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SERVICE EDUCATION TECHNOLOGY

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BY

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ABSTRACT

The loss-of-coolant accident (LOCA) can make structural demands on a nuclear power reactor system beyond normal requirements. Reliable predictions of the significant transient hydraulic loads are needed for the development of mechanical designs which will ensure coolability of the reactor core, even after such an accident.

Dynamic hydraulic forces during blowdown are exerted on coolant loop components. These forces include (a) the force $\int_{S_w} p\,\vec{n}\,dS$ which is due to fluid pressure that acts over the wetted surface and (b) the force $\int_{S_w} \vec{\tau}\,dS$ which is due to friction between the wetted surfaces and the fluid. S_w is the wall surface of the loop component, and dS is a surface element. The static pressure is represented by the symbol p, and $\vec{n}$ is a unit vector normal to the surface considered. The symbol $\vec{\tau}$ represents the force on the wetted wall due to the shear stress in the fluid. The dynamic forces can be calculated by performing these two spatial integrations; however, their evaluation may be difficult.

The preceeding two spatial integrals are two terms in the conservation-of-momentum equation. With one-dimensional subcooled-blowdown digital computer programs such as BURST (Blowdown Under a Rapid Sonic Transient) and WHAM (Water HAMmer), the calculation of the transient hydraulic force on a coolant loop component during blowdown is accomplished more easily and through only one spatial integration by evaluating the remaining terms in the momentum equation.

The calculation method was confirmed by experimental blowdown studies, which were carried out using two experimental facilities, the semiscale vessel and the pipe blowdown apparatus.

The information obtained using this calculational method is sufficiently reliable for use as forcing-function input for structural dynamics codes to establish the response of the components in a power reactor system to a loss-of-coolant accident.

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NOMENCLATURE FOR HYDRODYNAMIC EQUATIONS

Equations in the text are written in terms of a consistent set of units as follows: Dimensions are denoted by M = mass, L = Length, θ = time, $F = ML/\theta^2$ = force, and $H = FL = ML^2/\theta^2$ = energy.

Symbol	Description	Dimensions
$\vec{F}$	Force vector	F
$\vec{G}$	Mass velocity vector	$M/L^2\theta$
$\vec{n}$	Unit vector normal to surface considered	None
p	Static pressure	F/L^2
$\vec{p}$	The force per unit area acting on the surface element, dS -- a tensor quantity since it depends on the orientation of dS	F/L^2
S,dS	The surface of volume V and the magnitude of a surface element of S, respectively	L^2
S_w	Wall surface of loop component for volume V	L^2
S_1, S_2	Surfaces of volume V across which flow occurs	L^2
t	Time after the start of the transient	θ
V,dV	A fixed control volume for writing conservation laws and a volume element of V, respectively	L^3
v	Specific volume of fluid	L^3/M
ρ	Fluid density	M/L^3
$\vec{\tau}$	Force on wetted wall, due to shear stress in fluid, per unit wetted-wall surface area	F/L^2
$\vec{\psi}$	The body force vector per unit mass	$F/M = L/\theta^2$

SUBCOOLED-BLOWDOWN FORCES ON REACTOR-SYSTEM COMPONENTS: CALCULATIONAL METHOD AND EXPERIMENTAL CONFIRMATION

I. INTRODUCTION

If a large pressurized-water reactor should experience a severe loss-of-coolant accident, the reactor core and other system components would be subjected to large transient forces. Therefore, the mechanical designs of nuclear power reactor systems must be adequate to limit the movements of the reactor components and to ensure the coolability of the reactor core, even after such an accident. One part of the Loss-of-Coolant-Accident Analysis Program in support of the Loss-of-Fluid Test (LOFT) Integral Test Program involved (a) the development of a calculation method for predicting the dynamic hydraulic forces on reactor-system components during blowdown and (b) the confirmation of the calculational method with experimental measurements.

Dynamic hydraulic forces are exerted on reactor coolant-loop components. These forces include (a) the force $\int_{S_W} p \vec{n}\, dS$ which is due to fluid pressure which acts over the wetted surfaces and (b) the force $\int_{S_W} \vec{\tau}\, dS$ which is due to friction between the wetted surfaces and the fluid. The dynamic forces can be calculated by performing these two spatial integrations; however, their evaluation may be difficult.

As will be shown later, these two spatial integrals are two terms in the conservation-of-momentum equation[1,2,3]. With one-dimensional subcooled-blowdown digital computer programs such as BURST[1] (Blowdown Under a Rapid Sonic Transient) and WHAM[2] (Water HAMmer), the calculation of the transient hydraulic force on a coolant loop component during blowdown is accomplished more easily and through only one spatial integration by evaluating the remaining terms in the momentum equation.

The presentation in this report consists of two parts. In the first part is the development of the analytical expression for the calculation of the dynamic force on a fluid container. In the second part, calculated transient forces are compared with data from two experimental facilities, the semiscale vessel and the pipe blowdown apparatus. The report is concerned with the dynamic fluid forces during the subcooled portion of blowdown. Fluid forces that occur during the saturation portion of blowdown are not considered in this report.

II. ANALYTICAL EXPRESSION FOR FORCE ON FLUID CONTAINER

The development of the general analytical expression for force on a fluid container is based on the general vector form of the momentum equation[4]:

$$\underbrace{\frac{\partial}{\partial t}\left[\int_V \vec{G}dV\right]}_{\text{Temporal Acceleration}} + \underbrace{\int_S v\vec{G}\,(\vec{G}\cdot\vec{n})\,dS}_{\text{Spatial Acceleration}} = \underbrace{\int_S \vec{p}dS}_{\text{Surface Forces}} + \underbrace{\int_V \rho\vec{\psi}dV}_{\text{Body Forces}} \tag{1}$$

where the terms on the left represent the rates of change on fluid momentum and the terms on the right represent the forces acting upon the fluid.

The total surface, S, of a fluid element can be divided into the wetted surface, S_w, and the surfaces across which flow occurs, S_1 and S_2 (that is, $S = S_w + S_1 + S_2$). The surface integrals are then expressed as follows:

$$\int_S v\vec{G}\,(\vec{G}\cdot\vec{n})dS = \int_{S_1} v\vec{G}\,(\vec{G}\cdot\vec{n})dS + \int_{S_2} v\vec{G}\,(\vec{G}\cdot\vec{n})dS \tag{2}$$

$$\int_S \vec{p}dS = -\int_{S_1} p\vec{n}dS - \int_{S_2} p\vec{n}dS - \int_{S_w} p\vec{n}dS - \int_{S_w} \vec{\tau}dS. \tag{3}$$

The vector notation on the right-hand side of Equation (3) refers to the force on the fluid element acting upon its surroundings.

Forces on the wetted surface, S_w, are the only mechanisms for exerting forces on the walls of the container. These forces are:

$$\vec{F} = \int_{S_w} p\vec{n}dS + \int_{S_w} \vec{\tau}dS\ . \tag{4}$$

The substitution of Equation (4) into Equation (3) results in Equation (5).

$$\int_S \vec{p}\ dS = -\vec{F} - \int_{S_1} p\ \vec{n}\ dS - \int_{S_2} p\ \vec{n}\ dS \tag{5}$$

By substituting the expanded expressions for the surface integrals, Equations (2) and (5), back into the momentum equation, Equation (1), an alternate expression for the force on the container walls results:

$$\vec{F} = -\left\{ \frac{\partial}{\partial t} \int_V \vec{G} dV + \int_{S_1} v\vec{G} (\vec{G}\cdot\vec{n}) dS + \int_{S_2} v\vec{G} (\vec{G}\cdot\vec{n}) dS + \int_{S_1} p\vec{n} dS + \int_{S_2} p\vec{n} dS + \int_V \rho\vec{\psi} dV \right\} . \tag{6}$$

Equation (6) is the method for calculating transient forces on coolant-loop components during subcooled blowdown and is the subject of this report. The first term on the right-hand side of Equation (6) is temporal acceleration or the time rate of change of the total momentum of the fluid in the fluid element. The next two terms represent the rates of momentum influx and efflux by virtue of the bulk-fluid motion. The fourth and fifth terms represent pressure forces acting at the ends of the fluid element. The last term is the body force term. For subcooled-blowdown studies, the body force term is small and therefore was not included in the calculational results reported herein.

The application of this calculational method is illustrated in the next section, in which calculated fluid thrust forces are compared with experimental data. The purposes of these comparisons are to show the ability to model analytically and to predict correctly fluid thrust forces.

