UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

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MEMORANDUM FOR: Harold Denton, Director
Office of Nuclear Reactor Regulation

FROM: Robert B. Minogue, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER 119 DEVELOPMENT OF BEST-ESTIMATE COMPONENT CODE K-FIX (3D, FLX)

I. INTRODUCTION

A. Need for the K-FIX (3D, FLX) Component Code

There are many two-phase flow processes in reactor components which must be analyzed in more detail than can be accomplished by a systems code. Such processes include the details of flow near a break in a pipe, the behavior of injected ECC water into the downcomer or the upper plenum of a PWR, the initial mass and energy flow through a break into the containment, the hydraulic forces on the PWR core barrel caused by a large break in a pipe, and others. In order to study such processes, the Advisory Committee on Reactor Safeguards (Ref. 1), the American Physical Society (Ref. 2), and the NRC Office of Nuclear Reactor Regulation (Ref. 3) requested the development of a calculational tool. The K-FIX (3D, FLX) best-estimate component code was developed to meet these requests.

B. Evolution of K-FIX (3D, FLX)

The K-FIX (3D, FLX) Code evolved from the KACHINA Code (Ref. 4). The first, two-dimensional version, K-FIX, was issued in 1977 (Ref. 5). K-FIX used the implicit multifield calculational technique developed for the KACHINA code, but differed from KACHINA in that it implicitly coupled phase transition and interfacial heat transfer to the fluid dynamics in the iteration calculation for the pressure. The fully implicit exchange also led to significant reduction in computation time.

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The 2-D version of K-FIX was then extended to 3-D (Ref. 6) to achieve the goal of having this two-phase flow dynamics code perform detailed, state-of-the-art safety calculations in reactor system components. The 3-D capability was especially needed to calculate the asymmetric dynamics within the reactor vessel shortly after a cold-leg break. This latter problem involves the coupled dynamics between fluid flow and structural motion. In order to calculate this fluid-structure interaction, the K-FIX (3D) code, which calculated 3-D flows and pressure waves within the fluid, was coupled explicitly to the FLX code (Ref. 7), which solves the three-dimensional elastic-shell equations in the solid structural material. The resulting calculational tool is called K-FIX (3D, FLX). The code was completed and released to the National Energy Software Center in 1980.

K-FIX (3D, FLX) replaces an earlier code, SOLA-FLX (Ref. 7), because K-FIX can calculate 3-D effects with a two-fluid hydrodynamic model, while SOLA-FLX was restricted to 2-D with a drift-flux hydrodynamic model.

II. DESCRIPTION OF K-FIX (3D, FLX)

A. K-FIX (3D) (References 5 and 6)

K-FIX (3D) solves the two-fluid conservation equations in three-dimensional geometry, in either R-θ-Z or X-Y-Z coordinates. Each fluid phase is described by its own density, velocity, and temperature. The six field equations for the two phases are coupled through mass, energy, and momentum exchange. The code is written in a highly modular form to be easily adaptable to a variety of problems. Thus, there are separate modules, or subroutines, for each of the inter-phase exchange terms. These subroutines can be easily changed as improved models become available.

The viscous stress, viscous work, and the heat conduction terms within each fluid phase, exist only in the 2-D option; they are omitted in the 3-D option.

Several boundary conditions are programmed in the code: no-slip rigid walls; free-slip rigid walls; prescribed inflow; and continuous outflow. The rigid walls are adiabatic or nonconducting.

The equations are solved using an Eulerian finite difference technique that implicitly couples the rates of phase transitions, momentum, and energy exchange to determination of the pressure, density, and velocity fields. The implicit solution is accomplished iteratively without linearizing the equations, thus eliminating the need for numerous derivative forms.

B. FLX

The FLX code module (Ref. 7) solves the standard three-dimensional linear-elastic shell equations (Ref. 8) in core barrel geometry. The top of the core barrel is modeled mathematically as a clamped or built-in boundary. The bottom of the core barrel is a free boundary on which forces and moments vanish; only lateral deflections are considered.

The shell equations are solved numerically by explicitly integrating a system of finite-difference equations. The shell is subdivided into many computational cells that collectively form a two-dimensional computing mesh. The circumferential dimension of each cell is constant, while the axial dimensions can vary from one row of cells to the next. The maximum value of the time-step is limited by inequality conditions obtained from a linear stability analysis.

C. K-FIX (3D, FLX)

The fluid and structure code modules are coupled together explicitly (Ref. 9). For each calculation cycle, the fluid pressure field is used to determine the differential pressures that drive the shell motion through the radial acceleration equation. The shell equations are often integrated for several time steps per fluid time step, because of their more restrictive stability criteria. After integration through a fluid time step, the shell radial motion is assigned as a boundary conduction to the fluid. The core barrel motion causes a fractional change in volume of the fluid cells adjacent to the core barrel, which is responsible for additional terms in the fluid conservation equations.

This coupling technique has been used successfully within one-, two-, and three-dimensional fluid-dynamic simulations. The results with one-dimensional fluid dynamics that exhibit axial, circumferential, and radial motion separately have been compared with analytic effects (Ref. 10).

III. K-FIX MODEL DEVELOPMENT AND ASSESSMENT

In preparing K-FIX to address blowdown loads, hydrodynamic models were developed and assessed for the most relevant physical processes expected to occur. These included models for: the propagation of pressure waves through a single-phase or two-phase liquid; the nonequilibrium vapor generation that might occur near a break in a pipe; and the critical flow through a break in a pipe, especially for subcooled conditions just upstream of the break.

A. Shock tube calculations with no phase transitions

Analytical solutions were obtained for wave propagation in a tube separated, by a diaphragm, into two regions initially filled with saturated water-steam mixtures at different pressures (Ref. 11). After the diaphragm is conceptually broken, analytic solutions followed the wave propagation for the case of no-phase transitions between the steam and water. The K-FIX code was applied to this problem and comparison with the exact analytical solution was excellent, as shown in Figure 1 (Ref. 12). Initial phase change models were also used in this study (Ref. 12) as well as in a previous study using the KACHINA Code (Ref. 13). This initial phase change model was soon replaced with a more comprehensive model to be described in the next section.

