PERFORMANCE ASSESSMENT OF MASS FLOW RATE MEASUREMENT CAPABILITY IN A LARGE SCALE TRANSIENT TWO-PHASE FLOW TEST SYSTEM

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ABSTRACT

Mass flow is an important measured variable in the Loss-of-Fluid Test (LOFT) Program. Large uncertainties in mass flow measurements in the LOFT piping during LOFT coolant experiments requires instrument testing in a transient two-phase flow loop that simulates the geometry of the LOFT piping. To satisfy this need, a transient two-phase flow loop has been designed and built. The load cell weighing system, which provides reference mass flow measurements, has been analyzed to assess its capability to provide the measurements. The analysis consisted of first performing a thermal-hydraulic analysis using RELAP4 to compute mass inventory and pressure fluctuations in the system and mass flow rate at the instrument location. RELAP4 output was used as input to a structural analysis code SAPIV which is used to determine load cell response. The computed load cell response was then smoothed and differentiated to compute mass flow rate from the system. Comparison between computed mass flow rate at the instrument location and mass flow rate from the system computed from the load cell output was used to evaluate mass flow measurement capability of the load cell weighing system.

Results of the analysis indicate that the load cell weighing system will provide reference mass flows more accurately than the instruments now in LOFT.

INTRODUCTION

The hypothesized loss-of-coolant accident (LOCA) involving a double-ended break of a primary coolant pipe in a pressurized water reactor (PWR) is the most severe design basis nuclear reactor accident[1]. Loss-of-coolant experiments (LOCE) to investigate the response of a PWR to this accident are being performed in the Loss-of-Fluid Test (LOFT) Program conducted by EG&G Idaho, Inc., for the United States Nuclear Regulatory Commission. The LOFT system is a scaled down PWR in which experiments are being performed to assess code predictions of reactor behavior during a LOCA and to evaluate the performance of nuclear reactor safety systems[2].

One of the key variables measured during a LOFT-LOCE is mass flow rate. The difficulties encountered in fluid flow measurements are compounded in a LOFT-LOCE because the fluid is two-phase (steam and water), the blowdown phenomena are highly transient, and the LOFT piping geometry, designed to represent a PWR, is not conducive to easy measurement of mass flow.

Mass flow rate in the LOFT discharge piping (blowdown legs) is computed from the output of several combinations of instruments (drag disc-turbine, drag disc-gamma densitometer, turbine-gamma densitometer, and differential pressure across a nozzle-gamma densitometer). Except for differential pressure which is measured across nozzles, these instruments sample only discrete points in the cross section of the pipe. In addition, the instrument locations are near pipe bends which cause swirl and skew stratification unaccounted for by instruments. Consequently, uncertainty exists as to how well the instruments perform in LOFT making necessary instrument performance evaluation under transient flow conditions with the identical instrument and piping configuration in LOFT.

Performance testing of LOFT two-phase flow instrumentation under transient conditions will be carried out in a special test facility at Wyle Laboratories in Norco, California. The Wyle test system will duplicate the configuration of the LOFT discharge piping. In addition, initial test conditions will be identical to those during LOFT non-nuclear tests to simulate transient two-phase flow conditions in a LOFT-LOCE.

The results of an analysis of the system are presented to assess the accuracy of the reference mass flow measurements. The paper discusses the background of the performance tests, outlines the proposed test procedure, describes the Wyle test system, discusses the analyses and results, and finally presents the assessment of reference mass flow measurement accuracy.

BACKGROUND AND OUTLINE OF ANALYSIS

Figure 1 shows the plan view of the LOFT reactor vessel and discharge piping as far as the flow control discharge nozzles in the blowdown legs. The effect of the elbows and short pipe length upstream of the flow instrument locations on mass flow rate measurements are unknown because the LOFT flow instruments have never been tested or calibrated in LOFT size piping or piping with the LOFT piping configuration under two-phase flow conditions. However, an implication of the magnitude of the uncertainty is obtained from Figure 2 which shows mass flow rate computed from the output of the four instrument combinations in the blowdown loop cold leg for LOFT nonnuclear Test L1-4[3].

The differences between the computed mass flow rates are not completely understood. The differences are related to geometry, an insufficient number of measurements, and an inadequate two-phase mass flow rate measurement model.

Performance calibrations of two-phase flow instruments under steady state two-phase flow conditions have recently been conducted in small size pipes at Karlsruhe, Germany[4] and are planned for LOFT size piping in the near future. Although these performance calibrations will provide the basic two-phase flow measurement model and assessments of measurement accuracy, the final assessment of instrument and model performance must be made under transient conditions in a test system that duplicates the LOFT piping geometry.

The approach taken by Wyle Laboratories to provide the final performance test was to design and fabricate a test system that duplicated the essential geometric features of the LOFT system and is entirely supported on load cells. The load cell supports are designed to weigh the system continuously and provide the reference mass flow rate.

Mass flow rates computed from the output of the load cells is the most important reference parameter in assessing the overall performance of LOFT two-phase flow instruments and the associated two-phase flow measurement model. A thorough analysis of the response of the load cells during a blowdown is necessary to assess the accuracy with which reference mass flow rate can be measured.

ANALYTICAL PROCEDURE

The approach taken in this study was to perform a thermal-hydraulic analysis of a blowdown of the Wyle Transient Test System using RELAP4[5] to compute the pressures, differential pressures, mass inventories, mass flow rate from the system, and the mass flow rate at the location of the drag-disc turbine transducer (DTT) penetration. The RELAP4 output was used then as input to the SAPIV[6] structural code which was used to compute the reactions on the load cells supporting the vessel. Next, the computed output of the load cells was processed (combined, smoothed, and differentiated) the way the experimental data will be processed to compute reference mass flow rate. Finally, the reference mass flow rate was compared with the mass flow rate at the DTT penetration computed by RELAP4 and used to evaluate the use of load cells to provide reference mass flow rate measurements.

SYSTEM DESCRIPTION

The transient test system at Wyle Laboratories, illustrated in Figure 3, is configured to duplicate the LOFT blowdown loop cold leg. The test system consists of:

(1) System supports and load cells

(2) Pressure vessel including a removable downcomer simulator

(3) Discharge piping including flow initiation device (burst disc)

(4) Instrumented spool piece

(5) LOFT DTT rake penetration.

The proposed configuration for the test system blowdown loop cold leg is shown schematically in Figure 4 for clarity.

RELAP ANALYSIS

The thermal-hydraulic behavior of the blowdown in the transient test system at Wyle Laboratories has been analyzed using RELAP4/MOD5.

