Numerical Results Obtained from the
Three Dimensional Transient Single Phase
Version of the COMMIX Computer Code

by

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Prepared by
Components Technology Division
Argonne National Laboratory

for the

United States Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, D.C. 20555
Under Contract No. A 2045

October 1977

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Table of Contents

	<u>Page</u>
List of Figures.	i
Nomenclature	vii
Abstract	viii
I. Introduction	1
II. LMFBR Outlet Plenum	2
A. Plenum Problem Statement	2
B. Plenum Results	2
III. Flow Stratification in a Pipe.	4
A. Pipe Problem Statement	4
B. Pipe Results	4
IV. 19-Pin LMFBR Fuel Assembly in a Hexagonal Duct	6
A. Hex Fuel Assembly Problem Statement.	6
B. Hex Fuel Assembly Results.	7
V. Summary and Conclusions.	8
References	9

List of Figures

<u>Figure Number</u>	<u>Title</u>	<u>Page</u>
1. <u>1</u> 15	Scale FFTF Outlet Plenum.	10
2.	Initial Velocity Distribution at Constant Y-plane (Section B-B).	11
3.	Initial Velocity Distribution at Constant Y-plane (Section C-C).	12
4.	Initial Velocity Distribution at Constant X-plane (Section A-A).	13
5.	Inlet Temperature Transient.	14
6.	Velocity Distribution after 5 sec at Constant X-plane (Section A-A).	15
7.	Velocity Distribution after 10 sec at Constant X-plane (Section A-A).	16
8.	Velocity Distribution after 15 sec at Constant X-plane (Section A-A).	17
9.	Velocity Distribution after 20 sec at Constant X-plane (Section A-A).	18
10.	Velocity Distribution after 25 sec at Constant X-plane (Section A-A).	19
11.	Velocity Distribution after 30 sec at Constant X-plane (Section A-A).	20
12.	Initial Temperature Distribution at Constant X-plane (Section A-A).	21
13.	Temperature Distribution after 10 sec at Constant X-plane (Section A-A).	22
14.	Temperature Distribution after 20 sec at Constant X-plane (Section A-A).	23
15.	Temperature Distribution after 30 sec at Constant X-plane (Section A-A).	24
16.	Outlet Nozzle Temperature Transient.	25

List of Figures (Contd.)

<u>Figure Number</u>	<u>Title</u>	<u>Page</u>
17.	Temperature Transient Near Swirl Center Opposite Outlet. . .	26
18.	Pipe Inlet Flow and Temperature Transients	27
19.	Experimental vs. Calculated Isothermal Steady- state Axial Velocity Component Distribution Radially Across Pipe.	28
20.	Initial Velocity Distribution at Central Z-plane	29
21.	Velocity Distribution after 10 sec at Central Z-plane. . . .	30
22.	Velocity Distribution after 20 sec at Central Z-plane. . . .	31
23.	Velocity Distribution after 30 sec at Central Z-plane. . . .	32
24.	Velocity Distribution after 40 sec at Central Z-plane. . . .	33
25.	Initial Temperature Distribution at Central Z-plane.	34
26.	Temperature Distribution after 10 sec at Central Z-plane.	35
27.	Temperature Distribution after 20 sec at Central Z-plane.	36
28.	Temperature Distribution after 30 sec at Central Z-plane.	37
29.	Temperature Distribution after 40 sec at Central Z-plane.	38
30.	Temperature Variation along Pipe	39
31.	Initial Velocity Distribution at X=5.791 m from Inlet. . . .	40
32.	Velocity Distribution after 10 sec at X=5.791 m from Inlet.	41
33.	Velocity Distribution after 20 sec at X=5.791 m from Inlet.	42
34.	Velocity Distribution after 30 sec at X=5.791 m from Inlet.	43

List of Figures (Contd.)

