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THE
FLOW INDUCED VIBRATION PROGRAM
AT
ARGONNE NATIONAL LABORATORY

MASTER

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THE
FLOW INDUCED VIBRATION PROGRAM
AT
ARGONNE NATIONAL LABORATORY
(ACTIVITIES, FACILITIES, AND CAPABILITIES)

INTRODUCTION

Argonne National Laboratory, located 28 miles southwest of Chicago, Illinois, is one of America's major research and development establishments. Argonne serves as a major U.S. Department of Energy (DOE) center for energy research and development and carries out broad programs of basic research in the physical, biomedical, and environmental sciences. The Laboratory is operated under the provisions of a contract between the U.S. DOE and the University of Chicago.

Argonne National Laboratory has had a Flow Induced Vibration Program since 1967; the Program currently resides in the Laboratory's Components Technology Division. Throughout its existence, the overall objective of the program has been to

> Develop and apply new and/or improved methods of analysis and testing for the design evaluation of nuclear reactor plant components and heat exchange equipment from the standpoint of flow induced vibration.

Historically, the majority of the program activities have been funded by the U.S. Atomic Energy Commission (AEC), Energy Research and Development Administration (ERDA), and Department of Energy (DOE). Current DOE funding is from the Breeder Mechanical Component Development Division, Office of Breeder Technology Projects; Energy Conversion and Utilization Technology (ECUT) Program, Office of Energy Systems Research; and Division of Engineering, Mathematical and Geosciences, Office of Basic Energy Sciences. Testing of Clinch River Breeder Reactor upper plenum components has been funded by the Clinch River Breeder Reactor Plant (CRBRP) Project Office. Work has also been performed under contract with Foster Wheeler, General Electric, Duke Power Company, U.S. Nuclear Regulatory Commission, and Westinghouse.

ACTIVITIES

The program work scope consists of two classes of activities defined as base technology and project support.

The base technology studies are typically of a fundamental nature; often long range, with specific studies spanning several years; and generic, with application to a broad range of component designs. The ultimate goal of the base technology studies is to put the results into a form - equation or graphical - that is readily usable by designers. Design guides, then, represent an end product of this activity. Topical areas that have been, or are currently being, studied include the following:

- Parallel Flow Induced Vibration
- Flow Noise - Turbulence

- Crossflow Induced Vibration - Vortex Shedding
- Tubes on Multiple Supports
- Tubes Conveying Fluid
- Damping
- Added Mass
- Scaling Flow Induced Vibration Phenomena
- Fluid/Structure Coupling
- Tube/Support Interaction
- Fluidelastic Instability of Tube Bundles
- Random Fatigue
- Leakage Flow Induced Vibration

In addition, a number of state-of-the-art reviews and survey papers have been prepared.

The project support activities consist of work performed in support of particular projects. In carrying out such work, a close working relationship is maintained with the designer, as specific component designs are evaluated from the standpoint of flow induced vibration. In general, the work is typically short term, with a need to be responsive to project schedules. Support, in the form of component design evaluation, has been provided to the following projects:

- Argonne Advanced Research Reactor (AARR)
- Experimental Breeder Reactor-II (EBR-II)
- Fast Flux Test Facility (FFTF)
- Clinch River Breeder Reactor (CRBR)
- LMFBR Component Development (Steam Generator)
- Industrial-size Heat Exchangers

Results from the Flow Induced Vibration Program activities at Argonne National Laboratory are reported in technical society publications, technical journals, conference proceedings, and Argonne topical reports, technical memoranda, test reports, and design guides. A complete listing of unrestricted reports and open literature publications from the Argonne Flow Induced Vibration Program is given in Appendix A. In the Table of Appendix A, the publications are indexed to key word(s) defining the various topical areas addressed in the publications. Argonne topical reports are available from the U.S. Department of Energy, Technical Information Center, P. O. Box 62, Oak Ridge, TN 37830.

FACILITIES

Because of the complexities associated with the flow field, and, in particular, the associated difficulties in predicting fluid forces, there is necessarily a heavy reliance on experimentation and testing. Experimental results are used to guide the mathematical modeling, serve as a source of empirical coefficients, and are employed in the validation of prediction methods and design guides. Testing, both scale-model and prototypic, is used in the evaluation of specific component design from the standpoint of flow induced vibration. The Flow Induced Vibration Laboratory at Argonne includes two water flow loops, air flow capabilities, electrodynamic shakers, a heat exchanger test facility, and data acquisition systems. A facilities/equipment description is given in Appendix B.

CAPABILITIES

The program is staffed with engineers who are experienced in both the theoretical and experimental aspects of flow induced vibration. This experience includes the development of mathematical models, computer codes, and design relationships: development of new and/or improved instrumentation, excitation devices, measurement techniques, and data processing methods; conduct of experimental studies designed to facilitate the understanding of basic flow induced vibration phenomena; application of existing finite element computer codes; and the design and performance of sub-scale and prototypic model tests of specific components/systems. Brief resumes of the present staff are given in Appendix C. Publications of the individual staff, in the area of flow induced vibration, can be determined from the publications list in Appendix A.

WORK FOR OTHERS

While Argonne serves as a major center for DOE-funded energy research and development, its staff and facilities can often be made available to do work for organizations other than the U.S. DOE. Argonne is interested in exploring opportunities to do work for non-DOE organizations. However, certain conditions are required: the work must be of a research and development nature, and require unique scientific or technical capabilities and facilities which exist at Argonne. Work for organizations other than the DOE may be undertaken by the Laboratory with the approval of the DOE. Procedural guidelines for contracting to do work for others are outlined in Appendix D.

APPENDIX A

ARGONNE NATIONAL LABORATORY
FLOW INDUCED VIBRATIONS
PUBLICATIONS LIST

Journal Articles, Conference Proceedings, Technical Society Publications

1. A Simplified Dynamic Model for the Vibration Frequencies and Critical Coolant Flow Velocities for Reactor Parallel Plate Fuel Assemblies
   G. S. Rosenberg and C. K. Youngdahl
   Nucl. Sci. Eng. 13, 91-102 (1962)

2. Second-Order Effects as Related to Critical Coolant Flow Velocities and Reactor Parallel Plate Fuel Assemblies
   M. W. Wambsganss
   Nucl. Eng. Des. 5(3), 268-276 (1967)

3. Vibration of Reactor Core Components
   M. W. Wambsganss
   Reactor and Fuel-Processing Technology 10(3), 208-219 (1967)

4. On the Flow-Induced Vibration of Heat-Exchanger Tubes
   M. W. Wambsganss
   Trans. Am. Nucl. Soc. 11(1), 349 (June 1968)

5. Parallel-Flow-Induced Vibration of a Cylindrical Rod
   M. W. Wambsanss and B. L. Boers
   ASME Paper No. 68-WA/NE-15 (1968)

6. Displacement-Transducer Assembly Used in Studying the Parallel-Flow-Induced Vibration of Reactor Fuel Rods
   J. A. Jendrzejczyk and M. W. Wambsganss
   J. Acoust. Soc. Am. 46(3) Pt. 2, 826-827 (September 1968) (Letter to Editor)

7. Flow-Velocity-Dependence of Damping in Parallel-Flow-Induced Vibration
   M. W. Wambsganss and P. L. Zaleski
   Trans. Am. Nucl. Soc. 12(2), 839-840 (December 1969)

8. Response of a Flexible Rod to Near-Field Flow Noise
   S. S. Chen and M. W. Wambsganss
   Proc. Conf. Flow Induced Vibration in Reactor System Components, ANL-7685, pp. 5-31 (May 1970)

9. Measurement, Interpretation and Characterization of Nearfield Flow Noise
   M. W. Wambsganss and P. L. Zaleski
   Proc. Conf. Flow Induced Vibration in Reactor System Components, ANL-7685, pp. 112-140 (May 1970)

10. Proposed Analytical Model for the Crossflow-Induced Vibration of a Circular Cylinder
    H. Halle
    Proc. Conf. Flow Induced Vibration in Reactor System Components, ANL-7685, pp. 248-269 (May 1970)

11. Vibration and Stability of Tube Exposed to Pulsating Parallel Flow
    S. S. Chen and G. S. Rosenberg
    Trans. Am. Nucl. Soc. 13(1), 335-336 (June 1970)

12. Forced Vibration of a Cantilevered Tube Conveying Fluid
    S. S. Chen
    J. Acoust. Soc. Am. 48(3), Pt. 2, 773-775 (September 1970) (Letter to Editor)

13. Vibration of a Class of Nonconservative Systems with Time-Dependent Boundary Conditions
    S. S. Chen
    Shock and Vibration Bulletin 41(7), 141-150 (1970)