RELAP4 Model

The RELAP4 nodalization model of the Wyle Transient Test System is presented in Figure 5. The system configuration was nodalized so that system area changes and flow instruments that significantly change piping areas are represented by junctions, and the number and distribution of volumes are representative of and compatible with the distribution of system reference measurements.

RELAP4 Results

Representative results of the RELAP4 analysis are presented in Figure 6. The figure shows mass flow rate at the DTT rake penetration (Junction 13) as a function of time plotted to 30 s.

A comparison between Figures 2 and 6 illustrates the degree to which the proposed Wyle Transient Tests will simulate a typical LOFT nonnuclear LOCE. The largest qualitative difference between the results in Figures 2 and 6 is a 5-s period beginning at 19 s during which RELAP4 predicts large flow rate variations occurring at a frequency of 3 to 5 Hz. During this period, the flow varies between 50 and 200 kg/s. This behavior is caused by differential pressure oscillations between the upper and lower plenums (Volumes 1 and 2 in Figure 5) when the liquid level in the vessel drops to the bottom of the downcomer simulator. Similar behavior was not observed in LOFT Test L1-4. However, the presence of the nuclear reactor core in LOFT may dampen internal differential pressures and smooth out the flow.

STRUCTURAL ANALYSIS

The vertical dynamic response of the test system to blowdown loads was predicted using a linear elastic finite element structural model compatible with the SAPIV computer code. Loads applied to the structural model are derived from hydraulic data generated by the RELAP4 analysis. The dynamic vertical reactions at the load cell supports are defined for 30 s following initiation of blowdown.

Structural Model

The test system structural model is comprised of linear elastic beam and pipe-type finite elements with concentrated masses for nonstructural components lumped at nodes near the physical location in the system . A schematic of the system identifying components included in the structural model is shown in Figure 7. The blowdown vessel, downcomer simulator, straight piping, and supports are modeled using beam-type finite elements, with material and section properties consistent with the physical structure.

The downcomer simulator is assumed to be rigidly attached to the blowdown vessel at the upper vessel flange and at the bottom of the simulator. The physical system provides a rigid attachment at the upper flange, but the interface at the bottom provides lateral support only. The assumption is justified for this analysis because transfer of pressure and fluid weight loads from the vessel internals to the vessel supports is not influenced by the geometry of the lower vessel to downcomer simulator connection.

The load cell supports are represented by beam-type finite elements with fixed-pinned end conditions. The physical system load cells and concrete foundation are assumed to be rigid so that the pinned ends of the load cell supports interface directly with the ground. The piping support near the end of the discharge piping is modeled as a "soft" spring (k = 876 N/cm), which provides vertical support only, with a lumped mass on the piping to represent the concrete block to which the piping support is attached.

Hydraulic Load Development

The transient blowdown loads considered for this analysis include:

(1) Differential pressure from the top to the bottom of the blowdown vessel

(2) Differential pressure across the interface of the upper plenum and downcomer annulus

(3) Momentum loads on piping and spool piece components (pressure and flow loads)

(4) Weight of fluid in the blowdown vessel, piping, and spool piece.

The differential pressure loads in the blowdown vessel are determined from the product of the pressure difference (excluding elevation pressure) between the upper and lower plenums and the cross-sectional area of the vessel at the intersection of the cylindrical body and hemispherical heads. A similar type load exists at the interface between the upper plenum and downcomer annulus and is calculated from the product of the pressure difference between the upper plenum and downcomer annulus and the annulus cross-sectional area. These vessel loads are computed from RELAP4 data and are combined to yield an "equivalent" differential pressure load applied to the vessel in the vertical direction.

The momentum loads in the piping and spool piece considered act on the following components:

(1) The 45-degree elbow between the vessel nozzle and the spool piece

(2) The cold leg nozzle

(3) The orifice

(4) The tee at the end of the discharge piping.

These loads all act in a horizontal plane.

Structural Analysis Results

The forced dynamic response was computed using a direct integration scheme with damping at or below 2% of critical for the first 20 modes of vibration.

The vertical reactions at the load cells, summarized in Figure 8, are characterized by the following:

(1) Response in the first 1.5 s following blowdown initiation is driven by the initial and reflected pressure waves moving upstream from the burst disc into the vessel. Support reactions fluctuate at approximately 80 Hz about a mean defined by the transient fluid weight.

(2) The response to the vertical differential pressure loads at blowdown initiation is essentially damped out at 1.5 s and follows the change in system fluid weight to 18.5 s.

(3) The response of the system is driven by vertical differential pressure loads in the vessel from 18.5 to 24.0 s with dynamic fluctuations at approximately 3 to 5 Hz about a mean defined by the transient fluid weight. This response begins at the same time that hydraulic analysis predicts the flow level reaches the bottom of the downcomer.

(4) Response from 24.5 to 30.0 s follows the transient fluid weight with dynamic fluctuations in the 3- to 5-Hz range and amplitudes at the same order of magnitude as the fluid weight.

Note should be made that the predicted vertical differential pressure loads which govern the response from 0.0 to 1.5 s and from 18.5 to 24.5 s are subject to a high degree of error. Differential pressures of only 1 kPa can give rise to a vertical load of nearly 1 kN.

ANALYSIS OF COMPUTED LOAD CELL DATA

The computed load cell results, presented in Figure 8, are expected to be representative of the experimental results from the Wyle Transient Tests. The computed results for the first 2 s are very similar to results observed by Hutcherson[7] during critical flow experiments performed at Argonne National Laboratory in 1975.

Hutcherson's tests were very short (less than 3 s) and were virtually complete by the time the initial system vibrations damped out. He computed mass flow rate numerically by integrating load cell output using a small time step and then differentiating the results twice using a larger time step, smoothing his results. He estimated the accuracy of his mass flow rate measurements at $\pm 10\%$.

The computed load cell readings for the Wyle Transient Tests were smoothed using a combination of batch averaging and curve fitting. The smoothing procedure used was, first batch average, averaging 100 points at a time. Because the resulting data were smooth enough for most of the first 18 s, curve fitting was not required to smooth the data further. The "averaged" data for the 18- to 25-s period was still very irregular as can be seen in Figure 9, which presents remaining mass in the vessel as a function of time. Next, the averaged data for the 18- to 30-s period was fit to an exponential curve. The resulting curve is superimposed in Figure 9. For comparison, the RELAP4 predicted mass inventory is also overlayed on Figure 9.

"Reference" mass flow was computed by differentiating the smoothed load cell readings. The results are shown in Figure 10. The RELAP4 computed mass flow at the DTT penetration (Junction 13) is overlayed for comparison.