Figure Number	Title	Page
35.	Velocity Distribution after 40 sec at X=1.524 m from Inlet.	44
36.	Velocity Distribution after 40 sec at X=3.353 m from Inlet.	45
37.	Velocity Distribution after 40 sec at X=5.791 m from Inlet.	46
38.	Velocity Distribution after 40 sec at X=11.887 m from Inlet.	47
39.	Velocity Distribution after 40 sec at X=17.983 m from Inlet.	48
40.	LMFBR-FFM-Test Section Assembly for Bundle 2A.	49
41.	Axial Partitioning used in LMFBR Fuel Pin Bundle Analysis	50
42.	Normalized Radial Pin Power Density Distribution	51
43.	Steady Velocity Distribution at Z=0.0381 m from Inlet (Entrance Region).	52
44.	Steady Velocity Distribution at Z=0.1143 m from Inlet (Entrance Region).	53
45.	Steady Velocity Distribution at Z =0.1905 m from Inlet (Entrance Region).	54
46.	Steady Velocity Distribution at Z=0.2667 m from Inlet (Entrance Region).	55
47.	Steady Velocity Distribution at Z=0.3429 m from Inlet (Heated Region).	56
48.	Steady Velocity Distribution at Z=0.4191 m from Inlet (Heated Region).	57
49.	Steady Velocity Distribution at Z=0.4953 m from Inlet (Heated Region).	58
50.	Steady Velocity Distribution at Z=0.5715 m from Inlet (Heated Region).	59

List of Figures (Contd.)

<u>Figure Number</u>	<u>Title</u>	<u>Page</u>
51.	Steady Velocity Distribution at $Z=0.6477$ m from Inlet (Heated Region)	60
52.	Steady Velocity Distribution at $Z=0.7239$ m from Inlet (Heated Region)	61
53.	Steady Velocity Distribution at $Z=0.8001$ m from Inlet (Heated Region)	62
54.	Steady Velocity Distribution at $Z=0.8763$ m from Inlet (Exit Region)	63
55.	Steady Velocity Distribution at $Z=0.9525$ m from Inlet (Exit Region)	64
56.	Steady Axial Velocity Distribution at $Z=0.0381$ m from Inlet (Entrance Region)	65
57.	Steady Axial Velocity Distribution at $Z=0.1143$ m from Inlet (Entrance Region)	66
58.	Steady Axial Velocity Distribution at $Z=0.1905$ m from Inlet (Entrance Region)	67
59.	Steady Axial Velocity Distribution at $Z=0.2667$ m from Inlet (Entrance Region)	68
60.	Steady Axial Velocity Distribution at $Z=0.3429$ m from Inlet (Heated Region)	69
61.	Steady Axial Velocity Distribution at $Z=0.4191$ m from Inlet (Heated Region)	70
62.	Steady Axial Velocity Distribution at $Z=0.4953$ m from Inlet (Heated Region)	71
63.	Steady Axial Velocity Distribution at $Z=0.5715$ m from Inlet (Heated Region)	72
64.	Steady Axial Velocity Distribution at $Z=0.6477$ m from Inlet (Heated Region)	73
65.	Steady Axial Velocity Distribution at $Z=0.7239$ m from Inlet (Heated Region)	74

List of Figures (Contd.)

<u>Figure Number</u>	<u>Title</u>	<u>Page</u>
66.	Steady Axial Velocity Distribution at $Z=0.8601$ m from Inlet (Heated Region)	75
67.	Steady Axial Velocity Distribution at $Z=0.8763$ m from Inlet (Exit Region)	76
68.	Steady Axial Velocity Distribution at $Z=0.9525$ m from Inlet (Exit Region)	77
69.	Steady Temperature Distribution at $Z=0.0381$ m from Inlet (Entrance Region)	78
70.	Steady Temperature Distribution at $Z=0.1143$ m from Inlet (Entrance Region)	79
71.	Steady Temperature Distribution at $Z=0.1905$ m from Inlet (Entrance Region)	80
72.	Steady Temperature Distribution at $Z=0.2667$ m from Inlet (Entrance Region)	81
73.	Steady Temperature Distribution at $Z=0.3429$ m from Inlet (Heated Region)	82
74.	Steady Temperature Distribution at $Z=0.4191$ m from Inlet (Heated Region)	83
75.	Steady Temperature Distribution at $Z=0.4953$ m from Inlet (Heated Region)	84
76.	Steady Temperature Distribution at $Z=0.5715$ m from Inlet (Heated Region)	85
77.	Steady Temperature Distribution at $Z=0.6477$ m from Inlet (Heated Region)	86
78.	Steady Temperature Distribution at $Z=0.7239$ m from Inlet (Heated Region)	87
79.	Steady Temperature Distribution at $Z=0.8001$ m from Inlet (Heated Region)	88
80.	Steady Temperature Distribution at $Z=0.8763$ m from Inlet (Exit Region)	89