B. Vapor Generation Model

1. Description of Model (Ref. 14)

The rate of production of vapor mass per unit of the mixture volume is obtained from an equation describing the growth of a given number of bubbles. The rate of growth of the individual bubbles is controlled by conduction of heat within the liquid phase. The liquid thermal diffusivity and the average bubble radius used in this method take into account the combined effects of relative motion between phases and turbulence.

Stated differently, the model considers bubbles, with an initial radius determined by specification of initial values of the void fraction and number of nucleation sites. These bubbles grow at a rate close to but somewhat larger than the conduction controlled rate, because of the enhanced heat transfer from the bulk liquid to the bubble interface due to relative motion and turbulent fluctuations in the liquid. The bubbles continue to grow until they reach a critical size, determined by a Weber number criterion, and then begin to break up. From this point on, the typical bubble size is taken as the critical size and the number of bubbles is determined by the local void fraction.

Both the critical bubble size and the liquid thermal diffusivity depend on the relative velocity between the bubble and the surrounding liquid. The relative velocity is a combination of the difference between the average velocities of liquid and vapor and the contribution due to local turbulent fluctuations in the liquid. To minimize the complexities of the model, in view of the limited departure of the mechanical equilibrium calculations results from data, the model describes the combined effects of these contributing elements by expressing the relative velocity as a product of the liquid velocity and an empirically determined function of void fraction. This empirical function has been tested against critical flow data at both low and high pressures, as described below in Section III.B.2.

2. Comparison with Data

a) Single bubble

A two-dimensional calculation, with several computational cells, was made with K-FIX of the growth of a steam bubble in a 22°K superheated water pool. Comparison with data was good (see Figure 2). A similar calculation of a bubble condensing in a 9°K subcooled water pool was also made, with the evaporation model replaced by a symmetric condensation model. Comparison with data was equally good (Ref.15).

b) Critical Flow

i. Various nozzles at high pressure (Ref. 14)

A comparison of K-FIX calculations was made with critical flow data from two Semiscale tests and two Marviken tests. For each test, two calculations were made, one with the nonequilibrium vapor generation model described in the previous section and one with a very large vapor generation rate that produces, very nearly, continuous equilibrium states in which the liquid, saturation, and vapor temperatures are the same. The two Semiscale tests were S-02-4 with a Henry nozzle, and S-06-5 with a LOFT counterpart nozzle. The comparison of the measured and calculated flow rates for test S-06-5 are shown in Figure 3. Substantial nonequilibrium exists at an early time for these tests when subcooled water enters the nozzle and the nonequilibrium model agrees much better with the data than does the equilibrium model; the latter underpredicts the flow rate. Two-phase flow enters the nozzle at later times during which both equilibrium and nonequilibrium models give reasonable agreement with the data.

To investigate the predictive capability of the model at large scale, calculations were performed for two blowdown tests of a series made at the Marviken test facility. Test 1 featured a nozzle throat diameter 17 times larger than in the Semiscale tests while the nozzle used in Test 4 was 29 times larger. The comparison of K-FIX calculations with measured flow rates for Test 1 is shown in Figure 4. Subcooled water enters the nozzle for about 60 seconds. The nonequilibrium model gives a much better simulation of the data than does the equilibrium model.

ii. Various nozzles at low pressure (Ref. 16)

As a further check of the nonequilibrium vapor generation model, low pressure data from the MOBY DICK and BNL test facilities were analyzed. These tests involved fluid pressures between 0.1 and 0.4 mPa and temperatures around 373°K.

Extension of the nonequilibrium model to those low pressures was achieved by expanding the functional relationships for the turbulence intensity and the nucleation sites per unit volume to the lower pressure range. The calculational results obtained at higher pressures remain unchanged. Inlet pipe diameters to the test sections are 2 and 5 cm, for the MOBY DICK and BNL experiments, respectively. Detailed axial profiles of pressure and void fraction were measured in both facilities. A comparison of K-FIX results with measured axial pressure profile in MOBY DICK is shown in Figure 5. Similar good agreement was also obtained with the BNL data.

IV. FLX MODEL DEVELOPMENT AND ASSESSMENT

A description of the standard three-dimensional, linear-elastic shell equations solved by the FLX code is given in Reference 7. The FLX code has been checked by comparisons with a variety of analytic solutions (Refs. 17, 18, and 19). The comparisons include calculations of added mass effects, core barrel torsional vibration modes and frequencies, lateral vibration frequencies that include effects of both shear and bending, and breathing mode vibrations. Limited comparisons with small-scale test data have also been made (Ref. 20).

Two examples of comparison of FLX results with exact analytic solutions for core barrel geometry are given in Figures 6 and 7. The deflection profiles for the fundamental mode associated with the Timoshenko and classical beam equations' solutions and the FLX solution are compared in Figure 6. The FLX solution and the solution to the Timoshenko's equations are in quite good agreement.

The HDR test facility in Germany is investigating the loads on a core barrel, with an added mass ring on the bottom, during the initial stage of a cold-leg blowdown (Refs. 18 and 25).

The frequency and mode shape of HDR core barrel motion initiated by torsion about the longitudinal axis has also been determined analytically including the mass ring. The FLX calculation exhibits a torsional frequency of 22.0 Hz which agrees precisely with the analytic solution. The mode shapes are compared in Figure 7 at the end of one period and are also in excellent agreement.

V. K-FIX APPLICATIONS

A. Multidimensional Effects in Critical Flow (Ref. 21)

Flow multipliers are typically used to make one-dimensional critical flow calculations agree with data. Two-dimensional calculations were performed with K-FIX and compared with 1-D calculations, both without the use of any artificial flow multipliers or break models to see if multidimensional velocity distributions in the nozzle could explain the need for break flow mutipliers. The 2-D calculations gave good agreement with flow data while the 1-D calculations were typically higher than the data (Ref. 21). The calculated break flow multipliers needed to bring 1-D calculations in agreement with 2-D calculations for various length to diameter nozzle ratios are shown in Figure 8. The break flow multiplier curve does not represent a universal function for nozzles. In particular, it does not extend into very small L/D ratios typical of orifices. Nevertheless, calculations on a variety of practical entrance and exit geometries have shown that the corrective discharge multiplier shown in Figure 8 is correct to within a few percent.