14. On Tube-Baffle Impact During Heat Exchanger Tube Vibrations
    S. S. Chen, G. S. Rosenberg, and M. W. Wambsganss
    Proc. ASME Symp. Flow-Induced Vibrations in Heat Exchangers, New York (December 1, 1970), pp. 28-35

15. Flow-Induced Instability of an Elastic Tube
    S. S. Chen
    ASME Paper No. 71-Vibr-39 (1971)

16. Dynamic Stability of a Tube Conveying Fluid
    S. S. Chen
    J. Eng. Mech., ASCE 97(EM5), Proc. Paper 8420, pp. 1469-1485 (1971)

17. Instability of a Uniformly Curved Tube Conveying Fluid
    S. S. Chen
    J. Appl. Mech. 38(4), 1087 (December 1971) Note

18. Vibration and Stability of a Uniformly Curved Tube Conveying Fluid
    S. S. Chen
    J. Acoust Soc. Am. 51(Part 2), 223-232 (January 1972)

19. Flow-Induced In-Plane Instabilities of Curved Pipes
    S. S. Chen
    Nucl. Eng. Des. 23(1), 29-38 (October 1972)

20. Flow-Induced Vibration
    M. W. Wambsganss
    Pressure Vessels and Piping: Design and Analysis, ed. G. J. Bohm et al, ASME, Vol. 2, Chap. 3, Pt. III (October 1972)

21. Free Vibration of a Coupled Fluid/Structure System
    S. S. Chen
    J. Sound and Vibration 21(4), 387-398 (1972)

22. Parallel-Flow-Induced Vibration of Fuel Rods
    S. S. Chen and M. W. Wambsganss
    Nucl. Eng. Des. 18, 253-278 (1972)

23. Crossflow-Induced Vibration of a Circular Cylinder in Water
    H. Halle and W. Lawrence
    ASME Paper No. 73-DET-68 (1973)

24. Out-of-Plane Vibration and Stability of Curved Tube Conveying Fluid
S. S. Chen
Trans. ASME, J. Appl. Mech. 40(2), 362-368 (1973)

25. Coupled Twist-Bending Waves and Natural Frequencies of Multispan Curved Beams
S. S. Chen
J. Acoust. Soc. Am. 53(4), 1179-1183 (1973)

26. In-Plane Vibration of Continuous Curved Beams
S. S. Chen
Nucl. Eng. Des. 25, 413-431 (1973)

27. Free Vibrations of Fluid-Conveying Cylindrical Shells
S. S. Chen and G. S. Rosenberg
J. of Eng. for Ind., Trans. ASME, 96(2), 420-426 (May 1974)

28. namics of a Rod-Shell System Conveying Fluid
. S. Chen
Nucl. Eng. Des. 30(2), 223-233 (1974)

29. Vibration of Continuous Pipes Conveying Fluid
S. S. Chen
Flow-Induced Structural Vibrations, ed. E. Naudascher, Springer-Verlag Inc., pp. 663-675 (1974)

30. Parallel Flow-Induced Vibrations and Instabilities of Cylindrical Structures
S. S. Chen
Shock and Vibration Digest 6(10), 2-12 (1974)

31. Dynamics of a Coupled Shell/Fluid System
S. S. Chen and G. S. Rosenberg
Nucl. Eng. Des. 32, 302-310 (1975)

32. Dynamic Responses of Two Parallel Circular Cylinders in a Liquid
S. S. Chen
J. of Pressure Vessel Technology, Trans. ASME 97(2), 77-83 (1975)

33. Vibrations of Constrained Shells
R. Greif and Ho Chung
AIAA Journal 13(9), 1190-1198 (Sept 1975)

34. Analytical Method and Experimental Study of Two Concentric Cylinders Coupled by a Fluid Gap
T. M. Mulcahy, P. Turula, Ho Chung, and J. A. Jendrzejcayk
Proc. Third Int. Conf. on Structural Mechanics in Reactor Technology, London, England, F2/7 (Sept 1975)

35. Fluidelastic Tube Vibration in a Heat Exchanger Designed for Sodium-to-Air Operation
H. Halle, B. L. Boers, and M. W. Wambsganss
J. of Engineering for Power, Trans. ASME 97(4), 561-568 (Oct 1975)

36. An Exact Method for Vibrations of Circular Cylindrical Shells
Ho Chung
Trans. Am. Nucl. Soc. 22, 568-569 (Nov 1975)

37. Flow-Induced Vibrations of Reactor Internal and Plant Components
S. S. Chen
Proc. Int. Sym. on Nucl. Power and Economics, Taipei, Taiwan, 353-370 (1975)

38. Vibrations of a Row of Circular Cylinders in a Liquid
S. S. Chen
J. Eng. for Industry 97, 1212-1218 (1975)

39. Vibration of Nuclear Fuel Bundles
S. S. Chen
Nucl. Eng. Des. 35, 399-422 (1975)

40. Dynamics of Tube/Baffle Interaction in Heat Exchangers
Y. S. Shin, D. E. Sass, and M. W. Wambsganss
Trans. Am. Nucl. Soc. 22, 565-566 (Nov 1975)

41. Experimental Studies of Tube/Baffle Interaction in Heat Exchangers
Y. S. Shin, J. A. Jendrzejczyk, and M. W. Wambsganss
Trans. Am. Nucl. Soc. 22, 563-565 (Nov 1975)

42. An Evaluation of Flow-Induced Vibration Prediction Techniques for In-Reactor Components
T. M. Mulcahy and P. Turula
Trans. Am. Nucl. Soc. 22, 570 (1975)

43. Assessment of the Reliability of Computer Modeling to Predict Flow-Induced Vibration Response of Reactor Components
P. Turula, T. M. Mulcahy, and Ho Chung
Proc. ASCE Spring Convention, San Diego, Calif. (April 1976)

44. Added Mass and Damping of a Vibrating Rod in Confined Viscous Fluids
S. S. Chen, M. W. Wambsganss, and J. A. Jendrzejczyk
J. Appl. Mech. 43(2), 325-329 (June 1976)

45. Flow-Induced Vibration Scale Model Tests of CRBR-UIS
T. M. Mulcahy, T. T. Yeh, and J. A. Jendrzejczyk
Trans. Am. Nucl. Soc. 23 (June 1976)

46. Tube Vibration Analysis and Testing for U. S. LMFBR Steam Generators
M. W. Wambsganss, M. J. Gabler (AI), Y. S. Shin, and T. M. Yang (GE)
Proceedings Joint US/USSR Seminar on Reliability and Safety of LMFBR Steam Generators, USSR (July 1976)

47. Flow-Induced Vibration of Nuclear Reactor System Components
T. M. Mulcahy and M. W. Wambsganss
Shock and Vibration Digest 8(7), 33-45 (July 1976)

48. Vibration and Stability of Fluid-Conveying Pipes
H. C. Lin and S. S. Chen
Shock and Vibration Bulletin 46, Pt. 2, 267-283 (1976)

49. Vibrations of Two Concentric Cylindrical Shells Containing a Viscous Fluid
    T. T. Yeh and S. S. Chen
    J. Acoust. Soc. Am. 60(Suppl. No. 1) (Nov 1976)

50. Understanding Flow-Induced Vibrations, Part I: Basic Concepts; Fluid Forcing Functions
    M. W. Wambsganss
    Sound and Vibration 10(11), 18-23 (Nov 1976)

51. Flow-Induced Vibration in LMFBR Steam Generators: A State-of-the-Art Review
    Y. S. Shin and M. W. Wambsganss
    Nucl. Eng. Des. 40(2), 235-284 (Feb 1977)

52. Understanding Flow-Induced Vibrations, Part II: Fluid/Structure Coupling; Design Considerations
    M. W. Wambsganss
    Sound and Vibration 11(4), 18-21 (April 1977)

53. Vibration of a Group of Circular Cylinders in a Confined Fluid
    Ho Chung and S. S. Chen
    J. Appl. Mech., Trans. ASME 99(2), 213-217 (June 1977)

54. Acoustically Induced Vibration of Circular Cylindrical Rods
    H. C. Lin and S. S. Chen
    J. Sound and Vibration 51(1), 89-96 (1977)

55. A Mathematical Model for Crossflow-Induced Vibration of Tube Rows
    S. S. Chen
    Proc. Third Int. Conf. on Pressure Vessel Technology, Tokyo, Part 1, 415-426 (1977)

56. Crossflow-Induced Vibration of Tube Banks: Hydrodynamic Forces and Mathematical Models
    S. S. Chen
    Proc. 2nd Annual Eng. Mech. Div. Specialty Conf. ASCE, Raleigh, N.C., 210-212 (1977)
    Advances in Civil Engineering through Engineering Mechanics, ASCE, 210-216 (1977)

