas: the experimental rod array, the test section channel or flow housing, and the detection instrumentation. Since 1971, four rod arrays and two test section channels have been constructed. Prior to Fall 1972, the problems of the experimental facility were further compounded by limitations in the hydraulic facilities.

The first experimental mixing test facility was constructed in the MIT Heat Transfer Laboratory and connected to an existing hydraulic loop. A schematic of the hydraulic loop and a cross section of the experimental test section are shown in Figures 4.1 and 4.2, respectively. Experimental test section No. 1 was originally constructed and described by J. Turi (4.1). Basically this test section was a 5 X 6 parallelogram array of 1/4 inch diameter tubes with single

FIGURE 4.1 - SCHEMATIC OF HYDRAULIC LOOP NO. 1 USED FOR MIXING EXPERIMENTS

FIGURE 4.2 - CROSS SECTION OF EXPERIMENTAL TEST SECTION NO. 1

wire-wrap spacers maintaining an equilateral, triangular lattice on a 5/16 inch rod-to-rod pitch. The rod array was 72 inches long and had a 12 inch wire-wrap lead (axial pitch). The experimental test section was designed to be representative of the corner of a 217-pin LMFBR fuel assembly, cf. Figure 1.2. It was hoped that inter-channel coolant mixing results characteristic of interior, peripheral and corner subchannels could be obtained with this facility. Also, near-wall interior and deep interior (four rows of subchannels from any wall) were to be monitored so as to evaluate the influence of flow by-pass on mixing at the rod array edge. The experimental test section was constructed so as to accommodate up to a 6 X 8 array. By changing the number of rods in the array and using shims to fill the unoccupied flow areas, the effect of non-typical 60° corners could be assessed. The changes of bundle geometry of both the experimental, rhombus rod arrays and the regular, hexagonal rod arrays are tabulated in Table 4.1. The by-pass flow for a given rod diameter and rod-to-rod pitch is characterized by the inverse of the ratio of the number of interior subchannels to the number of peripheral subchannels (see also Table 6.2). It will be noted that the rhombus offers little, if any, flow advantage over the regular hexagonal geometries.

However, the construction of the flow channel is

Table 4.1

Geometrical Characteristics of Hexagonal and
Parallelogram, Triangular Lattice Rod Bundles of Interest

Array Geometry	Number of Rods	Rods/ Side	Number Corner Subch.	Number Interior Subch.	Number Perip. Subch.	Interior Peripheral
Hexagonal	7	2	6	6	6	1.00
"	19	3	6	24	12	2.00
"	37	4	6	54	18	3.00
"	61	5	6	96	24	4.00
"	91	6	6	150	30	5.00
"	127	7	6	216	36	6.00
"	169	8	6	294	42	7.00
"	217	9	6	384	48	8.00
"	271	10	6	486	54	9.00
"	331	11	6	600	60	10.00
"	397	12	6	726	66	11.00
"	469	13	6	864	72	12.00
Parallel- ogram	25	5x5	2,2*	32	16	2.00
"	30	5x6	2,2	40	18	2.22
"	35	5x7	2,2	48	20	2.40
"	36	6x6	2,2	50	20	2.50
"	40	5x8	2,2	56	22	2.55
"	42	6x7	2,2	60	22	2.73
"	45	5x9	2,2	64	24	2.67
"	47	7x7	2,2	72	24	3.00
"	48	6x8	2,2	70	24	2.92
"	54	6x9	2,2	80	26	3.08
"	56	7x8	2,2	84	26	3.23
"	63	7x9	2,2	96	28	3.43
"	64	8x8	2,2	98	28	3.50
"	72	8x9	2,2	112	30	3.73
"	81	9x9	2,2	128	32	4.00

*Number of 120° Corner Subchannels, Number of 60° Corner
Subchannels

simplified in the case of the rhombus. The test section flow channel was made in two sections, one with 3 - 120° elbow, one with 1 - 120° elbow, see Figure 4.2. These two pieces were held together with bolts every 2 inches. The hydraulic loop consisted of three main systems: (1) the main flow system, (2) the injection system and (3) the water storage and heating system. Three tanks, each made of two-55 gallon drums welded together, provided for 330 gallons of water storage. The tanks could be filled with either hot or cold water. One of the three tanks contained a steam fed, copper coil for heating and regulating the water temperature. The bypass loop on the main flow system was a valuable aid in regulating the temperature of the stored water and in deaerating the water during heating. The main flow system had a two-stage centrifugal pump, flow regulating and flow monitoring equipment. The main flow entered the lower plexiglas plenum (with flow straightener), flowed up through the test section, entered the plexiglas upper plenum and discharged by gravity either to the storage tanks or to a floor drain.

The tracer injection system was basically a commercial hot water tank pressurized by a compressed air cylinder. The tank was equipped with an electric heating element which could be used to maintain the temperature of the tracer solution. (This heating

element was completely destroyed by the strong salt solutions.) The tracer was monitored, regulated and then injected into the main flow. The hydraulic systems discussed above were a complete redesign of the original arrangement by Turi.

The original rod array built by Turi used a single stationary needle injector and multilevel conductance cells mounted over 6 inch intervals in the upper 36 inches of the array. Four interior subchannels were instrumented, the injection subchannel and the three contiguous subchannels. The cell electrodes were glued to holes drilled through the sides of the plexiglas (lucite) tubes making-up the array; they consisted of bright platinum discs soldered to copper lead wires. The electrode lead wires were fed through the tube and connected via a switching network to a simple AC Wheatstone bridge. The electrodes were not platinized and protruded markedly into the subchannels: the conductance measurements were, consequently, unacceptably frequency dependent.

The tracer was carried by a tube from the tracer tank to the injection tube. The injection tube was closed at the lower end so that the tracer solution was forced through the stationary needle mounted at about 20° from the tube axial centerline and pointed in the direction of the flow. During initial operation, the

plexiglas tube broke at a location which had been weakened in mounting the electrodes. The tube could not support the injection system pressure at the required tracer flows. This failure necessitated disassembly of the original No. 1 test section.

After disassembly, the design of the injection and detection systems was modified considerably by the author so as to improve the capabilities of the experimental facility. The injection tube was changed to provide for an axially moving injector; the conductance cells were located at one axial location and more subchannels were monitored. The moving injector needle was constructed using two concentric aluminium tubes. The outer $1/4$ inch outside diameter OD, thin-wall tube was slotted ($1/16$ inch wide) from 31 inches to 1 inch from the upper end of the tube. A $3/16$ inch OD tube (plugged on the lower end) was inserted inside the $1/4$ inch tube. A $1/16$ inch OD needle was inserted (at approximately 20° from the direction of flow) into the inner tube through the slot in the outer tube. The needle was ground down to be flush with the outside of the outer tube. The tube was next wrapped in the usual manner with the injector needle passing under the wire-wrap.

Disassembly of No. 1 test section revealed that the flow channel was both designed and manufactured in a manner which resulted in a poorly defined flow area.

With the second version of No. 1 rod array completed, it was found during assembly that the plexiglas tubes were structurally too weak and brittle for service in the test section. At this point, construction was initiated on the third version of No. 1 rod array using solid plexiglass rods instead of the tubes used previously. To simplify electrode construction and to increase the structural strength of the instrumented area of the rod, a 30 AWG (American Wire Gauge) copper wire was used to form the electrodes instead of the platinum disk. Figure 4.3 shows qualitatively how these electrodes were mounted on the plexiglas rods. First, a 1-3/8 inch deep hole is drilled down the centerline of the rod from the top. Then electrode mounting holes are drilled each 60° (at the proper orientation with respect to the rod support holes) so that an electrode would be in each subchannel around the rod. These mounting holes are drilled at 1-1/4 and 1-1/2 inches from the top of the rod. The holes should be backfilled with glue to hold the electrode wires in place. The wire should be held in place at the lower support hole with glue also.

A major consideration in designing and mounting the electrodes was the platinization of the electrode surfaces. Because the platinizing solution costs about \$10 per ounce, the electrodes must be arranged so that the cost of platinization is not prohibitive (electrodes should not be platinized before assembly as handling destroys the weakly bonded platinized surfaces).

FIGURE 4.3 - ROD-MOUNTED ELECTRODE DESIGN

To keep the volume of platinizing solution reasonable, the electrodes should be near the end of the rods. The multiple axial level, electrode mounting scheme would be impractical because of the electrode platinization expense.

4.4 The First Experiment

With the third version of test array No. 1, a series of experiments on interchannel coolant mixing were run. The first and only reasonable experiment in the series was made on 16 April, 1972; the results of this run are given in Figure 4.4 and are presented only for the sake of illustration. The following parameters were used for this experiment:

Main Flow = 72 lbm water/min, Water Temp = 140F
(Cambridge, Mass., City Water)

Tracer Concentration = 0.5 gram NaCl/lbm Water,
Injection Rate = 1.2 lbm/min

Subchannel Reynolds Number = 4500 (Approx.),
Subchannel Flow Rate = 0.95 lbm/min.

The tracer solution was injected into subchannel No. 1 (the subchannel arrangement is shown in the inset in Figure 4.4); measurements were taken each 1/2 inch over the first 10 inches, and every 2 inches from 10 to 16 inches. The 0.0 inch position is with the needle about 1/2 inch below the instrumentation plane. The wire-wrap was in the right hand direction so that any swirl flow

would be directed in the counterclockwise CCW direction (looking down from the top of the test array). The uncertainties in the geometry of the rod array and the flow channel necessitates the dismissal of any confidence in the fine axial structure of the data. The general exponential-like decay of the tracer concentration in the injection subchannel and dispersion to neighboring subchannels was expected. Unfortunately, this data is highly uncertain and of little quantitative value.

Subsequent runs in the first experiment series (with the third version of test array No. 1) revealed unexpected results after the data reduction. Even though injection was into subchannel 1, all of the tracer appeared in subchannel 2, and the trend was consistent for all but the first run of the series (4.2). Post disassembly examination revealed that bubbles of air left in the backfill adhesive had caused internal pressurization and subsequent ballooning of the plexiglas rods in the region just above the electrodes. The experiments were all run at elevated temperatures (140F) so as to increase the Reynolds number of the experiments. A two stage, high head-low flow centrifugal pump was being used in low head service; the resulting low flow rates required that the main flow be heated in order to establish turbulent flow. The viscosity of water reduces

by a factor of two between room temperature and 140F. So, for a fixed flow rate, the Reynolds number was doubled by heating the water.

Because the plexiglas loses strength very rapidly above 100F and because the backfill adhesive dried at room temperature, the slight pressurization of the bubbles upon heating to 140F caused an irregular ballooning of the instrumented array rods. These flow blockages were responsible for the unexpected mixing data; however, these blockages were totally unexpected, and no record of their location or size was made.

Also it should be noted that the wrap spacer on the aluminium injector tube had become loose due to adhesive failure in the hot water. The wrap was in-place but loose.

The array rods suffering from ballooning were replaced with new rods that were manufactured ascertaining there were no air bubbles in the backfill adhesive. The injector rod was rewrapped. The test section was reassembled with version four of test array No. 1, prepared for operation and stored for three months. Data taken on 8 October, 1972, was of an unexpected nature. Examination of the test array showed the rods to be distorted and out of position. The plexiglas rods had crept in storage and in general

were too flexible to use for the array; also, as previously noted, the flow channel was of very poor quality. Since the experimental work was now externally sponsored, funds were available to accurately rebuild the flow channel and to rebuild the rod array from metal rods. The design and construction of test section No. 2 (test array No. 2 and flow channel No. 2) is discussed next.

4.5 Facility Redesign and Reconstruction

With the MITF returned to the drawing boards after considerable operating experience, the design of the test section, particularly the instrumentation, was improved markedly. The No. 2 rod array was made entirely of 304 stainless steel (SS). The test section flow channel No. 2 was made of one inch thick plexiglas sheet and accurately machined. Stronger and lighter upper and lower plenums were made from aluminium, and the experiment was moved from the EPL (Engineering Projects Laboratory) - Heat Transfer Laboratory to the EPL - Experimental Engineering Laboratory No. 2 (EPL-EEL-@) where a flow test loop of broader capability could be constructed. Most importantly, a probe-type, electrode mount was used instead of the rod mounting scheme described earlier. This modification of instrumentation design considerably expands the capabilities and flexibilities of the facility as will be discussed later.

EPL-EEL-2 provided a larger volume of stored water since a 55,000 gallon subfloor canal was available. Here a large pumping facility (designed by A.S. Hanson) had already been built to provide flow for planned 61-pin, hexagonal bundle tests. The facilities of EEL-2 permitted experiments over a larger Reynolds number range at room temperature; thus, heating, deaeration, draining and storage did not limit the operation of the experimental facility. Numerous direct and indirect difficulties originating from limitations in the hydraulic facilities used with test section No. 1 were therefore not present in the experiments on test section No. 2. Figure 4.5 gives a schematic of the mixing investigation pump facility in EPL-EEL-2; each of the two 20 horsepower pumps is rated at 300 gallons per minute GPM at a 180 ft-water head (78 psig). The pumps can be run individually, in series or in parallel.

4.6 Test Section Redesign

The test section flow channel and its plenums were rebuilt to accurate dimensions. Flow channel No. 2 was constructed from one inch plexiglas sheet. The channel was bolted together every 2 inches over its 72 inch length and later cemented to seal the assembly (see Figure 4.6). The upper and lower plenums were made of 18 inch long, 6.75 inch OD, aluminium tubes with $\frac{3}{8}$ inch

FIGURE 4.5 - SCHEMATIC OF MIT MIXING PROJECT PUMP FACILITY

FIGURE 4.6 - CROSS SECTION VIEW OF THE TEST SECTION FLOW CHANNEL NO. 2

thick aluminium plates welded or bolted to the plenum ends. The upper plenum was open on the top to permit access to the top of the test array; the top plenum was drained by gravity to the canal from which the water was drawn (at a point about 30 ft. from the pump inlet). The lower plenum received the flow from the pumps and was internally equipped with a flow straightener to give a uniform inlet flow to the test section channel.

The rod array was rebuilt with type 304 stainless steel SS rods and wire-wrap. The rods were cut to length and faced-off on each end. On the lower end, two 1/8 inch diameter rod support holes were drilled transversely through the rod centerline at 1 and at 1-1/2 inches; at 2 inches a wire-wrap support hole, 1/16 inch in diameter was drilled parallel to the rod support holes through the rod center line. This wrap support hole establishes the relative angular orientation of the wrap with respect to the rod in the assembled array. At the upper end of the rod an upper rod support hole of 1/8 inch diameter was drilled down the rod centerline to a depth of 1/4 inch. Figure 4.7 shows the end details of the test array rods. The 304 SS wire-wrap was soldered into the wrap support and bent 90° to lie flat against the rod. The lower end of the injector rod was similar to the other array rods;

NOTE: SCALE 2X TRUE SIZE
RODS ARE 1/4 INCH O.D. 304 STAINLESS STEEL
WITH 12 INCH LEAD (RIGHT-HANDED) WIRE WRAP
SPACERS 1/16 INCH O.D.

FIGURE 4.7 - ARRAY ROD END DETAILS

FIGURE 4.8 - INJECTOR DETAILS

finally, the injector rod was wrapped in the usual manner.

The 25 test rods were assembled into a 5 X 5 rhombus array; on the lower end, the rods were supported and angularly oriented by mounting each rod on two 1/8 inch diameter support rods which passed through the two rod support holes. The support rods were held in place by 1/8 inch 304 SS plates mounted at the bottom of the channel and recessed into the walls. The assembled array was slid into the flow channel and held in place by bolting the lower plenum cover to the bottom of the flow channel. Next, the array rods were held in position at the top by an upper rod support plate which has 1/8 inch diameter rods extending 2 inches between the plate and the top of the array rods immediately below. The upper support rod extends 1/4 inch into the upper array rod support hole. Thus, the 25 array rods are held in position with respect to each other at the channel exit by the upper support rods extending down from the upper rod support plate. Figure 4.9 shows the upper assembly rod support plate, and Figure 4.10 shows a schematic of the upper rod support and instrumentation probe support.