The comparison is good everywhere except during the 19- to 25-s period when the pressure oscillations in the vessel are reflected directly in the load cell output and had to be smoothed out by curve fitting. Although the pressure fluctuations in the vessel cause some flow fluctuations at the location of the DTT, the flow fluctuations are not as severe as the computed load cell output would predict.

Since the load cells support the entire system and fluid contents (except for the small amount of fluid load transferred to the air bag), the reference mass flow computation predicts mass flow rate from the system rather than mass flow rate past the DTT rake.

The difference in mass flow rate between the DTT penetration and the end of the downstream piping is small except at the very beginning of the test when approximately 200 kg of water must fill the downstream piping before water can flow out of the system. Even if the system were not vibrating violently, the load cells would not show a change in system mass for approximately one-half second.

The mass flow computed from the load cells is within ±15 kg/s (±10% of reading for the period between 2 and 18 s) of the mass flow predicted by RELAP4 for the DTT penetration except during the initial 2 s and during the 20- to 25-s period.

A comparison between Figures 2 and 10 shows that when the LOFT flow instruments yield the most erratic results, the Wyle Transient Test System will produce the best results. The Wyle Transient Flow Tests will provide the measurement accuracy required to assess LOFT flow instrumentation and the associated two-phase flow mass measurement models.

CONCLUSIONS

A blowdown test system has been designed and is being installed to performance test two-phase flow instrumentation under test conditions and in a test geometry that duplicates the LOFT blowdown loop cold leg. The system has been analyzed to assess the accuracy of the reference mass flow rates computed from the load cell weighing system.

The results of the analysis show that during the relatively smooth portion of the blowdown the load cells will provide excellent reference mass flow data. The difference between the RELAP4 computed mass flow rate and the mass flow rate computed from the load cell readings is less than ±10% of reading. The accuracy of the reference mass flow measurements will be adequate for performance testing two-phase flow instrumentation, assessing the validity of two-phase mass flow rate measurement models under transient conditions and the effect of piping geometry on mass flow rate measurements.

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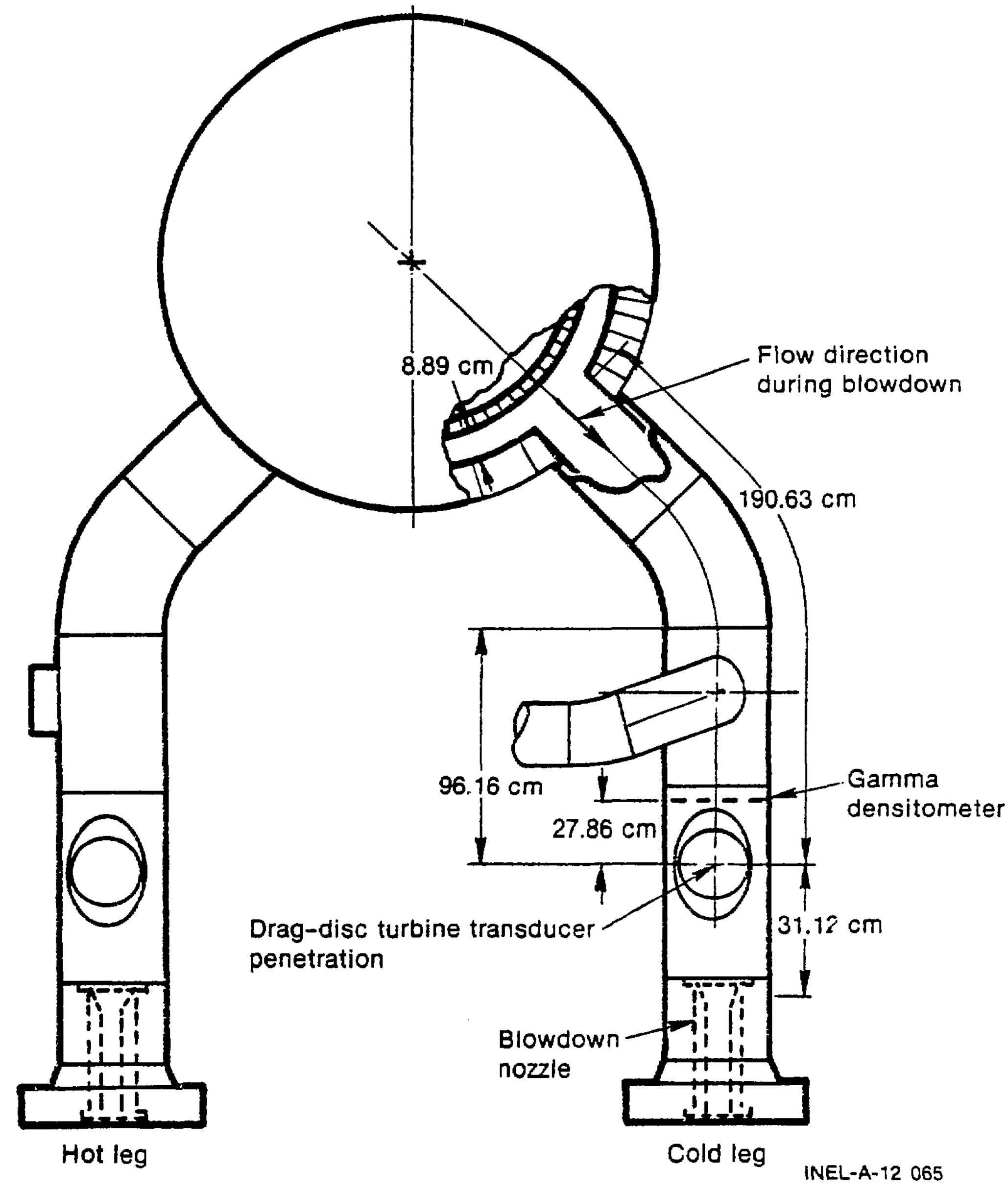

Fig. 1 LOFT blowdown loop piping layout.