57. Computer Modeling of Flow Induced In-Reactor Vibrations
    P. Turula and T. M. Mulcahy
    J. Power Division, ASCE 103(PO1), 37-50 (July 1977)

58. The Effect of Tube-Support Interaction on the Dynamic Responses of Heat Exchanger Tubes
    Y. S. Shin, J. A. Jendrzejczyk, and M. W. Wambsganss
    Proc. 4th Int. Conf. on Struct. Mechanics in Reactor Technology, Vol. F, Paper F6/5 (Aug 1977)

59. Dynamics of a Cylindrical Shell System Coupled by Viscous Fluid
    T. T. Yeh and S. S. Chen
    J. Acoust. Soc. Am 62(2), 262-270 (Aug 1977)

60. Dynamics of Heat Exchanger Tube Banks
S. S. Chen
J. Fluids Eng., Trans. ASME 99(3), 462-469 (Sept 1977)

61. Vibration of a Heat Exchanger Tube with Tube/Support Impact
Y. S. Shin, J. A. Jendrzejczyk, and M. W. Wambsganss
ASME Paper No. 77-JPGC-NE-5, ASME Joint Power Generation Conf.,
Long Beach, Calif. (Sept 1977)

62. Crossflow-Induced Vibration of a Row of Circular Cylinders in Water
H. Halle and W. P. Lawrence
ASME Paper No. 77-JPGC-NE-4, ASME Joint Power Generation Conf.,
Long Beach, Calif. (Sept 1977)

63. Flow-Induced Vibration Scale Model Test of the CRBR Instrument Post
T. M. Mulcahy, T. T. Yeh, and W. P. Lawrence
Fluid Structure Interaction Phenomena in Pressure Vessel and Piping
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Fluid Structure Interaction Phenomena in Pressure Vessel and Piping
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S. S. Chen
Shock and Vibration Digest 9(10), 25-38 (Oct 1977)

66. Flow Induced Vibrations of Circular Cylindrical Structures, Part II: Cross Flow Considerations
S. S. Chen
Shock and Vibration Digest 9(11), 21-28 (Nov 1977)

67. The Effect of Fluid Viscosity on the Vibrations of Two Concentric Tubes
T. T. Yeh and S. S. Chen
J. Acoust. Soc. Am. 62(Suppl. No. 1), S84 (1977)

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E. H. Novendstern (W-ARD), F. A. Grochowski, (W-ARD), T. M. Yang (GE),
J. A. Ryan (HEDL), and T. M. Mulcahy
Proceedings IAEA Specialists Meeting on LMFBR Flow Induced
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69. A Review of ANL Base Technology Studies in Support of the U.S. LMFBR Program
M. W. Wambsganss, S. S. Chen, T. M. Mulcahy, and Y. S. Shin
Proceedings IAEA Specialists Meeting on LMFBR Flow Induced
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70. Crossflow-induced Vibrations of Heat Exchanger Tube Banks
S. S. Chen
Nucl. Eng. Des. 47(1), 67-86 (May 1978)

71. Vibration Studies of Perforated Plates on CRBRP Mixing-Tee Model
H. Chung and H. Halle
Trans. Am. Nucl. Soc. 28, 434-435 (June 1978)

72. Experiments on Fluidelastic Vibration of Cantilevered Tube Bundles
S. S. Chen and J. A. Jendrzejczyk
J. Mechanical Design, ASME 100, 540-548 (July 1978)

73. The Effect of Fluid Viscosity on Coupled Tube/Fluid Vibrations
T. T. Yeh and S. S. Chen
J. Sound and Vibration 59(3), 453-467 (August 1978)

74. On the Added Mass Matrix and Acoustic Pressure of Multiple Circular Cylinders Vibrating in a Compressible Fluid
W. H. Lin and S. S. Chen
J. Acoust. Soc. Am. 64(Suppl. No. 1) (Fall 1978)

75. Vibro-Impact Responses of a Tube with Tube-Baffle Interaction
Y. S. Shin, D. E. Sass, and J. A. Jendrzejczyk
Trans. CSME 5(1), 15-23 (1978/79)

76. Dynamics of Component-Support Impact: An Elastic Analysis
E. C. Ting (Purdue University), S. S. Chen, and M. W. Wambsganss
Nucl. Eng. Des. 52(2), 235-244 (1979)

77. Dynamic Response of a Circular Cylinder Subjected to Liquid Cross Flow
S. S. Chen and J. A. Jendrzejczyk
J. Pressure Vessel Tech., Trans. ASME 101(2), 106-112 (May 1979)

78. Symposium on Flow Induced Vibrations
S. S. Chen and M. D. Bernstein (Foster Wheeler), Editors
ASME Publication (June 1979)

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C. D. Henry (ETA Engineering), G. E. Lee (General Atomic), and M. W. Wambsganss
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M. W. Wambsganss and J. A. Jendrzejczyk
J. Sound and Vibration 65(2), 251-258 (1979)

81. Flow-Induced Vibration of Nuclear Reactor Fuel - Part I: Modeling
M. W. Wambsganss and T. M. Mulcahy
Shock and Vibration Digest 11(11), 11-22 (November 1979)

82. Dynamic Responses of a Pair of Circular Tubes Subjected to Liquid Cross Flow
    J. A. Jendrzejczyk, S. S. Chen, and M. W. Wambsganss
    J. Sound and Vibration 67(2), 263-273 (1979)

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    M. W. Wambsganss and T. M. Mulcahy
    Shock and Vibration Digest 11(12), 11-13 (December 1979)

84. Turbulence and Rod Vibrations in an Annular Region with Upstream Disturbances
    T. M. Mulcahy, T. T. Yeh, and A. J. Miskevics
    J. Sound and Vibration 69(1), 59-70 (1980)

85. Dynamic Surface-pressure Instrumentation for Rods in Parallel Flow
    T. M. Mulcahy, W. P. Lawrence, and M. W. Wambsganss
    Experimental Mechanics 22(1), 31-36 (January 1982); also presented at 1980 SESA Spring Meeting

86. Fluidelastic Instability of Rectangular Tube Arrays Subjected to Liquid Cross Flow
    S. S. Chen, J. A. Jendrzejczyk, and W. H. Lin
    Proc. 4th Int. Conf. Pressure Vessel Technology 2, 193-200 (May 1980)

87. Cross-Flow-Induced Instabilities of Circular Cylinders
    S. S. Chen
    Shock and Vibration Digest 12(5), 21-34 (May 1980)

88. Fluid Forces on Rods Vibrating in Finite Length Annular Region
    T. M. Mulcahy
    Trans. ASME, J. Appl. Mech. 47(1), 59-69 (June 1980)

89. Determination of Velocity-Squared Fluid Damping by Resonant Structural Testing
    T. M. Mulcahy and A. J. Miskevics
    J. Sound and Vibration 71(4), 555-564 (August 1980)

90. Free Transverse Vibrations of a Uniform Circular Plate with an Eccentric Hole
    W. H. Lin and M. W. Wambsganss
    J. Acoust. Soc. Am. 68(Suppl. No. 1), p. S115 (Fall 1980) (Abstract)

91. Prediction of Random High-Cycle Fatigue Life of LWR Components
    Y. S. Shin
    J. Pressure Vessel Technology, Trans. ASME 102, 378-386 (November 1980)

92. Guided Waves in a Circular Duct Containing an Assembly of Circular Cylinders
    W. H. Lin
    J. Sound and Vibration 79(4), 463-477 (December 1981)

93. Flow Induced Vibration Testing Scale Modeling Relations
T. M. Mulcahy
Flow Induced Vibration Design Guidelines, ed. P. Y. Chen, ASME PVP-Vol. 52, 111-126 (1981)

94. Vibration of a Group of Circular Cylinders Subjected to Fluid Flow
S. S. Chen
Flow Induced Vibration Design Guidelines, ed. P. Y. Chen, ASME PVP-Vol. 52, 75-88 (1981)

95. Free Vibration Analysis of Circular Cylindrical Shells
H. H. Chung
J. Sound and Vibration 74(3) (1981)

96. On the Added Mass and Radiation Damping of Rod Bundles Oscillating in Compressible Fluids
W. H. Lin and S. S. Chen
J. Sound and Vibration 74(3), 441-457 (February 1981)

97. Heat Exchanger Tube Vibration: A Technical Problem in the Application and Development of Heat Recovery Systems
M. W. Wambsganss
Proc. IEA Conf. on New Energy Conservation Technologies and their Commercialization, Berlin, April 6-10, 1981

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H. Chung
Nucl. Eng. Des. 63(1), 55-80 (1981)