III. COMPARISON OF CALCULATED AND EXPERIMENTAL FLUID THRUST FORCES

The results presented in this section are for blowdown tests with the semiscale vessel and with the pipe blowdown apparatus. Two cases are presented for the semiscale vessel: one in which the vessel was void of internals and one in which internals were employed in the vessel to simulate the depressurization of a large pressurized-water reactor. In connection with the pipe blowdown apparatus, three cases are discussed: the fully open break, a break area equal to 30% of the cross-sectional area of the discharge pipe, and a 10% break area.

Two digital computer programs were employed in the prediction of the fluid thrust forces. The WHAM[2] (Water HAMmer) Code was used in connection with the semiscale vessel. WHAM accommodates flow-branching and multiple loops, and flow-branching is an important consideration in the semiscale vessel. The BURST[1] (Blowdown Under a Rapid Sonic Transient) Code was used in the prediction of fluid thrust forces on the pipe blowdown apparatus. BURST was developed as part of the Loss-of-Coolant-Accident Analysis Program. One of the reasons for the construction and operation of the pipe blowdown apparatus was to provide experimental data for testing the BURST Code.

1. SEMISCALE BLOWDOWN VESSEL WITHOUT INTERNALS

The first attempt to obtain experimental subcooled-blowdown fluid thrust data was made during blowdown studies with the semiscale blowdown vessel which is used in the Semiscale Blowdown and ECC Program. This vessel is shown in Figure 1. Experimental thrust forces in the vertical direction were calculated from the experimental pressures measured at locations P8 and P7 at the top and bottom of the vessel, respectively. As shown in Equation (7) this thrust force is the product of the vessel cross-sectional area (165.1 in.^{2}) and the pressure difference between the top and bottom of the vessel.

$$\text{Fluid Thrust Force} = 165.1\ (P8 - P7) \qquad (7)$$

The experimental subcooled-blowdown thrust forces for semiscale Test 704, in which the initial temperature and pressure were 540°F and 2330 psig, are given in Figure 2. For Test 704 an orifice was present in the discharge nozzle which had an area equal to 30% of the nozzle area. The calculated subcooled-blowdown thrust forces obtained through use of Equation (6) are also presented in Figure 2. The agreement is considered good, with respect to both the magnitude and the frequency of the fluid thrust forces.

Details concerning the WHAM calculational model are given in Figure 3. The back pressure and sonic velocity used in this WHAM calculation were 850 psig and 3460 ft/sec. The experimental and calculated pressures at the top and bottom of the vessel during the subcooled portion of blowdown are recorded in Figure 4.

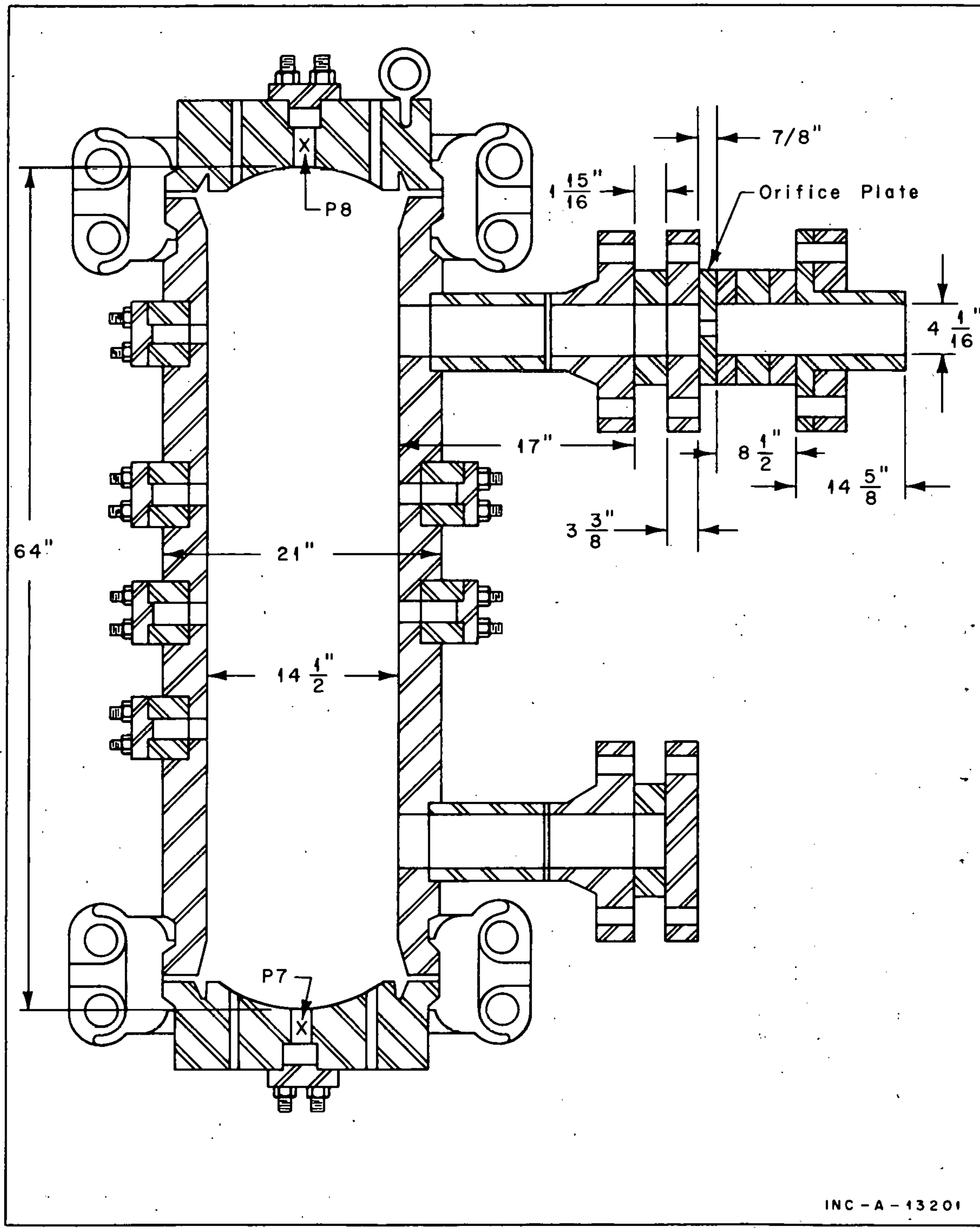


Fig. 1 Semiscale vessel.

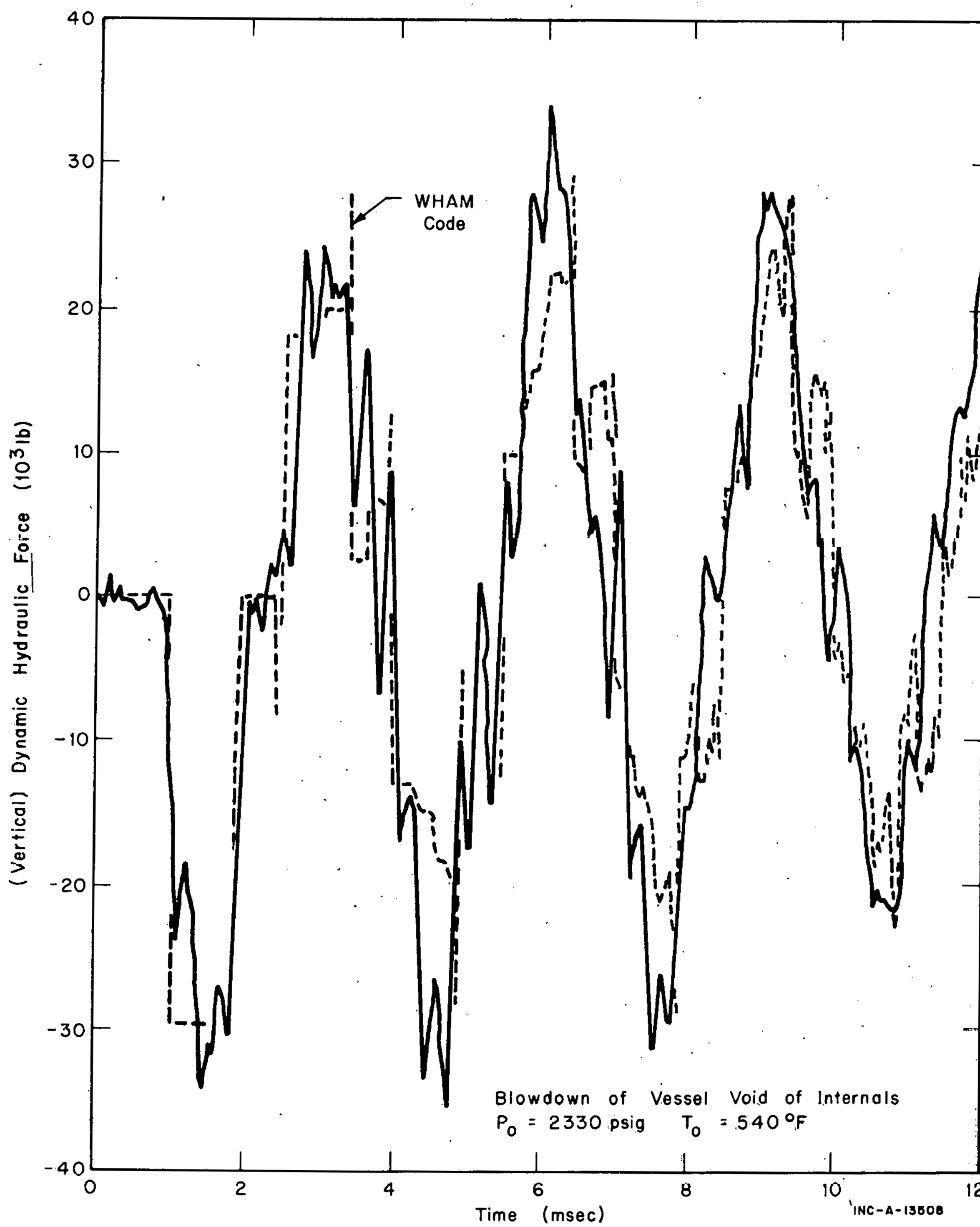
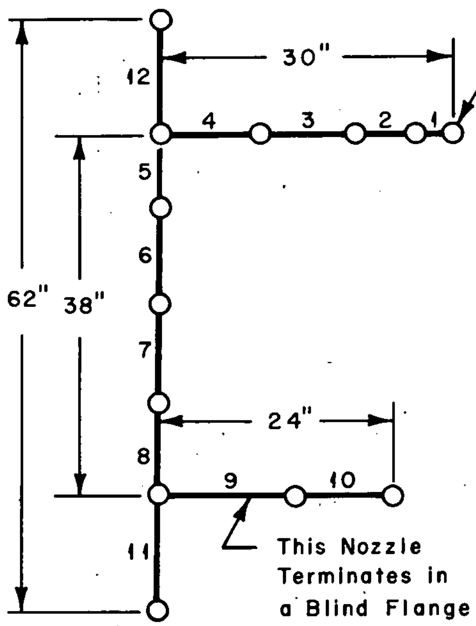