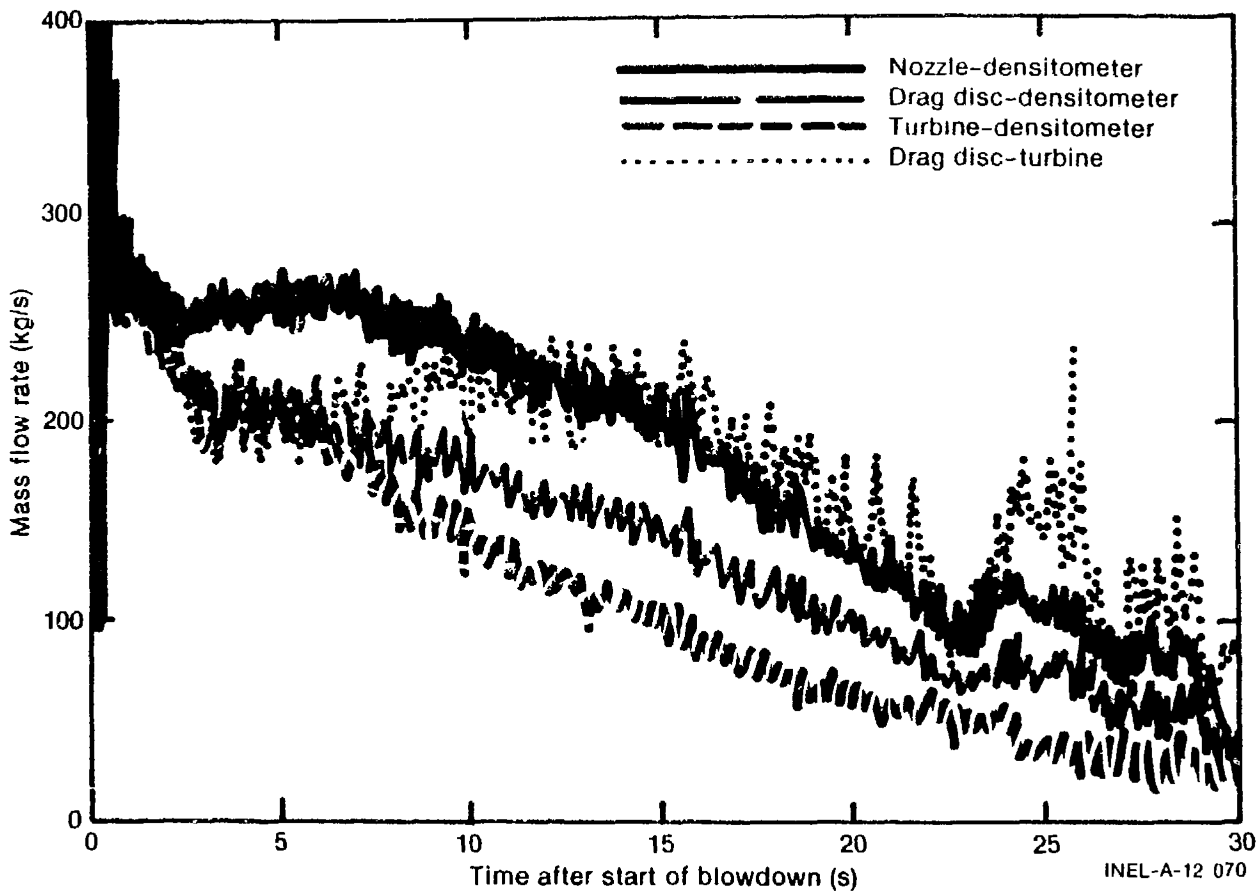

Fig. 2 Comparison between mass flow rates computed from output of instrumentation in blowdown loop cold leg for nonnuclear Test L1-4.

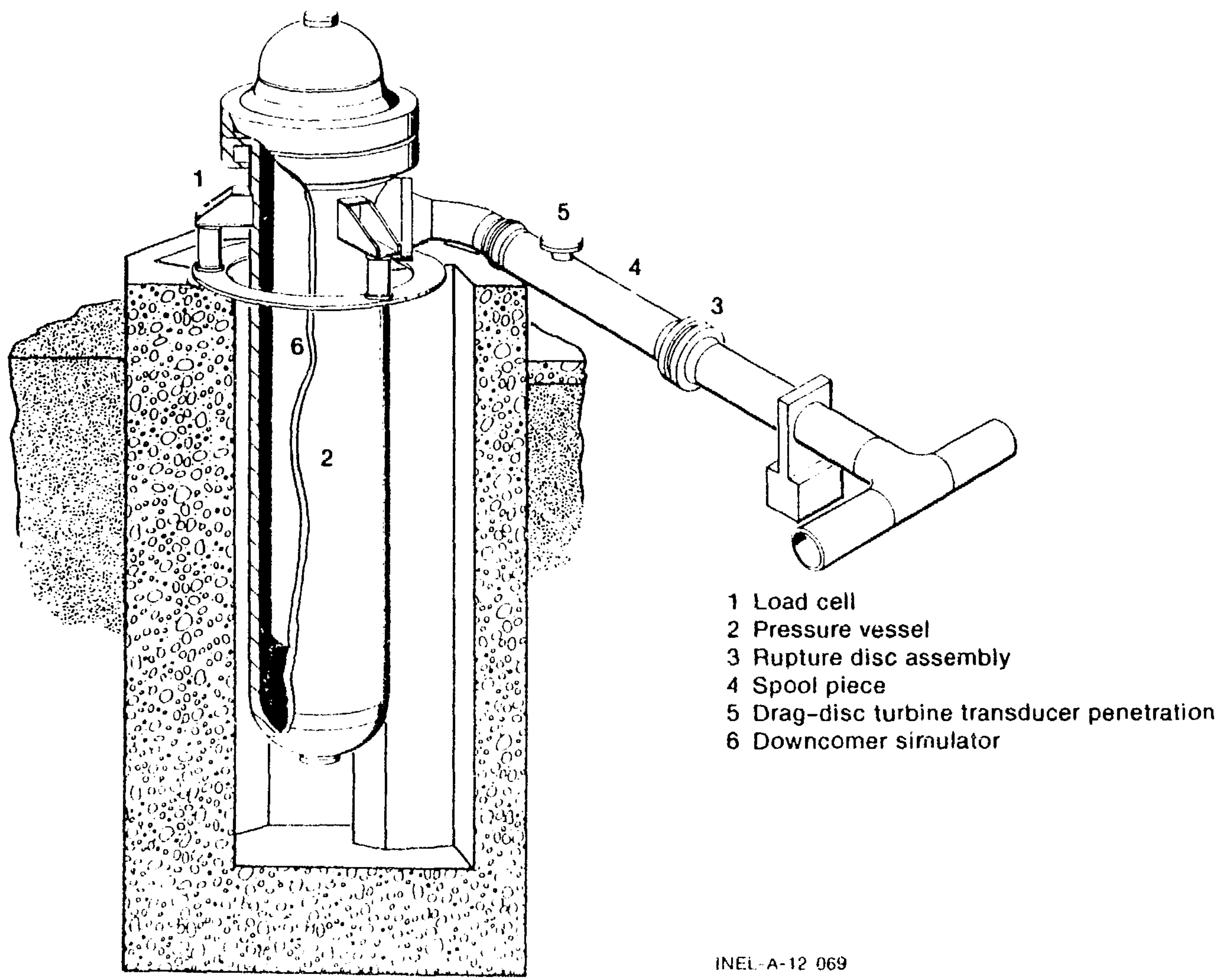

Fig. 3 Schematic of Wyle Transient Test System.