99. Fluid Damping for Circular Cylindrical Structures
S. S. Chen
Nucl. Eng. Des. 63(1), 81-100 (1981)

100. A Fluid Damping Distortion in FIV Scale Modeling
T. M. Mulcahy
Nucl. Eng. Des. 63(1), 101-108 (1981)

101. Analysis of a Cylindrical Shell Vibrating in a Cylindrical Fluid Region
H. Chung, P. Turula, T. M. Mulcahy, and J. A. Jendrzejczyk
Nucl. Eng. Des. 63(1), 109-120 (1981)

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S. S. Chen and J. A. Jendrzejczyk
J. Pressure Vessel Technology 103(2), 130-135 (May 1981)

103. Damping Measurement of Curved Heat Exchanger Tubes by Using an Electromagnetic Exciter
J. A. Jendrzejczyk
J. Sound and Vibration 76(3), 457-462 (June 8, 1981)

104. Tube Crossflow Force Measurement
T. M. Mulcahy
Proc. SESA Spring Meeting, Dearborn, Michigan, pp. 286-290 (May 31-June 4, 1981)

105. A DOE-Sponsored Program on Heat Exchanger Tube Vibration
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H. Halle, J. M. Chenoweth (HTRI), and M. W. Wambsganss
ASME Paper No. 81-DET-37 (1981)

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S. S. Chen
J. Vibration, Acoustics, Stress, and Reliability in Design, ASME 105, 51-58 (January 1983)

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    Ho Chung
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Topical Area/Publication Index

Topical Area	Publication
Category	Technical Papers (Topical Reports) [Design Guides]
Acoustics	54,74,92,96,110,113
Crossflow	10,23,55,56,60,62,66,70,77,82,86,87,104,106,114,120 (8,22,23,26,37,42,43) [5,6]
Damping	1,44,67,80,89,99,100,102,103 (2,10,25,27) [7]
Data Banks	(35,40,47,53,60)
Fatigue	91 (32,34)
Fluidelastic Instability in Tube Arrays	35,55,56,62,70,86,106,108,109,111,116,117,123,124 (23,26,42,43,51) [5]
Fluid/Structure Coupling Added Mass	21,32,34,38,39,44,49,53,60,64,67,72,73,74,88,92,96,101 (3,10,12,13,15,17,20,21,22,24,27,46) [4]
Fuel Rods	8,22,39,79,81,83 (17) [2]
HX Tube Vibrations	4,14,35,40,41,46,51,58,60,61,70,97,105,107,118 (4,16,22,35,36,40,41,44,47,52,53,56,60) [1]

Impacting Tube/Support Interaction	14,40,41,58,61,75,76 (5,19,25,29,30,59) [1]
Instability	1,2,11,15,16,17,18,19,24,30,48,72,106,108, 109,111 (1,7,11,42,43) [5]
Instrumentation and Excitation Devices	6,9,85,103,104,107,120 (36,44,49)
Leakage Mechanism	125 (57,58)
Natural Frequencies and Modes	25,26,98 (25) [1]
Nonlinear Analysis	2,118 (1)
Parallel Flow	1,2,5,6,7,8,9,22,30,39,65,79,80,84,85,112,122 (1,17,31,33,38,39,45,46,48) [1]
Pipes Conveying Fluid	11,12,13,15,16,17,18,19,24,27,28,29,48,119 (7,11,54)
Plates	1,2,71,90 (1,3)
Pressure Drop	(55)
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Scaling	45,63,93,100 (46,48,50,59)
Shells	28,31,33,34,36,49,59,95,101 (13,18,21,24)
Turbulence Excitation	8,9,84,85,112 (33,38,39,45,48) [6]
Vortex Shedding	4,10,23,82 (8,37)

ARGONNE NATIONAL LABORATORY

FLOW INDUCED VIBRATIONS

FACILITY/EQUIPMENT PROFILES

Flow-Induced Vibration Test Facility (FIVTF) (Figure 1)

The FIVTF has four pumps with flow rates of 500, 1000, 2500, and 4000 gpm at 150 psig discharge pressure. The pumps discharge individually through their own control and by-pass valves, flowmeters and piping (including pressure and temperature indicators) to an accumulator. Thus, the flow can be varied to provide discrete and stable water flow from 50 gpm to a maximum of 8000 gpm by operating combinations of the pumps and valving. To allow ease of operation by the experimenter, all pumps and valves are operated remotely via a control console.

To provide for "quiet flow," various design considerations have been employed. Piping with a minimum number of bends (all long radius), and of the largest diameter practical, is used to reduce turbulence. Structural-borne vibrations are minimized by using vibration attenuation pads at the pipe support locations, which are close together (for short span length). Flexible piping sections are used for connection to the pumps and at the entrance and exit to the test sections.

The 8000-gal accumulator at the entrance to the test legs has a maximum turnover rate of once per minute at the highest flow rate. This turnover rate, along with internal baffling and the small height-to-diameter ratio, tends to isolate the pump supply from the test item. Three large diameter nozzles (two horizontal and one vertical), for attachment of test items to the accumulator, are provided with isolation valves, so that one test can be performed while another is being assembled.

The pump supply tank is constructed of concrete to reduce vibration and has a large volume (~10,000 gal) to accommodate baffling and water-conditioning equipment. The conditioning equiment is used to maintain the quality of the water so that the transducers for the data acquisition system will not be adversely affected by variable water conditions. For example, during an experiment, water temperature will not vary enough to affect water viscosity, and water resistance is maintained at a high level so that transducer shorting-to-ground is minimized. Make-up water is circulated through the appropriate units so that its quality will be the same as that of the loop.

Water Quality Variables	Control Methods
Mean temperature	Cooling tower
Water resistance and chemical content	Ion exchange column
Particulate matter (up to 7μ)	Filters
Bacteria content	Ultraviolet sterilization unit

An overhead crane, with a 10-ton capacity, services the entire area occupied by the FIVTF.

Principal uses of the FIVTF include:

- Flow-induced vibration tests of nuclear and nonnuclear systems and plant components including valves, reactor upper plenum components, instrumentation wells, thermal liners, and flow-directing baffles.
- Experimental studies of tube bundles in crossflow, single cylinders in skewed flow, and cylinders subject to inflow turbulence and wake buffeting.
- Performance of tests, both scale-model and prototypic, to evaluate specific LMFBR component designs from the standpoint of flow-induced vibrations.

500-GPM Water Loop (Figure 2)

The loop features a single pump which supplies a maximum of 500 gpm of domestic water at controlled temperature at 150 psig from an open-top tank to a distribution header at the bottom of the 20-ft test section area. The header can service three test legs. Massive supports and loop-piping vibration isolators are employed to minimize structural-borne vibration of the test section.

The test section area extends 20 ft from the mezzanine to the grade level of a high-bay building. Ample space is available for either vertically or horizontally oriented test sections, and for local visual monitoring/recording equipment. The loop control console and the data acquisition and reduction equipment are located in a centralized control room which services all test facilities in the building. The facility is completely operated by remote control and is serviced by a 10-ton overhead crane.

Principal uses of the facility include studies of vibration of flexible rods and tubes in nominally axial and crossflow, including measurement of rod/tube motion, equivalent viscous damping, random, surface pressure fluctuations, and fluid forces; also scale-modeling flow-induced vibration phenomena, and component behavior in selected flow fields.

Wind Tunnels (Figure 3)

Two sets of blowers are available for use in air flow testing. One provides 5000 cfm at 3 in. of water for small scale tests. The other consists of two fans in parallel providing a total of 20,000 cfm at 40 in. of water.

Vibration Exciters (Figure 4)

This equipment consists of an electrodynamic shaker system, with 1200-lb (MBC10E) force vector capability for sinusoidal and random vibration testing at frequencies to 5000 Hz, and custom designed electromagnetic exciters. This equipment provides excitation sources for determination of component vibration characteristics (natural frequencies, damping, and mode shapes). These exciters can be used in combination with the water flow loops or the wind tunnels to provide controlled force inputs to test items undergoing flow testing.

Principal use of this equipment has been as excitation sources for studies of vibration response of structures, flow-velocity-dependent damping of rods and tubes in axial and crossflow, and beam-stop impacting.

Test Heat Exchanger (Figure 5)

The test exchanger simulates the shell side configuration of an industrial shell-and-tube heat exchanger. The general features of the nominally 0.6-m (2-ft)-diameter by 3.7-m (12-ft)-long segmentally baffled test heat exchanger are presented in the following Table:

Table 1 Description of the test heat exchanger

Shellside fluid	Water
Tubeside	No fluid, open tubes, ready insertion of instrumentation
Modular shell construction	Flexibility to change nozzle arrangement
Tube bundle	Removable unit, ready assembly/disassembly
Tubesheets	One stationary, one floating; special double-tubesheet construction to contain O-rings to seal tubes
Nozzles at shell midspan	Observation ports or alternative flow route (e.g., direct crossflow)
Shell (stainless steel), ID	0.59 m (23.25 in.)
Shell, inside length (tubesheet spacing)	3.58 m (140.75 in.)
Nozzles, inlet and outlet (3 sizes available); nominal size and ID (* reduced with inserts)	14-in. size; 337 mm (13.25 in.) 12-in. size*; 288 mm (11.328 in.) 10-in. size*; 241 mm (9.500 in.)
Tube (Admiralty brass), OD	19.1 mm (0.750 in.)
Tube, wall thickness	1.2 mm (0.049 in.)