Fig. 2 Dynamic hydraulic forces during subcooled blowdown: comparison of experimental and WHAM-calculated forces for Semiscale Test 704.



Leg Number	Leg Length (in.)	Number of Segments in Leg	Area (ft^2)
1	4	4	0.090
2	6	6	0.090
3	10	10	0.090
4	10	10	0.090
5	8	8	1.147
6	10	10	1.147
7	10	10	1.147
8	10	10	1.147
9	14	14	0.090
10	10	10	0.090
11	12	12	1.147
12	12	12	1.147

THE LENGTH OF THE RIGHT-CYLINDER MODEL REPRESENTATION IS 62 INCHES. THE LENGTH OF THE ACTUAL VESSEL, WITH ITS DOMED HEADS, IS 64 INCHES.

IN THIS MODEL THE PRESENCE OF A TWO-INCH-THICK INSTRUMENT WASHER IN THE BOTTOM NOZZLE PRIOR TO THE BLIND FLANGE WAS OMITTED BECAUSE IT WAS NOT SIGNIFICANT.

Fig. 3 WHAM-code representation of semiscale vessel.

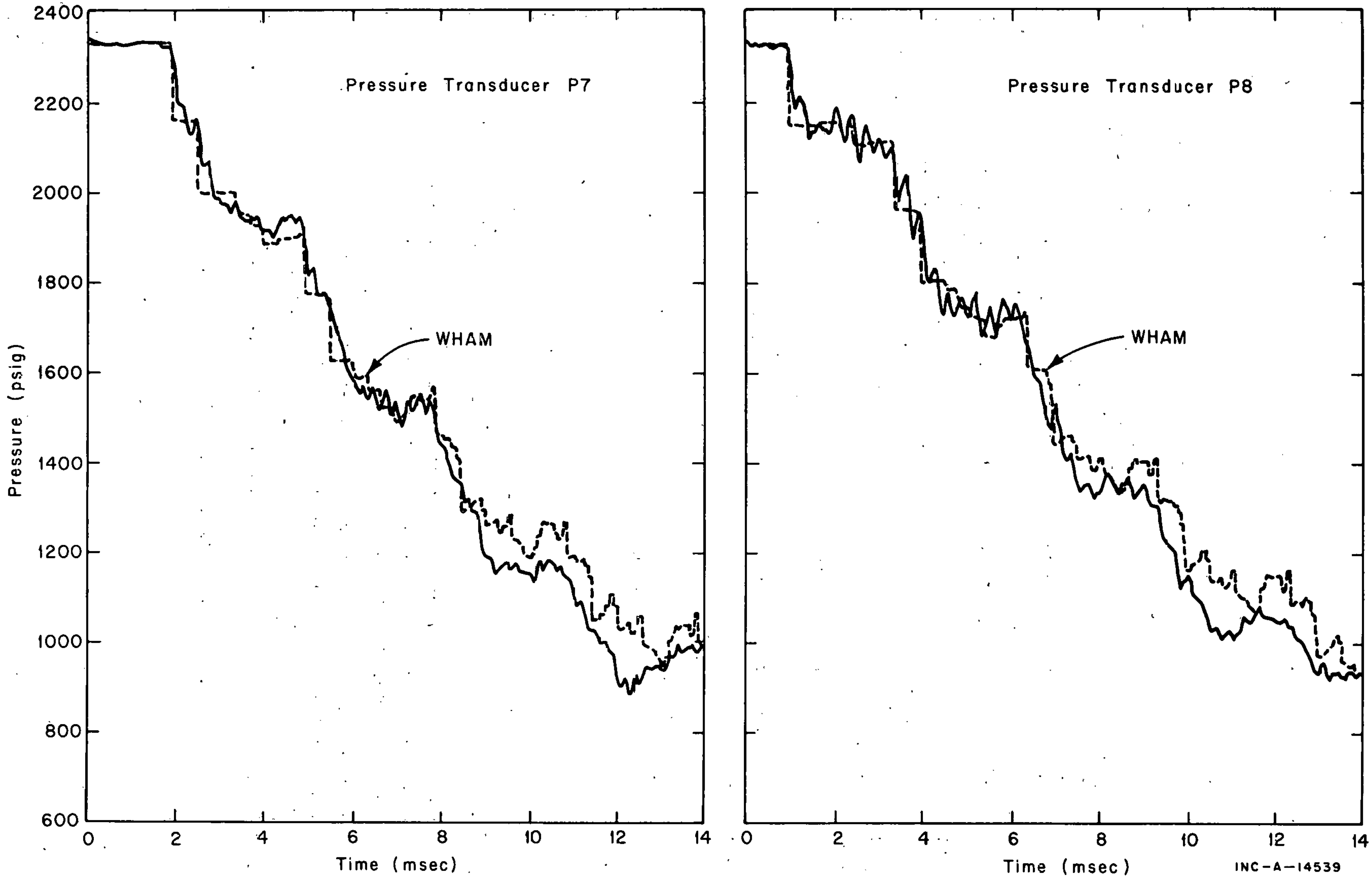


Fig. 4 Semiscale Test 704: comparison of experimental and WHAM-calculated subcooled-blowdown pressure transients

2. SEMISCALE BLOWDOWN VESSEL WITH INTERNALS

Blowdown studies with the semiscale vessel were extended to the more complex system shown in Figure 5. The vessel internals were designed to provide volumes and flow areas which would result in simulation of the depressurization of a large pressurized-water reactor. The subcooled-blowdown thrust forces in the vertical direction were developed from experimental pressure information. The experimental pressures from a transducer located at P8 in the vessel top head were assumed to represent also the transient pressure situation at the top of the simulated reactor core. Based on this assumption, the net cross-sectional area acted upon by the pressure information from the transducer at P8 is an area equal to the open area of the simulated reactor core, 78.5 in.^{2}. (Calculated information is presented at the end of this section to support the assumption regarding the limited transposing of experimental pressures in time and space, which is used in the development of experimental vertical thrust forces from available experimental pressures.)

