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		ABSTRACT: <p>A partial model of the reactor core was used, and demineralized water was circulated at flow rates determined by the Reynolds analogy to the prototype. Black plastic beads were introduced into the flow stream and photographed by using a Milliken camera recording at 500 frames per second.</p> <p>Calculations showed that seventy-nine percent of the total mass flow was accounted for by this method. The twenty-one percent of the mass flow that was not accounted for was presumed to be due to flow in non-channel areas and in two non-orificed channels. Some error could also be attributed to the use of non-spherical beads that created non-uniform velocities in the channels.</p> <p>The visibility through the SNAP 2/10A core section, for the purpose of visual observation and optical recording, was very good. The high speed pictures were clear and sharp. The velocity determination based on the frame by frame analysis of the film did not present any problem. The experiment demonstrated that clear Lucite can be used as the material for visual flow observation in a full scale SNAP 2/10A model core vessel.</p>			

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Nomenclature

N_{Re}	=	Reynold's Number
D_e	=	Hydraulic Diameter, ft
μ	=	Dynamic Viscosity, lb/hr-ft
V	=	Velocity, ft/hr
ρ	=	Density, lb/ft ³
$\dot{W}$	=	Mass Flow, lb/hr
A	=	Area, ft ²
D	=	Diameter, ft
P	=	Pitch, ft
$^{\circ}F$	=	Degrees Farenheit

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Introduction

The purpose of this test was to determine the feasibility of using clear Lucite as the material for a core vessel and fuel elements to visually observe the flow pattern inside a full scale SNAP 2/10A Reactor Core. Dark plastic beads with a specific gravity of approximately 1.0 were injected into the flow stream. The bead paths were visually observed and optically recorded by a Millikan camera, mounted about five feet from the vessel. The motion of the beads was then intended to indicate the flow pattern in the channels of the reactor core.

A partial model of the core section was constructed and a test completed. The results showed that the bead velocities were much greater than the calculated average velocities through the individual channels of the core section. This was presumed to be the result of the beads riding the peak of the flow profile in the channel and a correction factor of bead velocity versus average channel flow velocity had to be found. In view of this determination, the design and construction of a Single Channel Test was started for the sole purpose of determining the correction factors.

Theory

The model flow rate determination was accomplished through the Reynolds analogy* by equating the Reynolds Number for NaK to the comparative Reynolds Number for water.

$$(N_{Re})_{proto} = (N_{Re})_{model}$$

$$\left(\frac{\rho_{VD}}{\mu}\right)_{proto} = \left(\frac{\rho_{VD}}{\mu}\right)_{model}$$

* Reynolds Number is the ratio of the Dynamic forces to the viscous forces in the fluid.

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Since the channel geometry of the model was identical to the channel geometry of the SNAP 2/10A Reactor core, the respective diameters and areas were equal. Therefore, an appropriate cancellation of the equivalent diameters from each side, and multiplication by the channel areas gave:

$$\left(\frac{\rho_{AV}}{\mu}\right)_{\text{proto}} = \left(\frac{\rho_{AV}}{\mu}\right)_{\text{model}}$$

Noting that $\dot{W} = \rho_{AV}$, the equation was reduced to:

$$\left(\frac{\dot{W}}{\mu}\right)_{\text{NaK}} = \left(\frac{\dot{W}}{\mu}\right)_{\text{H}_2\text{O}} \quad (1)$$

The flow rate in grams per second, corresponding to the Reynolds equivalent, was measured by the use of a gram scale and a stop-watch from the actual flow through the model at temperatures at 70°F, 90°F, and 110°F.

SINGLE CHANNEL TEST

Test Setup

The single channel test consisted of one simulated full scale Tri-Cusp channel, and one Reflector channel. The Tri-Cusp channel was constructed with three full size fuel elements of clear Lucite banded together. The space between the elements formed the coolant flow channel. The Reflector channel consisted of two fuel elements and a protrusion of the reflector between the two elements. The two channel constructions were mounted in series, as in Figure 1.

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A stainless steel thirty-five gallon supply tank was employed to store the demineralized water, and two submergeable pumps (capable of eight gallons per minute at one foot of head) were used in series to circulate the water. A 3/4 inch inside diameter clear plastic tubing connected the pumps to the vessel. Another 3/4 inch inside diameter clear plastic tubing returned the water from the test section to the thirty-five gallon supply tank. The inlet tubing was equipped with a clamp to regulate the flow rate by allowing the correct amount of water to flow through the vessel.

The temperatures were regulated by a heating element submerged in the storage tank for increasing the temperature, and conversely, by the use of a copper tubing coolant sling for decreasing the temperature as required. By this method, the temperature was controlled and held constant to within $\pm 1^{\circ}\text{F}$ of the desired temperature at each temperature range.