4.7 Instrumentation Redesign

Of all modifications, perhaps the most significant

FIGURE 4.9 - UPPER ROD SUPPORT PLATE DRAWING

was the change in detection instrumentation design. Instead of mounting the detection instrumentation on the rods, it was supported from the upper array rod support plate as shown in Figures 4.9 and 4.10. The detector probes entered the rod array through 3/32 inch OD instrumentation shield tubes. This scheme enables the experimenter to exercise any one of several detection systems for the data acquisition process, i.e., internal conductivity cells, internal thermocouples or external conductivity cells (if the probe is replaced by a tube for sample withdrawal). Of course, either a salt solution or hot water tracer can be injected through the injection device, and the entire instrumentation system can be changed without disassembly of the test section. Figure 4.10 gives a schematic of the conductivity probes.

4.8 The EPL-EEL-2 Mixing Instrumentation Test Facility

The redesigned test section described in sections 4.4 - 4.6 was connected to the mixing project pump facility. The main flow rate to the test section was measured using two rotameters connected in parallel as shown schematically in Figure 4.11. The plenums, as noted, were rebuilt from aluminium; the lower plenum had a flow-straightener made of one inch diameter tubes, and the upper plenum was gravity drained. A pressurized

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Figure 4.11 - SCHEMATIC DIAGRAM OF THE EPL-EEL2 MIXING INSTRUMENTATION TEST FACILITY

injection tank delivered the tracer solution to the injector rod via a rotameter. A variable speed drive was connected to the moving inner injector tube so that it could be moved automatically. Note that the hydraulic systems were considerably simplified in the EEL-2 facility.

4.9 Design Modifications of the Injector Rod

Operational difficulties with the tracer injection rod were encountered due to assembly techniques and design and due to injector drive over-pull. The modifications required to overcome these difficulties are discussed below.

The injector rod design illustrated in Figure 4.8 and discussed in section 4.5 was modified early in the experimental program at EEL-2. The hypodermic tube (0.050 inch OD x 0.033 inch ID - 304 SS) was not suitable for maintaining the angular position of the internal injection tube within the slotted outer tube. Because the injector tube (needle) was also to serve as the upper and lower stop pin for the inner tube, this injector rod failed shortly after being placed in service.

After disassembly, an angular rod positioning hole was drilled two inches below the needle device. The needle was replaced and soldered in-place before inserting the inner tube into the slotted outer tube. The needle was next ground flush with the surface of the inside tube. Then the inner rod was inserted into the slotted outer tube and oriented angularly so that a 1/16 inch diameter stainless steel rod could be inserted into the inner rod angular positioning hole. The angular positioning pin was carefully soldered in-place such that no solder spilled over into the annular gap between the two concentric tubes making up the injector rod. Once in-place, the angular positioning pin served to locate the injector needle in the center of the slot in the outer tube and to stop the motion of the inner tube with respect to the outer tube when the angular positioning pin reached either the bottom or the top of the slot in the outer tube. The 1/16 inch diameter pin inserted into the inner injection tube for rod positioning proved to be unsatisfactory, but all work reported here was done using this design.

For future work it is recommended that a method of providing for angular position of the inner rod be developed using a flat spring mounted into a slot in the inner tube wall. A piece of 0.012 inch thick SS sheet metal,

1/16 inch wide and 1/4 inch long formed into a circular arc could be tack-welded to one end of the slot. The arc would be formed so that the center of the spring would protrude about 0.030 inch higher than the inner tube; thus, the strip would act as an angular positioning device. Importantly, such an inner tube could be readily installed into or removed from the outer tube of the injector rod, i.e., the spring would be compressed into the slot on the inner tube while traveling under the unslotted portion at the end of the outer tube.

With this scheme, it would not be necessary to perform the relatively difficult soldering operations discussed previously.

The inner, moving tube of the injection rod was made of 0.028 inch wall, 3/16 inch OD SS tubing which bends easily. Once bent, this tubing can be straightened only approximately. Moving an "unstraight" inner tube through the outer tube causes the slot in the outer tube to spread open. It is strongly recommended for future work that the moving injection tube be carefully guarded and handled to prevent bending of this inner tube. (Note, spreading of the slot introduces an injector needle, angle orientation error and thus influences the experimental results.)

4.10 Design and Modification of the Conductivity Cell Probe

The original design of the probe-type conductivity cell is shown schematically in Figure 4.10. Originally, two platinum electrodes about 1 inch long and 30 AWG (0.010 inch) were soldered to 30 AWG copper wire. These wires were fed through the inside of a 0.068 inch diameter glass capillary tube (3.94 inch long). Also, a piece of nylon string was fed through with the wires and positioned between the wires inside the tube. The tube was then heated with a match causing the nylon to foam. When the tube cooled, the wires were securely held in place. The upper and lower ends of the glass tube were sealed using plastic cement. The probe was inserted into a 3/32 inch OD SS tube (0.007 inch wall) to protect the glass tube.

Operational difficulties with these probes were caused by glass breakage, probe positioning and water in-leakage. These problems were eliminated by the various design modifications discussed below.

It is very important that there be no electrical connection between the electrodes or their lead wires anywhere other than at the electrodes themselves. To eliminate difficulties with lead wire current leakages (due to the presence of water inside the probe), all electrode wires were painted with electrical motor

insulating paint (General Electric Co. GLYPTAL) which was baked (cured) for two hours at 240F. This insulation covered the entire length of the platinum wire and the soldered platinum-copper joint (the copper wire was manufactured with a baked-on enamel insulation). This insulating process prior to assembly of the glass probe reduced water leakage problems.

The paint was scraped-off the 1/2 inch long platinum wire protruding from the glass tube. Then the glass probe was inserted into a 4 inch long, 3/32 inch OD SS shield tube (originally a 2-1/2 inch long shield tube was used with disastrous glass breakage results). The probe end of the glass tube was positioned 1/16 inch below the end of the shield tube, and each end of this shielded probe was sealed with a plentiful application of epoxy (plastic cement did not work). The epoxy was cured at 140F for two hours, and the electrode end of the probe was trimmed to the size of the shield tube. The epoxy end seals protected the probe from leakage in the event of internal glass breakage.

The electrodes of the probe were cut to a length which gave an optimum instrument reading, i.e., cell constant. For the work at hand 3/32 inch (nominal) long electrodes gave a balance bridge resistance of about 10,000 Ohms. This was the optimum balance point for the instruments used, and it gave sensitive measurements over

the required response range without the use of several instrument scales. Once cut to length, small adjustments to the cell constant were made by bending the electrodes. Note in Appendix 2 that the cell design determines the measured balance resistance and unbalanced bridge voltage.

Given a rugged probe with the required conductivity cell design, the final operational difficulty to be overcome was probe positioning at the array outlet. It was hoped that the probe could be inserted $1/4$ inch into the test array from the exit; however, mechanical interference between the probe and the wire-wrap prevented this. The wire-wrap was cut back $1/4$ inch from the top of all rods to allow insertion of the probes into the subchannel. Other probe positioning problems were caused by the proximity of rod array materials. A good rule for avoiding material proximity, electrode interference is to keep all electrode surfaces separated from all other materials by a minimum of $1/16$ inch of solution.

One final note on probe design concerns the length of the platinum electrodes. Because platinum wire is very expensive and because numerous probes are necessary to complete a mixing experiment, it is desirable to keep the length of the platinum electrode wire short. Also it is recommended that the copper lead wires to the cell be heavier than 24 AWG.

Chapter 5

EXPERIMENTAL RESULTS

5.1 A Summary of the Experimental Results

This chapter presents results of the instrumentation development experiments, the interchannel coolant mixing experiments and the flow visualization experiments done with the 25-rod rhombus array. For instrumentation development, experiments were performed to determine the influence of the following items on experimental results:

- (1) injection flow rate (injection velocity),
- (2) salt (NaCl) solution tracer concentration,
- (3) salt type (NaCl and NaNO_3),
- (4) injector design (needle and transverse hole),
- (5) Reynolds number, and
- (6) Injector mechanical behavior.

Interchannel coolant mixing experiments have been done for the following cases:

- (1) interior subchannel injection, turbulent flow,
- (2) interior subchannel injection, laminar flow,
- (3) peripheral subchannel injection, turbulent flow,
- (4) peripheral subchannel injection, laminar flow.

Flow visualization experiments were done for turbulent and laminar flow with injection into a peripheral subchannel. Table 5.1 summarizes the experiments done to determine the influence of experimental operating para-

Table 5:1

Experiments to Determine the Influence of Experimental
Operating Parameters on Results

RUN ⁺ IDENT. NUMBER	TRACER CONCENT. ($\frac{\text{gram NaCl}}{\text{lbm water}}$)	INJECT. FLOW ($\frac{\text{lbm}}{\text{min}}$)	MAIN FLOW ($\frac{\text{lbm}}{\text{min}}$)	WATER TEMP. (F)	DATE (1973)	NUMBER SUBCH. MONIT. No. AXIAL POINTS	INJECT. SUBCH. TYPE (INJ. TYPE)*
0/2 - A	2.0	0.35	450	66	17 June	4/228	I(N)
0/2 - B	2.0	0.66	450	66	17 June	4/\$	I(N)
0/2 - C	2.0	0.17	450	66	17 June	4/\$	I(N)
0/2 - D	2.0	0.51	450	66	17 June	4/\$	I(N)
0/2 - E	2.0	0.17	225	66	17 June	4/\$	I(N)
0/2 - F	2.0	0.35	225	66	17 June	4/\$	I(N)
0/1 - A	1.0	0.35	450	66	19 June	4/226	I(N)
0/1 - B	1.0	0.66	450	66	19 June	4/228	I(N)
0/1 - C	1.0	0.17	450	66	19 June	1/228	I(N)
0/1 - E	1.0	0.17	225	66	19 June	1/224	I(N)
0/3 - A	3.0	0.35	450	66	19 June	4/238	I(N)
0/3 - B	3.0	0.66	450	66	19 June	4/234	I(N)
0/3 - G	3.0	0.22	450	66	19 June	4/242	I(N)

Table 5.1 (Concluded)

0/3 - H	3.0	0.11	450	66	19 June	4/236	I(N)
0/2.9-A	2.9@	0.35	350 [#]	67	25 June	4/266	I(N)
3/2 - A	2.0	0.35	450	73	20 July	4/144	I(N)
3/2 - E	2.0	0.16	180	73	20 July	4/144	I(N)
4/2 - A	2.0	0.35	430	73	25 July	4/138	I(T)
4/2 - B	2.0	0.66	450	73	25 July	4/142	I(T)
4/2 - C	2.0	0.16	450	73	25 July	4/144	I(T)
4/2 - E	2.0	0.16	225	73	25 July	4/142	I(T)
1/2 - D	2.0	0.35	450	67	25 June	5/250%	I(N)
1/2 - E	2.0	0.35	450	67	25 June	7/284	I(N)
1/2 - F	2.0	0.35	450	73	12 July	7/240%	I(N)

* I = Interior Subch., P = Peripheral Subch., N = Needle Inj., T = Transverse Inj.

+ Run Series/Salt Tracer Concentration (grams/lbm) - Flow Conditions

\$ Data not Reduced due to Magnetic Recorder Failure, Original Data in (5.1)

Approximate Flow Given, Test Section Drain Valve Accidentally Left Open.

@ Salt Typed Changed - Sodium Nitrate, NaNO_3 instead of NaCl

% Data Reduction Difficulties, Refer to (5.1)

meters on coolant mixing results. Table 5.2 summarizes the experiments done to examine the interchannel coolant mixing behavior of wire-wrap spaced rod arrays. The flow conditions in each subchannel type during the various experiments are given in Table 5.3.

A total test section pressure loss (plenum-to-plenum) versus flow curve is given in Figure 5.1. The subchannel identification code used for all experiments (except RUN NO. 1B - IT, done in 1972) is given in Figure 5.2.

5.2 Data Collection and Processing

The method used to assimilate the experimental data was the same for all experiments done in 1973. For these experiments, a single detector (with about $3/32$ inch long electrodes) was located at the rod array outlet with the electrodes just inside the subchannel of interest; then the injector was pulled toward the bundle outlet at a constant speed (typically 1 ft/min) by a servomotor. For a given experiment, the detector would be moved from one subchannel to another and the injector re-inserted and withdrawn as many times as necessary (keeping the flow conditions constant).

An array proximity, electrode interference effect was known to be occurring in some subchannels into which the conductivity cell detector was inserted, that is, the metal of the experimental array was interfering with the

Table 5.2

Interchannel Coolant Mixing Experiments with a Wire-Wrap
Spaced Rod Array

RUN IDENT. NO. ⁺	TRACER CONCENT. ($\frac{\text{gram NaCl}}{\text{lbm H}_2\text{O}}$)	INJECT. FLOW ^{&} ($\frac{\text{lbm}}{\text{min}}$)	MAIN FLOW ($\frac{\text{lbm}}{\text{min}}$)	WATER TEMP. (F)	DATE (1973)	NUMBER SUBCH [@] MONIT./ NO. AXIAL POINTS
1 - IT	2.0	0.35	450	72	17 July	29/138
1A- IT	2.0	0.68	455	62	27 May	13/116
1B- IT [*]	1.0	1.2	72	140	17 May, 1972	11/27
2 - IL	2.0	0.044	50	82 [#]	19 July	25/128
5 - PT	2.0	0.39	450	74	27 July	19/134
6 - PL	2.0	0.053	38 ^{\$}	80 [#]	28 July	19/138

+ Run ID No.: I = Interior Subch., P = Peripheral Subch., T = Turbulent, L = Laminar
& Based on the Equal Average Velocity Criterion, EAVC

\$ Drain Valve Open, Approximate Flow Given

About 10F Temperature Rise due to Low Pump Flow

* Experiment done in Heat Transfer Lab with Test Section No. 1, Poor Flow Geometry

@ Fewer Subchannels shown in Results if No Salt Tracer was Observed

Table 5.3

Subchannel Reynolds Numbers and Flow Velocities for the Experiments*

RUN IDENT. NUMBER	MAIN FLOW ($\frac{\text{lbm}}{\text{min}}$)	TEMP. (F)	SUBCHANNEL TYPE			
			- 1 -	- 2 -	- 3 -	- 4 -
			REYNOLDS NUMBER (AVERAGE VELOCITY, ft/sec)			
PARAMETRIC EXPERIMENTS - - - - -						
0/2 -A,B, C,D.	450	66	13,600 (14.0)	19,100 (16.0)	11,900 (13.2)	22,400 (17.0)
0/1 -A,B,C.	"	"	"	"	"	"
0/3 -A,B,G,H.	"	"	"	"	"	"
0/2 -E,F.	225	"	6,790 (7.0)	9,530 (8.0)	5,950 (6.6)	11,200 (8.5)
0/1 -E.	"	"	"	"	"	"
1/2 -D,E,F.	450	67	13,700 (14.0)	19,300 (16.0)	12,100 (13.2)	22,600 (17.0)
0/2.9-A.	350	67	10,700 (10.9)	15,000 (12.4)	9,380 (10.3)	17,600 (13.2)
3/2 -A,B,C	450	73	14,900 (14.0)	20,900 (16.0)	13100 (13.3)	24,500 (17.0)
4/2 -A.	430	73	14,200 (13.3)	20,000 (15.3)	12,500 (12.7)	23,500 (16.3)
4/2 -E.	225	73	7,450 (6.98)	10,500 (8.00)	6,540 (6.63)	12,300 (8.52)
3/2 -E.	180	73	5,960 (5.59)	8,370 (6.40)	5,230 (5.30)	9,820 (6.82)

Table 5.3 (Concluded)

COOLANT MIXING EXPERIMENTS - - - - -						
1 - IT	450	72	13,900 (14.0)	19,500 (16.0)	12,200 (13.3)	22,900 (17.0)
1A- IT	455	62	13,100 (14.0)	18,300 (16.1)	11,500 (13.3)	21,500 (17.2)
1B- IT	72	140	4,850 (2.27)	6,800 (2.59)	4,250 (2.15)	8,000 (2.77)
2 - IL	50	82	1,580 (1.31)	2,900 (1.96)	1,250 (1.12)	3,870 (2.38)
5 - PT	450	74	15,100 (14.0)	21,200 (16.0)	13,300 (13.3)	24,900 (17.0)
6 - PL	38	80	1,173 (0.99)	2,160 (1.49)	930 (0.85)	2,880 (1.81)

* Numbers have been rounded, See Tables 5.1 and 5.2 for further details concerning the experiments.