List of Figures (Contd.)

<u>Figure Number</u>	<u>Title</u>	<u>Page</u>
81.	Steady Temperature Distribution at $Z=0.9525$ m from Inlet (Exit Region)	90
82.	COMMIX-1 vs. Experiment: Outlet Temperature Distribution.	91

Nomenclature

- I,J,K Indices for discrete locations of x,y,z, respectively.
- x,y,z Cartesian coordinates
- u,v,w Velocity components along x,y,z, respectively

Abstract

Results from the first three applications of the three-dimensional, transient, single-phase version of the thermal-hydraulics computer code, COMMIX, are presented. The applications include an LMFBR outlet plenum, a horizontal pipe, and a 19-pin LMFBR hexagonal fuel assembly. Each case is described and the results presented. All three applications use liquid sodium as the fluid. The plenum and pipe analyses are transient,[†] while the fuel assembly involves a steady-state analysis.

[†] Motion pictures have been made showing the transient velocity and temperature distributions for the plenum and pipe analyses.

I. Introduction

The COMMIX (COMponent MIXing) code⁽¹⁾ performs three-dimensional, transient, two-phase thermal-hydraulic analyses with non-equilibrium velocity and temperature. It solves conservation equations of mass, energy and momentum as a boundary value problem in space and an initial value problem in time. The two-fluid model⁽²⁾ and modified implicit, multifield numerical scheme are employed.

In developing the COMMIX code, a stagewise improvement has been undertaken. First, a basic single-phase version is developed, debugged, and checked out; then, more advanced concepts are progressively incorporated to improve rigor and efficiency. Finally a two-phase version is to be implemented. All along the way care has been taken not to inhibit the transient thermal-hydraulic analysis of LMFBR fuel assemblies under the natural convection condition.

At the present time, the single-phase version of the code, designated COMMIX-1, is working. This report summarizes some of our recent numerical results obtained from the COMMIX-1 code. From these results, both the range of applicability and the unique features of the COMMIX code are exhibited.

II. LMFBR Outlet Plenum

As the development of COMMIX-1 reached the capability of solving real problems, a first application was sought to verify the code and obtain operating experience. An ongoing experimental program had been gathering temperature data in a 1/15 scale LMFBR (FFTF) outlet plenum^(3,4) within the Components Technology Division of Argonne National Laboratory. Since the geometry of the plenum and resulting flow field are inherently 3-dimensional, the model plenum was chosen for the first application of the COMMIX-1 code.

A. Plenum Problem Statement

The problem is to numerically simulate the 3-dimensional temperature and velocity distributions within an LMFBR outlet plenum undergoing a particular scram. The geometry is the 1/15 scale FFTF outlet plenum shown in Fig. 1. Liquid sodium enters the plenum from the bottom through a 8.23 cm diameter pipe and exits through three outlet nozzles separated by 120°. Gravity is acting downward in the -y direction.

Initially, the plenum is at a uniform temperature of 481°C. Sodium is flowing through the inlet of the plenum in a steady fashion at a velocity of 0.3 m/sec. The steady-state velocity distribution is shown at various planar cuts in Figs. 2,3, and 4. Numerous recirculating flows can be identified from these figures.