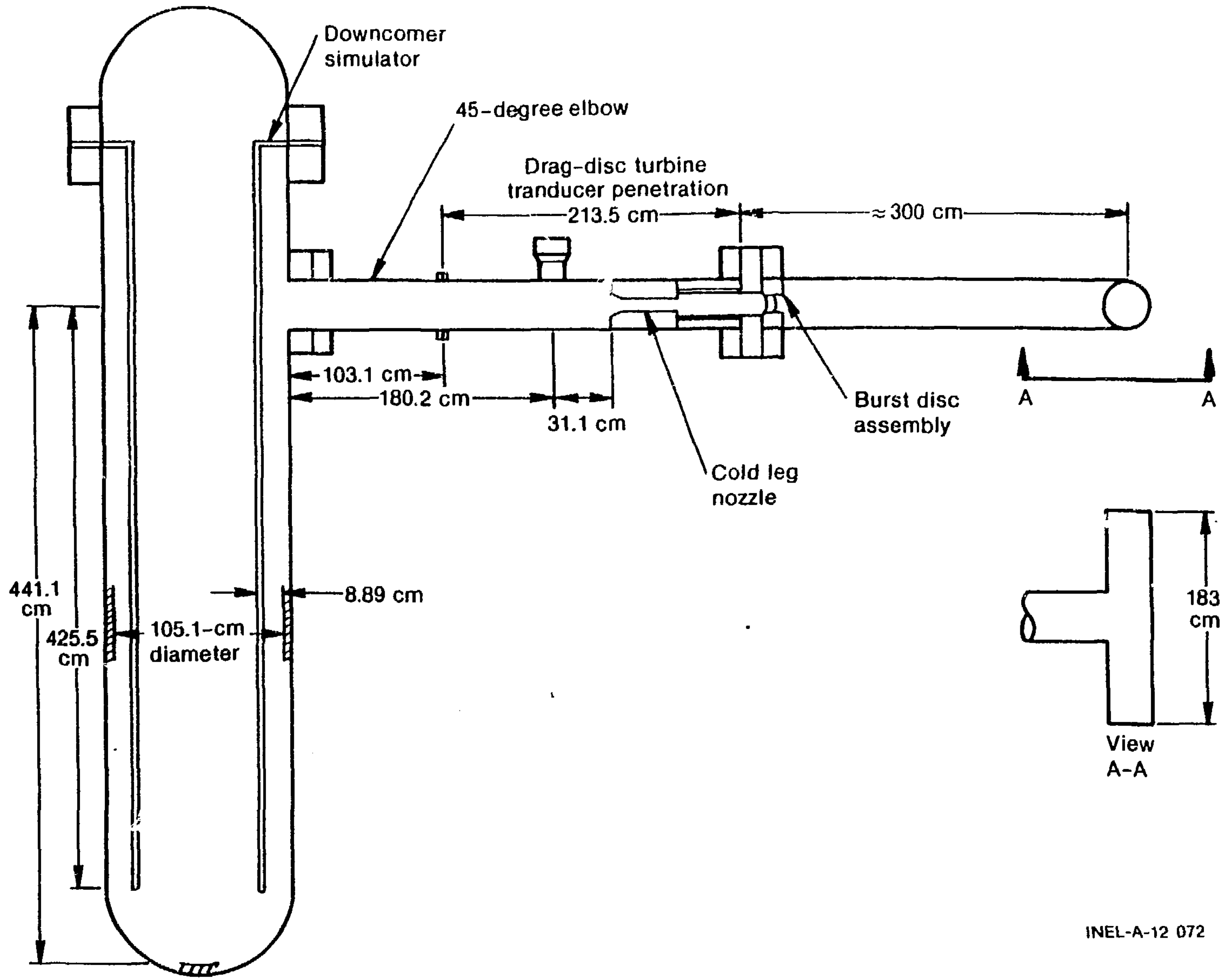

Fig. 4 Wyle Transient Test System containing the downcomer simulator and cold leg nozzle, configured to simulate the broken loop cold leg.