Note that no heat is transferred during the tests as no fluid is flowing on the tube side. Construction of the tube bundle permits ease of disassembly and reassembly, with versatility to create various geometric test configurations, e.g., different baffle spacings, baffle styles, tube field layout arrangements, and shell styles. The waterflow enters the shell side of the exchanger through an inlet connection that provides more than 12 diameters of straight pipe to reduce extraneous prior-to-entrance effects.

The exchanger currently provides a versatile test facility for the Argonne Heat Exchanger Tube Vibration Program. It is being used to generate tube vibration data under controlled conditions from a real heat exchanger for use in evaluating prediction methods and design criteria.

Data Acquisition/Processing Facility (Figure 6)

The data acquisition and data processing facility includes the following pieces of equipment:

- Two digital data reduction systems which are minicomputer-controlled systems (Hewlett-Packard 5451 Fast Fourier Analyzers). One system (5451B) has a minicomputer with 32K of memory, four channels of A-D and one output channel of D-A for experimental input. The other system (5451C) has a minicomputer with 64K of memory and a magnetic disk for additional memory. Both systems have four channel capability for analysis of data where time reference is needed (correlation). Both systems are controlled via special keyboards (similar to calculators). All of the standard mathematical relationships for random data can be determined (Fourier Transform, inverse Fourier Transform, transfer functions, etc.). The systems automatically retain amplitude calibration and provide (via digital display) the appropriate scale factors and units for all analyses performed.
- Three 14-channel 1-in. magnetic tape recorders for Wideband FM Record/Reproduce (Honeywell model 7600 and Ampex models PR2230 and PR2230A).
- An analog servo system (Spectral Dynamics equipment SD-1056 amplitude servo, SD-101B dynamic analyzer, SD-101BS slave) used for swept sine control of force generators for vibration testing and transducer calibration.
- A real-time spectrum analyzer (Spectral Dynamics model SD-330A) capable of 150-line spectrum analysis with cursor-controlled digital readout of frequency and amplitude values. The analyzer has built-in spectrum averaging and X-Y plotting of data simultaneous with viewing on a built-in CRT.
- Associated electronics (filters, amplifiers, scopes, plotters, and calibration equipment).

Instrumentation

Instrumentation is available to measure:

- Acceleration - Piezoelectric and piezoresistive accelerometers and their respective signal conditioning amplifiers.
- Displacement - Optical and eddy current type displacement transducers.

- Flow - Hot wire and laser anemometry, turbine flowmeters, and orifice plates.
- Force - Load cells and piezoelectric and custom designed transducers to measure fluid force.
- Pressure - Piezoelectric, strain gage-diaphragm, and bordon tube.
- Temperature - Digital thermometers, thermocouples, and mercury filled.
- Strain - Strain gages and associated signal conditioning equipment.

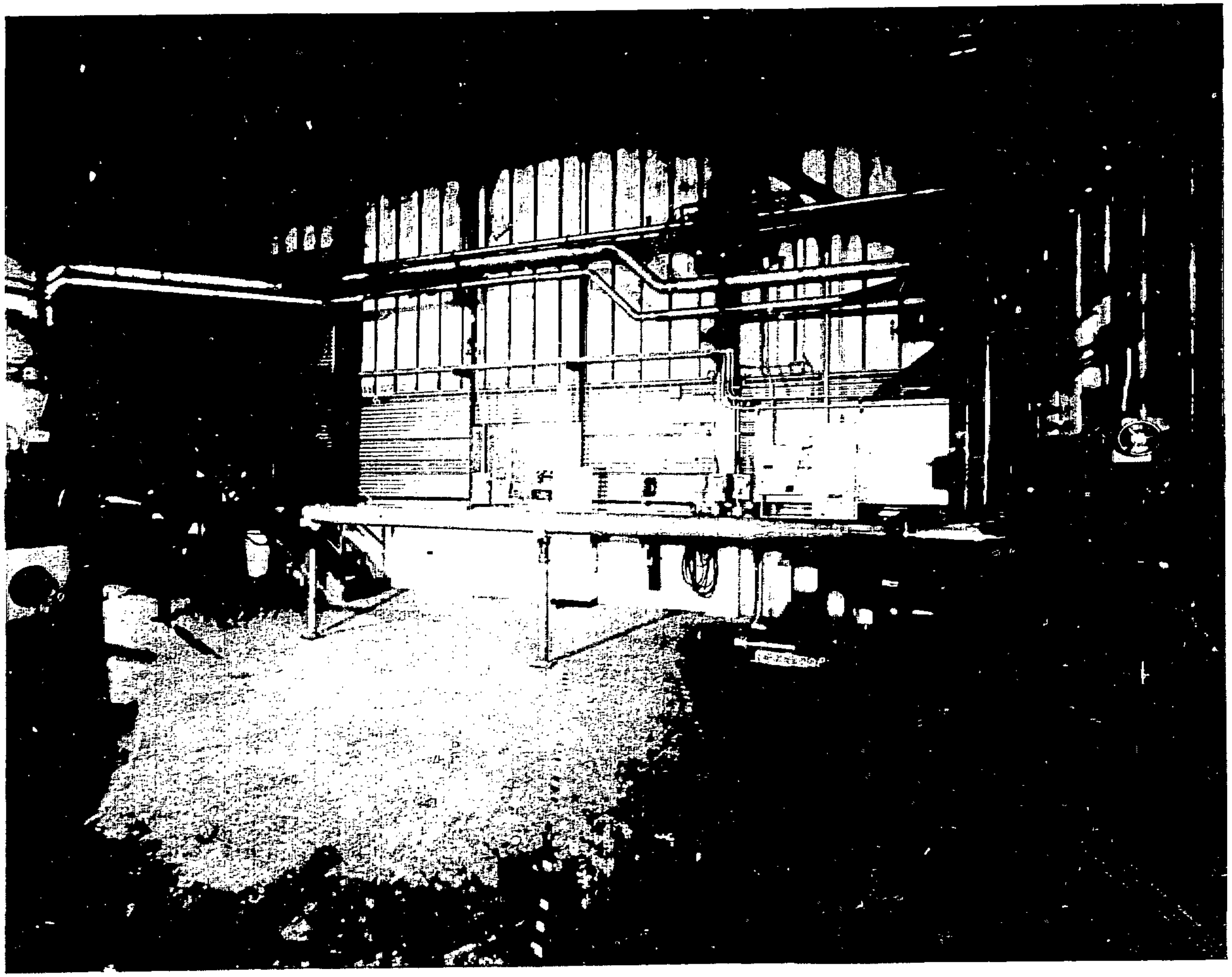

Fig. 1. Flow Induced Vibration Test Facility (FIVTF) - An 8,000 gpm water flow loop. ANL Neg. No. 113-76-351.