Black plastic beads with a specific gravity of approximately 1.0 were introduced into the flow stream at the inlet side of the test section. The introduction of the beads was accomplished by the use of a glass stop cock valve, in which the beads were loaded two at a time. The inlet and outlet tubing of the bead injector formed a bypass line in the 3/4 inch clear plastic tubing supplying the test section.

A flow section with a large flow area was inserted upstream of the bead injector to nearly stagnate the flow and use the recovered static pressure to drive the beads through the smaller bypass tubing and into the main stream of flow. The theory for this mechanism was: Total pressure = static pressure + velocity pressure. As a result of the enlarged section, the velocity

FIGURE 1

FIGURE 1

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pressure was decreased and therefore the static pressure increased. When the valve was opened, flow commenced through the bypass line, into the stop cock valve containing the beads, and then carried the beads into the main stream of flow. This method of introducing the beads did not upset the total flow rate, since there was no flow added to or subtracted from the total mass flow. (Figure 2)

As a time reference, a device was improvised consisting of an electric synchronous motor rotating at eighteen hundred revolutions per minute and a face marked off in one hundred divisions. Each division was equal to one-third of a millisecond. A stroboscope was used to verify the revolutions per minute of the electric synchronous motor. As a distance reference, a grid was placed behind the test section, which consisted of vertical lines spaced an inch apart on a white background. The motion of the beads was recorded optically by a Milliken high speed camera at 500 frames per second.

Test Procedure

The flow rates for the Tri-Cusp channel, corresponding to Reynolds numbers of one thousand through ten thousand, were calculated for temperatures of seventy degrees, ninety degrees, and one hundred ten degrees Fahrenheit. The three temperatures were used to verify the N_{Re} dependence of the correction factors and not velocity dependence.

Both test sections are connected in series, which made the mass flow through each section equal. The velocity varied with the flow area of each channel, and as a result each channel had a different Reynolds number at a given mass flow rate. The flow rates in grams per second, corresponding to the Reynolds equivalent,

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Figure 2

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were established by weighing the water being discharged versus the elapsed time, using a weight scale and a stopwatch. This was then converted to pounds per hour.

The flow rates at the different temperatures were set, and the beads were introduced into the flow stream through the bypass line. The beads were then visually observed and photographed.

Data Analysis

The Tri-Cusp channel was constructed with three full size fuel elements of clear Lucite bonded together. The space between the elements formed the coolant flow channel (Figure 3 and calculations). The Reflector channel consisted of two fuel elements and a protrusion of the reflector between the two elements. This geometry is described in Figure 4 which also contains the calculations.

The photographed data were analyzed on a Vanguard film analyzer. The one inch grid divisions were found to correspond to three hundred seventeen and thirty-three one hundredths divisions (317.31) on the analyzer's micrometer dial. The film was advanced frame by frame, and stopped as the bead crossed the one inch intervals. The micrometer dial reading, as well as the timing device reading was recorded. The data were in the form of:

$$\left(\frac{\text{in} \times 10^{-3}}{\text{sec} \times 10^{-3}} \right) = \text{in/sec, observed velocity}$$

These were then converted to feet per hour.

The bead location and the time was clearly visible. The distance determination of the bead motion, in conjunction with the elapsed time, gave an accurately determined bead velocity.

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CHECKED BY:		REPORT NO. 9405
DATE: 8-27-1963	SNAP 2/10A Single Channel Test	MODEL NO.

Flow Area of Tri-Cusp Channel = 0.06297 in²

$$\frac{P^2 \times \sqrt{3}}{4} - \frac{\pi \times D^2}{8} =$$

$$\frac{1.250^2 \times 1.732}{4} - \frac{3.1416 \times 1.250^2}{8} =$$

$$0.6765625 - 0.61359375 = \underline{\underline{0.06297 \text{ in}^2}}$$

$P = \text{Pitch} = 1.250''$

$D = \text{Diameter} = 1.250''$

$\sqrt{3} = 1.732''$

$\pi = 3.1416''$

Figure #3

$$D = \sqrt{.625^2 - .450^2} = .435"$$

$$\sin \frac{.435}{.625} = 44.2^\circ$$

Area:

$$\text{Rectangle "A"} = .175" \times .435" = \underline{0.0761 \text{ in}^2}$$

$$\text{Triangle "B"} = \frac{.435" \times .450"}{2} = \underline{0.0979 \text{ in}^2}$$

$$\text{Sector "C"} = \frac{3.1416 \times .625^2 \times 44.2^\circ}{360^\circ} = \underline{.1507 \text{ in}^2}$$