FIGURE 5.1 - PRESSURE DROP VERSUS FLOW RATE ΔP VS. Q FOR THE TEST SECTION

Figure 5.2-SUBCHANNEL ARRANGEMENT OF THE EXPERIMENTAL TEST SECTION SHOWING SUBCHANNEL IDENTIFICATION NUMBERS AND INJECTOR ROD LOCATIONS

operation of the electrical conductance probe. The effect was usually small (when it occurred) and was observed as a shift in the balanced bridge resistance of the main flow (with no tracer insertion). Because the interference was dependent on the exact positioning of the detector probe within a given subchannel, it was not possible to directly compensate for the interference by generating a calibration curve for each subchannel (This would be possible if a detector were permanently positioned in each subchannel to be monitored).

To accommodate the array proximity electrode interference effects occurring with the data collection technique used, the Wheatstone bridge was balanced for each subchannel with the probe in position. For example, suppose the balanced bridge resistance with no array interference was 9500 Ohms; with array interference, the balanced bridge resistance would range from 9500 Ohms to about 8900 Ohms.

It was shown that the effect of changing the bridge resistance (in the range of interest) did not significantly influence the calibration curve. Also, other experiments showed the array proximity, electrode interference effect was approximately independent of salt solution concentration.

It is believed that the significance of the accommodation procedure may be illustrated by attempting to superimpose the 3100 Ohm curve in Figure 5.3 onto the 3600

Figure 5.3 - THE INFLUENCE OF THE WHEATSTONE BRIDGE RESISTANCE SETTING ON UNBALANCED BRIDGE VOLTAGE MEASURED SHOWING THE VARIATION WITH SOLUTION CONCENTRATION

Ohm curve by moving the 3100 Ohm curve downward (see the dashed line); this corresponds to a background balanced bridge resistance change of 14%. (Note if the upper part of the 3100 Ohm and the 2600 Ohm curves were shifted to the right, instead of downward, all three curves would coincide).

Because the data reduction was primarily on the left side of the graph and because the actual interference background changes typically ranged from 0% to 6%, this was not felt to be a major error.

The data was recorded using the unbalanced Wheatstone bridge method (discussed in Appendix 2). The original data was simultaneously recorded onto graph paper using a X-Y plotter and onto a magnetic tape using a FM recorder. The magnetic tape provided an analog (continuous) reproduction of the data which was played into an analog computer that filtered and digitized (converted the analog signal to a digital signal) the playback of the magnetic tape signal, see Appendix 7. The digitized signal was received and averaged by a digital computer which produced a paper-tape record of the data. The paper-tape was used to generate a punched card record of the data. The punched cards were edited and assembled for processing using the MITMIX code (Appendix 3).

Considerable editing efforts of the data were required in order to ascertain the data used faithfully

reproduced the original data (plotted with the X-Y plotter during the experiment); this was because of various mechanical difficulties in the data generating and handling processes. Editing effort was further required to axially synchronize the data taken independently for each subchannel. As discussed in Appendix 7, it is felt that the error in axial synchronization or coincidence of the data is less than $\pm 1/3$ of an inch (the magnitude of this error is set by injector system design, in part).

MITMIX converted the data from an unbalanced bridge voltage into salt concentrations using a curve fit of calibration data. The calibration data was obtained by mixing known solutions of tracer and measuring the unbalanced bridge voltage using the same equipment and detector used for data acquisition. Two instrument scales were required for this work (a high scale for near the injector and a low scale for detection far from the injector); typical calibration data from each scale is shown in Figures 5.3.1 and 5.3.2; the lines drawn through the data were generated using the curve fitted through the calibration by MITMIX.

The recorded data was converted from an unbalanced bridge voltage to a salt concentration by first subtracting the balanced bridge voltage (the background voltage was 5 to 10 millivolts AC-RMS due to AC reactance effects)

from the unbalanced signal voltage. This voltage difference was converted to salt concentrations via calibration data (based on the voltage difference and the solution concentration of the calibration data) taken with no array interference during the measurements.

MITMIX reduced the data, calculated the experimental mass balance and generated plots of the results. The code also generated normalized and integrated plots of the data; these plots have not been presented here but may be reviewed in Eaton (5.1).

The data from RUN NO. 1A-IT and 1B-IT was reduced manually instead of by automatic data processing equipment. The data for all subchannels in RUN 1B - IT (see Figure 4.4) was taken (using a detector in each subchannel) with the injector stationary at each axial location. As noted previously, all other data was taken with a moving injector while monitoring a single subchannel at a time.

5.3 The Influence of Experimental Operating Parameters on Coolant Mixing Results

In order to control the length of this section, the results of the parametric studies for determining the influence of operating parameters on experimental results shall be presented without a lengthy presentation of figures; the original data and the reduced data used to arrive at

the conclusions in this section may be reviewed in Eaton (5.1) or in Appendix 9.

For this work, the standard for the injection flow rate was set by the equal average velocity criterion EAVC, i.e., the average velocity of the injection flow was equal to the average velocity of the subchannel into which the tracer was injected. Injection rates for EAVC are given in Table 5.4 for water at 60F; these values were used for all 1973 experiments.

Injection Flow Rate (Velocity): There was no unexpected influence of injection flow rate on experimental results; the general nature (that is, the overall shape and the magnitude of the normalized concentrations observed) of the tracer concentration versus injector travel curve was unchanged with changes in injection flow rate (velocity). Obviously, the amount of salt detected would change according to the change of injection rate (salt insertion rate).

A small influence of insertion rate was noted when the injection device was passing under the wire-wrap (over the slot in the injector tube). The tracer injection flow influence on mixing results decreased as the distance between the injector and the detector increased and was hardly noticable with the injector more than one lead (12 in.) from the detector. The perturbations were not noticable beyond the subchannels contiguous to the

Table 5.4
Equal Average Velocity Criterion
for Injection Operations *

Flow Regime-----Turbulent----Laminar		
Interior Subchannel		
Flow Fraction, w_i/w_b	0.00077	0.00065
Main Flow, w_b , lbm/min	450.	50.
Injection Flow, w_i , lbm/min,	0.35	0.033
cc/min	158	14.8
Peripheral Subchannel		
Flow Fraction, w_i/w_b	0.00089	0.00098
Main Flow, w_b , lbm/min	450.	50.
Injection Flow, w_i , lbm/min,	0.40	0.049
cc/min	181	22.2

* Based on Water at 60F; All subchannels assumed to be in the Same Flow Regime; Reynolds Number Exponent in the Friction Factor Correlation equal -0.20 for Turbulent Flow and -1.00 for Laminar Flow.

injection subchannel. As the injection flow varies from the EAVC, the perturbations decrease slightly as the flow decreases; however, as the flow increases, the perturbations become more pronounced; then as the injection flow increases further, say greater than 3 X EAVC, the effect again reduces because the local flow is highly disrupted by the turbulent jet mixing near the injector. Adding further flow disturbances does not have so great an effect in an already disturbed flow field. The results regarding the influence of tracer flow rate were verified with injection flows varying between one-third and twice the flow given by the EAVC (in informal experiments, this result was confirmed with injection flows over four times the EAVC flow).

Salt Solution Tracer Concentration: The effect of varying the salt solution concentration (using NaCl) holding the injection flow rate constant was observed to be similar to the effect of varying injection flow rate while holding the tracer concentration constant. The general nature of the data was similar in all cases; the only differences being due to the change in the amount of tracer observed. The perturbations due to changes in the tracer insertion velocity were not observed.

Salt Type: Experiment No. 0/2.9-A was done using sodium nitrate NaNO_3 instead of NaCl. Although mechanical difficulties with the injector were encountered during

this experiment; it was established that there was no significant differences between salt types and that the normalized results were the same. This results because the mass diffusivity was very low for both salts, particularly if compared to the momentum diffusivity of the flow.

It is necessary to compensate the injection solution concentration for differences in molecular weight when changing the salt tracer type, i.e., $M - NaCl = 58.4$ and $M - NaNO_3 = 85$. The $NaNO_3$ tracer experiment was run with a solution concentration of 2.94 grams/lbm which was analagous to a 2.0 gram/lbm solution of NaCl.

Injector Design: In order to compare the influence of injector design on coolant mixing results, a series of parametric experiments were done using a transverse hole injector design, i.e., RUN Nos. 4/2 - A, B, C & E. From comparison with RUN Nos. 3/2 - A & E, done using a needle injector and similar injection flows, the influence of injector design on mixing results was seen to be substantial, particularly in the region near the point, about 1/3 lead lengths below the end of injector travel, where the injector passes under the wire-wrap (closest to the detector). Note, RUNS 4/2 - A, B, C, & E must be compared with RUNS 3/2 - A & E because of evolution of the mechanical behavior of the injector tube since prior parametric experiments.

Because the transverse hole injector introduced an unnatural transverse momentum into the injection subchannel, it was decided to use a needle-type injector mounted as close as practical (15° - 20°) to the axial direction. This injector design was expected to give experimental results with the least injection subchannel flow perturbation, and therefore give results most compatible with typical assumptions of existing fuel assembly thermal-hydraulic analysis codes.

Reynolds Number: Momentum (eddy) diffusivity and therefore mass transfer within the experimental array is dependent on Reynolds number. Also, the flow regime, i.e., whether laminar or turbulent, is determined by the Reynolds number of the flow.

In all of the mixing experiments reported here, there was a noticeable effect of large-scale eddy diffusivity on the results. This effect was noted as flutter in the recording pin on the X-Y plotter (which directly recorded the conductance cell signal). Because of electronic flutter in the magnetic tape recorder, this flow flutter can not be shown in detail in the results of this report (because filtering and averaging the electronic flutter also filters and averages the flow flutter). Flow fluttering influences can be seen in some of the reduced data, nevertheless.

This flow induced tracer concentration fluttering

was most significant with the injector within one lead length (12 in.) of the detector, and in general it decreased with increases in injector-detector separation. The magnitude of this flutter was also dependent on subchannel location (with respect to the injection subchannel) and decreased with increases in distance from the injection subchannel.

The tracer concentration fluttering was strongly dependent on Reynolds number. For turbulent flows with $Re > 10,000$, little flutter was observed. The flutter effects were more and more apparent as the Reynolds number decreased toward flow transition ($Re \approx 2300$) and a notable increase could be determined between low turbulent flow and laminar flow.

To keep the discussion of flutter in perspective, note that the magnitude of flutter was seldom more than $\pm 10\%$ of the measured value and could be distinguished at very low values of fluctuation, say $\pm 0.05\%$ of measured value. The frequency of the tracer concentration variations was typically 0.5 - 3.0 cycles/second; the resulting plot of a fluttering signal (using 1 inch of graph for each 2 inches of injector travel and a graphing speed of 6 inches/minute) was not a blurred line but distinctly showed the wave-like nature of the flutter. Apparently the cause of the flow fluttering was a low-flow instability in the injection system which may have

been influenced by vortex shedding from the wire-wrap spacers.

Injector Mechanical Behavior: Of all the experimental parameters influencing the mixing results, the mechanical behavior of the injection device had the far greater effect.

The primary operational difficulty in performing the mixing experiments discussed in this chapter was failure of the injector device. In the handling, use and repair of the injector, the intended mechanical design was modified (evolved) by wear, minor bends, slot spreading, etc. - all which resulted chiefly in an angle positioning error of the injector rod with respect to the slotted injector rod: the error was always less than $\pm 4^\circ$, but increased with time and varied with axial position.

The mixing results were very dependent on this angular positioning error in the injection direction (see Figure A.19.1). This was particularly a sensitive problem because the injector had to be inserted and withdrawn to repeat the injection process as the detector was moved sequentially to each subchannel monitored in a given experiment.

It was found that the difficulties with the injector angular orientation could be overcome, for all practical purposes, by initially positioning the injector at the

same angular position before each withdrawal. The withdrawal process was identical for each subchannel and the results could be repeated. Therefore, similar injection conditions could be obtained for all subchannels monitored in an experiment. Nevertheless, for future work, this behavior problem can be eliminated by changes in injector design and careful handling as discussed in Chapter 4.

5.4 Interchannel Coolant Mixing Experiments

As noted in section 5.1, coolant mixing experiments were done for turbulent and laminar flow with injection into an interior and a peripheral subchannel, see Tables 5.2 and 5.3. Detection was accomplished with an electrolytic (salt solution) conductance probe positioned inside the rod array but within $1/4$ inch of the bundle exit. For each experiment, a scan of the exit concentration of all subchannels with the injector fully inserted showed which and how many subchannels needed to be monitored to ascertain that all tracer dispersion could be observed.

It will be noted that the detailed nature of the results of the coolant mixing experiments are dominated by the complex, wire-wrapped rod array geometry. These results for the coolant mixing experiments, presented next, include a mass balance versus injector travel curve for the experiment and a tracer concentration versus injector travel curve for each subchannel moni-

tored. The subchannel tracer concentration curves are presented in groups of four (because of limitations in computer plotting); the tracer concentration of the injection subchannel is given on all curves so as to maintain a perspective between all subchannels.

Note that the injector traveled over more than two lead lengths in the experiments. For any computations with this data, the axial reference mark (consistent for all experiments) should be taken at the point where the tracer concentration falls to zero in the injection subchannel (in the vicinity of $X/l = 2.0 - 2.2$); this drop occurs at $1/2$ inch from the top of the array, i.e., at the end of the injector tube slot. The detector was positioned about $5/32$ inch downstream of the slot end.

In order to determine the location of a wire-wrap at any axial position X refer to Figures 4.7 and 4.8. Briefly, the wraps start 70 inches from the top of the rods and have a lead length of 12 inches. The injector slot is 150° clockwise from the wrap support (start) hole. The wire-wrap is over the slot in the injector tube at $0.38 l$ ($4 \frac{1}{2}$ inches) and $1.38 l$ ($16 \frac{1}{2}$ inches) below the top of the slot. Attempts to visualize flow in a wire-wrap spaced, rod array geometry will come only with inherent (but not insurmountable) difficulty.

Interior Subchannel Injection, Turbulent Flow:

Figures 5.4.1 through 5.4.9 give the results of the

FIGURE 5.4.1 - INTERCHANNEL COOLANT MIXING EXPERIMENTAL RESULTS
FOR INTERIOR SUBCHANNEL INJECTION AND TURBULENT
FLOW CONDITIONS, RUN 1 - IT: SUBCHANNEL NOS. 1,
2, 3, 4.

FIGURE 5.4.2 - INTERIOR SUBCHANNEL INJECTION, TURBULENT FLOW,
RUN 1 - IT: SUBCHANNEL NOS. 1, 5, 6, 7.

FIGURE 5.4.3 - INTERIOR SUBCHANNEL INJECTION, TURBULENT FLOW,
RUN 1 - IT: SUBCHANNEL NOS. 1, 8, 9, 10.

FIGURE 5.4.4 - INTERIOR SUBCHANNEL INJECTION, TURBULENT FLOW,
RUN 1 - IT: SUBCHANNEL NOS. 1, 11, 12, 13.

FIGURE 5.4.5 - INTERIOR SUBCHANNEL INJECTION, TURBULENT FLOW,
 RUN 1 - IT: SUBCHANNEL NCS. 1, 14, 15, 16.

FIGURE 5.4.6 - INTERIOR SUBCHANNEL INJECTION, TURBULENT FLOW,
RUN 1 - IT; SUBCHANNEL NOS. 1, 27, 33, 34.

Note: No Salt Observed in SC Nos. 21, 22, 26, or 34.

FIGURE 5.4.7 - INTERIOR SUBCHANNEL INJECTION, TURBULENT FLOW,
RUN 1 - IT: SUBCHANNEL NOS. 1, 35, 50, 51.