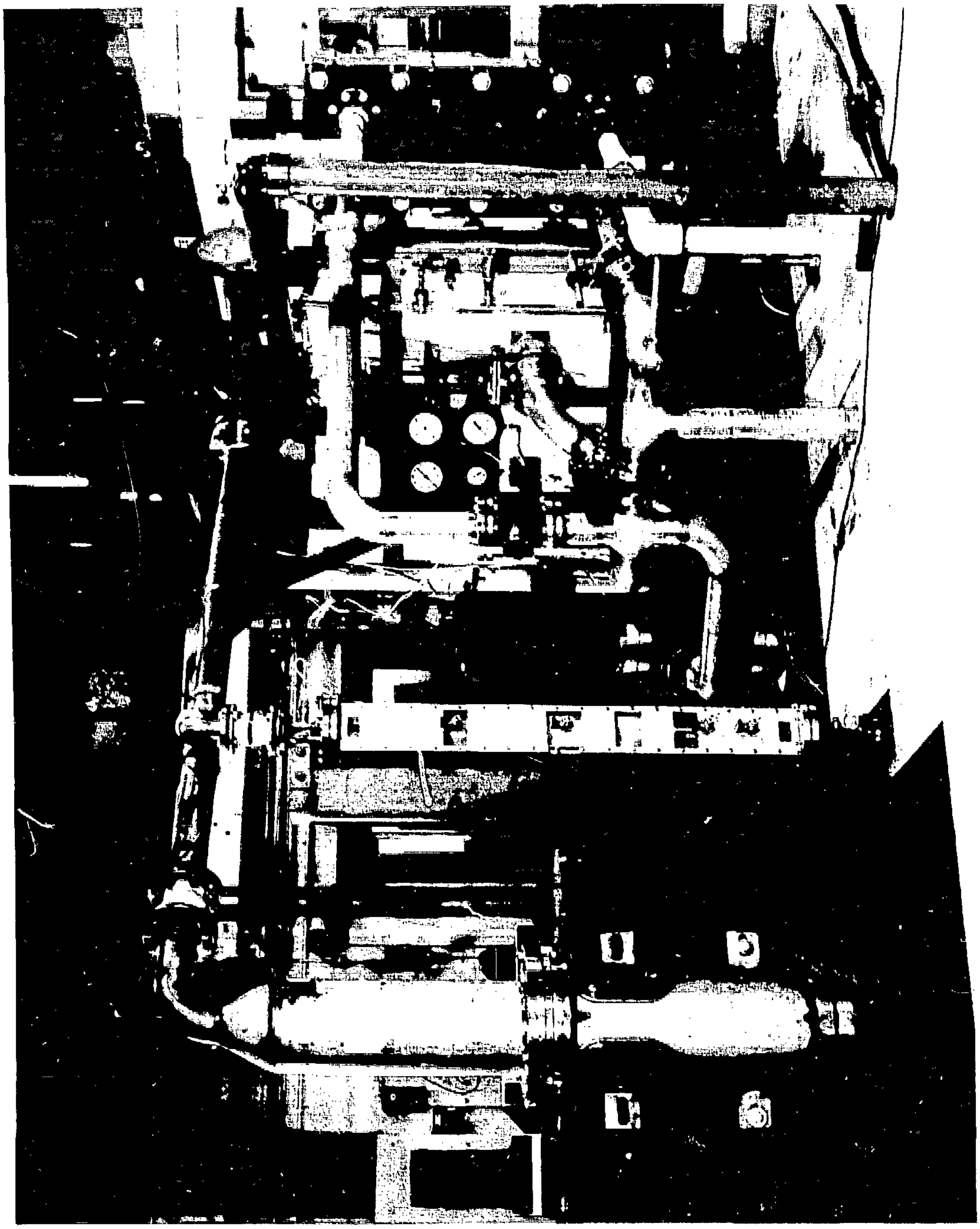

Fig. 2. 500-gpm Water Loop. ANL Neg. No. 113-78-55.

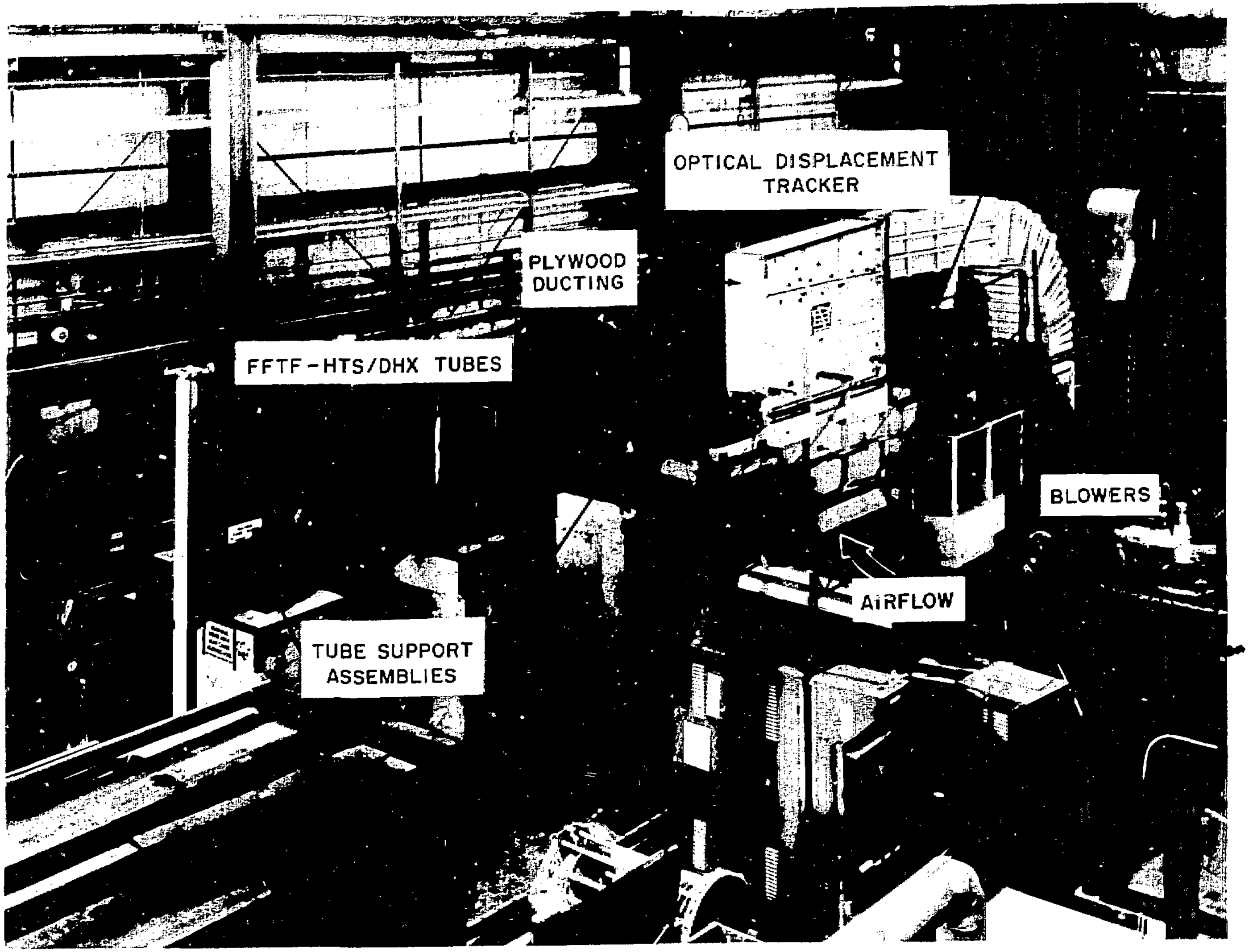

Fig. 5. Airflow testing of sodium-to-air dump heat exchanger U-tubes. ANL Neg. No. 113-4475A.