The pressure information from a transducer located at P1 in the instrument nozzle which is opposite the flow-discharge pipe is assumed to be applicable to that portion of the vessel head which is exterior to the core support barrel. The area of this portion is 37.5 in.^{2}. The experimental pressures from the transducer located at P7 in the vessel bottom head are also applied to the bottom of the core support barrel and the simulated reactor core, which has a total area of 49.1 in.^{2}. The net cross-sectional area acted upon by the pressures measured at P7 is 116.0 in.^{2} (165.1 in.^{2} minus 49.1 in.^{2}). The experimental fluid thrust forces in the upward direction on the semiscale vessel with internals were obtained through use of Equation (8).

$$\text{Force} = 78.5\ P8 + 37.5\ P1 - 116.0\ P7 \qquad (8)$$

The experimental and calculated dynamic hydraulic forces for the subcooled portion of a blowdown from an initial pressure of 2290 psig are presented in Figure 6. The initial temperature in the plenum above the simulated reactor core was 540°F. The initial temperature of the bottom plenum, annulus, and nozzles was 505°F. An average temperature, 523°F, was assumed to exist in the simulated reactor core, because no temperature measurements were obtained there. The agreement between the calculated and experimental thrust-force curves is considered good, with respect to both the magnitude and the frequency of the fluid thrust forces.

The WHAM calculational model is described in Figures 7 and 8. The back pressure and sonic velocities employed in the calculations are recorded in Table I. The experimental and calculated pressure information for locations P1, P7, P8, and also P2 are presented in Figure 9.

As indicated earlier, the development of thrust forces from experimental pressures measured at locations P1, P7, and P8 was based on an assumption which involved the limited transposing of experimental pressures in time and space. Three sets of computed curves are presented in Figure 10 to support this assumption. In the WHAM calculational model, Figure 8, the locations P1, P7, and P8 are the lower end of leg 7, the lower end of leg 14, and the upper end of leg 21, respectively. In the development of the experimental thrust forces, the pressures measured at P1, P7, and P8 were assumed to

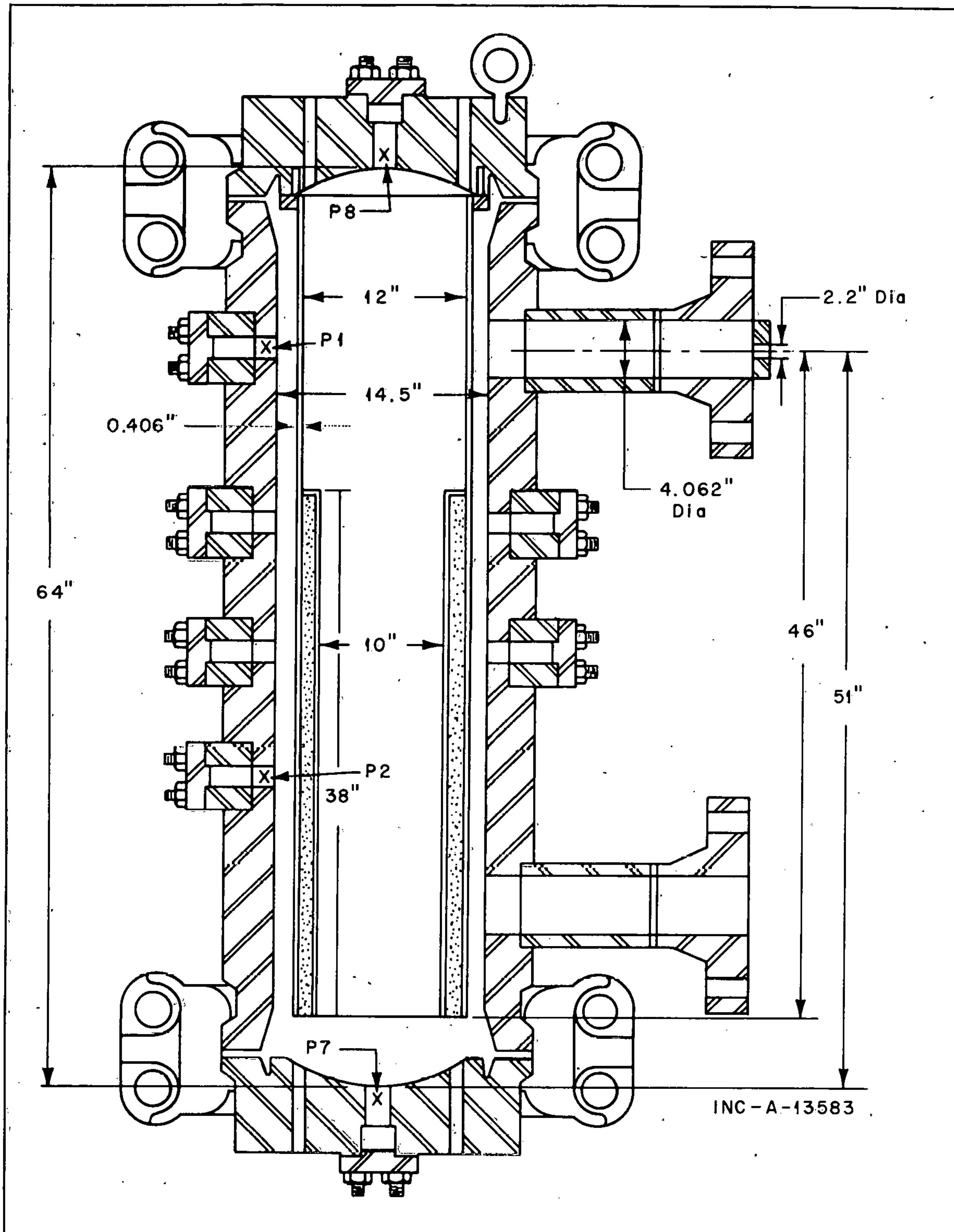


Fig. 5 Semiscale vessel with internals, to represent a large PWR configuration.

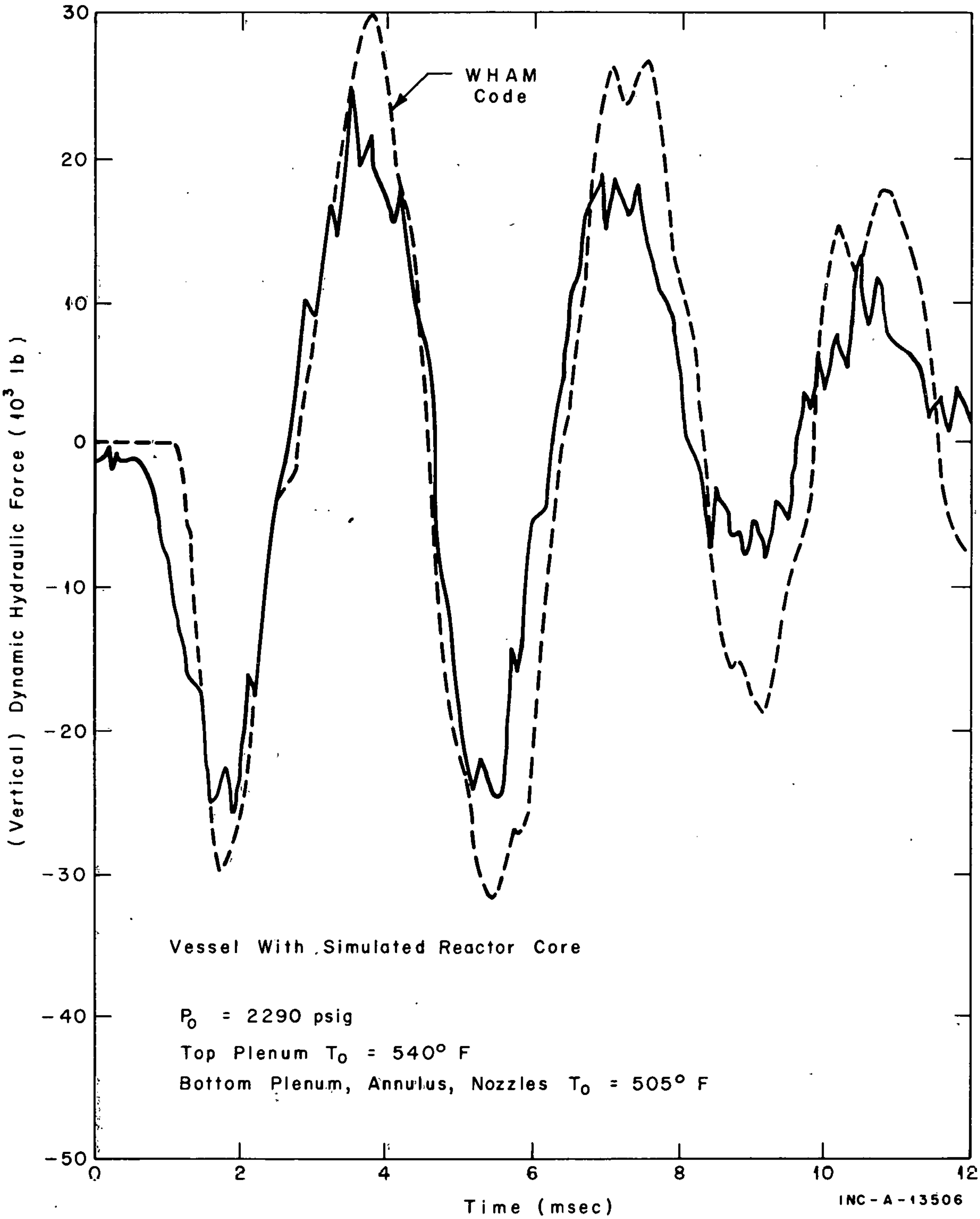


Fig. 6 Dynamic hydraulic forces during subcooled blowdown: comparison of experimental and WHAM-calculated forces for Semiscale Test 711.