No Salt Observed in SC No. 35

FIGURE 5.4.8 - INTERIOR SUBCHANNEL INJECTION, TURBULENT FLOW,
 RUN 1 - IT: MASS BALANCE VS. INJECTOR TRAVEL.

FIGURE 5.4.9 - TEST SECTION CROSS SECTION SHOWING SUBCHANNELS MONITORED WITH INJECTION INTO INTERIOR SUBCHANNEL NO. 1

coolant mixing experiment done with salt solution tracer injection into subchannel No. 1 (interior type) and with turbulent flow conditions, RUN No. 1 - IT. It was felt that subchannel No. 1 represented a typical interior type subchannel; i.e., it was independent of rod array perimeter effects. The interior injection subchannel was separated from peripheral subchannels by two or more interior type subchannels.

The general nature of the curves show that the wire-wrap spacers play an important role in interchannel coolant mixing via flow sweeping - especially when the injector is within one lead length of the detector. More than one lead length away from the detector, natural turbulent interchange becomes the more dominant of the coolant mixing processes.

It may be noted that the salt concentration is not symmetrically dispersed around the injection subchannel, cf. subchannels No. 3 and No. 5 or No. 2 and No. 6. It is interesting that the salt concentration reduces in progressing from subchannel No. 2 to No. 3 to No. 4 to No. 5, indicating a slight flow swirl around the central array rod. The large presence of salt in subchannel No. 15 results because the injection stream was being diverted by a wire-wrap passing from subchannel No. 1 to No. 15 via No. 7 - apparently streaming through No. 7 attached (underneath) to the wire-wrap.

The balance curve indicates that quite a lot of

the salt was not monitored in the first $3/4$ lead length of injector travel and that stripping was occurring in the final $1/4$ lead of travel. The mass balances of these experiments will be discussed in section 5.5.

RUN No. 1A - IT was made prior to the parametric studies and was done using 2 X EAVC injection. The results for this run were similar to those for RUN 1 - IT; perturbations were noted due to the higher injection velocity (the salt insertion rate was twice as much - $c_i = 2.0$ grams/lbm). However, the main differences were due to the mechanical behavior of the injector rod; the rod was new for RUN 1A - IT. The results of this run are given in Appendix 9. The mass balance curve was of the same general nature as the one for RUN 1 - IT; however, more mass loss in the first 18 inches of injector travel occurred because fewer subchannels were monitored in this run.

The results of RUN 1B - IT were obtained in 1972 with 4 X EAVC injection and have been shown in Figure 4.4 and discussed in earlier sections. It should be re-emphasized that the axial detail of the data was $1/2$ inch or more, that the data was reduced manually, and that the geometry was poor.

Interior Subchannel Injection, Laminar Flow: The interchannel coolant mixing results given in Figures 5.5.1 through 5.5.10 are for interior subchannel (No. 1)

FIGURE 5.5.1 - INTERCHANNEL COOLANT MIXING EXPERIMENTAL RESULTS
FOR INTERIOR SUBCHANNEL INJECTION AND LAMINAR
FLOW CONDITIONS, RUN 2 - IL: SUBCHANNEL NOS. 1,
2, 3, 4.

FIGURE 5.5.3.- INTERIOR SUBCHANNEL INJECTION, LAMINAR FLOW,
 RUN 2 - IL: SUBCHANNEL NOS. 1, 8, 9, 10.

FIGURE 5.5.5 - INTERIOR SUBCHANNEL INJECTION, LAMINAR FLOW,
RUN 2 - IL: SUBCHANNEL NOS. 1, 14, 15, 16.

FIGURE 5.5.6 - INTERIOR SUBCHANNEL INJECTION, LAMINAR FLOW,
RUN 2 - IL: SUBCHANNEL NOS. 1, 17, 18, 19.

Note: No. 19 greater than No. 18, neither are significant

FIGURE 5.5.7 - INTERIOR SUBCHANNEL INJECTION, LAMINAR FLOW,
RUN 2 - IL: SUBCHANNEL NOS. 1, 21, 26, 27.

FIGURE 5.5.8 -- INTERIOR SUBCHANNEL INJECTION, LAMINAR FLOW,
RUN 2 - IT: SUBCHANNEL NOS. 1, 33, 34, 50.

Note: No. 34 less than No. 33.

FIGURE 5.5.10 - INTERIOR SUBCHANNEL INJECTION, LAMINAR FLOW,
RUN 2 - IL: MASS BALANCE VS. INJECTOR TRAVEL

injection with laminar flow conditions, RUN No. 2 - IL. Subsequent to the experiment, it was found that the peripheral subchannels were operating above the critical Reynolds number. For all work reported for RUN 2 - IL, laminar flow conditions have been assumed throughout. Because most of the subchannels of interest were of the interior type and in laminar flow, this peripheral turbulence was probably not a significant error.

The generally jerky nature of the results was due to the flow flutter effects (low Reynolds number) discussed earlier. The tracer concentration versus injector travel behavior may be seen to be similar in shape for the various subchannels; however, note that all of the effects due to wire-wrap induced flow sweeping (characterized by the more abrupt changes in the curves, i.e., the hills and valleys) are more pronounced with respect to the injection subchannel concentration, e.g., subchannels No. 2, No. 3, No. 6 and No. 15. However, in subchannel No. 7, there is little difference between the magnitude of the laminar and turbulent flow results.

The mass balance curve (detection balance) for this run shows stripping effects in the last $1/4$ lead of travel. Less mass loss occurred in the first $1/2$ lead of injector travel in the laminar flow case than in the turbulent flow case. Further, because of mechanical interference which prevented making concentration

measurements in some of the subchannels (No. 19 and 52), a small amount of salt is known to be missing.

Peripheral subchannel Injection, Turbulent Flow:

Figures 5.6.1 through 5.6.6 show the results of salt solution tracer injection into peripheral subchannel No. 50 with turbulent flow conditions, RUN No. 5 - PT. The results are again dominated by wire-wrap spacer effects, but with peripheral injection, the effects of wire-wrap flow sweeping dominates the tracer dispersion over the entire length of injector travel (2 1/2 lead lengths). The data clearly shows a large swirl flow around the rod bundle periphery in the clockwise (wire-wrap rotational) direction, cf. subchannels No. 49 (note the absence of tracer), 50, 51, 52, 33, 34, 35, 36, and 37. It is also interesting to note that the turbulent interchange coolant mixing between the peripheral subchannels and the interior subchannels is relatively insignificant; perhaps because the swirl flow remains near the walls of the channel and away from the rod gaps. Further discussion of swirl flow at the bundle periphery will be given in section 5.6 on flow visualization.

The turbulent flow mass balance for peripheral subchannel injection was very similar to that for interior subchannel injection. Significant stripping occurred in the last 1/4 lead of the injector travel

FIGURE 5.6.1 - INTERCHANNEL COOLANT MIXING EXPERIMENTAL RESULTS
FOR PERIPHERAL SUBCHANNEL INJECTION AND TURBULENT
FLOW CONDITIONS, RUN 5 - PT: SUBCHANNEL NOS. 50,
27, 26, 49.

FIGURE 5.6.2 - PERIPHERAL SUBCHANNEL INJECTION, TURBULENT FLOW,
 RUN 5 - PT: SUBCHANNELS NO.50, 51, 13, 12

FIGURE 5.6.6 - PERIPHERAL SUBCHANNEL INJECTION, TURBULENT FLOW,
RUN 5 - PT: MASS BALANCE VS. INJECTOR TRAVEL

FIGURE 5.6.7 - TEST SECTION CROSS SECTION SHOWING SUBCHANNELS MONITORED WITH INJECTION INTO PERIPHERAL SUBCHANNEL NO. 50.

is known to be due to lack of data for subchannels No. 38 and 39.

Peripheral Subchannel Injection, Laminar Flow:

Figures 5.7.1 through 5.7.7 show the laminar flow results of interchannel coolant mixing with injection into a peripheral subchannel (No. 50), RUN No. 6 - FL (Note that the subchannel plotting order is different in RUN 6 - PL and RUN 5 - PT). During this run a test section drain valve was accidentally left open so that the exact main flow was unknown, but the peripheral subchannels were definitely in laminar flow. It was estimated that about 75% of the metered flow went to the test section (using crude calculations and post-experiment observations).

Again for laminar flow, the roughness of the curves is the result of fluttering in the original data. Comparing laminar and turbulent flow, coolant mixing results for peripheral subchannel injection gives results similar to the comparison with interior subchannel injection. That is, the general trends are similar for both cases; the effects of wire-wrap sweeping are more pronounced and the extremes in behavior are more noticeable. This is due to the loss of natural turbulence and due to changes in the drag coefficient of the wire-wraps. The increased tracer concentration fluttering for the laminar flow cases may be due in part to vortex shedding from the wire-wraps and/or due to a low-flow instability in the injection system.

FIGURE 5.7.2 - PERIPHERAL SUBCHANNEL INJECTION, LAMINAR FLOW,
RUN 6 - PL: SUBCHANNEL NOS. 50, 13, 12, 52.

FIGURE 5.7.4 - PERIPHERAL SUBCHANNEL INJECTION, LAMINAR FLOW,
RUN 6 - PL: SUBCHANNEL NOS. 50, 7, 35, 18.

FIGURE 5.7.5 - PERIPHERAL SUBCHANNEL INJECTION, LAMINAR FLOW,
RUN 6 - PL: SUBCHANNEL NOS. 50, 16, 36, 28.

FIGURE 5.7.6 - PERIPHERAL SUBCHANNEL INJECTION, LAMINAR FLOW,
RUN 6 - PL; SUBCHANNEL NOS. 50, 19, 37.

The behavior of the mass balance curve was similar to the previous laminar flow case, i.e., less stripping effects in the bundle exit region and less loss of mass in the first lead of injector travel than was the case for turbulent flow results in the same subchannels.

5.5 Comments on the Mass Balance Results

Stripping, the failure to meet a mass balance due to the presence of large inhomogeneities of tracer concentration in the flow field, is not surprising during injector travel within the $1/2$ a lead length of the detector; this stripping is an inherent limitation of the axially moving injection technique when using internal detectors. However, failure to meet the mass balance criterion with the injector well separated (over one lead length) from the detector was surprising, and it was not due to stripping effects.

It is felt that this "loss of salt tracer" or loss of mass effect in the first lead of injector travel is due to one of the following reasons;

- (1) calibration curve errors due to array rod proximity, electrode interference,
- (2) inadequate flow regulation,
- (3) a leak in the injection system downstream of the injection flow meter, and/or
- (4) electronic interference in the data storage system.

The calibration curves used for the data reduction were generated with the detector probe (only one was used) in a large plastic barrel (for mixing solutions of known concentration). It is possible that array proximity, electrode interference (due to the presence of rod array metal near the probe), not present with the gathering of calibration data, is responsible for the loss of mass problems in the experimental mass balance results.

An experiment done on 24 June 1973, at the suggestion of D.D. Lanning, revealed that the effect of array interference was independent of salt concentration (and flow), but that it always gave the appearance of more salt than was actually present. Further, the interference was different from subchannel to subchannel and was dependent upon positioning, e.g., angular orientation of the electrodes, of the probes inside each subchannel. The effects did not appear significant because they were typically a 0% to 3% change in the balanced bridge voltage of the main flow water with no tracer; occasionally the change was more than 3% but was never more than 10%.

Initially, a detector for each subchannel was planned and calibration in-position was intended. The initially large inventory of glass probes quickly dwindled to a few redesigned (reinforced) probes. Since positioning errors could not be overcome with the data collection technique required (repositioning the probe many times

for each experiment), the interference effect was accommodated by balancing the Wheatstone bridge with the probe in-position. Conversion of unbalanced bridge voltage data to salt solution concentrations was done using the same calibration curves for all data. The unbalanced bridge voltage versus salt concentration calibration curves were nearly linear in the range of interest for the experiments, so this was a small error for each subchannel. However, the accumulation of all the error of this data reduction process is present in the balance curves. Further, as the injector-detector separation is increased, any such errors might become larger because more subchannels are involved.

It is important to note that the intended injection lines on the balance curves are the way things were supposed to be - not the way they were. Because an inadequate flow regulating valve was being used, flow control of the injection system was difficult. Every effort was made to keep the injection flow within $\pm 10\%$ of the intended value. Nevertheless, the differences between actual injected flow and intended injection flow are not reflected in the straight line shown in the balance curves; the differences are definitely in the actual mass balance curve, as well as, in the individual subchannel results.

The plastic tube connecting the injection flow meter

to the injector rod was press fitted onto the top of the moving steel tube of the injector rod. It is possible that an undetected leak was occurring at this connection. Further, the leak would have been greatest and most noticable with the injector fully inserted because of the increased injection system pressure required to inject into the bundle upstream of the exit. But when the injector was fully inserted, the connection was submerged in the discharge flow of the outlet plenum (and remained wet after withdrawal) so that a small leak would not have been noticed. The amount of tracer solution missing is something less than 0.10 lbm/minute - a very small (drip-like) flow. If a leak was occurring, it would explain why less mass was lost in the laminar flow mass balances than in the turbulent flow cases (due to the lower test section pressure loss).

As was noted earlier, the calibration data was taken with the same electronic equipment as was the mixing data. But the X-Y plotter was not used when recording calibration data. It was noted that the plotter did interfere slightly with the signal when both the plotter and the magnetic recorder (see Figure A2.4) were connected to the AC voltmeter amplifier. This electronic interference was observed as a small reduction in the voltage measured by the plotter when connecting the magnetic tape recorder to the circuit. The nature of this electronic complication

would also explain the loss of mass phenomenon as it was observed.

Unfortunately, the significance of the above seemingly insignificant difficulties could not be assessed during experimental operations due to the long and complicated data handling and processing methods required for this work (due to lack of the appropriate equipment).

It is the author's opinion that if accurate flow regulation and in-position calibration of stationary conductance probes is used for future work, the mass balance "loss of mass" phenomenon will be greatly reduced or eliminated. The calibration data should be recorded in a manner identical to the mixing data, and needless-to-say, the injection system should be leak-tight.

5.6 Flow Visualization Experiments

A solution of methyl violet indicator was injected into the peripheral injection subchannel in order to do flow visualization studies. Earlier flow visualization efforts in interior subchannels had been unsuccessful using inking pen fluids and potassium permanganate (a strong oxidant of dark purple color). However, injection of methyl violet tracer into the peripheral subchannel (# 50) provided valuable information about the fluid mixing behavior in the wire-wrap spaced rod array.

Using the dye tracer, an approximate value of the

average angle of the tracer dispersion path (in the peripheral subchannels) with respect to the rods was measured to be $5.5^{\circ} \pm 1.0^{\circ}$ (at an average bundle Reynolds number of 17,500) while the angle of the wire-wrap is 4.7° , i.e., a 12 inch lead on a 1/4 inch OD rod. The observed peripheral, swirl flow angle was somewhat greater than the wire-wrap angle which is perhaps not expected because the maximum expected flow deflection would occur with the tracer path synchronized with the wire-wrap at 4.7° .

Recently, Lorenz, et al. (5.2) have done flow visualization experiments on the ANL 91-pin bundle and have observed a similar bulk swirl generated by wire-wrap spacers at the periphery of the bundle. Lorenz has measured a peripheral tracer dispersion angle with an average value of 3.15° ; the maximum angle observed was 5.85° (wire-wrap angle = 4.5°). The average angle represents the swirl velocity while the maximum angle represents superimposed diffusion of the tracer.

E.U. Khan (5.3) has mentioned that one theory concerning the peripheral swirl flow velocity observed (particularly concerning the observation of tracer at angles greater than the wire-wrap angle) notes that the observed transverse velocity of a swirl flow should appear higher than the wrap angle because between peripheral subchannels the rod and wall act as a nozzle which increases the average, peripheral swirl flow velocity (in the proximity of the rod-to-wall gap).