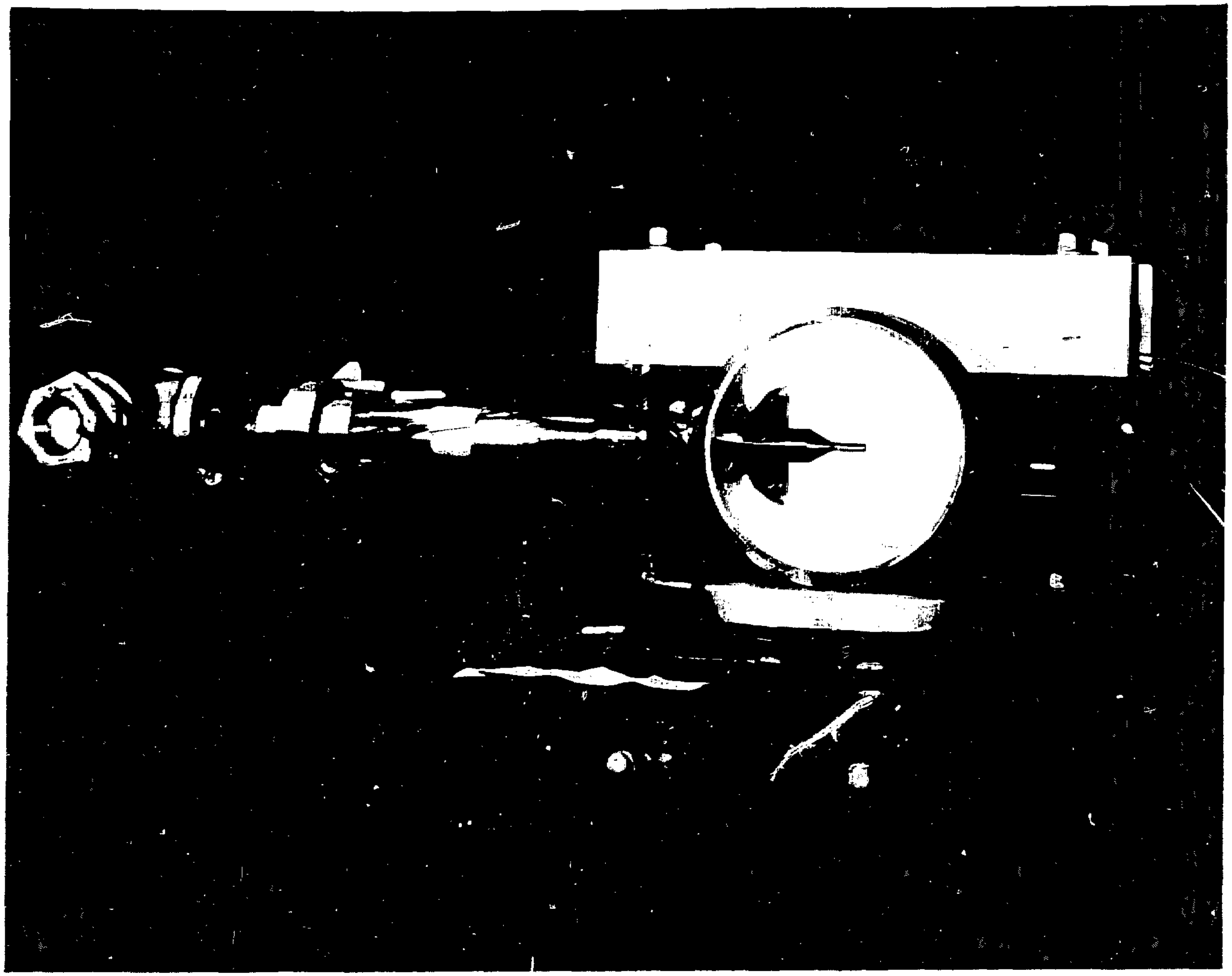

Fig. 4. Thermowell mounted on vibration exciter for natural frequency determination. ANL Neg. No. 113-4927.

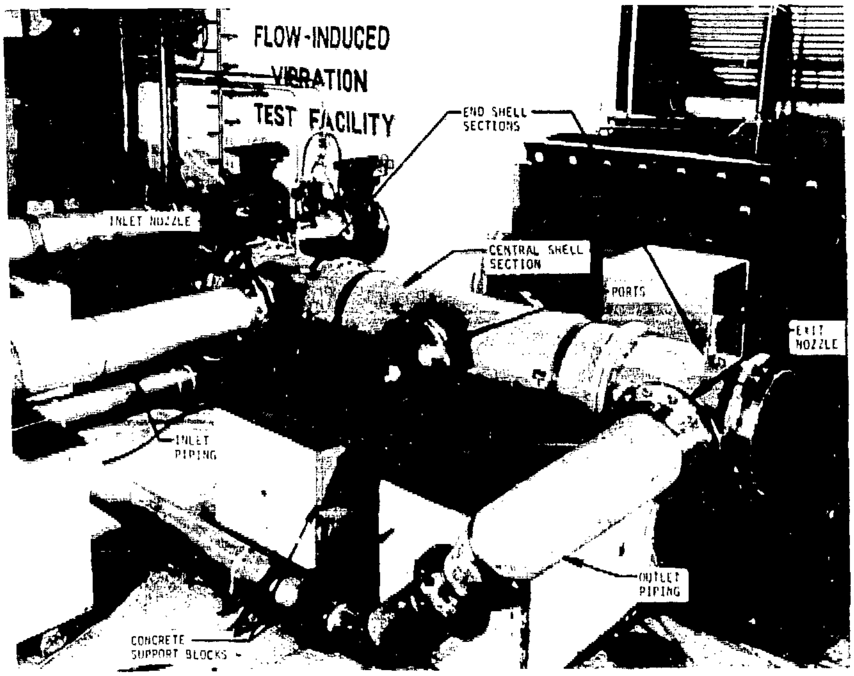

Fig. 5a. Test Exchanger installed in Flow-Induced Vibration Test Facility. ANL Neg. No. 113-79-100A.

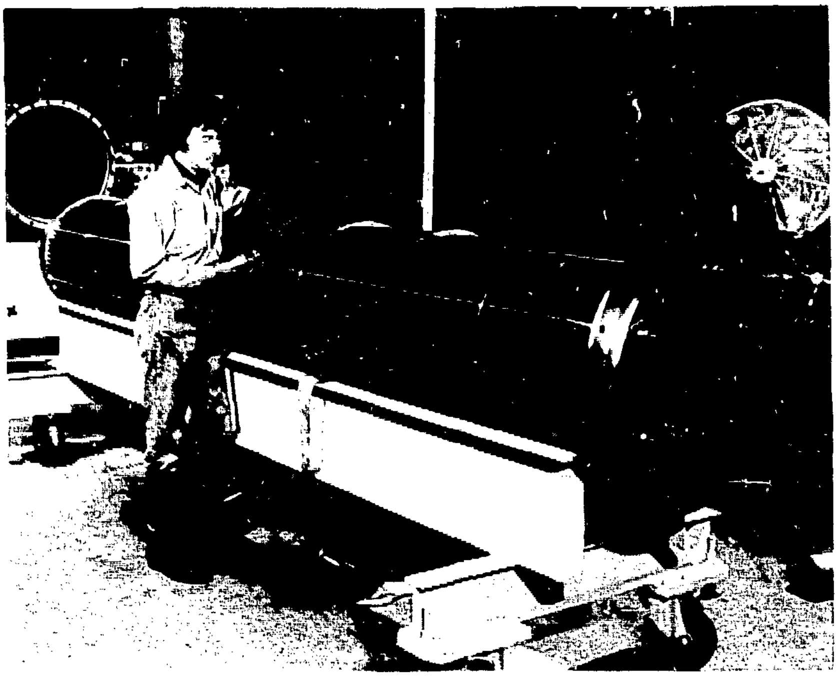

Fig. 5b. Test Exchanger in eight-crosspass, full tube bundle configuration. ANL Neg. No. 113-81-43.

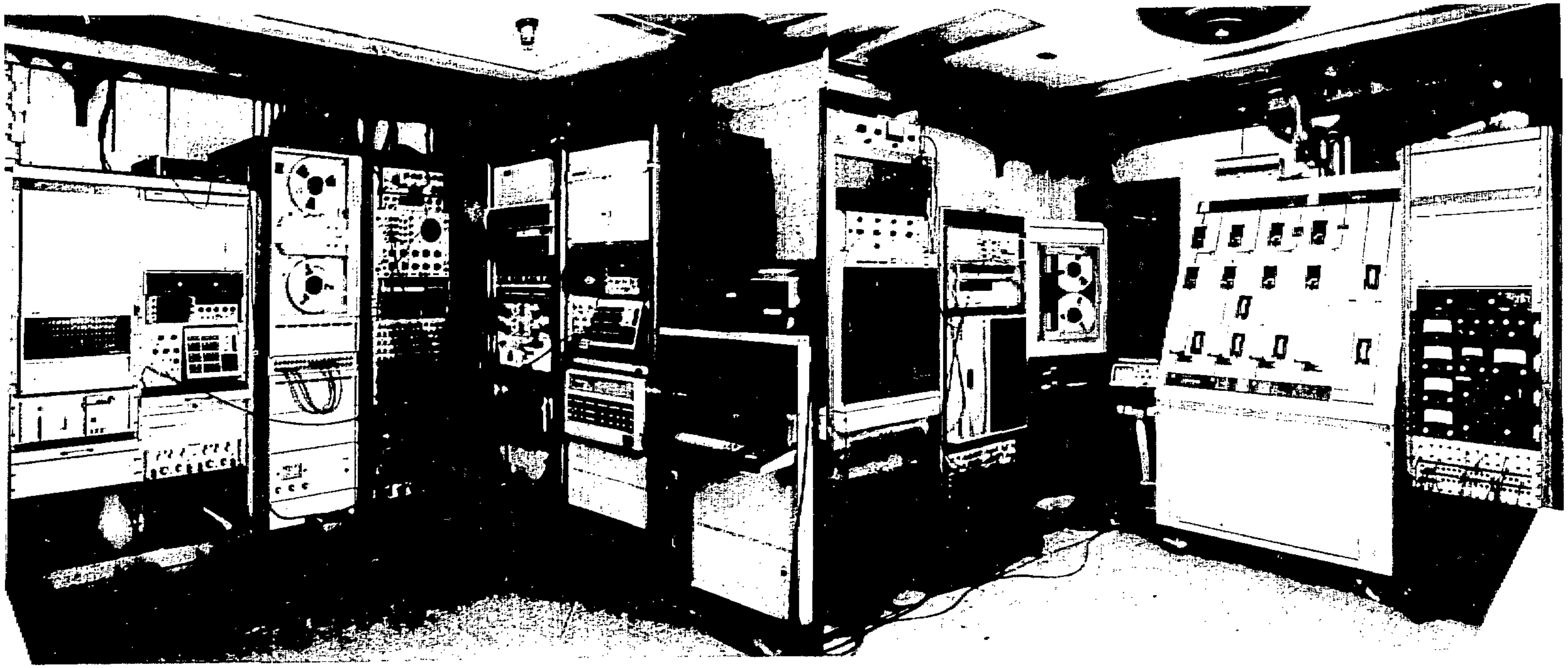

Fig. 6. Data acquisition/processing and facility control room. ANL Neg. Nos. 113-78-50 and 113-78-51.