The transient of interest is a constant inlet flow with decreasing inlet temperature. Figure 5 shows the inlet temperature transient used in the simulation. The temperature falls rapidly for about 10 seconds, then levels out at 424°C.

B. Plenum Results

As the constant flow, temperature transient develops, a higher density or heavier fluid enters the plenum. This relatively colder sodium brings buoyancy forces into play thus changing the flow field within the plenum. The interaction between buoyancy forces and inertial forces during the first 30 seconds of the transient can be seen in Figs. 6 through 11. This cross section includes the inlet and one of the outlet nozzles. On

the side opposite the outlet, the recirculation zone suddenly drops for the first 10 sec, then gradually rises to its original position as the remaining hot sodium is washed through the plenum and is replaced by cold sodium. On the side next to an outlet, the recirculation zone moves toward the wall, then toward the central region before returning to the isothermal flow pattern.

The transient temperature distribution is shown in Figs. 12 through 15. The presentation is a perspective view of the temperature surface across section A-A. As the transient develops, the cold sodium flows up to the top suppressor plate and then is deflected along the walls to exit at an outlet. The warm sodium is seen to persist in the central portion of each recirculation zone. Comparisons of COMMIX-1 calculations (solid line) with experimental measurements^(3,4) (circles) are shown in Figs. 16 and 17. Figure 16 is located at an outlet nozzle while Fig. 17 is near the swirl center opposite an outlet.

Based on this analysis, it is concluded that this type of numerical simulation yields detailed flow field and temperature distribution information which would be very helpful in the design of outlet plenums. The temperature and velocity field calculations across section A-A during the 30 second transient have been combined into a motion picture.

III. Flow Stratification in a Pipe

As the development of COMMIX-1 continued, a horizontal pipe undergoing a velocity and temperature transient was considered as an application to gain further operating experience. Furthermore, this particular application represents a severe test of the code's capability in analyzing stratification under very low velocity flow. This numerical calculation was funded by ERDA under 189a GA055. ⁽⁵⁾

A. Pipe Problem Statement

The pipe is horizontal with gravity acting in the -y direction, has a diameter of .46 meters, and is 21.34 meters long (x-axis). Initially, the pipe has 360°C sodium isothermally flowing through it in a steady fashion. The temperature and inlet velocity transients are shown in Fig. 18. The period of 40 to 80 seconds is considered in the present analysis. A comparison of axial velocity in a fully developed region between the COMMIX-1 predicted and experimental data ⁽⁵⁾ is shown in Fig. 19. The initial axial velocity distribution across the pipe cross section is shown by the velocity vectors in Fig. 20.

B. Pipe Results

The transient axial velocity distribution across the central plane through the pipe is shown in Figs. 20 through 24. As the transient develops, a region of flow reversal can be seen at the top of the pipe and as time continues, the reversal propagates toward the exit.

The transient temperature across the central plane of the pipe is shown in Figs. 25 through 29. As the cold sodium enters, it falls to the lower portion of the pipe pushing the warmer sodium to the top. Temperature profiles at several axial locations are presented in Fig. 30.

The next series of Figs. 31 through 39 shows the velocity vectors as projected in various axial planes along the pipe. At 5.791 meters from the inlet, a dual secondary flow can be seen as the transient develops. This is due to the cold sodium rushing to the bottom of the pipe.

It is to be noted that the results presented in this section have not been validated since there are no experimental data available. However, it becomes clear that a two-dimensional approach is absolutely inadequate for flow stratification analysis.

IV. 19-Pin LMFBR Fuel Assembly in a Hexagonal Duct

To realistically simulate the velocity and temperature distributions in an LMFBR fuel assembly required some modifications of the continuum approach. These modifications are to introduce distributed resistance and porosity^(7,8) to account for the presence of fuel rods.