As was confirmed by experimental salt tracer measurements, in both turbulent and laminar flow, the tracer migrated a considerable transverse distance. Over the range of Reynolds numbers tested, tracer (both dye and salt) was present at the bundle outlet in subchannels No. 36, 37 and 38 with injection into No. 50 two lead lengths (24 inches) downstream. Using the salt tracer data, a flow deflection of about four rod-to-rod pitches (from subchannel No. 50 to 35) was observed with the injector 13 inches from the detector; this data gives a flow angle of $4.9^{\circ} \pm 1.4^{\circ}$.

Varying the injection rate in turbulent flow visualization experiments had little influence on the gross tracer distribution in the rod bundle. The primary visual effect of injection velocity changes were in the region near the injection device. For increased tracer insertion velocity, these changes were characterized by more turbulent jet mixing and more jet ricocheting (particularly with injection near a wire-wrap). Away from the injector, the primary influence of injection rate variation was a small change in the darkness, not the position, of the dispersing tracer (the concentration was the same for all work - dark).

For laminar flow ($Re \approx 1500$), the flow was observed to be "fluffy," possibly due to vortex (large eddy) shedding from the wire-wrap. A rule of thumb equation

for vortex shedding frequency is

$$f = 0.2 V / d_w \quad \text{Eq. 5.1}$$

where f is the vortex shedding frequency (sec^{-1}), V is the fluid velocity (ft/sec) and d_w is the diameter of the flow obstruction (ft.). The 0.2 coefficient is empirical and varies from 0.2 to over 0.8, but for this approximate treatment 0.2 will suffice. The frequency of wire-wrap vortex shedding may be calculated to be about 60 sec^{-1} ; such a frequency would explain the fluffy nature of the flow, but is too high to explain the fluttering in the original data. (Vortex shedding may have been an exciting mechanism in the low-flow instabilities, nevertheless).

The tracer dispersion pattern in laminar flow was characterized by a more dominant "turbulent jet" type of dispersion superimposed on a swirl flow similar to that in turbulent flow. With increases in injection velocity, the dispersing jet would spread into a wider dispersion angle. Flow perturbations near the injector also increased with injection velocity.

Detailed data of the flow visualization experiments were not taken; however, an abbreviated photographic record of this work is given in Appendix 8.

Chapter 6

RECOMMENDATIONS FOR FUTURE WORK

Using the moving injector instrumentation technique a variety of illuminating experiments could be conducted in order to provide a better understanding of rod bundle thermal-hydraulics. A list of such experiments is given in Table 6.1 and discussed below. The influence of rod array geometrical parameters, i.e., rod diameter, rod-to-rod pitch and wire-wrap lead and the influence of the total number of array rods on interchannel coolant mixing are important in the thermal-hydraulic and thermal-mechanical design of LMFBR fuel and blanket assemblies and in the interpretation of mixing results from various experimental rod bundles.

6.1 Influence of Rod Bundle Geometrical Parameters on Coolant Mixing

This work has provided preliminary mixing results for a wire-wrap spaced rod bundle in a rhombus shaped flow channel. In order to give a more realistic experimental flow field, future work should be done with hexagonal rod bundles.

The influence of both the wire-wrap axial pitch (lead) l and the pitch-to-diameter ratio P/D on inter-

Table 6.1

Recommendations for Future Experimental
Work in Interchannel Coolant Mixing

Section

- 6.1 Influence of Rod Array Wire-Wrap Lead and Pitch-to-Diameter Ratio
- 6.1 Influence of Rod Diameter (Bundle Scale)
- 6.2 Influence of Hexagonal Rod Array Size, i.e., Number of Rods or Bundle Size
- 6.3 Mixing Behavior in Different Subchannel Types: Interior, Peripheral and Corner
- 6.3 Influence of Channel Walls and Corners on Rod Array Mixing
- 6.4 Flow Blockage and Distorted Rod (or Wall) Studies; the Effect of Bundle Looseness
- 6.4 Coolant Mixing in Bare Bundles and the Influence of Spacer Grids on Mixing Behavior
- 6.4 Transient Experiments
- 6.4 Outlet Velocity Profile Measurements: Experimental Mass Balance Calculations
- 6.5 Data Reduction with Moving Injection and Stationary Detection
- 6.6 Comparison of Results with Salt Solution and Hot Water Tracers
- 6.7 Integral Experiments: A Comparison of Heated Rods and Axially Integrated, Injected Tracer Results

channel coolant mixing is of interest. Varying the wire-wrap lead length varies the mixing rate and pressure losses so that an optimization is necessary. The P/D parameter influence is also of interest because it changes from one reactor type to the next and because blanket assemblies have a lower P/D than fuel assemblies. The influence of the rod diameter D (bundle scale or overall size) on coolant mixing behavior is of interest. Bundle scale or rod diameter varies with fuel assembly designs, and blanket assemblies have a larger rod diameter than fuel assemblies.

Understanding coolant mixing parameters over the range of rod bundle geometrical parameters, i.e., wire-wrap lead, fuel rod pitch-to-diameter ratio (equilateral triangular lattice) and fuel rod diameter shall be important in future fast breeder reactors in which the fuel assembly design reflects changes in fuel cycle economics and reactor development. In addition, these influences are an important part of assessing existing experimental data taken on bundles with varying rod array geometrical parameters.

6.2 Influence of The Number of Array Rods

Blanket assemblies typically have 61, 91 or 127 rods, a smaller number of rods than fuel assemblies (typically 217 rods). Further, it is a common practice

to conduct experiments with rod bundles that have less rods than is characteristic of reactors. An important part of interchannel coolant mixing studies will involve examining the influence of the number of rods used for a hexagonal shaped test section on observed mixing behavior. It has been suggested by Markoczy [6.1] that the effect of the number of rods might decrease monotonically as the number of rods increases. Figure 6.1 (also refer to Table 4.2) shows the ratio of the number of exterior-to-interior type subchannels versus the number of rods for hexagonal rod bundles; this illustrates that the channel walls or flow duct should be expected to have an influence on the average or overall rod bundle mixing rate which varies with the number of rods in the array. This effect would be most noticeable around the outermost rod rows of the array. The 217 pin bundle characteristic of LMFBR cores has a peripheral-to-interior subchannel ratio of 0.125 while the 19, 37, 61 and 91 pin arrays most commonly used for experiments have respective ratios of 0.500, 0.333, 0.250 and 0.200; this ratio varies from 0.250 to 0.167 for typical blanket assemblies.

6.3 Influence of Subchannel Location

Anamolies in coolant flow areas do not influence the flow field further than about two rod rows from the perturbation [6.1]. Fuel assembly channel walls are a marked deviation in flow geometry, but away from the walls,

the rod array tends to behave similarly to an infinite rod array. Obviously, interchannel coolant mixing in interior subchannels is influenced by the wall if the subchannel is near the wall. The coolant mixing in both interior and peripheral subchannels is influenced by the proximity of a corner subchannel [the salt tracer technique could be used (with injection into all subchannels of interest)] in order to establish the influence of these geometrical irregularity proximities. It would be necessary to examine mixing behavior in several interior subchannels of differing proximity to peripheral subchannels to determine the influence of a wall on rod bundle mixing behavior. Examining mixing behavior in several interior and several peripheral subchannels of different proximities to a corner subchannel could establish the influence of hexagonal duct corners on rod array coolant mixing.

6.4 Miscellaneous Rod Bundle Mixing Experiments

Using the instrumentation methods herein developed, a series of experiments could be done illuminating fluid mechanical phenomenon in the vicinity of flow blockages, bowed rods, distorted rods and distorted channel walls. The methods could also be used to investigate single phase mixing in bare rod arrays and to examine the influence of spacer grids on coolant mixing. Coolant mixing

behavior during flow transients might also be examined.

It is recommended that, in future work, velocity profiles at the rod array outlet be measured using a pitot tube to experimentally check the flow split analysis used in the MITMIX code balance calculations, see Appendix 3. In addition to measuring outlet velocity, it may be possible to measure any swirl flow component as well.

6.5 The Role of Diffusivity in Computer Code Data Analysis

The purpose of the work herein reported is to aid in the thermal-hydraulic design of LMFBR fuel assemblies. Further observations regarding diffusivities might be useful, particularly if the computer codes for thermal-hydraulic analysis of LMFBR's were to be required to perform a comparative analysis of data generated in various mixing experiments which used either sodium flow or water flow. Extensive experimental results exist for tracer insertion using salt solution injection, heated water injection and heated rods with water flow and for tracer insertion using heated rods with sodium flow. In order to utilize this data, an analytical procedure having a highly flexible energy mixing capabilities is required.

The molecular (mass) diffusivity of a salt tracer and the thermal diffusivity of the main flow (with heat tracers) plays an important role in the dispersion of

either the salt solution or the heat in a rod array. Table 6.2 gives the interrelationship of the various diffusivities of interest. The cases of interest in code analysis include:

- (1) LMFBR Fuel Assemblies, continuous heat addition, $Pr \approx 0.005$,
- (2) Experimental Rod Arrays with Sodium Flow, tracer insertion via heated rods - continuous heat addition, $Pr \approx 0.005$,
- (3) Experimental Rod Arrays with Water Flow, tracer insertion via heated water injection at a point or heated rods, continuous heat addition, $Pr \approx 5.0$, and
- (4) Experimental Rod Arrays with Water Flow, tracer insertion via salt solution injection at a point, $Sc \approx 500$.

In the cases above, the fluid mixing is similar and is governed by the flow conditions; however, in progressing from (1) to (4), the level of energy mixing, i.e., thermal diffusivity or mass diffusivity, changes by several orders of magnitude with respect to the momentum diffusivity. The energy mixing is governed by both the flow media and the tracer type.

Table 6.2

Diffusivity Ratios in Experimental Rod Arrays and LMFBR
Fuel Assemblies⁺

Flow Media (Single Phase)	WATER	SODIUM
Geometry	EXPERIMENTAL	EXPERIMENTAL OR LMFBR FUEL ASSEMBLY
Pr^*	$\approx 5.0 (10^3)^\phi$	$\approx 0.005 (1)$
$1/Le^*$	≈ 0.01	NA
Sc^*	$\approx 500.0 (10^5)$	NA
Insertion Technique	CONTINUOUS Heat POINT@ Heat Salt Solution	CONTINUOUS Heat

+

+ See also section 2.5

ϕ The relative significance of momentum diffusivity in transport of heat or mass, normalized to LMFBR fuel assembly conditions

@ Axial integration of point insertion data may give results characteristic of continuous insertion over the range of injector travel

$$* Pr = \frac{\text{Momentum Diffusivity (Flow Media)}}{\text{Thermal Diffusivity (Heat Tracer)}}$$

$$1/Le = \frac{\text{Thermal Diffusivity (Heat Tracer)}}{\text{Mass Diffusivity (Salt Tracer)}}$$

$$Sc = \frac{\text{Momentum Diffusivity (Flow Media)}}{\text{Mass Diffusivity (Salt Tracer)}}$$

6.6 Data Analysis

A class of interchannel coolant mixing computer codes for rod bundles are written to "follow the fluid" so that these codes, such as the COBRA series, are suited for data reduction of experiments with moving detection and stationary injection. This is an important distinction because with stationary injection, the tracer insertion is constant with respect to the wire-wrap angular orientation; however, with moving injection, the angular orientation of the wrap and the injector coincide only once each lead length.

Data analysis or comparison with results of the class of predictive codes above with data from moving tracer injection presents a geometrical dilemma. The straightforward method is quite bulky and would require running a separate data reduction run for each injector-detector axial separation distance of interest (within one lead length). An alternative method of data analysis, which requires further consideration, would attempt to predict the integrated results. This method would be similar to a single heated rod experiment (with heat or mass addition into one subchannel), and is discussed in more detail in section 6.7.

One other difficulty with salt insertion is the high injection-to-background concentration ratio. Conveniently, the COBRA code would use heat transport in data reduction

calculations to model mass transport. Using the heat transfer analogy for mass transfer calculations is quite acceptable; however, the codes, in order to perform the analogous calculations with high injection/background concentrations, would require insertion temperatures of the order 800 - 1000F, perhaps more. This high insertion temperature would result in two problems with existing codes. First, high pressures would be forced to prevent change of phase; also in the high pressure and temperature range the specific heat of water deviates markedly from unity. A false water enthalpy table would be required. Second, adding this much heat would lead to a significant change in bundle average and local thermal-physical properties so that a false fluid property table would be necessary, also. Another possibility would be to modify the code to accommodate mass transfer. The problems of data analysis using available computer codes are not major obstacles; however, some effort will be required to adapt a code, e.g., COBRA, to analyze salt tracer experiment data.

The COBRA II and III (6.2, 6.3, 6.4, 6.5, 6.6) codes have been modified by the author (6.7) during work not related to this project, so that the high tracer injection-to-background difficulties would present little or no difficulty during data analysis of salt tracer experiments. This activity consisted basically of modification of the

COBRA codes to do compressible (or incompressible), single-phase coolant calculations. The coolant properties in these modified codes are calculated, and the coolant transport properties are determined using correlations.

6.7 Integral Experiments

An interesting possibility arises in comparing axially traversing salt injection experiments with heated rod experiments. If one integrated the tracer detected (as the injector was axially traversed) at a stationary probe using a moving injector, would this be analogous to the signal received at a detector (at the same location with an equal, uniform tracer insertion into the same subchannel over the entire injector travel length, e.g., a heated rod? Further consideration of this question might lead to an extension of the capabilities of rod bundle, mixing experiments.

6.8 Flow Visualization

Injecting dye type tracers, such as methyl violet (suggested by W. Kirchner, MIT), can provide a visual record of mixing phenomenon occurring in the bundle. Flow visualization experiments literally illuminate salt tracer type experiments because the molecular diffusivity of dye tracers is quite low compared to the momentum

diffusivity, i.e., dye tracers have high Schmidt numbers as do salt tracers. Because flow visualization offers such a rapid and lucid view of the mixing phenomenon, it is recommended that such experiments be included as part of peripheral subchannel investigations (where transparent channels are used). A primary difficulty with flow visualization is quantifying the results with sufficient accuracy to provide meaningful information. The method of presenting the results of flow visualization experiments used by Lorenz, et al. (5.2) overcomes this difficulty, in part, by outlining the boundaries of the tracer dispersion.

6.9 Recommendations for Future Experiment Design and Operation

This section presents recommendations regarding the design and operation of coolant mixing experiments based on experiences with the MITF described in Chapter 4. The discussion is oriented towards salt tracer, coolant mixing experiments.

From the results presented, one finds that in order to observe the complete behavior of coolant mixing in wire-wrap spaced rod arrays, detailed data is required in the axial direction (5 points/inch or more). This data is most conveniently obtained using a moving injection device holding the detectors at a fixed position.

The injector should be designed to inject the

tracer solution stream in a radial direction toward the centroid of the injection subchannel and in an axial direction about 15° to 20° from the injection rod centerline. A hypodermic tube, soldered in-place and ground flush with the moving inner rod, is recommended for the injection device geometry. The salt tracer insertion rate should be based on an injection velocity equal to the average velocity of the injection subchannel (the EAVC - Equal Average Velocity Criterion) and on a mass insertion rate which gives instrument responses of the appropriate range, i.e., 0% to 50% of the applied bridge voltage; mass insertions of 0.5 to 1.0 grams/minute are typical of the latter requirement. The injection system must be designed to supply an accurately measured and constant flow to the injector rod; with moving injection, variation of the back-pressure in the experimental rod array must be considered.

The recommendations for the mechanical design of the injection rod have been discussed in section 4.9. The primary requirement of injector design, construction, and handling is the avoidance of error in the angular positioning of the needle injector; to accomplish this, the inner tube must be kept perfectly straight, the sliding, angular positioning device must be wear resistant, the inner rod must move freely, and the injection rod must be accurately constructed.

