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FIDAS : A THREE-FLUID SUBCHANNEL CODE FOR DRYOUT PREDICTION IN ROD BUNDLES

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ABSTRACT

A numerical code called FIDAS (film dryout analysis code in subchannels) has been developed with the main objective of simulating dryout and post-dryout heat transfer in rod bundles. This code features three-fluid representation of two-phase flow, in which the third fluid is liquid droplets entrained in the vapor phase. Since the code is able to predict the dryout occurrence by the film dryout criterion, no empirical CHF correlation is required. FIDAS gave good predictions of the onset of dryout when compared with experimental results from full-scale dryout tests on a 36-rod bundle. Furthermore, FIDAS gave better accuracy in predicting a wide range of thermalhydraulic conditions when compared with other subchannel codes.

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

FIDAS has been developed at the Power Reactor and Nuclear Fuel Development Corporation (PNC), mainly to predict onset of dryout and post-dryout heat transfer in rod bundles.[1] Validation studies of the developed code and models have been performed against experiments conducted under the conditions covering water-cooled reactor operation.[1][2][3] However, sufficient validation has not been so far performed for dryout in rod bundle geometry.

An especially challenging problem for codes like FIDAS has been the prediction of flow quality in subchannels and the prediction of dryout power of rod bundles. In the validation process, it is also useful to compare predictions with those generated by similar codes. Hence, as a first step of validation for rod bundle geometry, examinations were carried out on subchannel quality, by comparison with experimental data and with predictions by similar codes. Moreover, as a second step, the prediction capability is examined for dryout power of a 36-rod bundle to be used in the Japanese pressure tube type heavy water reactor; comparison will be made with full-scale dryout experiments in which dryout power has been measured in pressure tubes with varying inside diameter.

2. THE FIDAS FORMULATION AND CALCULATIONAL FEATURE

FIDAS provides a three-fluid, three-field representation of two-phase flow in rod bundles. The three fields are specified by continuous liquid film, continuous vapor and entrained liquid droplets suspended in vapor as shown in Fig.1(a). Thus a set of 12 basic field equations is built into the code, namely three continuity, three energy, and six momentum equations. The 12 field equations together with the volume fraction conservation relation among three fields enable us to obtain analytical information for the following 13 parameters: three axial and three lateral velocities, three volume fractions, three specific enthalpies, and pressure. In order to predict dryout occurrence and post-dryout temperature behavior of the heated surface, the code provides the capability to simulate flow regime evolution in subchannels; i.e. single-phase liquid flow at the entrance, bubbly/slug flow formulation by evaporation, transition to a liquid-vapor-droplet annular flow, a further transition to vapor-droplet mist flow due to liquid film disappearance on the heated surface, and superheated single-phase vapor flow formulation due to complete evaporation of all droplets. In this evolution process, the onset of dryout is defined as the disappearance of liquid film adhering to the heated surface as shown in Fig.1(b). The liquid film flow rate is determined by mass transfers of droplet deposition, entrainment and vaporization from the liquid film.[1],[2]

As the inter-subchannel mixing model between adjacent subchannels, three types of mixing model are assumed : diversion cross flow, turbulent mixing and void drift. Diversion cross flow is caused by radial pressure gradients. The diversion cross flow can be obtained from the force balance of the lateral pressure gradient and the the lateral friction force at the wall-fluid and fluid-fluid interfaces. Turbulent mixing results from the natural eddy transport between subchannels. Turbulent mixing is based on Prandtl's mixing length theory.[1] Void drift is a phenomenon in which vapor tends to diffuse toward unobstructed regions. It was originally introduced by Lahey[4]. In FIDAS, these three types of mixing have been considered.

The conservation equations, as well as the constitutive relations for various models, are described in detail in Ref.[1]

3. CODE VALIDATION I: Prediction of Flow Quality in Subchannels

Experiments and Calculational Procedure

Two sets of experiments were compared with the FIDAS-3DT code predictions : the General Electric (GE) 9-rod bundle measurements by Lahey et al.[4], and the ISPRA 16-rod bundle measurements by Herkenrath and Hufschmidt [5]. In both sets, flow quality was measured at the exits of various subchannels of a square lattice bundle, in which electrically heated rods simulated nuclear fuel rods. Measurements were made using channel splitters and an isokinetic probe technique. The flow conditions were those of a normally operating boiling water reactor, in which the coolant reaches bubbly and slug flow. The main differences between the GE and ISPRA tests were the bundle size (9 and 16 rods respectively) and the bundle length (1.80 and 3.66 m). The cross-sections for the test bundles are shown in Fig.2, as well as the subchannel configurations used in the code analysis.
The conditions of pressure, total mass flux, power, and inlet enthalpy under which the test were performed are listed in Table 1.

The subchannel configurations used in the present analysis is indicated in Fig.2 for both GE and ISPRA tests The conventional coolant-centered subchannel layout is used for comparison with other codes described later. The number of physical cells (axial nodes) is 40, and as a result, axial node length is approximately 50mm which had been confirmed to be short enough from the result of parametric studies which were done in advance of validation analysis to examine numerical error. Length of lateral junction cell between subchannels is defined as the distance between mass centers of adjacent subchannels.

Results and Discussions

The flow quality for the corner subchannel is the most difficult to predict accurately. Since the corner has the smallest size and the highest power density, it is most sensitive to flow conditions. Consistent experimental measurements were difficult for the same reason ; corner data for both GE and ISPRA test sets are characterized by large scatter, as shown in Fig.3 and 4.

THERMIT-II and COBRA-IV were compared here with FIDAS in the prediction of flow quality in subchannels. COBRA-IV [6] assumes a homogeneous vapor/liquid mixture. THERMIT-II [7] is similar to FIDAS, but it is a two-fluid code which uses empirical correlations for dryout, and does not simulate entrained droplets as a third fluid.