B. PRETEST PREDICTIONS FOR HDR BLOWDOWN TESTS USING K-FIX (3D, FLX)

Under an agreement with the Federal Republic of Germany, the USNRC is supplying pretest prediction for selected blowdown load tests run on the HDR facility. Prior to performing these pretest predictions, a series of check-out and sensitivity calculations were run on HDR geometry with the K-FIX (3D, FLX) Code (Refs. 18 and 22). Pretest prediction results were submitted to both the USNRC (Ref. 23) and the HDR project (Ref. 24). The results of the two calculations were almost identical, but the one submitted to the NRC included the effect of two large pipes connected to the vessel.

The sample comparisons of these pretest prediction results with data measured in HDR Test V 31.1 are shown in Figures 9 and 10 for the pressure difference across the core barrel and for the local core barrel displacement, respectively (Ref. 25). The agreement of K-FIX (3D, FLX) results with the data for this test was excellent.

C. DISTRIBUTION OF WATER INJECTED INTO A PWR UPPER PLENUM

As part of the USNRC commitment to provide calculations for the 2D/3D International Refill/Reflood Program, K-FIX was used to calculate the multi-D distribution of water injected from a hot leg into the upper plenum of a German design PWR (Ref. 26). Calculations were first compared with proprietary KWU data on water injected into a full-size PWR upper plenum filled with air at room temperature and pressure. Considering the uncertainties in the data, the agreement of K-FIX was quite adequate. The calculations were then repeated, this time considering the effects of steam condensation on the injected water. Comparison of the air-water and steam-water calculations gave a first indication of the potential effectiveness of hot-leg ECC injection.

VI USE OF K-FIX FOR NRC SAFETY CONCERNS

K-FIX (3D, FLX) is a valuable calculational tool for addressing the Generic Issue A-2, effect of asymmetric blowdown loads on vessel supports and vessel internals. This code, along with HDR test results, can also be used for auditing and assessing vendor calculations of blowdown loads.

K-FLX (3D, FLX) can be used either with or without fluid-structure coupling to assess the vendor codes that either do or do not include this effect.

DF Ross/for

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Enclosures: Figures 1
through 10

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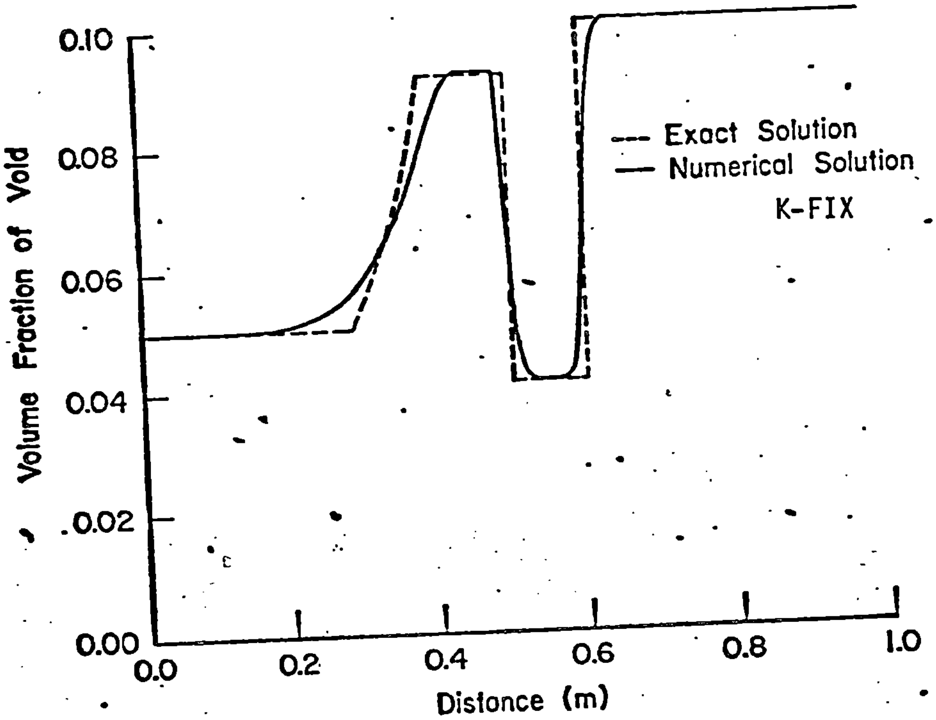


FIG. 1 Volume fraction of void profiles at t = 2 ms without phase change.