The detection system should have a conductivity cell detector positioned near the bundle outlet in each subchannel of interest. The probes should be positioned such that a minimum electrode interference occurs due to the proximity of the rod array. The electrodes should be made of platinum metal and be platinized prior to being placed in-service. A cell constant of about 3.0 should give Wheatstone bridge balance points which will give accurate unbalanced Wheatstone bridge voltage measurements, i.e., approximately 10,000 Ohms. The electrodes, typically $3/32$ inch long, should be positioned just inside the subchannel near the rod array outlet. Most importantly, a calibration curve should be taken for each probe only after it has been positioned in the rod array. If repositioning is required or if the water temperature changes more than 5F, a new calibration curve should be generated for each probe. Care must be taken to prevent electric current leakages between the lead wires connecting the probe electrodes to the instruments; this is especially troublesome in the submerged part of the connection. Also, the probes must be as far as possible from any materials of the rod arrays; a $1/16$ to $1/32$ inch clearance should give minimal electrode interference. The cells cannot function if in contact with any extraneous materials. See section 4.10 for other details on the conductivity probe design.

The experimenter is urged to become familiar with Appendix 5, Appendix 2 and Chapter 3 before attempting conductance measurements.

Chapter 7

CONCLUSIONS

Understanding interchannel coolant and energy mixing behavior in wire-wrap spaced geometries is an important requirement in the thermal-hydraulic and thermal-mechanical design of fuel assemblies for LMFBR's. This report discusses the design of tracer injection experiments, particularly instrumentation, to examine the coolant mixing behavior of wire-wrapped rod arrays. Also reported are a series of experiments run to determine the influence of various experimental operating parameters on coolant mixing results. Results of coolant mixing experiments with turbulent and laminar flow are presented for a 25-pin, rhombus shaped, wire-wrap spaced rod bundle with geometrical parameters typical of a LMFBR, i.e., a rod diameter = 0.25 inch, a rod pitch-to-diameter ratio = 1.25 and a wire-wrap lead = 12.0 inches.

7.1 Instrumentation Design

The primary concerns in the design of the tracer injection, coolant mixing experiments are injection system design, detection system design and tracer selection. The primary concerns of injection system design are location, mobility and insertion duct geometry. The primary concerns of detection system

design are instrument type, set by the tracer type, and instrument location with respect to the rod array. Tracer selection was discussed in detail in the report with salt solutions and heat tracers considered the preferred types.

For this work, a concentric tube, injector rod design, movable over the upper thirty inches ($2\frac{1}{2}$ lead lengths) of the rod bundle, was used with a hypodermic needle injector mounted about 20° from the tube centerline. Results using a needle injector were compared with a transverse hole injector and found to have less main flow perturbations. Electrolytic conductance cells were used as detection instruments and were mounted on externally supported probes and positioned near the rod array outlet, inside the upper one-quarter inch of the rod array. A salt (NaCl) solution was used for this work and was considered better than heat as a tracer because it offered a higher tracer concentration-to-background concentration ratio, because the non-linear nature of electrolytic conductance versus solution strength is better suited for coolant mixing experiments, and because low mass diffusivity is preferred for coolant mixing experiments.

7.2 The Influence of Operating Parameters on Experimental Results

Experiments to determine the influence of various

operating parameters on coolant mixing results showed that the results were independent of salt insertion rate, i.e., either injection solution concentration or injection velocity. With injection velocity changes more main flow perturbations were noted due to the injection flow, however. A comparative experiment using sodium nitrate gave results similar to those for NaCl indicating no influence of salt type. The major influence of Reynolds number was a decrease in detection noise with increases in main flow. The most significant effect on experimental results was due to the mechanical behavior of the moving injection device. Careful design, handling and use of the injector rod would eliminate all such mechanical difficulties.

7.3 Interchannel Coolant Mixing Results - Interior Subchannel Injection

The average injection velocity used for the work was equal to the average velocity of the subchannel into which injection occurred. A tracer insertion rate of about 1.0 grams/minute lead to detection in the optimum response range of the AC measuring equipment. A tracer solution strength of 2.0 grams-NaCl/lbm-water gave optimum detection conditions with injection flow set by the equal average velocity criterion.

Using the salt solution tracer technique, laminar

and turbulent flow, coolant mixing experiments were done with injection into an interior and a peripheral subchannel. The axially-detailed mixing results were taken over thirty inches of injector travel. From the interior subchannel injection data, it may be concluded that flow sweeping has a dominating effect on the tracer dispersion with the injector within about one foot of the detector. At greater injector-detector separations, the influence of natural turbulent interchange becomes increasingly significant in determining the dispersion of the tracer. Furthermore, the axial behavior of interchannel coolant mixing can not be properly assessed using experimental data with axial separation greater than one inch (or less).

The tracer dispersion pattern was unaltered by the change from turbulent to laminar flow; however, the magnitude of the amount of tracer mixed or dispersed with respect to the amount present in the injection subchannel was markedly increased. This increase was apparently due to the absence of eddy diffusivity (natural turbulence) and due to an increase in the wire-wrap drag coefficient (the sweep flow driving force). The turbulent noise detected considerably increased in changing from turbulent to laminar flow; apparently due to vortex shedding from the wire-wrap spacers and,

again, due to the absence of natural turbulent interchange. A low-flow, injection system instability may have been the cause, also.

7.4 Interchannel Coolant Mixing Results - Peripheral Injection

The differences between laminar and turbulent flow with peripheral subchannel injection were similar to those noted for interior subchannel injection; however, with peripheral subchannel injection, the tracer dispersion was dominated by flow sweep over the entire thirty inches of injector travel. A swirl flow around the bundle periphery was clearly present and was determined to be at an average angle of $4.9^{\circ} \pm 1.4^{\circ}$ from the bundle axis using salt tracer data. Also, the swirl flow did not mix with the flow in adjacent interior subchannels but remained near the flow channel walls.

7.5 Instrumentation Performance

The criterion for assessing the performance of the injection and detection system design used was that the mass of salt tracer detected should equal the amount of salt injected. Mass balance calculations indicated stripping, the failure to meet mass balance criteria due to inhomogeneous solution concentrations, occurred somewhat in the six inches of injector travel closest to the detector; this was an inherent design limitation. An unexpected and significant "loss of mass" occurred in the region

with eighteen to thirty inches of injector-detector separation. This error is due to either the use of inadequate calibration curves, poor flow regulation or (and) a possible leak in the injection system. Nevertheless, changes in design and procedure have been discussed which would reduce or eliminate this error.

7.6 Flow Visualization Results

Flow visualization experiments done with peripheral subchannel injection qualitatively verified results of operating parameter influences discussed earlier. The average swirl flow angle was visually determined to be $5.5^{\circ} \pm 1.0^{\circ}$ from the bundle axis.

REFERENCES

- 1.1 Rogers, J.T. and N.E. Todreas, "Coolant Interchannel Mixing in Reactor Fuel Rod Bundles, Single-Phase Coolants," Heat Transfer in Rod Bundles (N.Y., ASME, 1968), pp. 1 - 56.
- 1.2 Brodkey, R.S., "Fluid Motion and Mixing," Chapter 2, Mixing Theory and Practice, Volume 1, Ed. by V.W. Uhl and J.B. Gray (N.Y., Academic Press, 1966), pp. 7 - 110.
- 1.3 Todreas, N.E. and J.A. Turi, "Interchannel Mixing in Wire-Wrapped Liquid Metal Fast Breeder Fuel Assemblies," Nuclear Technology, V13, N1, January 1972, pp. 36 - 52.
- 1.4 Markoczy, G., "Core Heat Transfer and Fluid Flow in the GCFR," Paper presented at the 17th ANS Annual Meeting, Boston, June 1971.
- 2.1 Personal Communications with T. Ginsberg, Argonne National Laboratory, August 1971.
- 2.2 Lorenz, J.J. and T. Ginsberg, "Results and Analysis of 7-pin Wire Wrap Mixing Tests," ANS Transactions, V15, N2 (Washington, ANS, November 1972), pp. 867-868.
- 2.3 Lorenz, J.J., "survey of Current Thermal Hydraulic Studies Applicable to LMFBR Fuel Assembly Design," USAEC Report, ANL-CT-73-05, March 1973.
- 2.4 Lorenz, J.J., "Liquid Metal Heat Transfer in Pin Bundle," USAEC Report, ANL-RDP-14, February 1973, pp. 3.2 - 3.3.
- 2.5 van Erp, J.B. and T.C. Chawla, "Experimental Evaluation of Subchannel Coolant Crossflow in LMFBR Subassemblies with Wire-Wrap Spacers," ANS Transactions, V15, N2 (Washington, ANS, November 1972), pp. 856 - 857.
- 2.6 van Erp, J.B., "Out-of-Pile Studies, Fuel Element Failure Propagation," Reactor Development Progress Report, USAEC Report, ANL-RDP-9, September 1972, pp. 9.14 - 9.15.

- 2.7 Graves, A.W., "Pre-Test Predictions of the ANL 91-Pin Hot Water Injection Mixing Experiment," TI-707-240-016, Atomics International, March 1973.
- 2.8 Marian, V.R. and D.P. Hines, "Transfer of Coolant Between Adjacent Subchannels in Wire-Wrap Spacer and Grid Spacer Bundles," ANS Transactions, V14, N2 (Boston, ANS, June 1971) pp. 807 - 808.
- 2.9 Collingham, R.E., W.L. Thorne and J.D. McCormack, "217-Pin Wire-Wrapped Bundle Coolant Mixing Test," USAEC Report, HEDL-TME-71-146, 1971.
- 2.10 Personal Communications with A.S. Hanson, MIT, Cambridge, Mass., April 1973.
- 2.11 Skok, J., "Mixing of the Fluid Due to Helicoidal Wires of Fuel Pins in a Triangular Array," DRP/SEMTR/CAD, r. 605, May 1970.
- 2.12 Baumann, W., H. Hoffman and K. Rust, "Selection of Spacers for the Fuel Assemblies of FBR," Karlsruhe ANS Meeting, 1970.
- 2.13 Okamoto, Y., M. Hishida and N. Akino, "Hydraulic Performance of Rod Bundles of Fast Reactor Fuels - Pressure Drop, Vibration and Mixing Coefficient," IAEA/SM-130/5, Monaco, March 1970.
- 2.14 Okamoto, Y., N. Akino, E. Emori and M. Tarida, "Hydraulic Tests of FBR Fuel Sub-Assemblies (JEFR), Part 2 Final Report," PNC-SJ-250-71-37, JAPFNR-24, Japan Atomic Energy Research Institute, September 1971.
- 2.15 Davidson, C.R., "AI FBR Single Channel Developmental Test Results," TR-097-210-001, Atomics International, 1972.
- 2.16 Bolz, R.E. and G.L. Tuve, editors, Handbook of Tables for Applied Engineering Science (Cleveland, Chemical Rubber Co., 1970), pp. 452 - 453.
- 2.17 1967 ASME Steam Tables (New York, ASME, 1967).
- 2.18 Land, N.S., "A Compilation of Nondimensional Numbers," NASA-SP-274 (Washington; NASA 1972).
- 3.1 Bender, R.J., "Why Water Desalting Will Expand," Power, V113, N8, August 1969, pp. 171-178.

- 3.2 Glasstone, S., Introduction to Electrochemistry (New York, van Nostrand, 1942).
- 3.3 Harned, H.S. and B.B. Owen, The Physical Chemistry of Electrolytic Solutions (N.Y., Reinhold, 1968).
- 3.4 Malmstadt, H.V., C.G. Enke and E.C. Toren, Electronics for Scientists (N.Y., Benjamin, 1963), pp. 273-283.
- 3.5 Robinson, R.A. and R.H. Stokes, "The Measurement of Conductivities and Transport Numbers," Chapter 5, Electrolytic Solutions (London, Butterworths, 1959), pp. 87 - 102.
- 3.6 Kohlrausch, F., Wied. Ann., V60, 1897, p. 315.
- 3.7 Jones, G. and D.M. Bollinger, "The Measurement of the Conductance of Electrolytes, VII. On Platinization," Journal of the American Chemical Society, V57, N2, 1935, pp. 280 - 284.
- 3.8 "4959 Conductivity Bridge Directions," Manual 177335 - Issue 1, Leeds and Northrup Company.
- 4.1 Turi, J.A., "An Investigation of Interchannel Mixing in Wire Wrapped Liquid Metal Fast Breeder Reactor Fuel Assemblies," M.S. Thesis, Nuclear Engineering Department, MIT, Cambridge, Sept. 1970.
- 4.2 Eaton, T.E., "Spring 1972, Mixing Experiment Data File," Not Communicated.
- 5.1 Eaton, T.E., "Summer 1973, Mixing Experiment Data File," Not Communicated.
- 5.2 Lorenz, J.J., D.R. Pedersen and R.D. Pierce, "Peripheral-Flow Visualization Studies in a 91-Element Bundle," USAEC Report, ANL/RAS 73-17, June 1973.
- 5.3 Khan, E.U., Personal Communication, August 1973.
- 6.1 Markòczy, G., Personal Communication, June 1973.
- 6.2 Rowe, D.S. and C.W. Angle, "Crossflow Mixing Between Parallel Flow Channels During Boiling," USAEC Report, BNWL-371, "Part I: COBRA - Computer Program for Coolant Boiling in Rod Arrays," March

- 6.2 1967, "Part II: Measurements of Flow and Enthalpy
cont. in Two Parallel Channels," December 1967, "Part
III: Effect of Spacers on Mixing Between Two
Channels," January 1969.
- 6.3 Rowe, D.S., "CCBRA II - A Digital Computer Program
for Thermal Hydraulic Sub-Channel Analysis of Rod
Bundle Nuclear Fuel Elements," USAEC Report,
BNWL-1229, February 1970.
- 6.4 Wheeler, C.L., G.C. Main and D.C. Kolesan, "COBRA
II-A: A Program for Thermal Hydraulic Analysis of
Very Large Bundles of Fuel Pins," USAEC Report,
BNWL-1422, August 1970.
- 6.5 Rowe, D.S., "COBRA III - A Digital Computer Program
for Steady State and Transient Thermal-Hydraulic
Analysis of Rod Bundle Nuclear Fuel Elements, USAEC
Report, BNWL-B-82.
- 6.6 Rowe, D.S., "COBRA-III C: A Digital Computer Program
for Steady State and Transient Thermal-Hydraulic
Analysis of Rod Bundle Nuclear Fuel Elements,"
USAEC Report, BNWL-1695, March 1973.
- 6.7 Project Staff, "Gas-Cooled Fast Breeder Reactor,
Quarterly Progress Report for the Period August
1, 1972 through October 31, 1972," USAEC Report,
Gulf-GA-A12421.
- A1.1 Sangster, W.A., "Calculation of Rod Bundle Pressure
Loss," ASME Paper 68-WA/ht-35 (N.Y., ASME, 1968)
- A7.1 Tobey, G., J. Graeme, and L. Huelsman, Operational
Amplifiers - Design and Application (N.Y., McGraw-
Hill, 1971).

NOMENCLATURE

- A_e - Conductance Cell Electrode Area, cm^2 .
- A_i - Flow Area of Subchannel Type i , in^2 .
- C - Salt Solution Concentration
- C_D - Mass Diffusion Coefficient, ft^2/hr .
- c_i - Salt Solution Injection Concentration, $\text{grams-NaCl}/\text{lbm-water}$.
- c_p - Specific Heat at Constant Pressure, BTU/lbm .
- C_s - Conductivity Cell Electrode Surface Capacitance.
- C_v - Variable Wheatstone Bridge Capacitance.
- D - Fuel Rod Diameter, in .
- De_i - Equivalent Hydraulic Diameter of Flow Area Type i , in .
- d_w - Wire-Wrap Diameter, in .
- f - Friction Factor.
- f - Vortex Shedding Frequency, sec^{-1} .
- G - Analog Circuit Gain
- i - Subchannel Identification Subscript: 1 = Interior, 2 = Peripheral, 3 = 120° Corner, 4 = 60° Corner.
- ID - Tube Inside Diameter, in .
- k - Thermal Conductivity, $\text{BTU}/\text{hr-ft-F}$.
- K_c - Conductivity Cell Constant, Ohm-cm .
- K_{cr} - Reference Conductivity Cell Constant, Ohm-cm .
- K_u - Unknown Conductivity Cell Constant, Ohm-cm .
- k_s - Salt Solution Specific Conductance, mho-cm .
- l_e - Conductance Cell Electrode Length, cm .
- Le - Lewis Number.