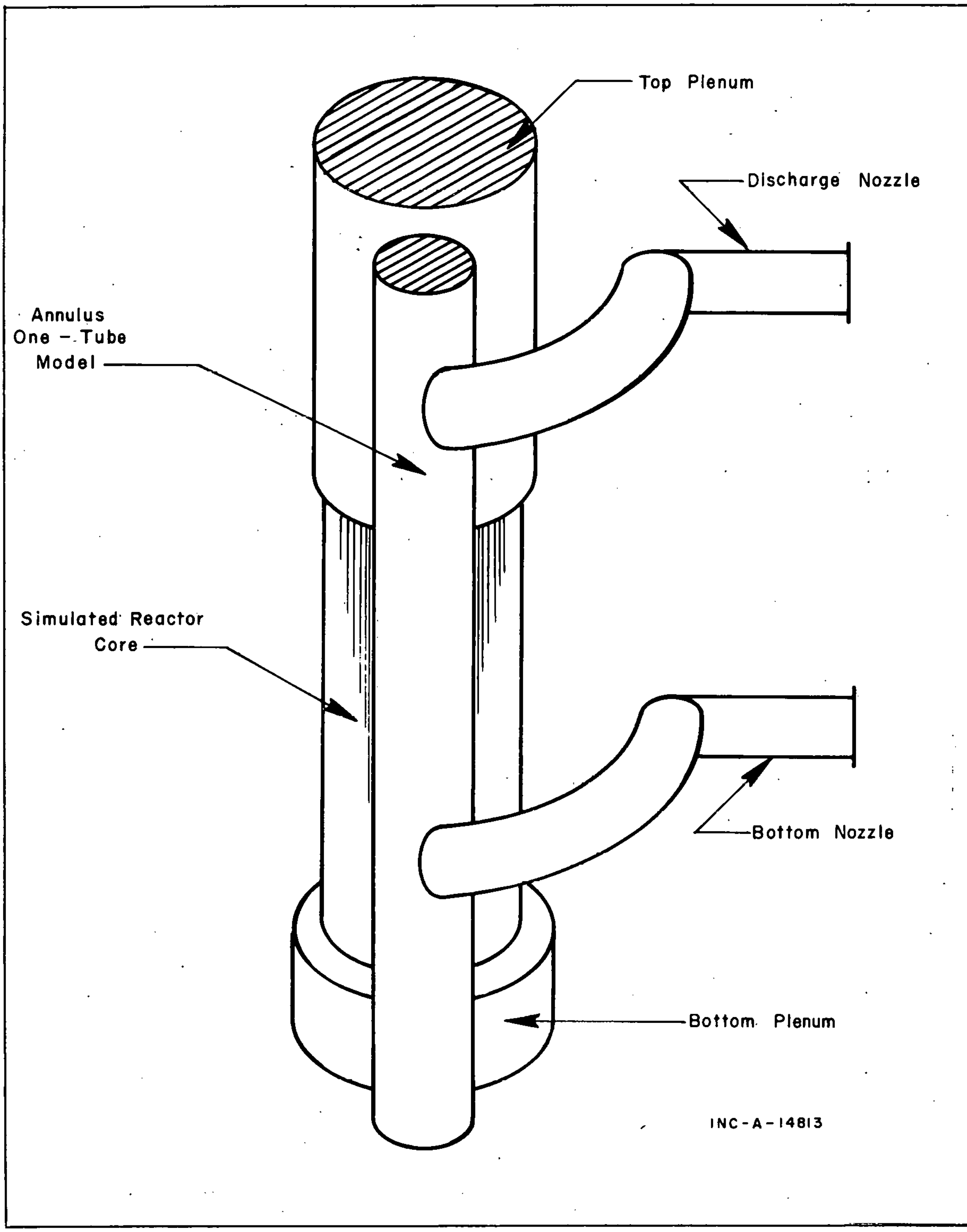
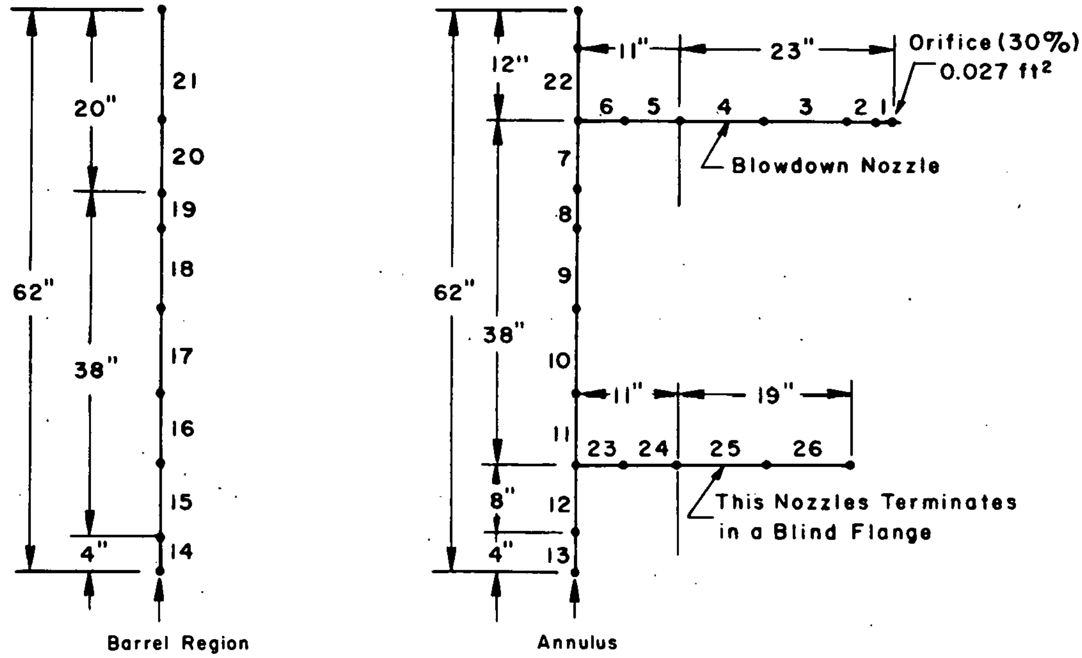


Fig. 7 One-tube-annulus calculational model of semiscale vessel with internals.



Leg Number	Leg Length (in.)	Number of Segments in Leg	Area (ft2)	Leg Number	Leg Length (in.)	Number of Segments in Leg	Area (ft2)
14	4	4	0.8865	1	2	2	0.0900
15	8	8	0.5475	2	3	3	0.0900
16	8	8	0.5475	3	9	9	0.0900
17	8.5	9	0.5475	4	9	9	0.0900
18	9.5	10	0.5475	5	6	6	0.1300
19	4	4	0.5475	6	5	5	0.1300
20	8	9	0.7773	7	8	8	0.2600
21	12	13	0.7773	8	4	4	0.2600
				9	9.5	9	0.2600
				10	8.5	9	0.2600
				11	8	8	0.2600
				12	8	8	0.2600
				13	4	4	0.2600
				22	12	12	0.2600
				23	5	5	0.1300
				24	6	6	0.1300
				25	10	10	0.0900
				26	9	9	0.0900

The length of the right-cylinder model representation is 62 inches. The length of the actual vessel, with its domed heads, is 64 inches.

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Fig. 8 WHAM-code one-tube-annulus representation of semiscale vessel with internals.

TABLE I

ADDITIONAL WHAM INPUT -- BACK PRESSURE AND SONIC VELOCITY

		Initial Conditions			
Test	System	Temperature (°F)	Pressure (psig)	Back Pressure (psig)	Sonic Velocity (ft/sec)
704	Vessel	540	2330	850	3460
711[a]	PWR Representation	505[b]	2290	825	3440[c]

[a] One-tube WHAM model of annulus.

[b] Temperature in bottom plenum, annulus, and nozzles was 505°F. Temperature in top plenum was 540°F. An average temperature, 523°F, was assumed to exist in the simulated reactor core.

[c] Sonic velocity used for the bottom plenum, annulus, and nozzles was 3440 ft/sec; the sonic velocity used for the top plenum was 3170 ft/sec; for the simulated reactor core an average value of 3305 ft/sec was used.