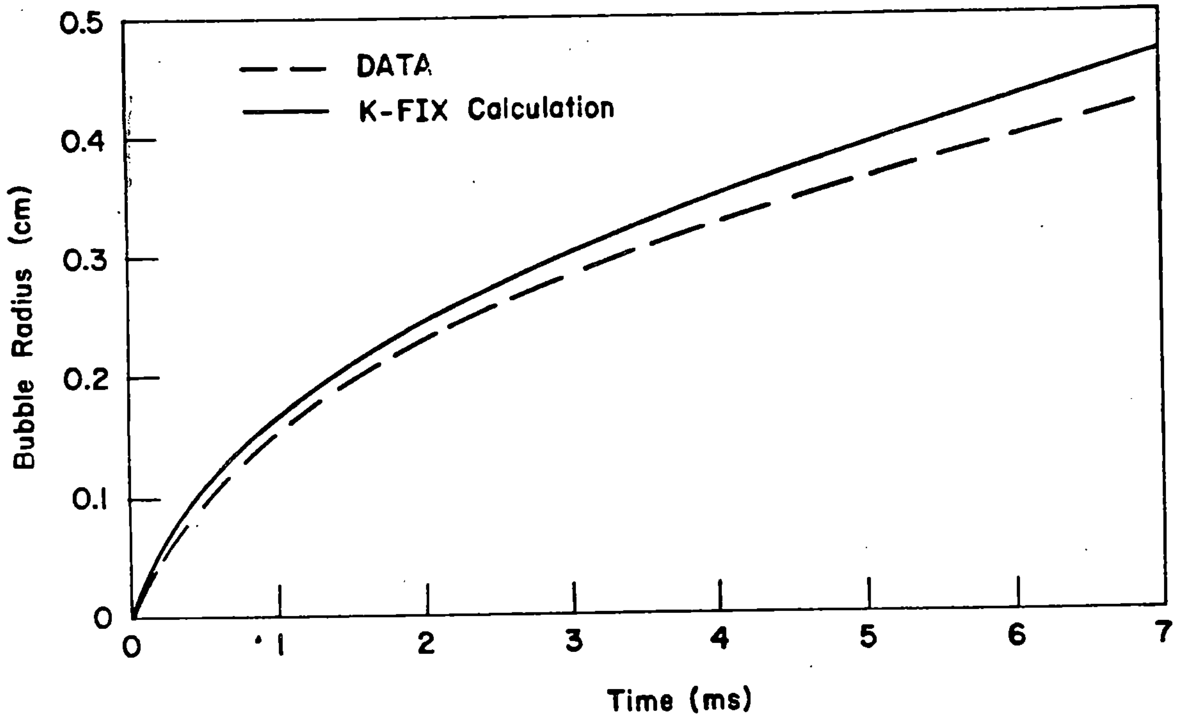


FIG. 2 Radius of an isolated steam bubble growing in a superheated water pool.

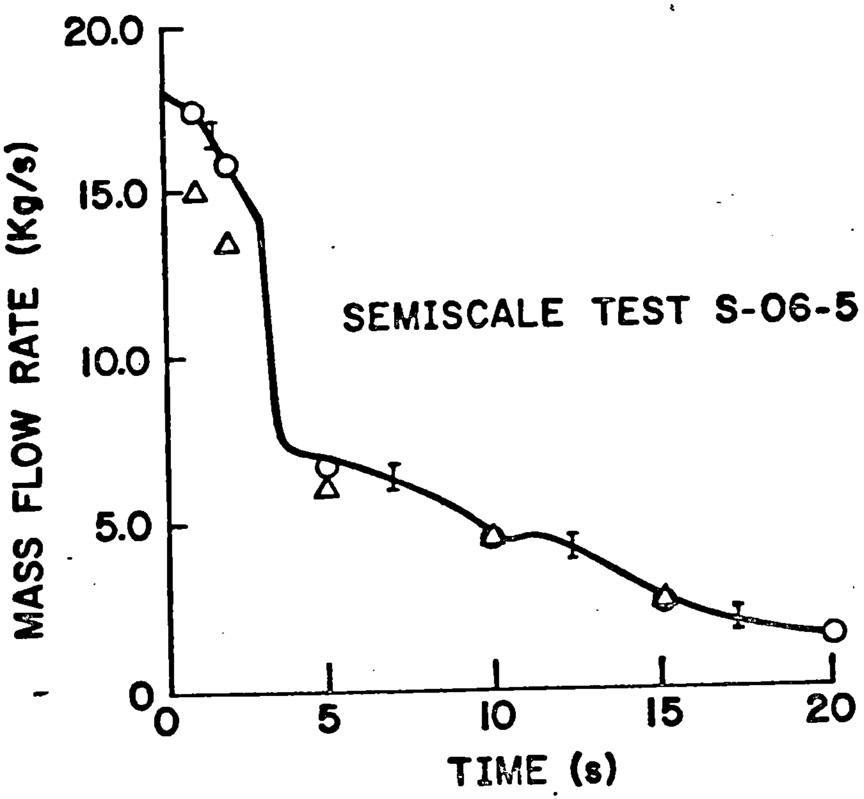


FIG. 3 Comparison of the measured mass flow rate (—) from Ref. 20, the computed mass flow rate with the nonequilibrium model (o), and the computed mass flow rate for equilibrium (Δ).

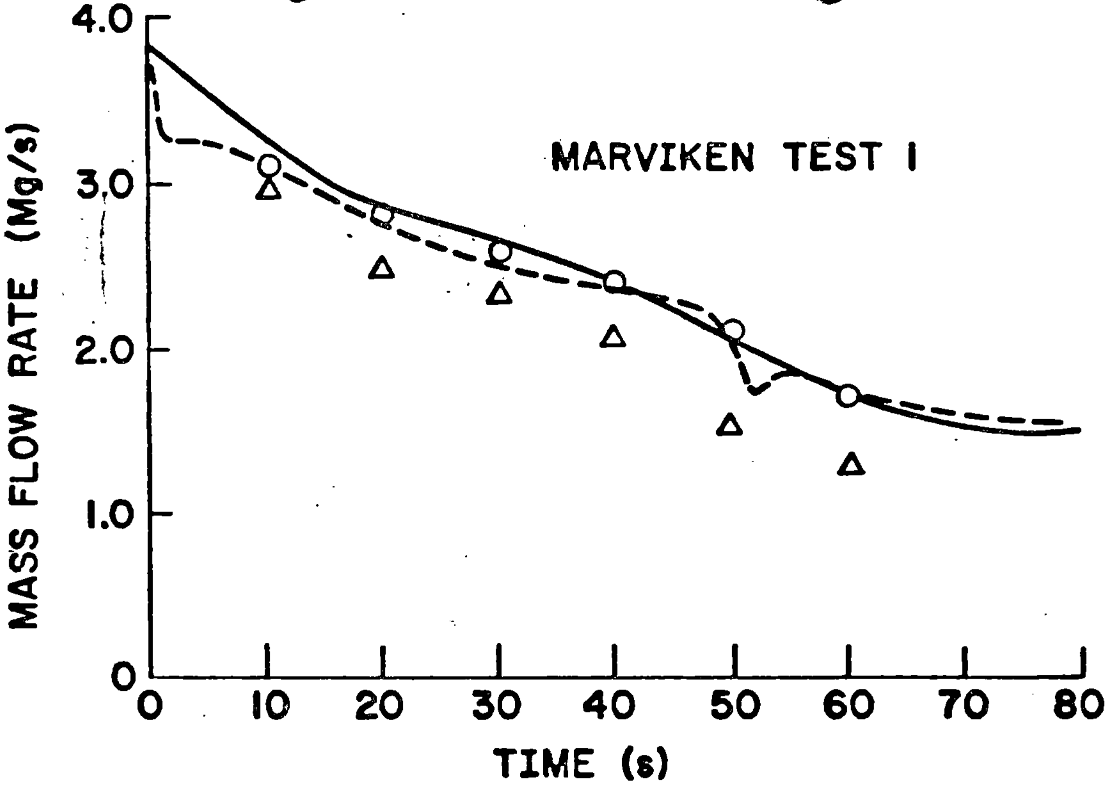


FIG. 4 Comparison of the measured mass flow rate determined by vessel mass change (—) and pitot-static velocity profile (---), the computed mass flow rate with the non-equilibrium model (o), and the computed mass flow rate for equilibrium (Δ).