- MODE- Time Constant on Analog Computer, sec.
- OD - Outside Tube or Rod Diameter, in.
- P - Rod-to-Rod Pitch, in.
- P - Potentiometer Voltage, Volts (Appendix 7)
- Pe_h - Peclet Number, Heat Transfer.
- Pe_m - Peclet Number, Mass Transfer.
- Pr - Prandtl Number.
- Q - Total Bundle Flow Rate, lbm/min or GPM.
- R - Electrical Resistance, Ohms.
- R_b - Fixed Wheatstone Bridge Resistance, Ohms.
- Re - Reynolds Number.
- R_m - Measured Electrical Resistance, Ohms.
- R_{mr} - Resistance Measured with Reference Cell, Ohms.
- R_{mu} - Resistance Measured with Cell having Unknown Constant, Ohms.
- R_s - Conductivity Cell Electrode Surface Resistance.
- R_u - Unknown Resistance, Ohms.
- r_s - Salt Solution Specific Resistance, Ohms-cm.
- R_v - Variable Wheatstone Bridge Resistance, Ohms.
- s - Laplace Transform Variable.
- Sc - Schmidt Number.
- T - Temperature, F or C.
- V - Fluid Velocity, ft/sec.
- V_a - Applied Wheatstone Bridge Voltage, Volts AC-RMS.
- V_m - Measured Wheatstone Bridge Voltage, Volts AC-RMS.
- W_b - Total Bundle (Main) Flow Rate, lbm/min.
- w_i - Injection Flow Rate, lbm/min or cc/min.

- w_i - Flow in Subchannel Type i , lbm/min (Appendix 1).
 - w_s - Electrode Surface, Warburg Impedance Effect.
 - X - Axial Injector Travel, inches.
 - X_i - Flow Split Fraction to Subchannel of Type i
(Fraction of Main Flow), lbm/min.
 - x - Analog Computer Input Signal
 - y - Analog Computer Output Signal
-

- ΔP - Pressure Loss, psig.
- ρ - Fluid Density, lbm/ft³.
- η_i - Number of Subchannels of Type i .
- μ - Fluid Viscosity, lbm/hr-ft.
- τ - Time Constant, sec.
- ω - Frequency, sec⁻¹.

Appendix 1

HYDRAULIC ANALYSIS OF THE EXPERIMENTAL FACILITY

This appendix presents the results of flow calculations for the 25-pin rhombus array of $1/4$ inch rods used for experiments reported in the text. This rod array was assembled into a triangular lattice configuration with a rod pitch-to-diameter ratio of 1.25 such that the cross section geometry was a parallelogram with 5 rods on each side, see Figure A1.1. The unit flow areas, or subchannels, have been indicated in the figure. Subchannel type 1 refers to an interior flow passage, type 2 to a wall or peripheral subchannel, type 3 to a 120° corner subchannel, and type 4 to a 60° corner subchannel. The analysis reported here is significant because it is used to determine the appropriate injection flow rate for the salt solution tracer, also the results are used to establish the flow regime, i.e., laminar, transition or turbulent, within the experimental array.

Using the method described by Sangster (A1.1), the fraction of the total flow passing through each subchannel is calculated assuming that the flow is fully turbulent and that there are no transverse pressure gradients. The turbulent friction factor is calculated

FIGURE A1.1 - CROSS SECTION OF EXPERIMENTAL ROD BUNDLE SHOWING
THE VARIOUS SUBCHANNEL TYPES

using the Blasius smooth tube correlation:

$$f = 0.316/(\text{Re}^{0.25}) \quad (\text{A1.1})$$

For this work, the only significance of Eq. A1.1 is the exponential dependence of the Reynolds Number. The calculations proceed by determining the fraction w_1 of the total rod bundle flow w_b passing through a sub-channel type 1:

$$w_1 = X_1 w_b \quad (\text{A1.2})$$

X_1 is the flow split factor and is determined by the geometry of the rod array and by the Reynolds number dependence of the friction factor:

$$X = 1 / \left[\eta_1 + \eta_2 \left(\frac{A_2}{A_1} \right) \left(\frac{D_{e2}}{D_{e1}} \right)^{0.715} + \eta_3 \left(\frac{A_3}{A_1} \right) \left(\frac{D_{e3}}{D_{e1}} \right)^{0.715} + \eta_4 \left(\frac{A_4}{A_1} \right) \left(\frac{D_{e4}}{D_{e1}} \right)^{0.715} \right] \quad (\text{A1.3})$$

The flow in other subchannel types w_i is related to w_1 by

$$\frac{w_i}{w_1} = \left(\frac{A_i}{A_1} \right) \left(\frac{D_{ei}}{D_{e1}} \right)^{0.715} \quad (\text{A1.4})$$

The results of the rod bundle geometry calculations and of the flow split analysis are given in Table A1.1. The effect of the wire-wrap spacers on the geometry has been averaged into the calculations. Table A1.1 gives the fraction of the total flow in the rod bundle X passing through a typical subchannel of the type indicated; also, the local velocity and Reynolds number for these coolant passages are given as a function of the main flow w_b . The variation with main flow Reynolds number and flow velocity in the various flow areas is shown in Figure A1.2 and A1.3, respectively.

TABLE A1.1

Hydraulic Calculations for the Experimental Facility*

Item/Area	Bundle Average	Type 1	Type 2	Type 3	Type 4
Area	1.149	0.0162	0.0325	0.0116	0.0435
Perimeter	31.28	0.491	0.803	0.380	0.977
d_e	0.1470	0.132	0.162	0.122	0.178
n	--	32	16	2	2
X	1.0	0.0130	0.0301	0.00878	0.0431
V/W_b	0.0337	0.0310	0.0358	0.0293	0.0384
Re/W_b	32.3	26.7	37.9	23.4	44.6
W_b -CRIT	70.1	86.1	60.7	98.3	51.6

* 25 rod Rhombus array, rod diameter = 0.250"
wrap diameter = 0.063"

Area (=) in²

Perimeter (=) in

Hydraulic diameter (=) in

W_b (=) lbm/hr

W_b -CRIT (=) lbm/hr, flow at which $Re = 2300$

V (=) ft/sec

Average effect of wire-wrap included in geometric calculations

Specific flow conditions for water at 60°F and Turbulent Flow

FIGURE A1.2 = REYNOLDS NUMBER vs. FLOW RATE FOR VARIOUS FLOW AREAS IN THE EXPERIMENTAL TEST SECTION

FIGURE A1.3 - FLOW VELOCITY vs. TOTAL FLOW RATE FOR VARIOUS FLOW AREAS IN THE EXPERIMENTAL TEST SECTION

Appendix 2

CONDUCTANCE MEASUREMENT METHODS AND EQUIPMENT

The conductivity cell was discussed in detail in Chapter 3. It should be remembered that the cell is used to measure the specific electrical resistivity of a solution so as to determine the concentration of solute within the solution. This chapter shall discuss the methods and equipment used in the project for measuring the specific conductance of solutions. Briefly, two methods are discussed - (1) the balanced Wheatstone bridge method and (2) the unbalanced Wheatstone bridge method. The use of a fast data acquisition (magnetic tape recording) system is an invaluable tool for expediting the experiments; fast data acquisition requires the use of an unbalanced Wheatstone bridge.

The common method for measuring solution specific conductance is the balanced Wheatstone bridge. Figure A2:1 shows a schematic diagram of Wheatstone bridge conductance measurement equipment. A variable frequency, variable voltage oscillator (power supply) was used to apply a voltage to bridge points 1 and 3. The unknown resistance R_u of the conductivity cell is connected across leg 1-2; when the variable resistance R_v

FIGURE A2.1 - SCHEMATIC OF WHEATSTONE BRIDGE CONDUCTANCE MEASUREMENT EQUIPMENT

in bridge leg 2-3 is adjusted to equal R_u , the voltage between points 2 and 4 of the bridge goes to zero. With the voltage nulled, the bridge is referred to as balanced. Bridge legs 1-4 and 3-4 are constant resistances R_b built into the bridge. The null detector is a standard alternating current (root-mean squared) AC-RMS voltmeter. Both the oscillator and the voltmeter are connected to the Wheatstone bridge via bridge isolation transformers so as to eliminate stray DC currents from the bridge circuit. The capacitors in parallel with the variable resistance in bridge leg 2-3 are included in the circuit to balance the reactive (inductive and capacitive) effects in the conductivity cell circuit. These capacitances were seldom required, and their major value was in accentuating the null point during the iterative bridge balancing procedure. This use of these capacitors did not alter the resistance measured; however, the necessity of using large capacitance in parallel with the variable bridge resistor is an indication of cell problems, e.g., loss of polarization or cell electrical interference. The capacitor on the voltmeter null detector reduces needle flutter due to turbulent noise (from inhomogeneous solutions) within the detector. Normally it is recommended that this capacitor not be used because turbulent noise is meaningful

information about the experiment. The oscillator should be operated normally at 1000 Hertz and with a specified output voltage. For this work the oscillator output voltage was 1.5 Volts AC-RMS which gave a bridge voltage variation of 0.0 - 0.4 Volts AC-RMS. As mentioned in Chapter 3, resistance measurements of the same solution at three frequencies, say 100 (200 gives a sharper null), 1000, and 10,000 Hertz gives a measure of polarization errors.

The unbalanced Wheatstone bridge technique keeps the variable resistance R_v constant and correlates the electrolytic solution concentration directly to the measured voltage on the null detector. Figure A2.2 shows a typical calibration curve of unbalanced bridge voltage (AC-RMS) versus salt concentration. As would be expected, the unbalanced voltage is sensitive to small salt concentrations and insensitive to changes at higher concentrations. This is an ideal behavior for mixing experiments; however, the unbalanced voltage should be kept below about 0.3 volts AC-RMS to avoid large errors in the deduced concentrations due to the nonlinearity in the calibration curve, cf. Figure A2.2. This error growth restriction may be accomplished by regulating the mass insertion rate of the tracer salt. Figure A2.3 shows a plot of unbalanced Wheatstone bridge voltage versus balanced bridge resistance,

where the resistance used for the unbalanced voltage measurement was that of the channel water (solvent). The relationship between unbalanced bridge voltage and balanced bridge resistance (directly proportional to solution specific resistance) is nearly linear which might have been predicted. Given the general behavior of the unbalanced Wheatstone bridge, as indicated by Figures A2.2 and A2.3, this method is well suited to salt solution concentration measurements. The unbalanced bridge voltage responds similarly to the balanced Wheatstone bridge resistance. The unbalanced Wheatstone bridge is well suited for fast data acquisition. For this work, the data was actually taken in a continuous manner. The voltmeter signal was amplified and output to a x-y plotter, see Figure A2.4. This continuous analog signal may be recorded, say on a high quality, magnetic FM (frequency modulated) tape recorder and then converted into punched computer cards for use with the MITMIX code (Appendix 3).

Some form of continuous data recording is vital to the experiments. Preferably the data should ultimately appear as punched computer cards. As mentioned above, the data may be recorded on a tape recorder; it also could be recorded on a paper tape punch or feed directly into a small computer. Any of these methods may be used to generate discontinuous

FIGURE A2.2 - MEASURED VOLTAGE VERSUS SOLUTION CONCENTRATION
USING UNBALANCED WHEATSTONE BRIDGE METHODS

FIGURE A2.3 -MEASURED UNBALANCED BRIDGE VOLTAGE VERSUS
BALANCED BRIDGE RESISTANCE

FIGURE A2.4 - SCHEMATIC OF THE CONDUCTANCE MEASUREMENT EQUIPMENT

(digital) punched card data from the analog (continuous) signal detected. Using this method, the plotted continuous signal is not transformed into salt concentration but remains in the form of a detected voltage. A function generator might be employed to generate the calibration curve so that the plotted continuous signal would reflect the mass detected instead of the voltage. The punched card output for use with MITMIX is still necessary in order to provide a calculated mass balance, to prepare plots of the results, and to transform the detected voltage to detected mass using a more accurate calibration curve than is available with a function generation.

Appendix 3

MITMIX - A DATA REDUCTION PROGRAM FOR THE
MIT MIXING PROJECT EXPERIMENTS

In order to expediate the reduction of data from interchannel coolant mixing experiments done at MIT, a simple computer program called MITMIX has been written as part of this work and is available from the MIT Nuclear Engineering Department Computer Code Library. The code has been written in two similar versions - one for use with the MIT Information Processing Center IBM 370/165 digital computer and one for use with the MIT Laboratory of Nuclear Science IBM 360/65 digital computer. The primary functions of MITMIX are

- (1) to prepare a curve fit of the calibration data for salt tracer experiments,
- (2) to translate the measured resistances or voltages into salt solution concentrations using the calibration curve,
- (3) to perform a hydraulic flow split calculation for use in the mass or heat balance computations,
- (4) to calculate mass or heat balances from the flow split analysis and experimental data supplied,
- (5) and to prepare plots of the experimental data and the balance calculation results.

The experimental data for the various subchannels monitored are input as a function of injection displacement. A flow split analysis similar to that reported in Appendix 1 is calculated using the method of Sangster (A1.1); MITMIX has the internal capability to calculate subchannel geometrical parameters for an equilateral triangular lattice, rod bundle. The flow split calculations are used to establish the rate at which tracer, either BTU/min for the case of heated water injection or grams/min for the case of salt tracer injection, has been detected. Obviously, the rate at which tracer flows past the instrumentation should equal the rate at which tracer is injected into the main flow field.

For the salt tracer:

$$w_1(C_i - C_B) = \sum_{j=1}^n w_j(C_j - C_B), \quad (A3.1)$$

$$(\text{injected tracer}) = (\text{detected tracer})$$

where C_i is the injected salt solution concentration; C_B is the background equivalent salt concentration; w_1 is the tracer injection flow rate; w_j and C_j are the calculated flow rate (from the flow split analysis and measured main flow rate) and the salt concentration (from the transformed experimental data) of subchannel j , respectively. Similarly for heated water injection:

$$w_1 c_p(T_i - T_B) = \sum_{j=1}^n w_j c_p(T_j - T_B) \quad (A3.2)$$

where T_B is the background or main flow temperature; c_p is the specific heat of water; T_j is the temperature measured in subchannel j . The balance calculations done in MITMIX are simply the difference between the detected tracer flow rate and injected tracer flow rate.

The flow split analysis is an important part of the balance calculations. It should be noted that the MITMIX flow split calculations are simple in nature; detailed considerations of the flow field have been neglected. Only average subchannel velocities are calculated, and no allowance is made for tracer injection. Changes of fluid thermalphysical properties have been neglected also. The influence of these flow details on the final results is small compared with other errors in the experiments.

The specific heat of water is nearly constant over the temperature range of interest (50 F - 180 F) so that temperature is a direct measure of enthalpy (the actual tracer being monitored) for heat balance calculations. But, the non-linear nature of the specific resistance versus solution strength curve for salt tracers necessitates a translation of specific resistance or unbalanced bridge voltage data to salt solution concentration using a curve fitting procedure. MITMIX establishes a data reduction curve using calibration data generated by mixing homogeneous solutions of the tracer (which have known concentrations) and measuring the specific resistance (or an

unbalanced bridge voltage - see Appendix 2). An analytical curve is fit through the calibration data using the method of least squares. This calibration curve is then used to translate the data taken during the experiments into solution concentrations. The solution concentrations are used for mass balance calculations and for presentation of the results of tracer dispersion due to interchannel coolant mixing mechanisms. An important assumption in the mass balance computation is that the measured salt concentration is uniform over the subchannel of interest. No allowance has been made for nonuniform salt concentrations; however, the results of the mass balance calculations will be an indication of any difficulties due to inhomogeneous salt solutions.

It may be convenient or desirable to present the data in normalized form. For a heated water tracer, the normalized, measured temperature in subchannel j , T_{Nj} may be determined by:

$$T_{Nj} = (T_j - T_B) / ((w_i/w_1) \times T_i - T_B) \quad (A3.3)$$

And for a salt tracer, the normalized, measured salt concentration in subchannel j , C_{Nj} is similarly given by:

$$C_{Nj} = (C_j - C_B) / ((w_i/w_1) \times C_i - C_B) \quad (A3.4)$$

In the normalization equations, A3.3 and A3.4, the injection temperature or salt concentration has been multiplied by w_i/w_1 , the ratio of the injection flow rate to the

injection subchannel flow rate; without this multiplier the "normalized" results would not range between 0.0 and 1.0 because the injection flow is less than the injection subchannel flow.