ARGONNE NATIONAL LABORATORY
FLOW INDUCED VIBRATIONS

Program staff:

M. W. Wambsganss, Manager
S. S. Chen
H. Halle
J. A. Jendrzejczyk
T. M. Mulcahy

NAME Martin W. Wambsganss

PRESENT POSITION

Senior Mechanical Engineer and
Manager, Vibrations Analysis Section
Components Technology Division
Argonne National Laboratory

EDUCATION

Valparaiso University	BSME	1960
Purdue University	MSME	1961
Purdue University	PhD	1966

EXPERIENCE

Experienced in the areas of structural dynamics and vibrations, fluid mechanics, systems analysis, experiment design, testing, and the definition and coordination of research and development-test programs.

Joined the staff of Argonne National Laboratory in 1965 and since that time has focused on studies of flow-induced vibration. Has contributed to the understanding and characterization of fluid excitation mechanisms and fluid/structure interaction, the development of pertinent analysis methods, and the design evaluation (via analysis and/or test) of reactor internal and plant components for the Argonne Advanced Research Reactor, EBR-II, FFTF, and CRBR.

Before joining Argonne, from 1961 to 1963, employed as a Research Engineer in the Research and Development Division of the Johnson Service Company, Milwaukee, Wisconsin. At Johnson Service performed dynamic analyses of pneumatic control systems and participated in the development of fluidic amplifiers and related components.

Former consultant to the advisory Committee on Reactor Safeguards; Member of the ASME and IASMiRT; Member ASME Task Force on Vibration Monitoring of Nuclear Plant Heat Exchangers; and Member of ASME Technical Committee on Flow-Induced Noise and Vibration, Noise Control and Acoustics Division.

NAME Shoei-sheng Chen

PRESENT POSITION

Senior Mechanical Engineer
Components Technology Division
Argonne National Laboratory

EDUCATION

National Taiwan University	BSCE	1963
Princeton University	MSCE	1966
Princeton University	MA	1967
Princeton University	PhD	1968

EXPERIENCE

Joined the staff of Argonne National Laboratory in 1968 and has conducted extensive studies on flow-induced vibration. Contributed to the analysis technique, mathematical model, testing, and understanding of the complex flow-structure interaction phenomena. A short-term Technical Cooperation Expert for the International Atomic Energy Agency to assist several countries in the area of flow-induced vibration in 1977, 1979 and 1980.

Member of the ASME, ASA, AAM and I. Diag. E.; Editorial Adviser of Journal of Condition Monitoring and Fault Diagnosis; active in the Pressure Vessel and Piping Committee, Nuclear Engineering Division; Chairman of Subcommittee on Structural Dynamics, OAC Committee, Pressure Vessel and Piping Division, ASME; and Member of ASME Technical Committee on Flow-Induced Noise and Vibration, Noise Control and Acoustics Division.

NAME Henry Halle

PRESENT POSITION

Mechanical Engineer
Components Technology Division
Argonne National Laboratory

EDUCATION

Illinois Institute of Technology BSME 1949

EXPERIENCE

Principally involved with experimental work: test planning, design of test articles and facilities, instrumentation, test performance, data analysis and correlation with theory. For the past eleven years investigated the flow-induced vibration response of model and prototype reactor and industrial plant components such as heat exchanger tubes and thermowells. Served Argonne National Laboratory as principal investigator for on-site and as technical representative for off-site experimental programs.

Previously engaged in diverse fields such as stress and deformation analysis, fluid mechanics, and heat transfer, and prior to joining Argonne in 1964, machine design, cryogenics, and plasma arc technology.

Member of the ASME, AIAA, and SESA. Member Vibration Task Force, Heat Transfer Research, Inc.

NAME Joseph A. Jendrzejczyk

PRESENT POSITION

Mechanical Engineer
Components Technology Division
Argonne National Laboratory

EDUCATION

DeVry Technical Institute Associate of Applied Science 1957

EXPERIENCE

Experienced in the planning and design of experiments; development of special-purpose dynamic transducers and measurement techniques; design and development of vibration excitation devices; fabrication of test articles and their installation in the test facilities; operation of test facilities; and acquisition, processing, interpreting, and reporting of test data.

Joined Argonne National Laboratory in 1958 and, from 1958 to 1965, worked in the Remote Control Division on electronics and servo controls in support of the design and development of manipulators for use in hot cells. From 1965 to date, worked on the experimental phase of flow-induced vibration programs, currently within the Components Technology Division. The programs involve both fundamental studies and component design evaluations in support of the LMFBR (Liquid Metal Fast Breeder Reactor) and LWR (Light Water Reactor) programs and of industrial heat exchanger design.

Member of the American Society of Mechanical Engineers. Recipient of 1981 University of Chicago Award for Distinguished Performance at Argonne National Laboratory.

NAME Thomas M. Mulcahy

PRESENT POSITION

Mechanical Engineer
Components Technology Division
Argonne National Laboratory

EDUCATION

University of Illinois	BS	1961	Engineering Mechanics
University of Illinois	MS	1963	Theoretical and Applied Mechanics
University of Illinois	PhD	1966	Theoretical and Applied Mechanics

EXPERIENCE

Active in many phases of analytical and experimental mechanics research at all levels: definition, design, participation, and direction. After joining Argonne in 1973, developed prediction methods for the inelastic thermal ratcheting response of structural components. Since 1973 have been involved in flow-induced vibration (FIV) research of LMFBR and LWR reactor components including: consultation with the FFTF and CRBR projects to assess potential for FIV of component designs, performance of several FIV scale model tests of FFTF and CRBR components, and basic analysis and experiment on the response and damping of rods in parallel and crossflow in order to establish design guidelines.

Before joining Argonne was an Engineering Mechanics faculty member at the University of Illinois at Chicago Circle teaching most of the courses in solid mechanics and dynamics at the undergraduate and graduate level. Research included: photoelastic stress analysis of pressure vessel intersections for design codes formulation, development and application of phenomenological models of the plastic response of metals, and evaluation of the effectiveness of clinical and surgical prostheses utilizing custom dynamic force transducers.

Currently an active member of ASME and SESA, and a member of the Structural Dynamic Working Group preparing a flow-induced vibration Appendix to the ASME Code.

FLOW INDUCED VIBRATION PROGRAM
COMPONENTS TECHNOLOGY DIVISION
ARGONNE NATIONAL LABORATORY

PROCEDURES FOR INITIATING WORK FOR SPONSORS OTHER THAN THE U.S. DEPARTMENT OF ENERGY

I. PRELIMINARY DISCUSSIONS

- Preliminary discussion is conducted between technical staff of ANL and the organization seeking assistance.
- Non-federal organizations supporting the work with non-DOE funds are informed that they may request the benefit of a class waiver for patent and data rights. The organization must acknowledge in writing to ANL that they have been made aware of the availability of the waiver and they must specify whether or not they are requesting the benefit of a class waiver.
- Preliminary, informal document is prepared and submitted to sponsoring organization detailing items covered in discussion, and outlining scope of effort.

II. FORMAL PROPOSAL

- A formal proposal is prepared based upon the work scope agreed to by the sponsor and ANL.
- Following ANL Management review and approval, the proposal is sent to the U.S. DOE and the sponsor for their review and approval. The letter specifying the sponsor's intention relative to the request for the benefit of a class waiver for patent and data rights should accompany the Laboratory's submittal of the formal proposal to DOE.

III. PROPOSAL REVIEW

- The U.S. DOE and the sponsor review the proposal.
- The sponsoring organization is notified when the U.S. DOE has completed their review. Work for organizations other than the U.S. DOE may be undertaken by the Laboratory with the approval of the U.S. DOE.

IV. CONTRACTUAL AGREEMENT

- Work for other federal agencies is conducted by means of an interagency agreement between the agency and the U.S. DOE.
- Work for non-federal organizations is conducted by means of an agreement between the organization and ANL. ANL standard agreements address U.S. DOE and ANL requirements which must be met.

V. US DOE REVIEWS CONTRACTUAL AGREEMENT

- All agreements into which ANL enters require prior U.S. DOE review and approval.

VI. BEGIN PROJECT WORK

- Work commences upon execution by the sponsor and ANL of the agreement.