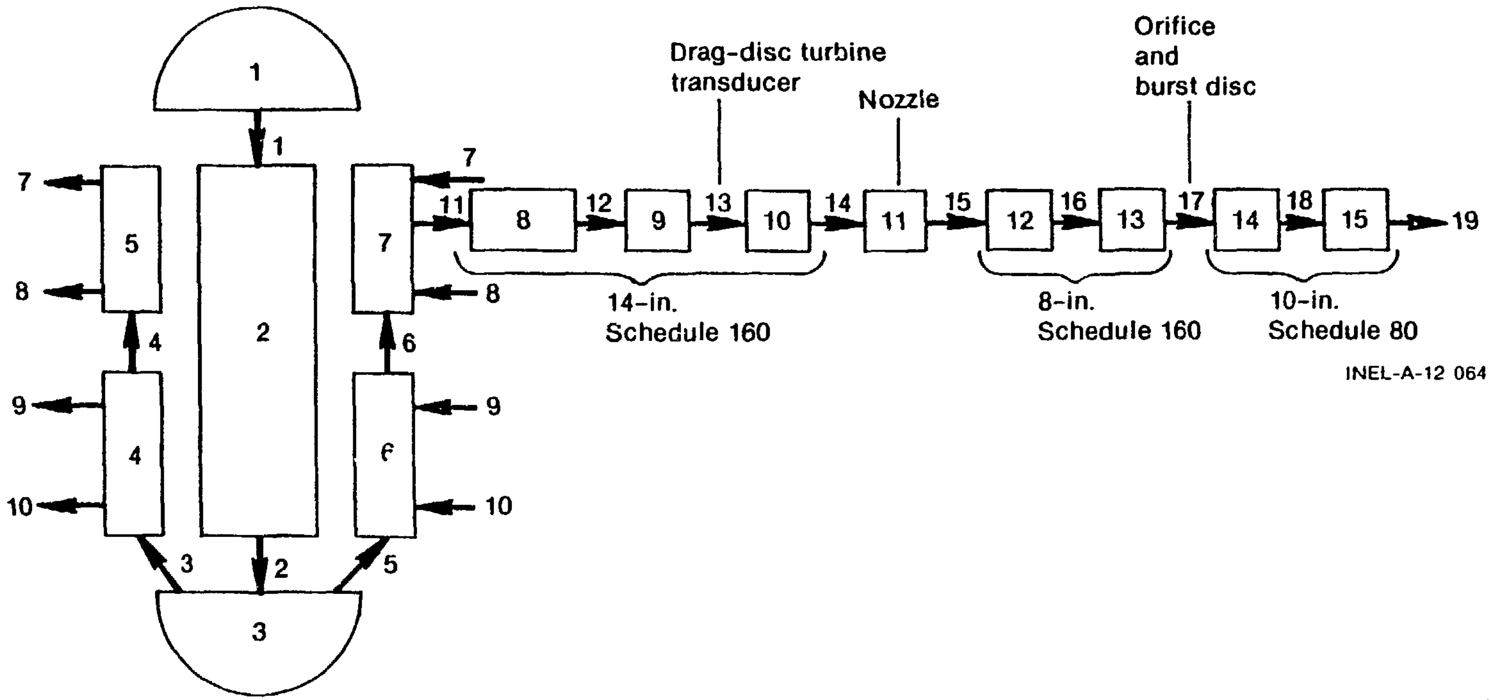

Fig. 5 Nodalization diagram of the RELAP4 model of the Wyle Transient Test System containing the downcomer configured to simulate the blowdown loop cold leg.

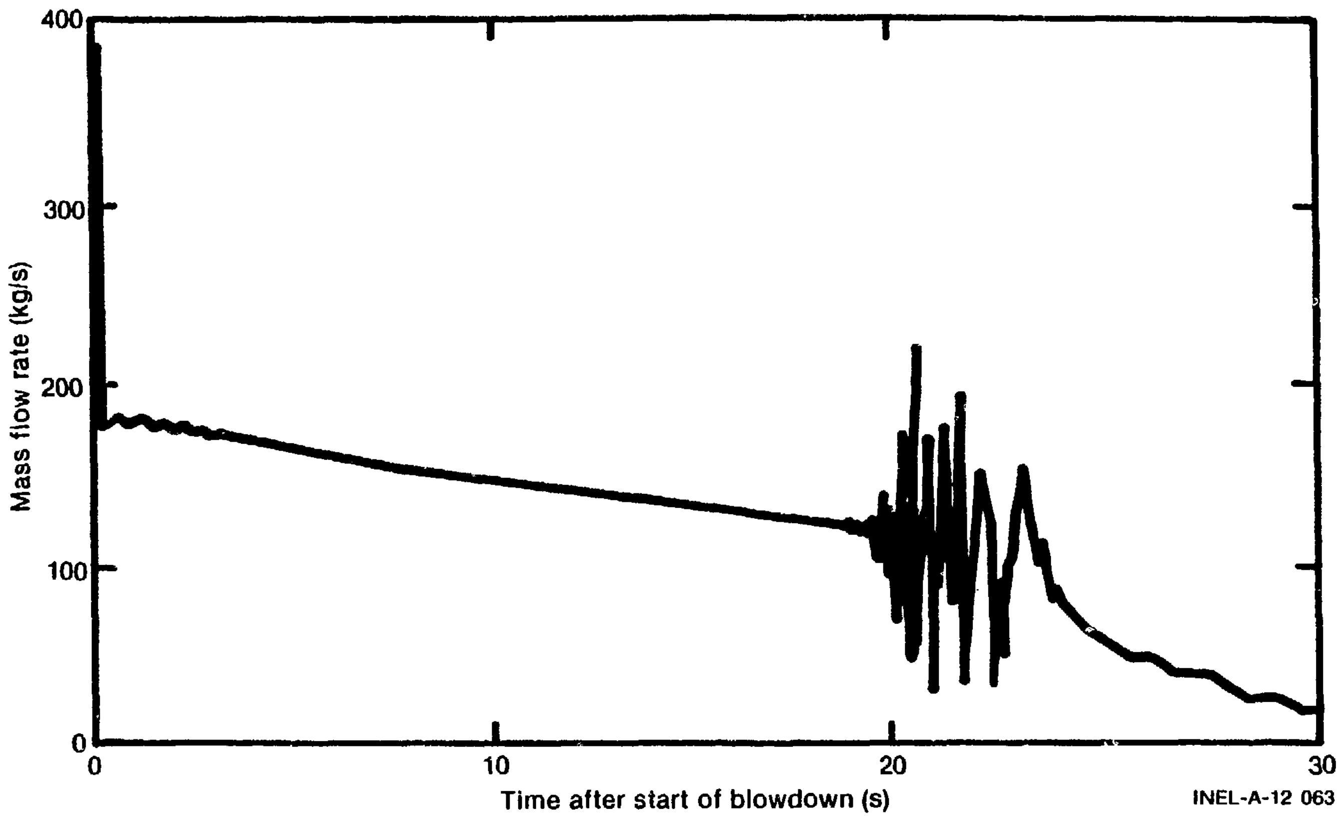

Fig. 6 RELAP4 prediction of mass flow rate versus time.