The third application of the COMMIX-1 code is to compute the temperature and velocity distributions in a fuel assembly. These results are then compared with experimental data obtained at Oak Ridge National Laboratory in 1973.⁽⁹⁾ The LMFBR fuel assembly contains 19 rods arranged in a hexagonal duct and is referred to as FFM bundle 2A (Fuel Failure Mockup). The test section used for the experiments is shown in Fig. 40. The current analysis consists of a 0.3048 meter entrance region followed by a 0.5334 meter heated length and a 0.1524 meter exit region. The overall axial length is partitioned into 13 equal divisions as shown in Fig. 41. The z-axis is aligned with the axial flow direction. Gravity is in the -z direction. The partitioning of transverse planes is shown in Fig. 42. The quasi-continuum formulation is used to analyze the fuel pins.

A. Hex Fuel Assembly Problem Statement

Sodium at 309.4°C is entering the bundle at the bottom uniformly at a velocity of 0.127 meter/sec. As the sodium flows through the duct, it is non-uniformly heated. The radial power density distribution is shown in Fig. 42. The total amount of heat added to the sodium over the heated section is 10.3 KW. Since the COMMIX-1 code is a transient code, a suitable initial condition was chosen and a transient analysis performed until steady state was reached. In order to speed the convergence, an educated guess of the initial condition is chosen. This guess was taken as the axial 1-D solution, assuming no variation over a given axial plane.

B. Hex Fuel Assembly Results

The steady-state velocity distribution is shown in Figs. 43 through 55. Each is a projection of the velocity vectors in axial planes along the hexagonal duct. After the flow enters the duct uniformly, it spreads toward the walls due to the relatively high resistance in the central region and low resistance near the duct walls. Towards the end of the entrance region (Fig. 46), the first effects of the nonuniformly heated rods are seen. This is due to an unbalanced up-draft set up by the pins with relatively high power density. This skewed up-draft continues to the end of the heated region where the flow begins to return toward an isothermal flow pattern. Figures 56 through 68 show this skewed up-draft action with the axial velocity components shown as a surface across the duct along the axial length. The temperature distributions over a duct cross-section at the axial positions are shown in Figs. 69 through 81. A comparison between measured and COMMIX-1 calculated outlet temperatures is shown in Fig. 82. As can be seen, agreement is excellent.

Only cartesian coordinates can be handled by the present version of plot routine (Figs. 56-81); modification is planned to account for hex geometry.

V. Summary and Conclusions

This report has presented the results from three applications of the COMMIX-1 computer code. In all three cases COMMIX-1 code calculations compare favorably with available measurements.

Currently, COMMIX-1 is being applied to other LMFBR fuel assembly problems with blockage and inlet transients. This report has demonstrated that the COMMIX-1 code is a very useful, versatile and powerful tool which can be used in analyzing many reactor components.

References

1. W. T. Sha, H. M. Domanus, and R. C. Schmitt, "COMMIX-1-Three-dimensional, Transient, Single-phase Thermal-hydraulic Analysis Code," ANL - to be published, 1978.
2. Amsden, A. A., Harlow, F. H., "KACHINA: An Eulerian Computer Program for Multifield Fluid Flows," Los Alamos Scientific Laboratory, LA-5680 (Dec. 1974).
3. Lorenz, J. J., and Carlson, R. D., "An Investigation of Buoyancy-Induced Flow Stratification in a Cylindrical Plenum," Proc. 1976 Heat Transfer and Fluid Mechanics Institute, University of California (June 21-23, 1976).
4. Lorenz, J. J., Carlson, R. D., and Howard, P. A., "An Investigation of LMFBR Outlet Plenum Thermal-Hydraulic Behavior During Reactor Scram Transients," ANL-CT-76-18 (Sept. 1975).
5. K. E. Kasza, R. C. Schmitt, and W. T. Sha, "Thermal Buoyancy Phenomena in a Horizontal Pipe During a Flow Coast-down Thermal-hydraulic Transient (Scoping Studies)," ANL-CT-77-31 (Sept. 1977).
6. "Boundary-Layer Theory," by H. Schlichting, McGraw Hill, 1968.
7. Sha, W. T. and Launder, B. E., "A Model for Turbulent Momentum and Heat Transport in Large Rod Bundles," ANL - to be published (1977).
8. Whitaker, S., "Advances in Theory of Fluid Motion in Porous Media," Industrial and Engineering Chemistry, Vol. 61, No. 12, (Dec. 1969).
9. Fontana, M. H., MacPherson, R. E., Gnadt, P. A. Parsly, L. F. and Wantland, J. L., "Temperature Distribution in a 19-Rod Simulated LMFBR Fuel Assembly in a Hexagonal Duct (Fuel Failure Mockup Bundle 2A)-Record of Experimental Data," ORNL-TM-4113 (Sept. 1973).