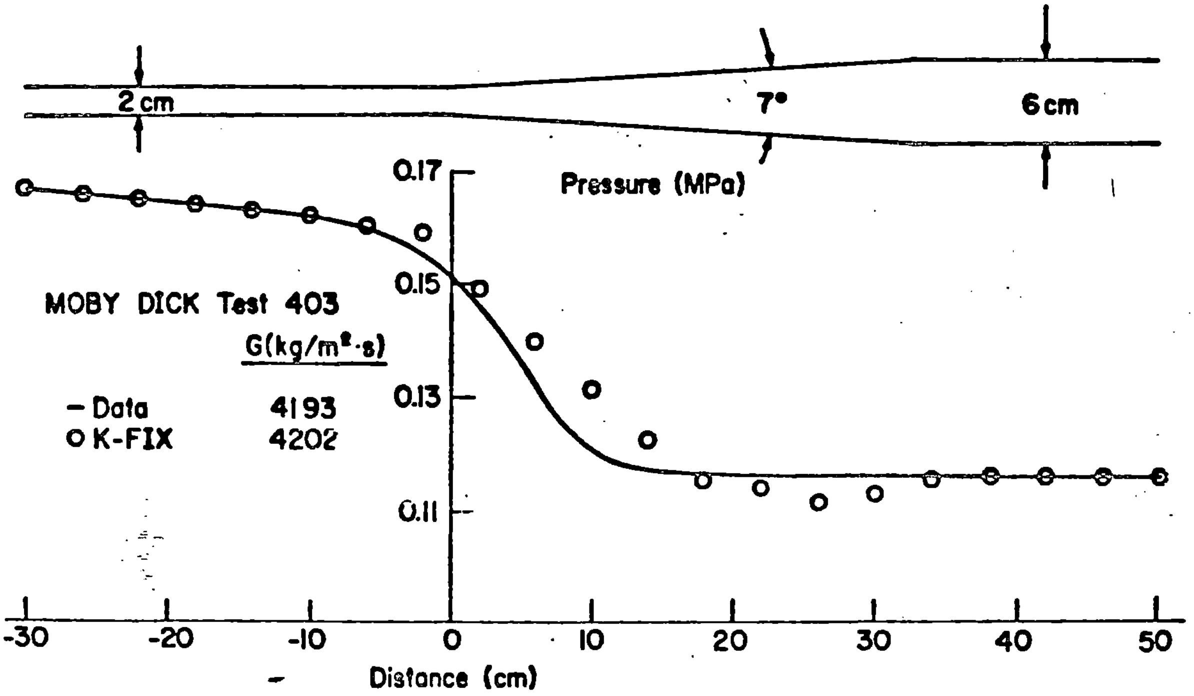


FIG. 5 MOBY DICK nozzle geometry and measured axial pressure profile for test 403. The calculated values were obtained for non-equilibrium (O) vapor production.

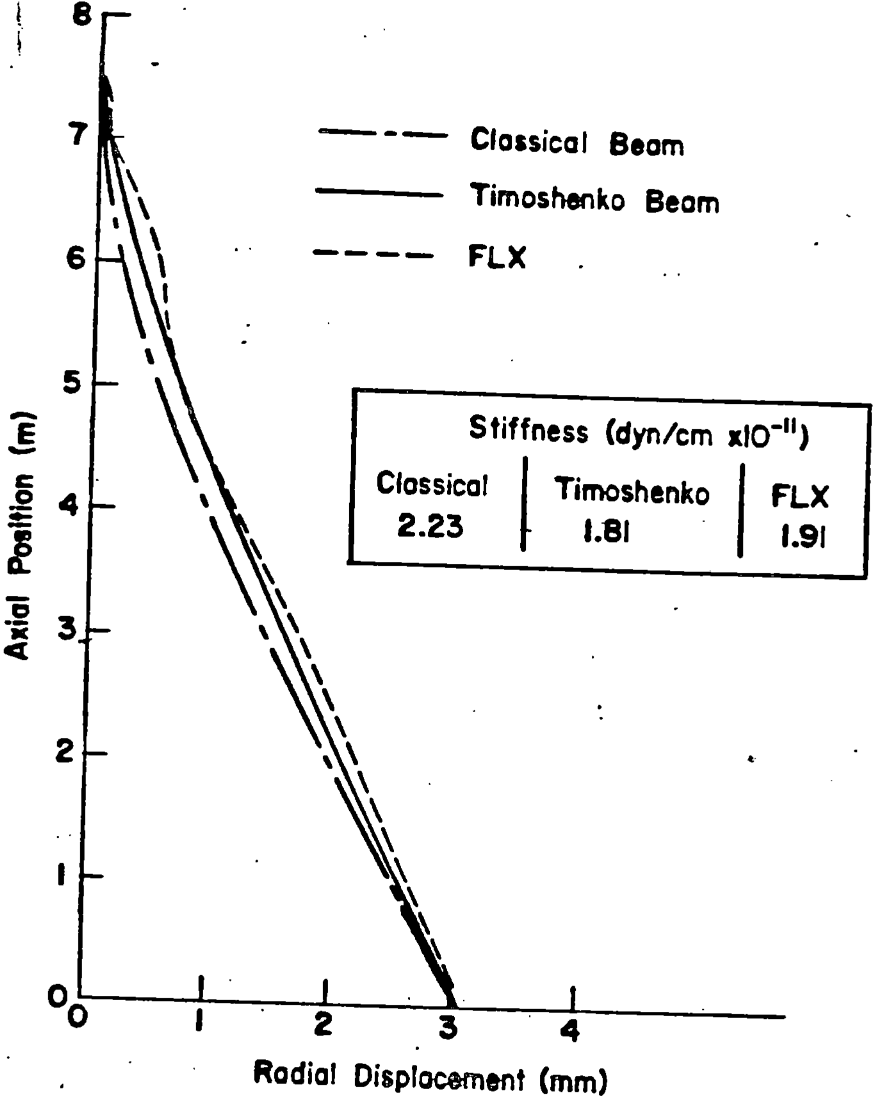


FIG. 6 Fundamental mode shape calculated with FLX compared with analytic results for solutions of the classical and Timoshenko beam equations.