Flow area Reflector Channel

$$[(\text{Rect "A"} + \text{Triangle "B"}) - (\text{sector "C"})] \times 2$$

$$[(.0761 + .0979) - (.1507)] \times 2 = \underline{0.0466 \text{ in}^2}$$

Figure # 4

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The average calculated velocity of the channel was based on the individual channel geometry. The average velocity calculated from the mass flow was found as follows:

$$\text{Velocity} = \frac{\dot{W}}{\text{Flow area} \times \rho}$$

A tabulation of the calculated average velocity and the observed velocity was made and from this the correction factors were calculated.

$$\text{Correction factor} = \frac{\text{calculated average velocity}}{\text{observed velocity}}$$

The calculation of the Reynolds number was made from

$$N_{\text{Re}} = \frac{\rho V D_e}{\mu}$$

The correction factors were plotted versus the Reynolds number (Figures 5 and 6) calculated from the average channel velocity. The correction factors are to be applied to the observed bead velocities in the model core section to determine the average channel velocities and therefore the radial flow profile.

Figure 7 shows a graphic comparison between the correction factors for the Reflector Channel and the Tri-Cusp Channel, and the correction factors for Smooth Circular Tubes. The factors for Smooth Circular Tubes were obtained from data by Nikuradse and by Stanton and Pannell.⁽⁴⁾ The experimental data by Nikuradse and by Stanton and Pannell indicates a turbulent flow starting at Reynolds number 2000. The data of the Reflector and Tri-Cusp Channels indicate the existence of turbulent flow at lesser Reynolds number.

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SNAP 2/10A Single Channel Test
Reflector Channel
Correction Factor vs $NRe \times 10^3$

H₂O @ 70°F
90°F
110°F

Figure # 5

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SNAP 2/10A Single Channel Test
Tri-Cusp Channel
Correction Factor vs $NRe \times 10^3$

H₂O @ 70°F
90°F
110°F

Figure #6

Figure #7
Correction Factors for Channels and Smooth Circular Tubes

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SNAP 2/10A CORE SECTION TEST

Test Setup

A vessel containing five fuel elements, an internal reflector, two gridplates and an orifice plate in a core section was used (Figure 8 and Figure 9). The dimensions of the fuel elements and their spacing were to full scale. The gridplates and orifice plate, the reflector, the coolant inlet and outlet areas, and the flow rate, were scaled down by the relative flow areas of the experimental model compared to the actual reactor core.

The core model test was accomplished using the same flow equipment as in the Single Channel Test. The tank, plastic tubing, heater elements, coolant sling, bead injector and timing device were the same. The two submergeable pumps were replaced by a single pump with a greater capacity. In addition to this, a mirror was placed under the vessel at an angle providing a bottom view of the vessel to determine which channel the beads entered. As a distance reference, a grid was placed behind the vessel, which consisted of a frame divided into one inch squares (Figure 10). The plastic beads, with a specific gravity of approximately 1.0 were used. The bead activities were photographed by the Milliken camera.

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FIGURE 8

*Core model consisting of 5 Fuel Elements
and 8 channels*

Reflector Channel: 1, 2, 4, 7 and 8

Tri-Cusp Channel: 3, 5 and 6

Figure #9

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Scale 1:2 Figure #10

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Test Procedure

The Reynolds equivalent mass flow was based on the fraction of total core flow used in the proof model. Measurement of the mass flow was made with a gram scale by weighing the water being discharged versus the elapsed time (Ref. Equation 2). After establishing the required flow rate, the beads were introduced into the flow stream through the bead injector. As in the Single Channel Test, the beads were visually observed and photographed by using the Milliken camera. The camera was operated at a rate of five hundred frames per second.

Data Analysis

The geometry of the flow channels in the 3NAP 2/10A Core section was different from the Single Channel geometry in that the single channel elements were bonded tightly together and the vessel elements maintained a separating gap. The fuel elements surrounding the Reflector channels were spaced nine thousandths of an inch apart (Figure 11) and the Tri-Cusp channels had a ten thousandths of an inch clearance (Figure 12).

The film was analyzed on the Vanguard film analyzer. The one inch grid divisions were found to correspond to two hundred and sixty divisions (260) on the micrometer dial of the analyzer. The film was advanced frame by frame, and stopped when a particular bead crossed each one inch interval. The micrometer dial reading, as well as the timing device reading, was recorded. The data were in the same form as the Single Channel Test and were reduced by the same equations (Ref. Equations 3 and 4). The individual channel velocities were determined by applying the correction factors to the observed velocities. The initial correction factor was selected from a graph of correction factors versus Reynolds numbers corresponding to an anticipated Reynolds number for the average corrected

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velocity in the channel. The initial correction factor was then applied to the observed bead velocity. From the corrected observed velocity and the hydraulic diameter of the respective channels, the Reynolds number was calculated.

$$\text{Actual } N_{\text{Re}} = \frac{\rho \times (V \times \text{CF}) \times D_e}{\mu} \quad (2)$$

The correction factor corresponding to this Reynolds number was then checked against the correction factor initially selected. If the two factors did not agree, a new correction factor was selected and the corresponding Reynolds number was calculated. This trial and error process was continued until the selected correction factor agreed with that corresponding to the channel Reynolds number.