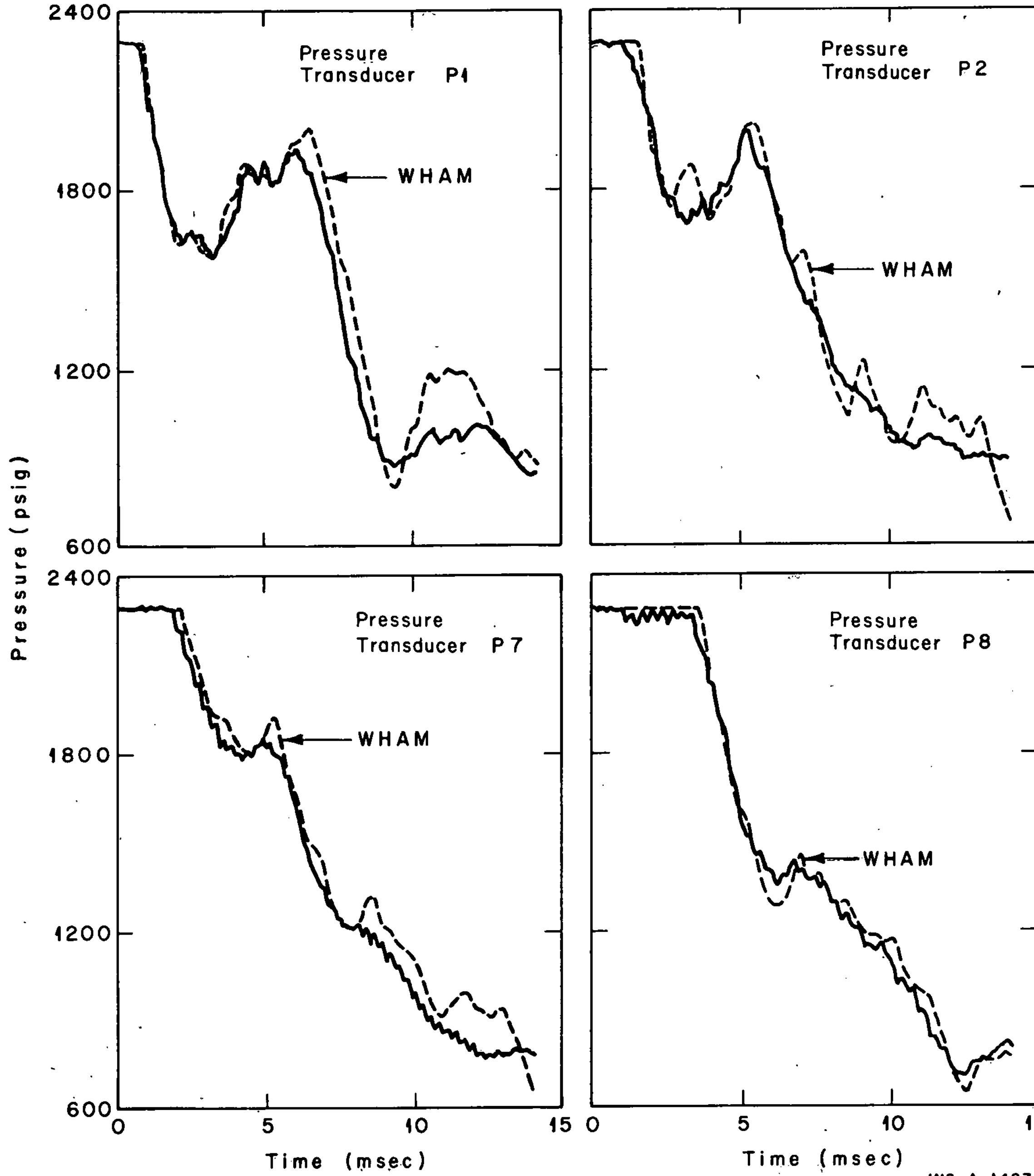


Fig. 9 Semiscale Test 711: comparison of experimental and WHAM-calculated subcooled-blowdown pressure transients.

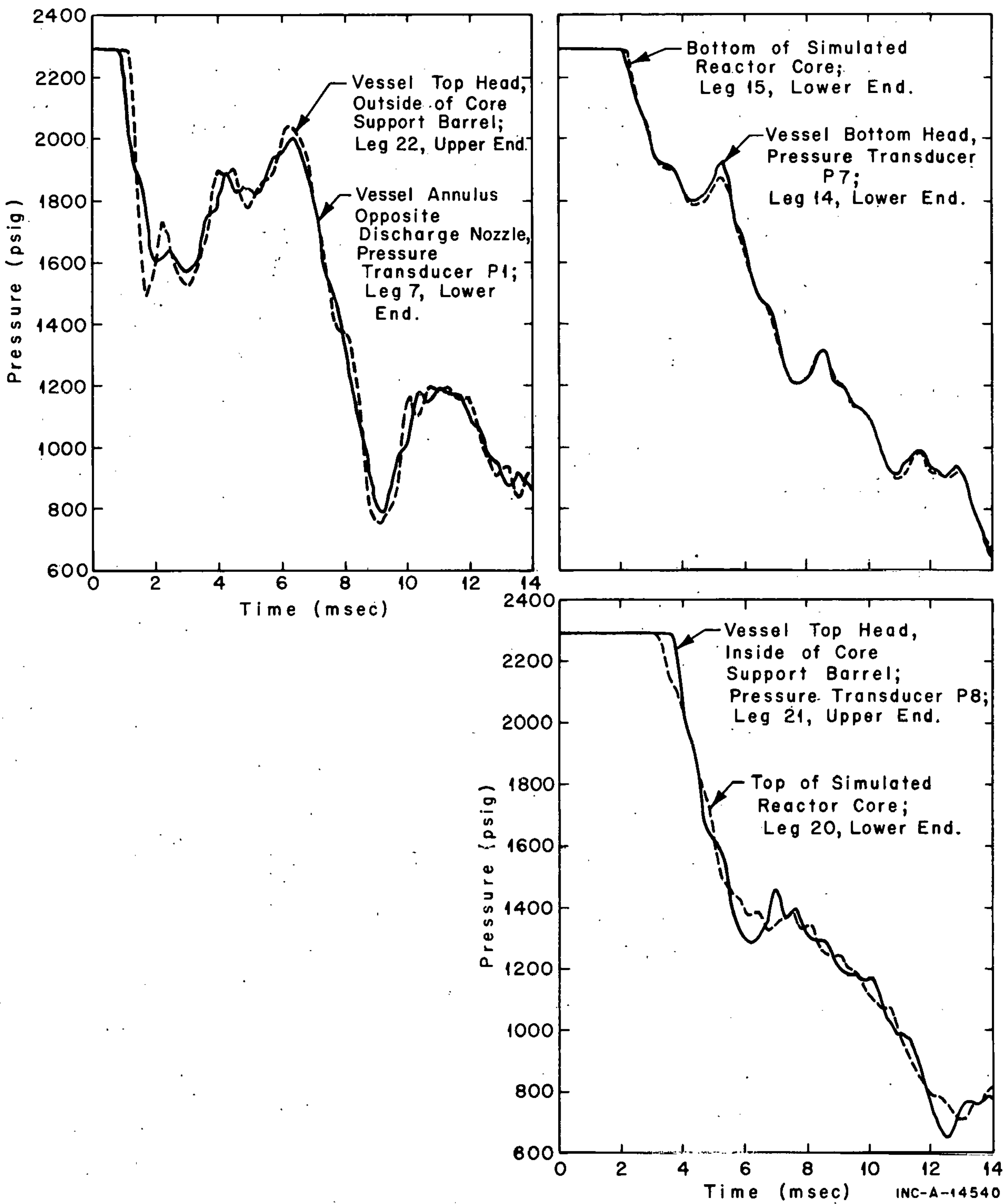


Fig. 10 Calculational support for the assumption employed in establishing experimental vertical fluid forces on semiscale vessel containing internals.

represent also the subcooled-decompression pressure histories at three nearby locations. In the calculational model these nearby locations are: the upper end of leg 22, the lower end of leg 15, and the lower end of leg 20. The calculated pressure histories for these three pairs of locations are given in Figure 10. The agreement obtained is considered support for the assumption employed in the development of experimental vertical thrust forces from available experimental transient-pressure data.