Appendix 6

A DISCUSSION OF EXPERIMENTAL ERRORS

No experiment is complete until the various causes of error and their influence on the experimental data has been considered. For the work reported here, errors were introduced into the results by experimental operations, by data handling and reduction, and by calculational approximations. Although there are numerous error sources, a few sources were responsible for most of the error. The items listed in Table A6.1 which contribute most to error in the experimental results have been indicated with an asterisk (*).

Measurement in accuracy of instruments introduced a small experimental error. The flow meters used for this work were accurate to $\pm 1\%$, and the thermometer was accurate to $\pm 1^\circ\text{F}$. The main flow had variations of $\pm 2\%$. The injection flow variations were as much as $\pm 10\%$ due to difficulties with the flow regulating system; for a given experiment, the injection flow was relatively consistent (either high or low). The other sources of instrument error were in the data acquisition system. The applied bridge voltage introduced an experimental error if its value differed between experimental data collection and calibration curve data collection. The

Table A6.1

Sources of Error in the Experimental Results

Experimental Operation Errors - - - - -

- (1) Injection flow meter - error in flow measurement
- (2) Main flow meters - error in flow measurement
- (3) Main flow thermometer - error in temperature measurement
- (4)* Injection system flow variations
- (5) Main flow system variations
- (6) Oscillator output voltage - variation of bridge applied voltage (calibration curve error)
- (7) Loss of platinization on detector electrode surfaces
- (8)* Injector drive speed variations (this is a synchronization error - an error between the actual location of the injector and the location recorded during data collection).
- (9)* Data recording system electronic interference (flutter and commercial noise - see Appendix 7)
- (10) Array geometry errors - (angular location of wire-wrap, assembly tolerance, etc.)
- (11)* Array proximity, electrode interference,
- (12)* Injector angular location error (due to wear)
- (13)* Injector tube, slot spreading error (also an injector angular positioning error)
- (14) Injector tube slot (flow area increase in the injection subchannel)
- (15) Background salt concentration shift
- (16) Amplifier time constant
- (17)* Calibration curve inadequacy
- (18)* Probe Positioning

Data Conversion and Handling Errors - - - - -

- (1) Axial resolution, data points/inch injector travel.
- (2)* Filtering and averaging

Table A6.1 (Concluded)

(3) Data synchronization (digitization frequency)

(4)* Data assembly and editing

Calculational Error - - - - -

(1) Simplified flow split analysis

(2) Calibration curve data fit

applied bridge voltage was kept within $\pm 5\%$, and its influence would have been consistent for a given set of data. The measured unbalanced bridge voltage signal was amplified by a voltmeter and recorded onto a magnetic tape recorder. Although a small consistent voltage measurement error was introduced by the voltmeter amplifier, the main experimental error from signal amplification was due to the time response. The amplifier had a slight dampening influence on the Wheatstone bridge output signal. The data acquisition error due to electronic equipment was considered quite small because the calibration data, and the experimental data were recorded and processed using the same electronic equipment.

Errors were introduced into the experimental results by mechanical tolerances in the rod array. The rod-to-rod pitch was accurate to within $\pm 2\%$, and the flow channel dimensions were accurate to $\pm 2\%$. The wire-wrap angular orientation was accurate to $\pm 5^\circ$. In the injection subchannel, the slot in the injector rod introduced a subchannel flow area increase of about 10%. Because the moving injector tube was slightly bent in handling, it caused the outer slotted tube to spread; this caused a needle angular positioning error of up to $\pm 4^\circ$; the experiments were done, however, so that the angular needle location error would be consistent.

Error in the experimental results was introduced by

converting the data from a recorded analog signal to a digital output for use with digital computers. In order to keep the volume of data within reasonable limits, the recorded signal was filtered (electronically averaged) and numerically averaged. Each point plotted in the results was the average of 100 - 200 points and a point was plotted for each second of actual experiment operation. One point per second corresponds to an axial data frequency (axial resolution) of 0.2 or 0.1 inch of injector travel.

The major sources of error were inadequate injection flow regulation, array proximity electrode interference, injector angular positioning, and axial data misalignment (due to the data collection technique). Further details on these more significant errors is given in Chapters 4 and 5. Briefly, most of the error in the data of this report may be eliminated in future experiments of this type by using the herein recommended injector rod design changes and by using numerous, stationary, conductance probes with immediate data digitizing equipment.

Appendix 7

ANALOG-TO-DIGITAL CONVERSION

The FM recording of the unbalanced Wheatstone bridge voltage was played back into an analog computer where the signal was filtered and digitized, i.e., converted from a continuous analog signal to a discontinuous digital signal (for use with digital computers). This digitized signal was read by a digital computer; the digital computer was programmed to take a multiple point (nominally 200-400 points) average for each point recorded. The averaged points were stored on a magnetic disc. Because of software limitations at the MIT Joint Computer Facility (JCF - the Mechanical and Civil Engineering Departments share the facility), another digital computer was used to read the averaged data from the magnetic disc and then to produce a punched paper tape as well as a listing of the data. The paper tape was taken to the MIT Information Processing Center where punched computer cards were made from the punched paper tape. These punched cards were edited and used for the data input to MITMIX, a data reduction code discussed in Appendix 3.

The FM recording of the unbalanced Wheatstone bridge voltage (recorded as 0.0-1.7 VDC) when played back into an oscilloscope for signal analysis was found to have a

commercial frequency (60 Hertz) noise and a small component of 5 Hertz (nominal) tape recorder flutter; the alternating current AC components were superimposed on the recorded direct current DC signal. To obtain the desired part of the playback signal (the DC component) the analog computer was programmed to act as a "low pass filter", i.e., a filter which prevents the passage of signals above a given maximum (this statement is oversimplified, for a more detailed treatment see Tobey et al. (A7.1)).

Figure A7.1 shows the circuit diagram used to filter the recorder playback signal. The input signal x is related to the output signal y :

$$y = x \frac{(R_1 P_1)/(R_2 P_2)}{1 + \frac{(\text{MODE})}{(R_2 P_2)} s} \quad (\text{A7.1})$$

where s is introduced by Laplace transformation of the integration. This may be more conveniently written as

$$y = x \frac{G}{1 + \tau s} \quad (\text{A7.2})$$

where the gain of the circuit G is given by

$$G = \frac{R_1 P_1}{R_2 P_2} \quad (\text{A7.3})$$

and the response time constant τ is

$$\tau = \frac{\text{MODE}}{R_2 P_2} = \frac{1}{\omega} \quad \frac{\text{seconds}}{\text{radian}} \quad (\text{A7.4})$$

Iv - Inverter
 I - Integrator
 P - Potentiometer
 R - Resistance
 x - Input from Recorder

$$G = \frac{R_1 P_1}{R_2 P_2} = \text{Gain}$$

$$\tau = \frac{M O D E}{R_2 P_2} = \text{Time Constant (sec/radian)}$$

y = Output to Analog-to-Digital Converter

A7.1 - LOW-PASS FILTER CIRCUIT DIAGRAM

The frequency beyond which signals are attenuated ω is

$$\omega = \frac{1}{2\pi\tau} \text{ Hertz} \quad (A7.5)$$

For this work ω should be about 40 Hertz and the gain should be adjusted to give a maximum signal of ± 10 volts input to the ADC. After ADC, the signal is normalized (10 volts maximum).

Making τ too large, say $\omega = 5$ Hertz, causes difficulties with data reduction because the filter circuit has a time response which is too slow to follow the variations of the recorded data.

Appendix 9

GRAPHICAL RESULTS OF THE PARAMETRIC EXPERIMENTS

This appendix presents the graphical results of the experiments used to establish the influence of operating parameters on the results. The experiments have been listed in Table 5.1; refer to Tables 5.2 and 5.3 for further details regarding the experiments. The results of experiments 0/2 - B, 0/2 - C, 0/2 - D, 0/2 - E and 0/2 - F are not given here because the magnetic recorder was malfunctioning during the experiments; the original data was recorded with the X -Y recorder and may be reviewed in Eaton (5.1).

The reader is cautioned that the mechanical behavior of the injection rod varied between the different dates of the experiments because of handling, repair and wear. Comparison of experimental results should only be made for data taken on the same day. The large losses of mass in the mass balance curves is due chiefly to the low number of subchannels monitored and to error in the tracer insertion rate. Array proximity, electrode interference effects were also present but are not responsible for the large absence of detected tracer.

For the parametric experiments, only the injection subchannel and the three contiguous subchannels were monitored, subchannel Nos. 1, 2, 6 and 7, respectively. It was felt that any influence of experimental operating

parameters could be determined by monitoring only the injection region of the rod array.

For all results in Appendix 9, injection was into interior subchannel No. 1; the various experimental data comparisons used to establish the influence of operating parameters on the experimental, interchannel coolant mixing results have been listed in Table A9.1.

Table A9.1
Comparative Data*

VARIABLE	COMPARATIVE DATA (RUN NOS)	DATA PRESENTATION (FIGURE NO.)
Salt Type		
NaCl	1/2 - D	A9.17.1
NaNO ₃	0/2.9-A	A9.10.1
Tracer Insertion Rate		
Salt Solution Concentration		
2.0 grams/lbm (NaCl)	0/2 - A	A9.1.1
1.0 grams/lbm	0/1 - A	A9.2.1
3.0 grams/lbm	0/3 - A	A9.6.1
2.0 grams/lbm	0/2 - B	Ref. 5.1
1.0 grams/lbm	0/1 - B	A9.3.1
3.0 grams/lbm	0/3 - B	A9.7.1
2.0 grams/lbm	0/2 - C	Ref. 5.1
1.0 grams/lbm	0/1 - C	A9.4.1
2.0 grams/lbm	0/2 - E	Ref. 5.1
1.0 grams/lbm	0/1 - E	A9.5.1
Tracer Solution Injection Velocity		
EAVC ^{&}	0/2 - A	A9.1.1
EAVC X 2	0/2 - B	Ref 5.1
EAVC X 1/2	0/2 - C	Ref 5.1
EAVC X 1-1/2	0/2 - D	Ref 5.1
EAVC	0/2 - E	Ref 5.1
EAVC X 2	0/2 - F	Ref 5.1
EAVC	0/1 - A	A9.2.1
EAVC X 2	0/1 - B	A9.3.1
EAVC X 1/2	0/1 - C	A9.4.1

Table A9.1 (Continued)

EAVC	0/3 - A	A9.6.1
EAVC X 2	0/3 - B	A9.7.1
EAVC X 2/3	0/3 - G	A9.8.1
EAVC X 1/3	0/3 - H	A9.9.1
EAVC	4/2 - A	A9.13.1
EAVC X 2	4/2 - B	A9.14.1
EAVC X 1/2	4/2 - C	A9.15.1
EAVC	1 - IT	5.4.1 - 7
EAVC X 2	1A - IT	A9.20.1 - 4
<hr/>		
Injector Geometry		
Needle (Tube)	3/2 - A	A9.11.1
Transverse Hole	4/2 - A	A9.13.1
Needle	3/2 - E	A9.12.1
Transverse Hole	4/2 - E	A9.16.1
<hr/>		
Reynolds Number		
Flow Variation ⁺		
(Turbulent Flow Only)		
450 lbm/min	0/2 - A	A9.1.1
225 lbm/min	0/2 - E	Ref. 5.1
(EAVC)		
450 lbm/min	0/2 - B	Ref. 5.1
225 lbm/min	0/2 - F	Ref. 5.1
(EAVC X 2)		
450 lbm/min	0/1 - A	A9.2.1
225 lbm/min	0/1 - E	A9.5.1
(EAVC)		
450 lbm/min	3/2 - A	A9.11.1
180 lbm/min	3/2 - E	A9.12.1
(EAVC)		
450 lbm/min	4/2 - A	A9.13.1
225 lbm/min	4/2 - E	A9.16.1
(EAVC)		

Table A9.1 (Concluded)

Flow Regime		
Turbulent	1 - IT	5.4.1 - 7
Laminar	2 - IL	5.5.1 - 9
<hr/>		
Turbulent	5 - PT	5.6.1 - 6
Laminar	6 - PL	5.7.1 - 6
<hr/>		
Injector Mechanical Behavior*		
17 July	1 - IT	5.4.1 - 7
New, 27 May	1A- IT	A9.20.1 - 4
25 June	1/2 - D	Ref. 5.1
10 July	1/2 - F	Ref. 5.1
17 June	0/2 - A	A9.1.1
<hr/>		
Data Reduction Technique		
Machine	1 - IT	5.4.1 - 7
Manual	1A- IT	A9.20.1 - 4
<hr/>		
Data Collection Technique		
Moving Injector	1 - IT	5.4.1 - 7
Stationary Injector	1B- IT	A9.20.1 - 4
<hr/>		
Data Frequency (As reduced)		
10 points/inch	0/2 - A	A9.1.1
5 points/inch	3/2 - A	A9.11.1

NOTES:

* Due to changes in injector mechanical behavior, similar data will not be the same if taken on different dates.

+ See Table 5.3 for details of the flow conditions.

& EAVC - Equal Average Velocity (Injection) Criterion.

FIGURE A9.1.2 - RUN 0/2 - A: MASS BALANCE VS. INJECTOR TRAVEL

FIGURE A9.2.2 - RUN 0/1 - A: MASS BALANCE VS. INJECTOR TRAVEL.

FIGURE A9.3.2 - RUN 0/1 - B: MASS BALANCE VS. INJECTOR TRAVEL

FIGURE A9.4.1 - RUN 0/1 - C: SUBCHANNEL NO. 1.

FIGURE A9.8.2 - RUN 0/3 - G: MASS BALANCE VS. INJECTOR TRAVEL

FIGURE A9.9.2 - RUN 0/3 - H: MASS BALANCE VS. INJECTOR TRAVEL

FIGURE A9.11.1 - RUN 3/2 - A: SUBCHANNEL NOS. 1, 2, 6, 7.

FIGURE A9.11.2 - RUN 3/2 - A: MASS BALANCE VS. INJECTOR TRAVEL

FIGURE A9.12.1 - RUN 3/2 - E: SUBCHANNEL NOS. 1, 2, 6, 7.

FIGURE A9.13.1 - RUN 4/2 - A: SUBCHANNEL NOS. 1, 2, 6, 7.

FIGURE A9.13.2 - RUN 4/2 - A: MASS BALANCE VS. INJECTOR TRAVEL

FIGURE A9.14.1 - RUN 4/2 - B: SUBCHANNEL NOS. 1, 2, 6, 7.

FIGURE A9.14.2 - RUN 4/2 - B: MASS BALANCE VS. INJECTOR TRAVEL

FIGURE A9.15.2 - RUN 4/2 - C: MASS BALANCE VS. INJECTOR TRAVEL

FIGURE A9.16.2 - RUN 4/2 - E: MASS BALANCE VS. INJECTOR TRAVEL

FIGURE A9.17.1 - RUN 1/2 - D: SUBCHANNEL NO. 1.

COMPARE WITH RUN 1/2.9 - A TO ESTABLISH EFFECT OF SALT TYPE
DATA FOR SUBCHANNEL NOS. 2, 3, 4, 5, 6, AND 7 AVAILABLE IN (5.1)

FIGURE A9.20.1 - RUN 1A - IT: SUBCHANNEL NOS. 1, 2, 3, 4.

INJECTION INTO SUBCHANNEL NO. 1

THIS DATA WAS TAKEN WITH A NEW INJECTION ROD, I.E., NO INJECTOR MECHANICAL BEHAVIOR EFFECTS.

FIGURE A9.20.2 - RUN 1A - IT: SUBCHANNEL NOS. 1, 5, 6, 7.

FIGURE A9.20.5 - RUN 1A - IT: MASS BALANCE VS. INJECTOR TRAVEL