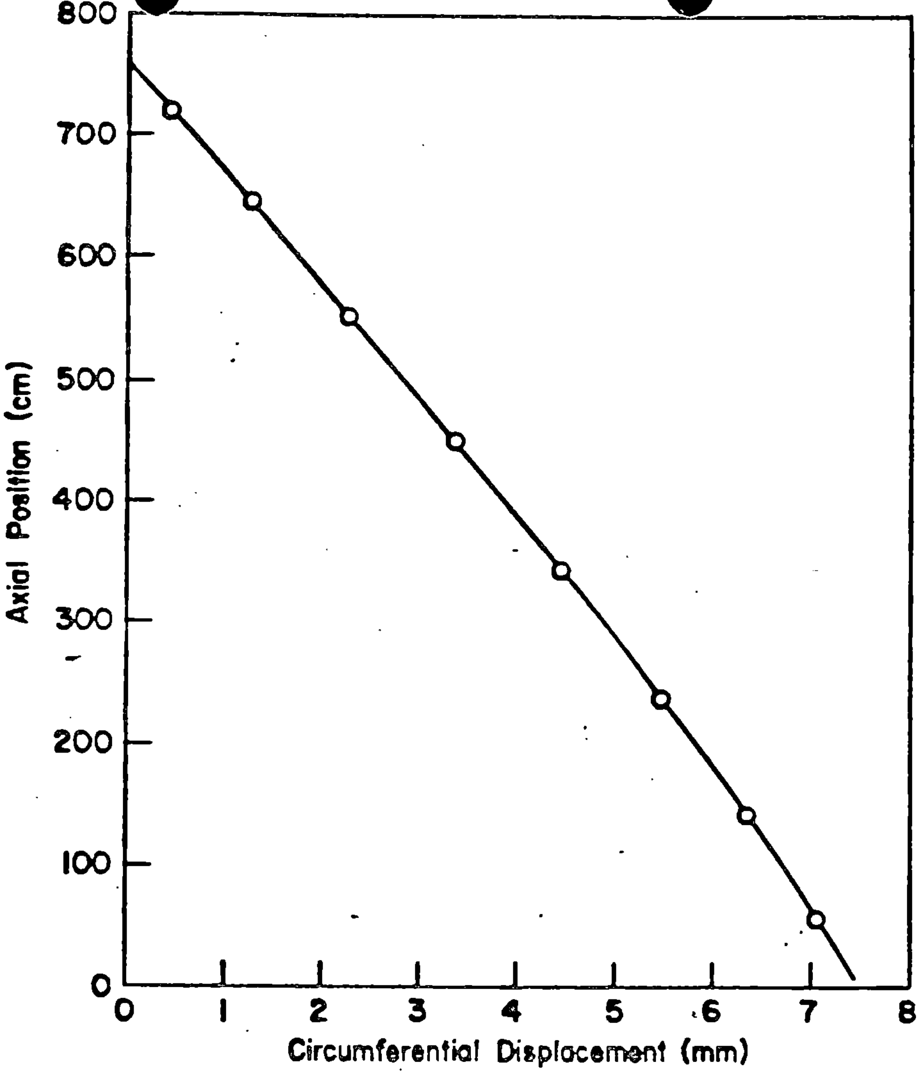


FIG. 7 Fundamental torsional mode shape calculated with FLX compared with the analytic result. The calculated torsional frequency is 22.0 Hz, which agrees precisely with the analytic solution.