3. PIPE EXPERIMENT

The experimental study of fluid thrust forces during subcooled blowdown was continued with the simplified blowdown apparatus shown in Figure 11. The vessel is constructed of 2-1/2-inch-diameter pipe and the nozzle from 1-1/2-inch pipe. The internal cross-sectional areas are 4.236 and 0.950 $in.^2$, respectively. The pipe assembly is mounted in a load cell[a]. The tests were conducted with water at ambient temperature. A pipe break is initiated by over-pressurizing a single rupture disc in the blowdown nozzle with a positive displacement pump. The system pressure at rupture was about 2000 psi. The locations of the pressure transducers are shown in Figure 11. For some blowdown tests an orifice was installed immediately upstream of the rupture-disc assembly. The orifices used had flow areas equal to 30 and 10% of the cross-sectional area of the discharge pipe, 0.292 and 0.093 $in.^2$, respectively.

Experimental horizontal fluid thrust forces, F, were obtained from transient pressure data by using Equations (9), (10), and (11).

For a fully open break:

$$F = 4.236\ P1 - 3.286\ P3. \qquad (9)$$

For a 30% orifice:

$$F = 4.236\ P1 - 3.286\ P3 - 0.658\ P2. \qquad (10)$$

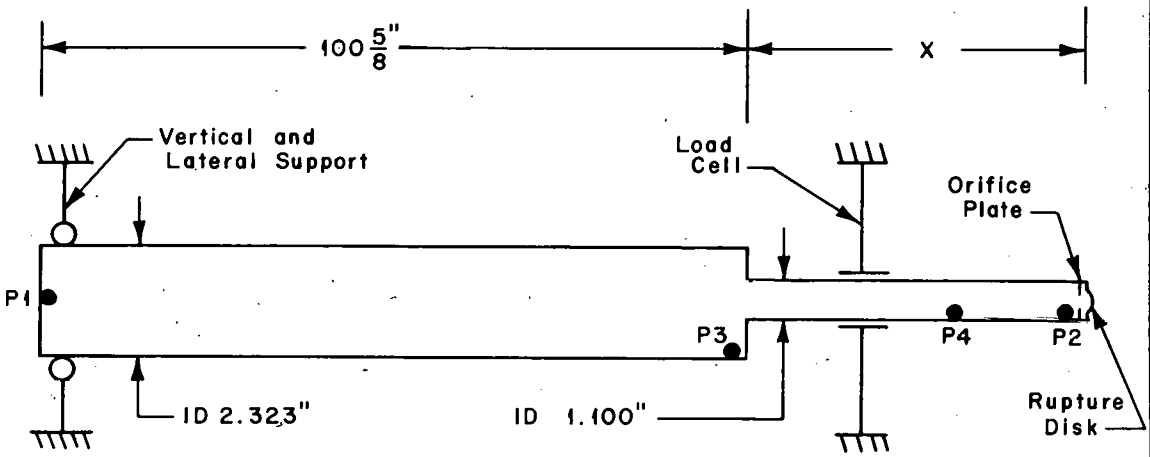
For a 10% orifice:

$$F = 4.236\ P1 - 3.286\ P3 - 0.857\ P2. \qquad (11)$$

Three illustrative comparisons of experimental and calculated subcooled-blowdown fluid thrust forces are presented in Figures 12 through 14. For the three tests, the length of the discharge pipe was 54 inches. The force curves shown in Figure 12 concern a fully open break. The force curves presented in Figures 13 and 14 resulted from blowdowns in which 30 and 10% orifices were present, respectively, just upstream of the rupture-disc assembly.

The calculated force curves were obtained by using the BURST code[1]. One important input information required for blowdown calculations is the

[a] The interaction of the elastic behavior of the pipe assembly and the decompressing fluid is not considered in this report.



X = LENGTH OF SMALL PIPE, INCHES

WITH NO EXTENSION	21 INCHES
WITH EXTENSION A	28–1/2 INCHES
WITH EXTENSION B	54 INCHES

P = PRESSURE TRANSDUCER

P2 IS 1–3/4 INCHES FROM RUPTURE DISC
P4 IS 19–1/4 INCHES FROM AREA CHANGE

WHEN NO PIPE EXTENSION WAS PRESENT, THERE WAS NO PRESSURE TRANSDUCER P4.

ORIFICE DIAMETERS OF 39/64 AND 11/32 INCH ARE USED; AREAS ARE 30 AND 10% OF SMALL PIPE. THICKNESS OF ORIFICE PLATE IS 3/16 INCH.

ORIFICE PLATE IS REMOVED FOR STUDIES WITH FULL–OPEN BREAK.

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Fig. 11 Idaho Nuclear Corporation pipe experiment.

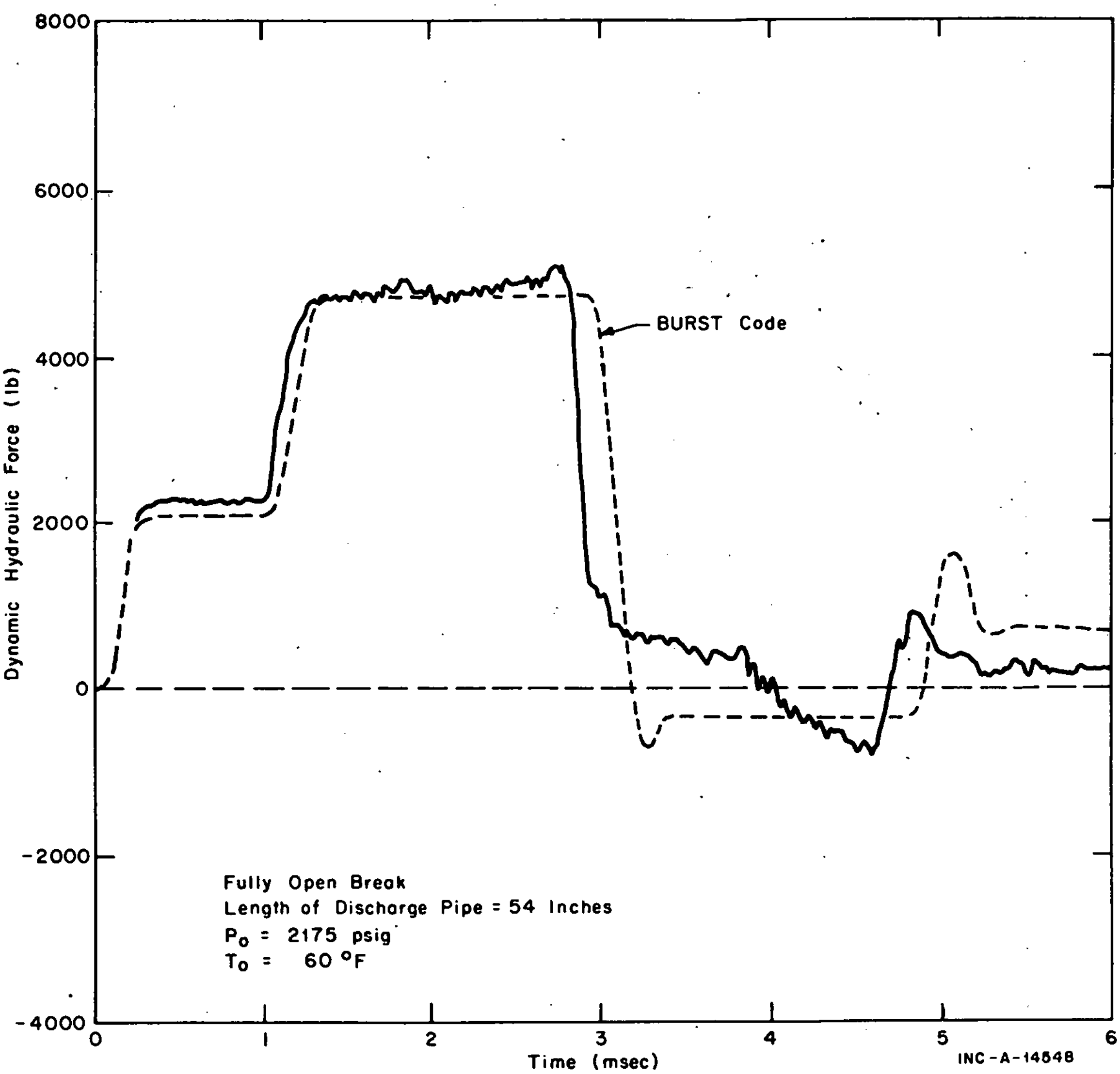

Fig. 12 Dynamic hydraulic forces during subcooled blowdown: comparison of experimental and BURST-calculated forces for pipe experiment Test 29 (fully open break).