Fig. 1. $\frac{1}{15}$ Scale FFTF Outlet Plenum.

VELOCITY DISTRIBUTION

Y = 81.50 mm J = 4
Time = 0.0 s

Fig. 2. Initial Velocity Distribution at Constant Y-plane (Section B-B).

VELOCITY DISTRIBUTION

$Y=104.79$ mm $J= 5$

Time= 0.0 s

Fig. 3. Initial Velocity Distribution at Constant Y-plane (Section C-C).

Fig. 4. Initial Velocity Distribution at Constant X-plane (Section A-A).

THERMOCOUPLE NO. 21
INLET TEMPERATURE MEASUREMENT

Fig. 5. Inlet Temperature Transient.

VELOCITY DISTRIBUTION

X=221.15 mm I= 11

Time= 5.00 s

Fig. 6. Velocity Distribution after 5 sec at Constant X-plane (Section A-A).

VELOCITY DISTRIBUTION

X=221.15 mm I= 11

Time= 10.00 s

Fig. 7. Velocity Distribution after 10 sec at Constant X-plane (Section A-A).

VELOCITY DISTRIBUTION

X=221.15 mm ± 11

Time= 15.00 s

Fig. 8. Velocity Distribution after 15 sec at Constant X-plane (Section A-A).

VELOCITY DISTRIBUTION

X=221.15 mm l= 11

Time= 20.00 s

Fig. 9. Velocity Distribution after 20 sec at Constant X-plane (Section A-A).

VELOCITY DISTRIBUTION

$X=221.15 \text{ mm}$ $I=11$
Time = 24.99 s

Fig. 10. Velocity Distribution after 25 sec at Constant X-plane (Section A-A).

VELOCITY DISTRIBUTION

$X=221.15 \text{ mm}$ $I=.11$

Time= 29.99 s

Fig. 11. Velocity Distribution after 30 sec at Constant X-plane (Section A-A).

Fig. 12. Initial Temperature Distribution at Constant X-plane (Section A-A).

Fig. 13. Temperature Distribution after 10 sec at Constant X-plane (Section A-A).

Fig. 14. Temperature Distribution after 20 sec at Constant X-plane (Section A-A).

Fig. 15. Temperature Distribution after 30 sec at Constant X-plane (Section A-A).

THERMOCOUPLE NO. 26
MEASUREMENT AND COMMIX CALCULATION

Fig. 16. Outlet Nozzle Temperature Transient.

THERMOCOUPLE NO.14
MEASUREMENT AND COMMIX CALCULATION

Fig. 17. Temperature Transient Near Swirl Center Opposite Outlet.

PIPE INLET FLOW AND TEMPERATURE TRANSIENTS

Fig. 18. Pipe Inlet Flow and Temperature Transients.

Fig. 19. Experimental vs. Calculated Isothermal Steady-state Axial Velocity Component Distribution Radially Across Pipe.

VELOCITY-TEMPERATURE DISTRIBUTION

Time= 0.0 s

Fig. 20. Initial Velocity Distribution at Central Z-plane.

VELOCITY-TEMPERATURE DISTRIBUTION

Time= 10.02 s

Fig. 21. Velocity Distribution after 10 sec at Central Z-plane.