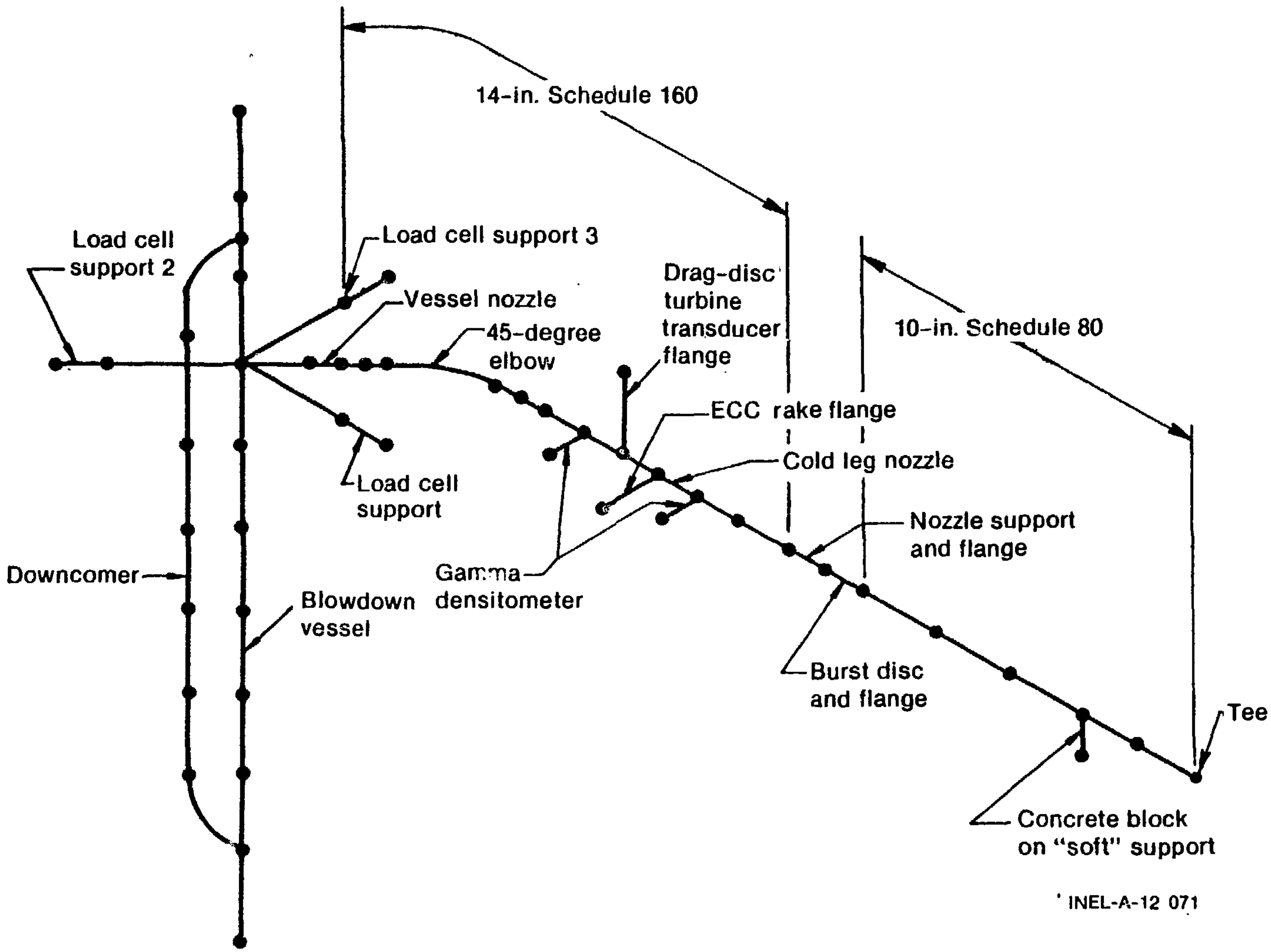

Fig. 7 Structural model component identification and location for the Wyle Transient Test System configured to simulate the broken loop cold leg.

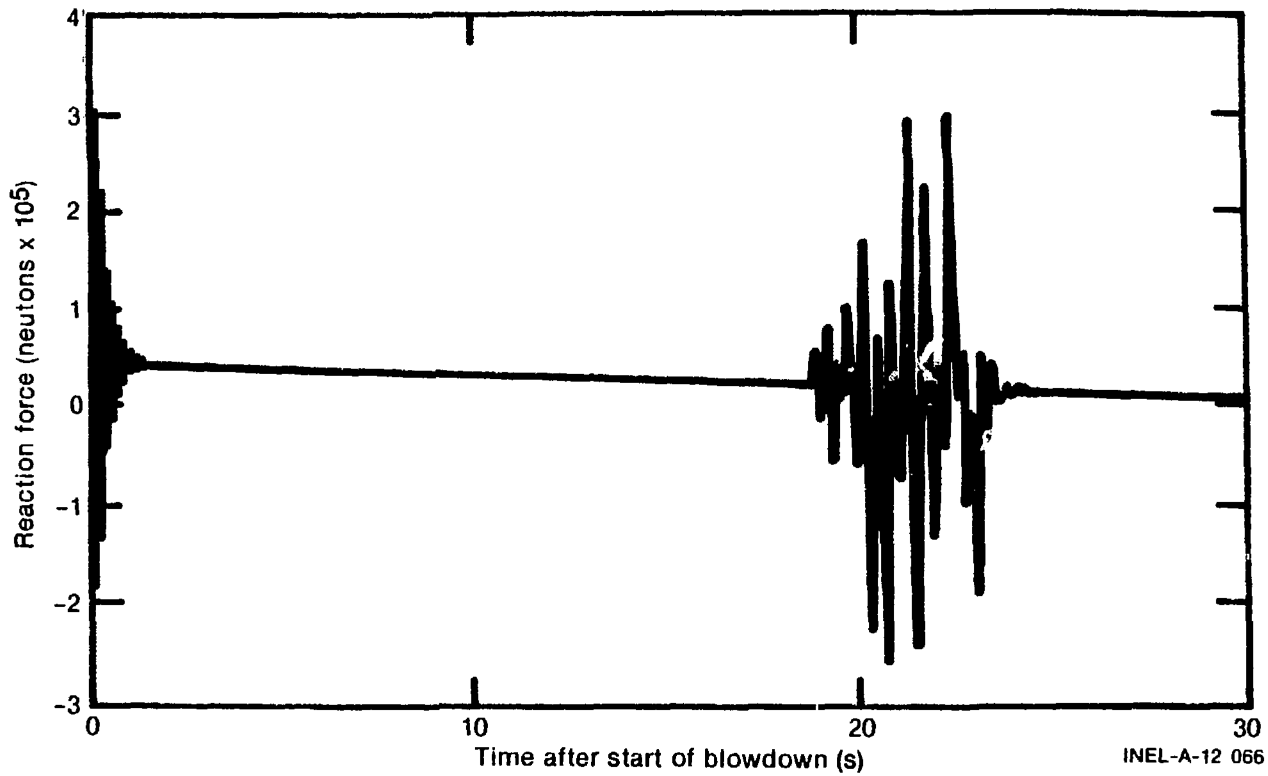

Fig. 8 Combined dynamic vertical reaction force on load cells.