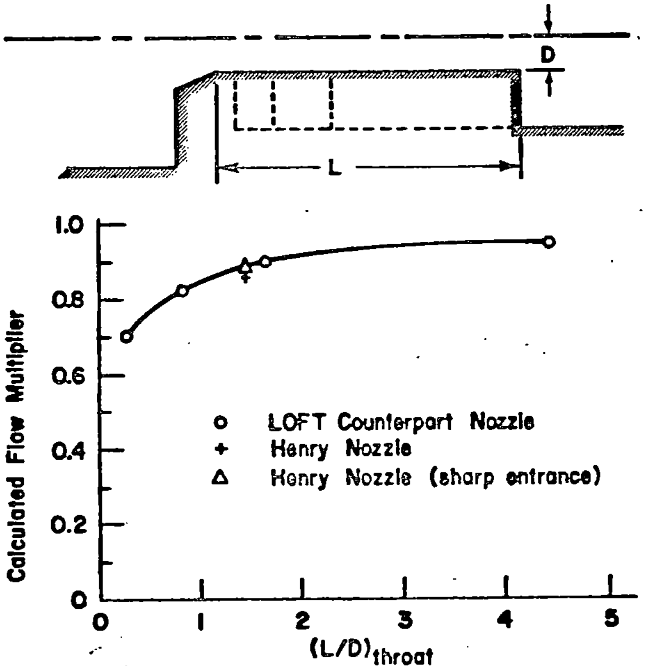
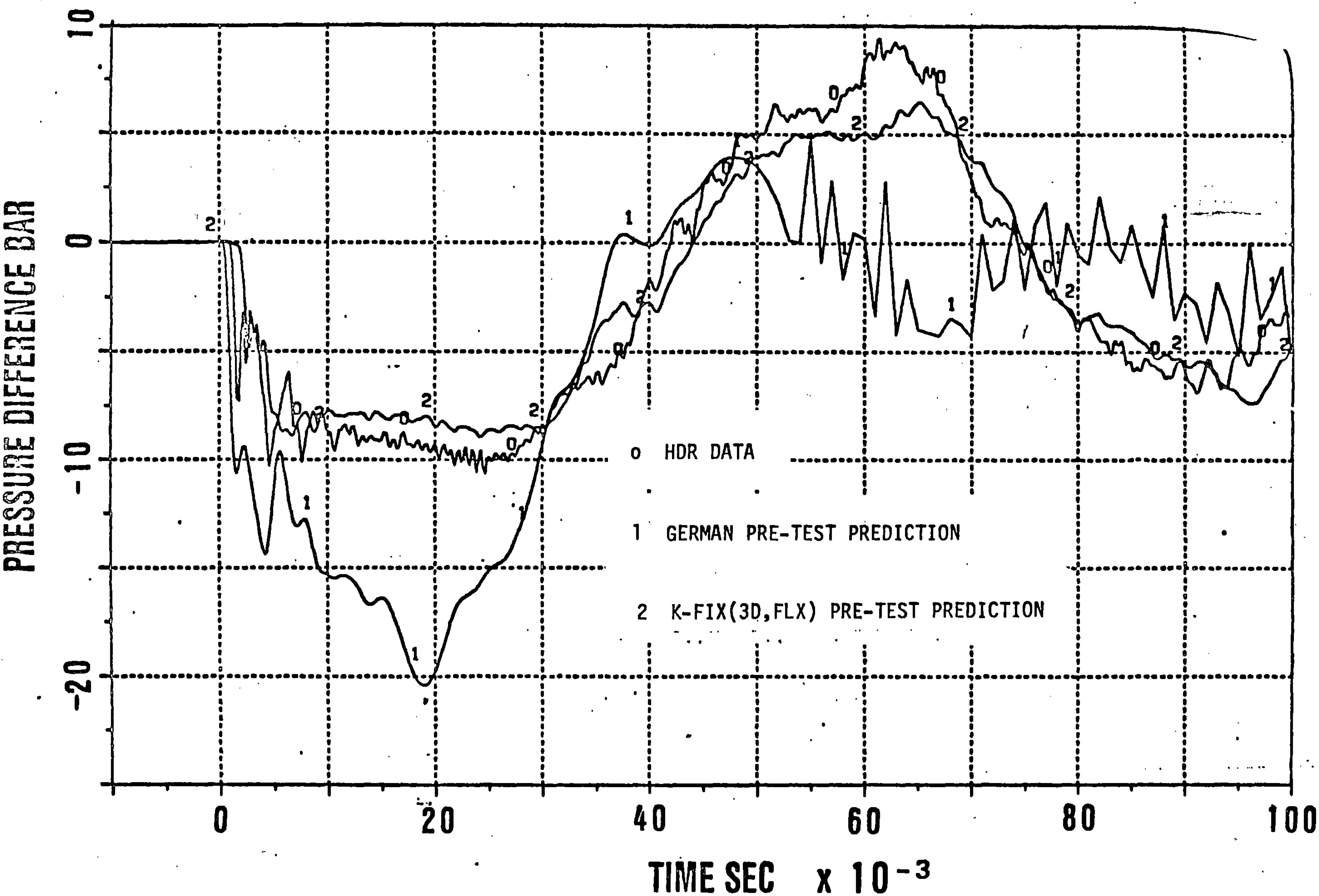
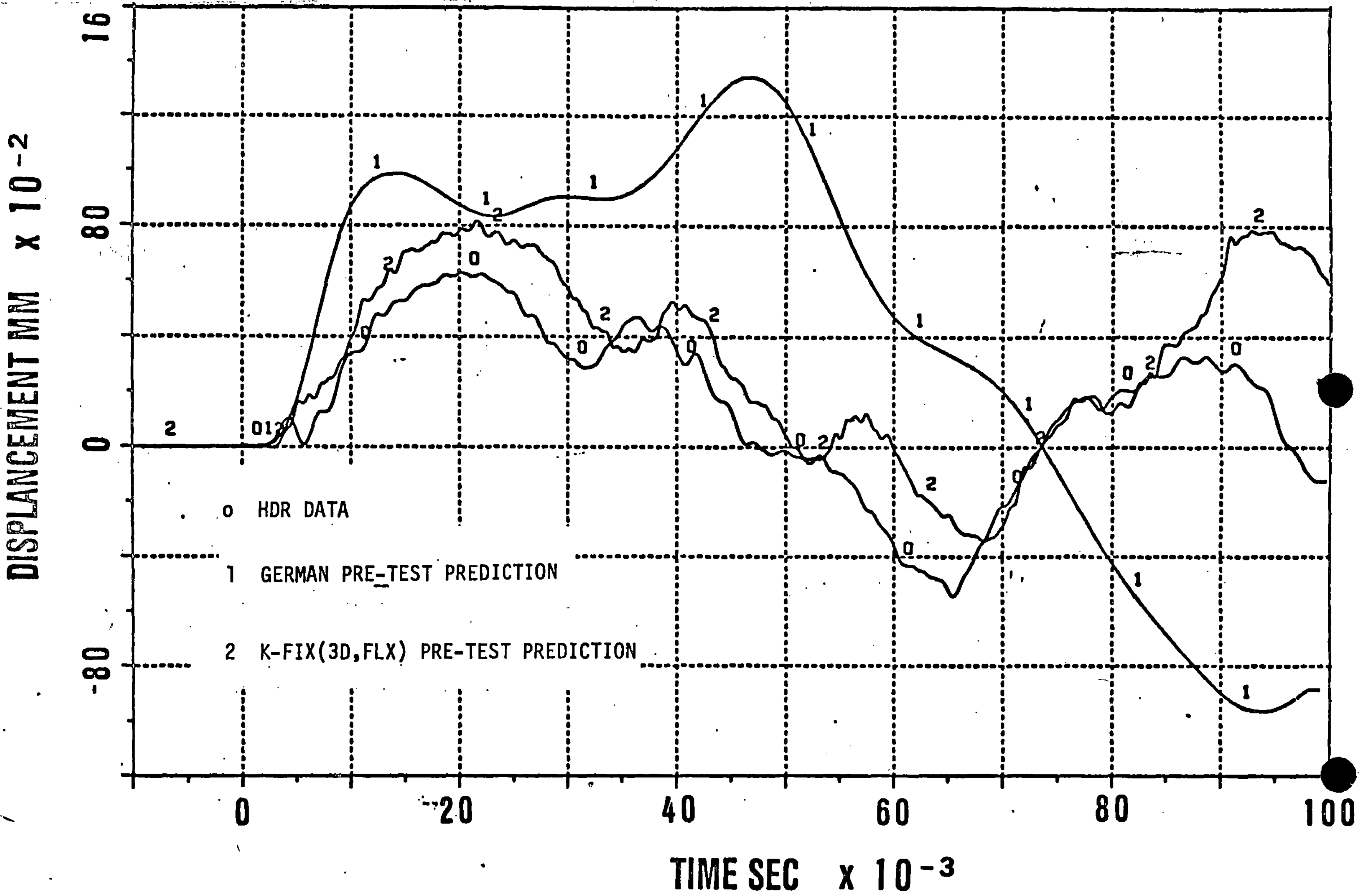