Flow area =

$$[(\text{Rect. "C"} + \text{Triangle "A"}) - (\text{sector "B"})] \times 2$$

$$\left[(.150 \times .432 + \frac{.432 \times .4795}{2}) - \left(\frac{3.1416 \times .625^2 \times 42.1^\circ}{360} \right) \right] \times 2$$

$$\underline{\underline{.0498 \text{ in}^2}}$$

Figure #11

Model

$$\text{Flow arc} = \frac{P^2 \times \sqrt{3}}{4} - \frac{\pi \times D^2}{8} = \frac{1.260^2 \times 1.732}{4} - \frac{3.1416 \times 1.250^2}{8} =$$

$$\underline{0.07389 \text{ in}^2}$$

$$P = \text{Pitch} = 1.260''$$

$$D = \text{Dia} = 1.250''$$

$$\sqrt{3} = 1.732$$

$$\pi = 3.1416$$

Figure #12

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Results

All the data for each individual channel were averaged and then analyzed. The mass flow for the individual channels was then added to obtain a total vessel flow rate as indicated by the beads. This should have equaled the measured mass flow through the core (Ref. Table 1). The calculations showed that only seventy-nine percent of the total flow was accounted for. Recalling from the calculations of the flow areas (Figures 11 and 12) the fuel elements did not form a closed channel, but had a gap between them. By the existence of a cross flow, there would be a decrease in the channel velocity due to the water flowing in non-channel areas. Also, there were two non-orificed channels containing some flow by the same cross flow mechanism. Hence, the sum of the individual channel velocities would expectedly be less than the actual mass flow measured through the core. Some error would also be attributed to using non-spherical beads which created non-uniform velocities in the channels.

The visibility through the SNAP 2/10A core section, for the purpose of visual observation and optical recording of the bead activities, was very good. The Milliken high speed camera, recording at five hundred frames per second, was sufficiently fast and the pictures were clear and sharp. Therefore, the velocity determination, based on the frame by frame analysis of the film, did not present any problems.

We may therefore conclude that the feasibility experiment has proven that clear Lucite can be used as the material for a full scale SNAP 2/10A core vessel.

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CHECKED BY:	<i>Proof Model</i>	NAA-SR-TDR- REPORT NO. <i>9405</i>
DATE: <i>12-10-63</i>	<i>SNAP 2/10A Lucite Vessel</i>	MODEL NO.

Channel #	Bead #	T=Tri-Cusp R=Reflector	Avg. Observed Vel. ft/sec.	Avg. Observed Vel. ft/sec of Beads in same channel	Initial CF	NRe with Initial CF	New CF	NRe with New CF	Vel ft/sec with New CF	Calculated W° Lb/Hr	Total w° Lb/Hr Calculated	Measured w° Lb/Hr
1	10	R	4.44	4.44	.65	3752	.66	3810	2.930	337	W° = 2283 Lb/Hr	W° = 2880 Lb/Hr
2	12	R	3.68									
2	6	R	3.58	3.57	.65	3018	.66	3063	2.356	271		
2	8	R	3.44									
3	3	T	5.17									
3	9	T	5.02	5.12	.70	4287	.70	4287	3.584	278		
3	11	T	5.18									
4	7	R	3.30	3.30	.65	2789	.65	2789	2.145	247		
5	1	T	3.45	3.45	.70	2889	.69	2848	2.381	185		
6	2	T	4.32	4.32	.70	3618	.69	3566	2.981	231		
7	5	R	4.85	4.84	.65	4091	.66	4153	3.194	367		
7	4	R	4.82									
8		R		4.84	.65	4091	.66	4153	3.194	367		

Table # 1

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Table 1
Water and NaK Properties

<u>WATER</u>	<u>NaK</u>
<u>Density (ρ)</u> at	<u>Density</u> at
70°F = 62.3 lb/ft ³	1080°F = 45.8 lb/ft ³
90°F = 62.1 lb/ft ³	1200°F = 44.8 lb/ft ³
110°F = 61.85 lb/ft ³	
<u>Dynamic Viscosity (μ)</u> at	<u>Dynamic Viscosity (μ)</u> at
70°F = 2.35 lb/hr-ft	1080°F = 0.38 lb/hr-ft
90°F = 1.85 lb/hr-ft	1200°F = 0.36 lb/hr-ft
110°F = 1.50 lb/hr-ft	

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