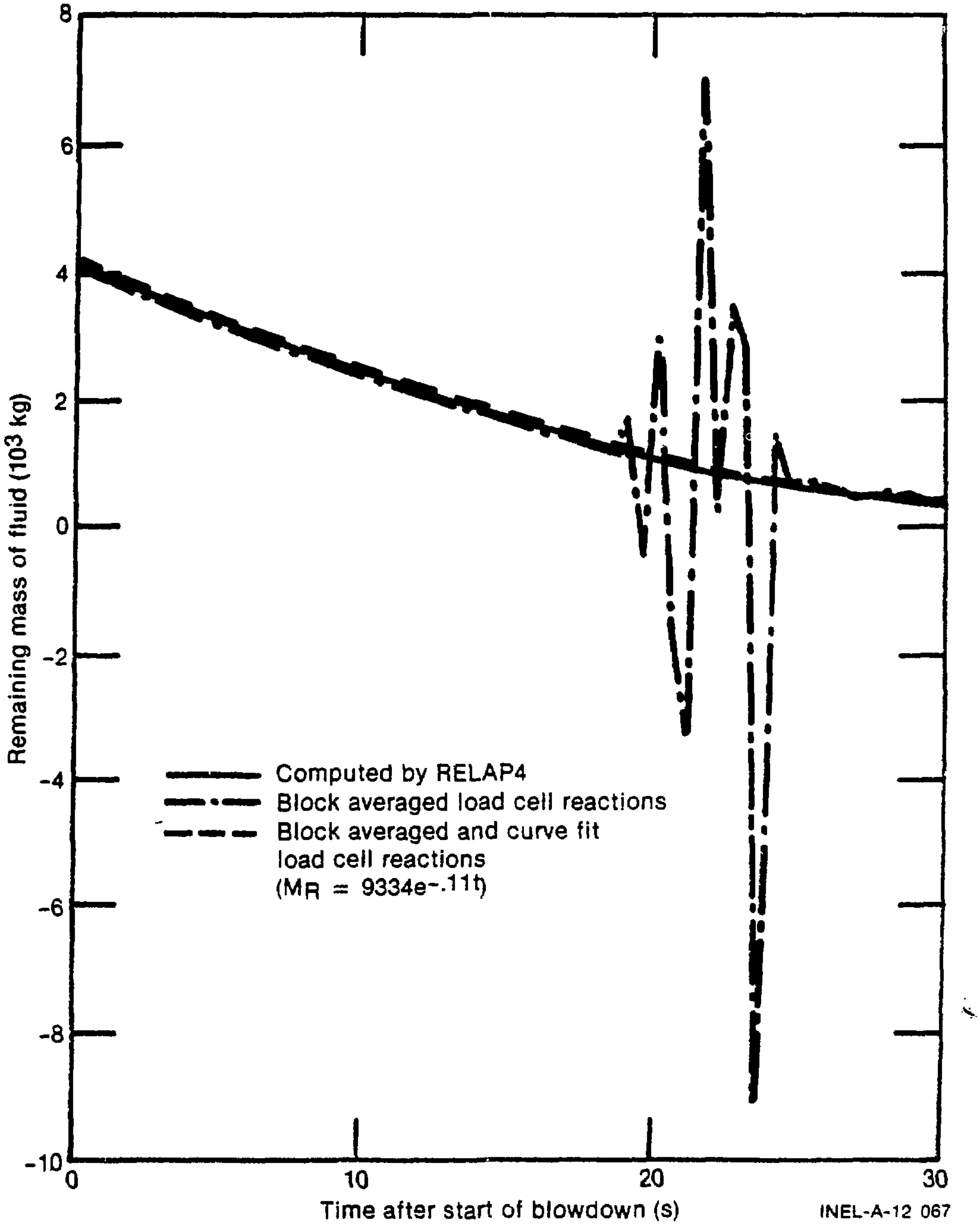

Fig. 9 Comparison between mass remaining in system computed by RELAP4 and computed for load cell reactions.

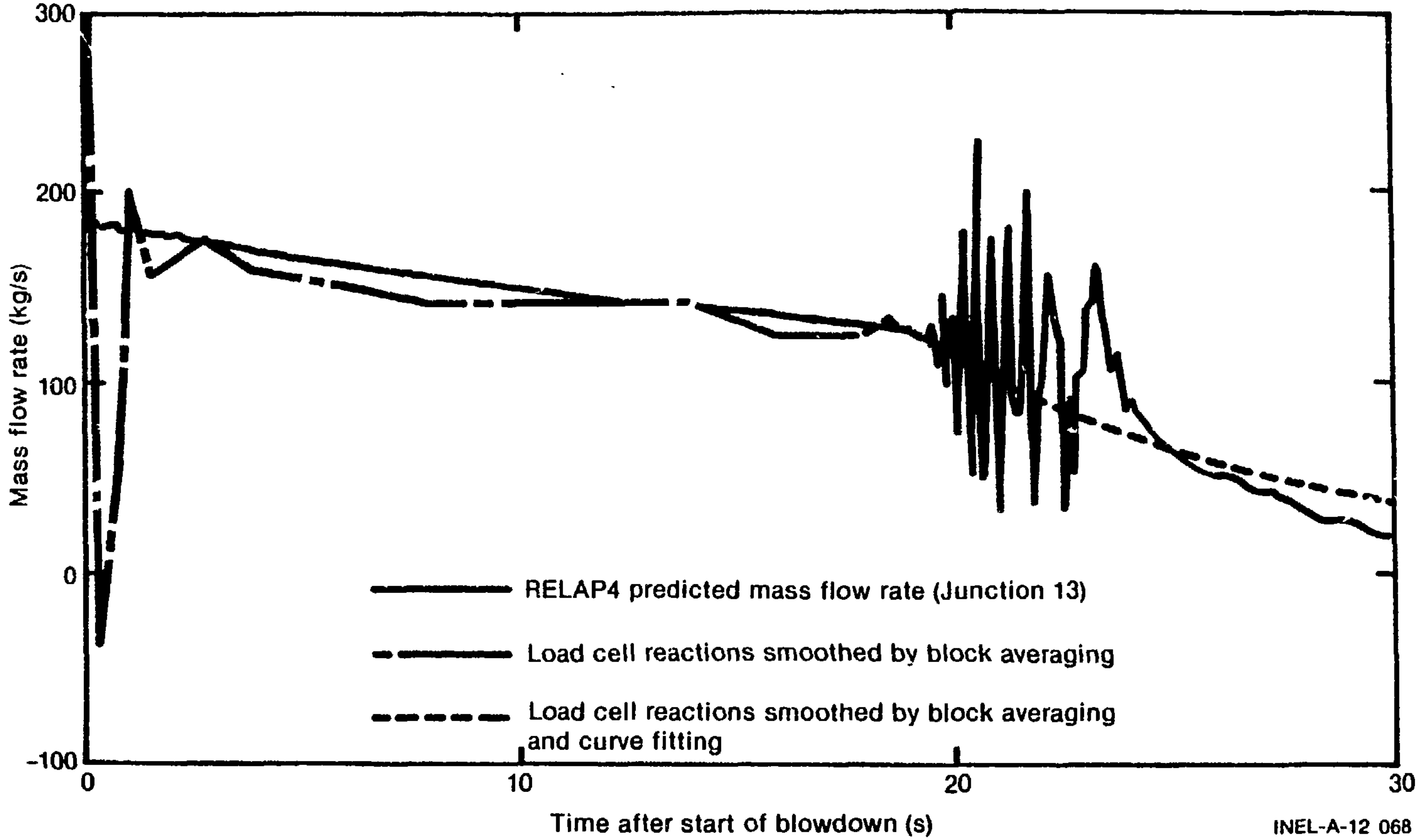

Fig. 10 Comparison between RELAP4 predicted mass flow rate at drag-disc turbine transducer rake location (Junction 13) and mass flow rate computed from load cell reactions.