VELOCITY-TEMPERATURE DISTRIBUTION

Time= 20.04 s

Fig. 22. Velocity Distribution after 20 sec at Central Z-plane.

VELOCITY-TEMPERATURE DISTRIBUTION

Time = 30.02 s

Fig. 23. Velocity Distribution after 30 sec at Central Z-plane.

VELOCITY-TEMPERATURE DISTRIBUTION

Time= 40.84 s

Fig. 24. Velocity Distribution after 40 sec at Central Z-plane.

Fig. 25. Initial Temperature Distribution at Central Z-plane.

Fig. 26. Temperature Distribution after 10 sec at Central 2-plane.

Fig. 27. Temperature Distribution after 20 sec at Central Z-plane.

Fig. 28. Temperature Distribution after 30 sec at Central Z-plane.

Fig. 29. Temperature Distribution after 40 sec at Central Z-plane.

TEMPERATURE PROFILES

AT $T = 40.41$ s

Fig. 30. Temperature Variation Along Pipe.

VELOCITY-TEMPERATURE DISTRIBUTION

Time= 0.0 s

Fig. 31. Initial Velocity Distribution at X=5.791 m from Inlet.

VELOCITY-TEMPERATURE DISTRIBUTION

Time= 10.02 s

Fig. 32. Velocity Distribution after 10 sec at X=5.791 m from Inlet.

VELOCITY-TEMPERATURE DISTRIBUTION

Time= 20.04 s

Fig. 33. Velocity Distribution after 20 sec at X=5.791 from Inlet.

VELOCITY-TEMPERATURE DISTRIBUTION

Time= 30.02 s

Fig. 34. Velocity Distribution after 30 sec at X=5.791 m from Inlet.

VELOCITY-TEMPERATURE DISTRIBUTION

Time= 40.84 s

Fig. 35. Velocity Distribution after 40 sec at X=1.524 m from Inlet.

VELOCITY-TEMPERATURE DISTRIBUTION

Time= 40.84 s

Fig. 36. Velocity Distribution after 40 sec at $X=3.353$ m from Inlet.

VELOCITY-TEMPERATURE DISTRIBUTION

Time= 40.84 s

Fig. 37. Velocity Distribution after 40 sec at X=5.791 m from Inlet.

VELOCITY-TEMPERATURE DISTRIBUTION

Time= 40.84 s

Fig. 38. Velocity Distribution after 40 sec at X=11.887 m from Inlet.

VELOCITY-TEMPERATURE DISTRIBUTION

Time= 40.84 s

Fig. 39. Velocity Distribution after 40 sec at X=17.983 m from Inlet.

Fig. 40. LMFBR - FFM - Test Section Assembly for Bundle 2A.

Fig. 41. Axial Partitioning Used in LMFBR Fuel Pin Bundle Analysis.

● Thermocouple location

Fig. 42. Normalized Radial Pin Power Density Distribution.

VELOCITY DISTRIBUTION

Fig. 43. Steady Velocity Distribution at $Z=0.0381$ m from Inlet (Entrance Region).

VELOCITY DISTRIBUTION

Fig. 44. Steady Velocity Distribution at $Z=0.1143$ m from Inlet (Entrance Region).

VELOCITY DISTRIBUTION

Fig. 45. Steady Velocity Distribution at $Z=0.1905$ m from Inlet (Entrance Region).

VELOCITY DISTRIBUTION

Fig. 46. Steady Velocity Distribution at $Z=0.2667$ m from Inlet (Entrance Region).

VELOCITY DISTRIBUTION

Fig. 47. Steady Velocity Distribution at $Z=0.3429$ m from Inlet (Heated Region).

VELOCITY DISTRIBUTION

Fig. 48. Steady Velocity Distribution at $Z=0.4191$ m from Inlet (Heated Region).

VELOCITY DISTRIBUTION

Fig. 49. Steady Velocity Distribution at $Z=0.4953$ m from Inlet (Heated Region).