FIG. 8 Effect of throat length to throat diameter ratio



Comparison Between Experiment and Predictions for the Pressure Difference (V3 1.1)

FIG. 9



Comparison Between Experiment and Predictions for the Displacement (V31.1)

FIG. 10

REFERENCES

1. ACRS, "Review and Evaluation of the NRC Safety Research Program," NUREG-0392 (1977), NUREG-0496 (1978), NUREG-0603 (1979).

2. Report to the American Physical Society by the study group on LWR Safety, Rev. of Mod. Phys., 47 (Supp. 1), Summer 1975.

3. Letter, E. Case to S. Levine, "NRR Requirements for LOCA Analysis Computer Programs," 6/23/77 (RR-NRR-77-5).

4. A. A. Amsden and F. H. Harlow, "KACHINA: An Eulerian Computer Program for Multifield Fluid Flows," Los Alamos Scientific Laboratory report LA-5680 (1974).

5. W. C. Rivard and M. D. Torrey, "K-FIX: A Computer Program for Transient Two-Dimensional, Two-Fluid Flow," Los Alamos Scientific Laboratory report LA-NUREG-6623 (1977); also, "PERM: Corrections to the K-FIX Code," LA-NUREG-6623, Suppl. I (1978); also, "PRESBC: Pressure Boundary Conditions for the K-FIX Code," NUREG/CR-1536 (1980).

6. W. C. Rivard and M. D. Torrey, "K-FIX: A Computer Program for Transient, Two-Dimensional, Two-Fluid Flow: THREE D: An extension of the K-FIX Code for Three-Dimensional Calculations, LA-NUREG-6623, Suppl. II (1979).

7. J. Dienes et al., "FLX: A Shell Code for Coupled Fluid-Structure Analysis of Core Barrel Dynamics," NUREG/CR-0957, (1979).

8. S. Timoshenko, Theory of Plates and Shells, McGraw-Hill (1940).

9. W. C. Rivard and M. D. Torrey, "Numerical Simulation of 3-D Fluid-Structure Response," Proceedings of ANS Topical Meeting on Computational Methods in Nuclear Engineering, Williamsburg, Virginia. April 1979.

10. J. K. Dienes, "Comparison of Numerical and Analytical Shell Model Results," NUREG/CR-1201 (1979), p. 75. LASL Quarterly Progress Report, July 1-September 30, 1979.

11. B. Wendroff, "Shock Propagation in Variable Area Docts with Phase Changes: An Extension of Chisnall's Method," LA-UR-76-851 (1976).

12. W. C. Rivard and M. D. Torrey, "Numerical Calculation of Two-Phase Flow in a Shock Tube," Proceedings of the Specialists Meeting on Transient Two-Phase Flow, Toronto, Canada, August 1976; Report No. LA-UR-76-917 (1976).

13. W. C. Rivard and M. D. Torrey, "Numerical Calculation of Flashing from Long Pipes Using a Two-Field Model," LA-6104-MS (1975).

14. W. C. Rivard and J. R. Travis, "A Nonequilibrium Vapor Production Model for Critical Flow," Nuclear Sci. and Eng. 74, 40 (1980).

15. LASL Quarterly Progress Report for October-December 1976, LA-NUREG-6698-PR, 1977, p. 46.

16. LASL Quarterly Progress Report for October-December 1979, NUREG/CR-1516, 1980, p. 64.

17. LASL Quarterly Progress Report for July-September 1979, NUREG/CR-1201, 1979, p. 75.

18. W. C. Rivard, "Numerical Simulation of Hydroelastic Motion with Application to the Full-scale HDR Tests," Seventh WRSR Information Meeting, November 1979.

19. J. K. Dienes, "On the Cantilevered Timoshenko Beam," J. Appl. Mechanics, to be published, 1981. (Copy available in Analytical Models Br., RES.)

20. J. K. Dienes et al, "A Comparison of SOLA-FLX calculations with Experiments at Systems, Science, and Software," LA-NUREG-6752-MS, 1977.

21. J. R. Travis, C. W. Hirt and W. C. Rivard, "Multidimensional Effects in Critical Two-Phase Flow," Nucl. Sci. & Eng., <u>68</u>, 338 (1978).

22. W. C. Rivard and M. D. Torrey, "Fluid-Structure Response of a PWR Core Barrel During Blowdown," LA-7404, 1978.

23. Letter, W. C. Rivard to L. M. Shotkin, May 2, 1980, with attached calculation results.

24. Letter, W. C. Rivard to L. Wolf, 1/28/80, with attached calculation results.

25. L. Wolf, "Results of the First Preliminary Blowdown Tests with Reactor Pressure Vessel Internals at the HDR Facility," Paper presented at the Pressure Vessel and Piping Technology Conference, San Francisco, August 1980.

26. W. C. Rivard and M. D. Torrey, "The Deflection by Upper Plenum Columns of a Water Jet Issuing From an Outlet Pipe," 2D/3D Coordination Meeting, Munich, Germany, July 1980.

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Enclosures: Figures 1 through 10

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