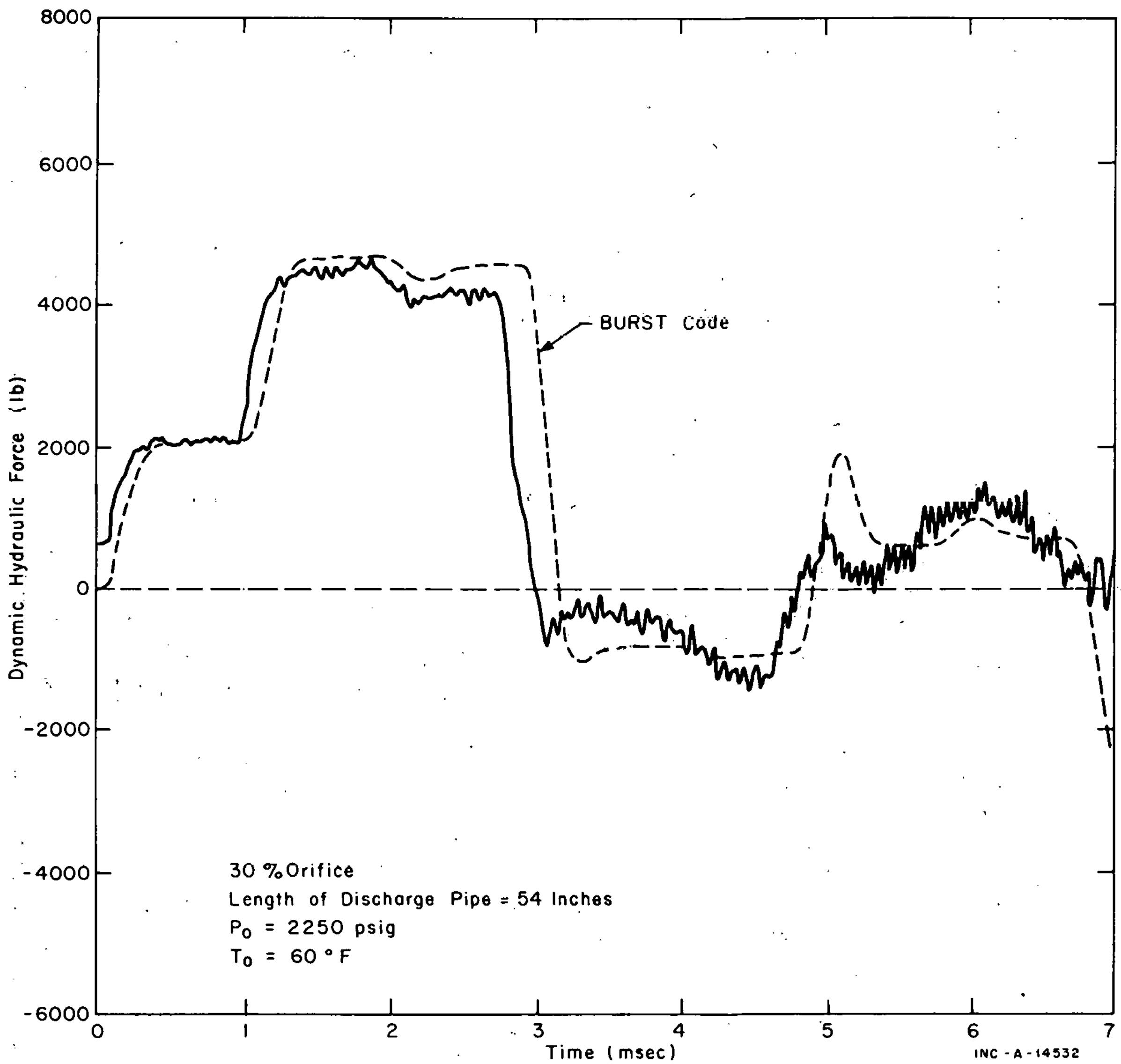

Fig. 13 Dynamic hydraulic forces during subcooled blowdown: comparison of experimental and BURST-calculated forces for pipe experiment Test 28 (with 30% orifice).

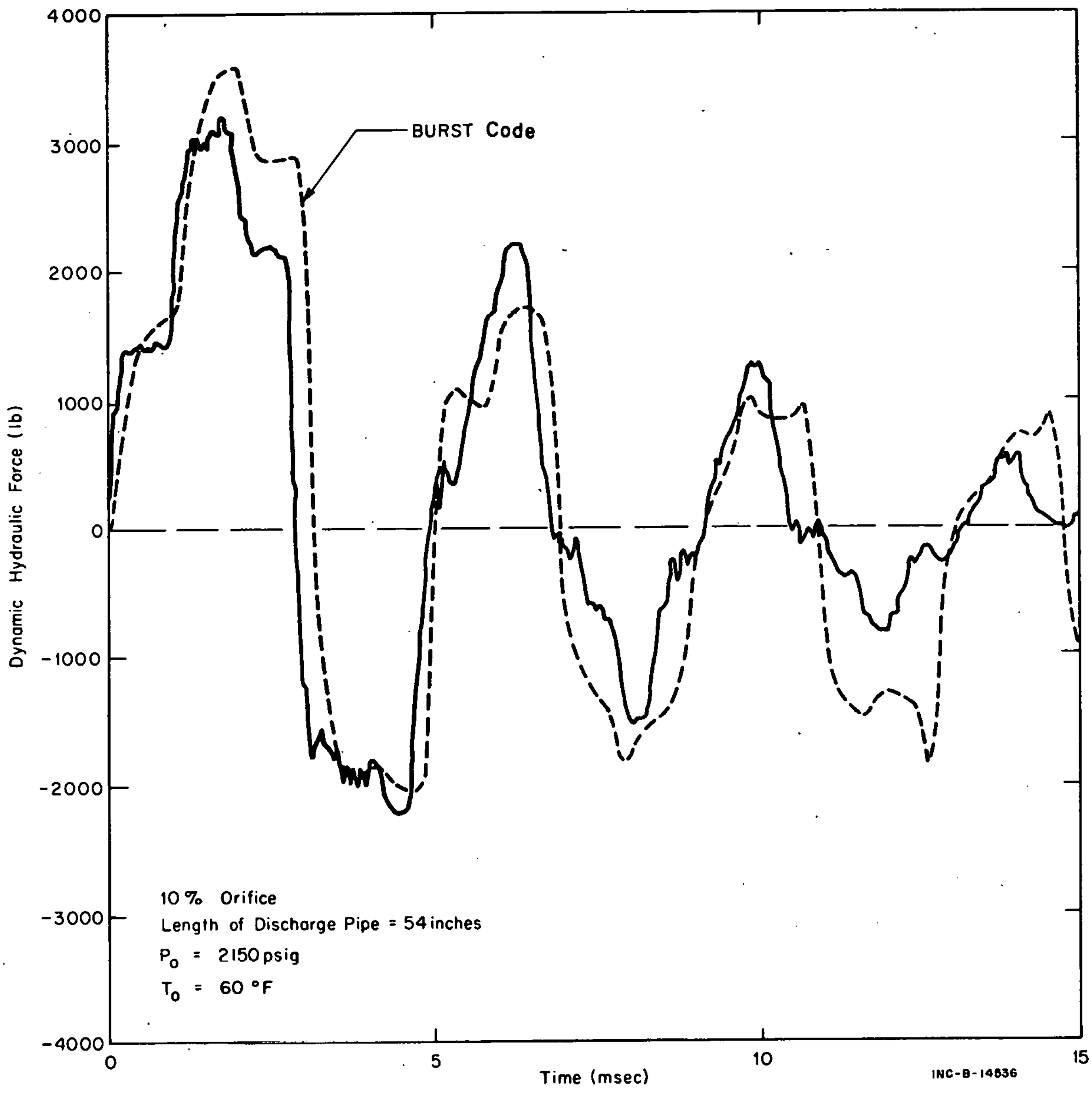

Fig. 14 Dynamic hydraulic forces during subcooled blowdown: comparison of experimental and BURST-calculated forces for pipe experiment Test 30 (with 10% orifice).

effective sonic velocity in the fluid during the decompression event. The calculated force curves presented in Figures 12 through 14 are based on an effective sonic velocity of 4400 ft/sec. A rupture-disc opening time of 0.35 msec was used in these calculations. The agreement between the experimental and calculated fluid transient forces is considered quite good, with respect to both the magnitude and the frequency of the fluid thrust forces.

IV. CONCLUSIONS

Information concerning dynamic fluid forces is useful in the design and analysis of nuclear power reactor systems for accident conditions.

The conclusion was reached that the calculational method based on Equation (6), which is one form of the conservation-of-momentum equation, is a reliable tool for predicting the dynamic hydraulic forces to which reactor loop components would be subjected during a loss-of-coolant accident.

The good agreement between the calculated and experimental fluid thrust forces, with respect to both their magnitude and their frequency, provides credence for applying these calculational tools and modeling techniques in the study of large pressurized-water reactors. The information obtained using this calculational method is sufficiently reliable for use as forcing-function input for structural dynamics codes to establish the response of the components in a power reactor system to a loss-of-coolant accident.

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