VELOCITY DISTRIBUTION

Fig. 50. Steady Velocity Distribution at $Z=0.5715$ m from Inlet. (Heated Region).

VELOCITY DISTRIBUTION

Fig. 51. Steady Velocity Distribution at Z=0.6477 m from Inlet (Heated Region).

VELOCITY DISTRIBUTION

Fig. 52. Steady Velocity Distribution at $Z=0.7239$ m from Inlet (Heated Region).

VELOCITY DISTRIBUTION

Fig. 53. Steady Velocity Distribution at $Z=0.8001 \text{ m}$ from Inlet (Heated Region).

VELOCITY DISTRIBUTION

Fig. 54. Steady Velocity Distribution at $Z=0.8763$ m from Inlet (Exit Region).

VELOCITY DISTRIBUTION

Fig. 55. Steady Velocity Distribution at $Z=0.9525 \text{ m}$ from Inlet (Exit Region).

Fig. 56. Steady Axial Velocity Distribution at $Z=0.0381$ m from Inlet-(Entrance Region).

Fig. 57. Steady Axial Velocity Distribution at $Z=0.1143$ m from Inlet (Entrance Region).

Fig. 58. Steady Axial Velocity Distribution at $Z=0.1905$ m from Inlet (Entrance Region).

Fig. 59. Steady Axial Velocity Distribution at $Z=0.2667$ m from Inlet (Entrance Region).

Fig. 60. Steady Axial Velocity Distribution at $Z=0.3429$ m from Inlet (Heated Region).

Fig. 61. Steady Axial Velocity Distribution at $Z=0.4191$ m from Inlet (Heated Region).

Fig. 62. Steady Axial Velocity Distribution at $Z=0.4953$ m from Inlet (Heated Region).

Fig. 63. Steady Axial Velocity Distribution at $Z=0.5715$ m from Inlet (Heated Region).

Fig. 64. Steady Axial Velocity Distribution at $Z=0.6477$ m from Inlet (Heated Region).

Fig. 65. Steady Axial Velocity Distribution at $Z=0.7239$ m from Inlet (Heated Region).

Fig. 66. Steady Axial Velocity Distribution at $Z=0.8001$ m from Inlet (Heated Region).

Fig. 67. Steady Axial Velocity Distribution at $Z=0.8763$ m from Inlet (Exit Region).

Fig. 68. Steady Axial Velocity Distribution at $Z=0.9525$ m from Inlet (Exit Region).

Fig. 69. Steady Temperature Distribution at $Z=0.0381$ m from Inlet (Entrance Region).

Fig. 70. Steady Temperature Distribution at $Z=0.1143$ m from Inlet (Entrance Region).

Fig. 71. Steady Temperature Distribution at $Z=0.1905$ m from Inlet (Entrance Region).

Fig. 72. Steady Temperature Distribution at $Z=0.2667$ m from Inlet (Entrance Region).

Fig. 73. Steady Temperature Distribution at $Z=0.3429$ m from Inlet (Heated Region).

Fig. 74. Steady Temperature Distribution at $Z=0.4191$ m from Inlet (Heated Region).

Fig. 75. Steady Temperature Distribution at $Z=0.4953$ m from Inlet (Heated Region).

Fig. 76. Steady Temperature Distribution at $Z=0.5715$ m from Inlet (Heated Region).

Fig. 77. Steady Temperature Distribution at $Z=0.6477$ m from Inlet (Heated Region).

Fig. 78. Steady Temperature Distribution at $Z=0.7239$ m from Inlet (Heated Region).

Fig. 79. Steady Temperature Distribution at $Z=0.8001$ m from Inlet (Heated Region).

Fig. 80. Steady Temperature Distribution at $Z=0.8763$ m from Inlet (Exit Region).

Fig. 81. Steady Temperature Distribution at $Z=0.9525$ m from Inlet (Exit Region).

Fig. 82. COMMIX-1 vs. Experiment: Outlet Temperature Distribution.