As shown in Fig.3, FIDAS and THERMIT trace well the experimental data of corner subchannel quality. For the corner of the 9-rod bundle, COBRA fails to represent the quality accurately. This is due to the absence of void drift modeling in which turbulent mixing dominates completely and the subchannel quality approaches average bundle quality. For the 16-rod bundle(Fig.4), FIDAS also agree well in predicting flow quality. In general, FIDAS gives better predictions for subchannel quality comparing with other codes under normal reactor operating conditions. It is considered that this improvement depends on suitable value of mixing length for each phase and void drift parameters. Indeed, the fact that FIDAS considers mass flux droplets as a third fluid, and offers a mechanistic (rather than empirical) dryout model, may make it a better code for simulations of dryout and post-dryout heat transfer in rod bundles.

4. CODE VALIDATION II: Prediction of Dryout Power

Experimental Apparatus

Over ten thousand points of full scale dryout data for several kinds of ATR (a pressure tube type HWR developed by PNC in Japan) fuel bundles have been accumulated by using the 14MW Heat Transfer Loop (HTL) in PNC over the last decade.[8][9][10]

As shown in Fig.5, HTL consists of a test section housing a heater-rod bundle, an electric power supply system connected with the bundle, a steam drum, a high pressure condenser, a subcooler, a pressurizer, circulating pumps, etc. The maximum operating condition of HTL is 10MPa of pressure, 310 °C of temperature, and 22.2 kg/s of flow rate.

The objective of this series of experiments was to investigate the effect of pressure tube inner diameter on dryout power. A 36-rod test bundle was used for this series of experiments. And the bundle was settled in the pressure tube vertically. In the 36-rod test bundle, heater rods are arranged in three concentric circular layers surrounding a non-heated center-rod, with ring type spacers which have the same shape as those used in an actual bundle. The rod diameter is 14.5mm, and the average pitch-to-diameter ratio is 1.17. The bundle has a heated length of 3.7m and heat transfer area of 6.06m^2. Electric DC current was supplied to the heater rods. The heat is generated by the Joule effect due to electric resistance inherent in the heater tube. Heat flux distribution is axially uniform and laterally non-uniform such as 1.11/1.01/0.65 from outer to inner layer.

Surface temperatures of heater rods were measured with chromel-alumel thermocouples of 0.5mm outer diameter. As shown in Fig. 6, thermocouples were welded immediately upstream of spacers on heater rods of No.21, No.24, No.27, No.30 and No.33

which face to narrow subchannels, since previous burnout experiments showed that dryout usually occurs at these locations.

Simulated pressure tubes used in the experiment were made of Al_2O_3 ceramic and had different inside diameters. The inside diameters chosen in the experiments were 117.8mm as a nominal case, 120.0 and 122.4mm for enlarged cases as shown in Fig.7. Tolerances of pressure tube I.D. in production were between -0.0mm and +0.1mm. The test bundle is centered in the pressure tube accurately within 0.1mm eccentricity.

Experiments were carried out under the following conditions:

Pressure	:	7	MPa
Mass flow rate	:	2.78 - 11.1	kg/s
Inlet subcooling	:	42	kJ/kg
Pressure tube I.D.	:	117.8, 120.0, 122.4	mm

Thermal-hydraulic conditions were decided from normal operating conditions of the ATR plant. Measuring accuracies were estimated as ±0.5K for inlet temperature, ±0.5% for system pressure, ±3% for inlet flow rate, and ±1% for electric power supplied to the heater bundle.

After thermal-hydraulic conditions including system pressure and coolant temperature at the inlet of test section and coolant flow rate in the test section were sufficiently stabilized, bundle power was increased so gradually that steady state condition could be kept. The onset of dryout was recognized by the rapid rise in temperature of the heater rod surfaces.

Calculational Procedure

A 1/12 sector subchannel model was used in the present study, as shown in Fig.7. Subchannel layout is combined-fine type, and the cross section was divided into 19 cells. Each cell has only one wet-wall surface. Hence, liquid film flow rates adhering to heater or cold wall surfaces which have different heat fluxes can be calculated separately. In enlarged cases of pressure tube I.D., the flow area in outermost subchannels of No.1, No.2 and No.3 were varied. The heated length of 3.7m was divided into 37 axial nodes, as a result, axial node length is 100mm. Dryout power has a tendency of decreasing with increase of axial node length. The axial node length had been confirmed to be short enough from the result of parametric study done to examine numerical error.

In FIDAS, flow rates of liquid film and entrained droplets are calculated based on the deposition and entrainment correlations which were developed and validated on the basis of experimental data in smooth circular tubes[2]. In bundle geometries, however, there are spacers which are considered to affect entrainment and deposition phenomena. In order to take into account the spacer effect, the droplet deposition rate was tuned as approximately 80% of the value for smooth circular tubes.

Results and Discussion

As shown in Fig.8, experimental data show that the dryout power decreases clearly with the increase of pressure tube inside diameter. Measured dryout power for pressure tube I.D. of 120.0mm were approximately reduced to 97.5% of the value for nominal pressure tube I.D. of 117.8mm. Furthermore, in a case of 122.4mm, dryout power data were reduced to 90% of the value for the nominal case. Presumably, the enlargement of flow area in outer subchannels leads to the enhanced imbalance in quality and mass flux distributions between subchannels, since coolant tends to flow in broader subchannels. Consequently, this enhanced imbalance in quality and mass flux distribution is considered to reduce the dryout power.

FIDAS prediction indicates by comparisons with experimental data that FIDAS can predict well the measured dryout power without any empirical CHF correlations over the entire range of experimental flow rate, and that FIDAS satisfactorily traces the decrease of dryout power with increase of pressure tube inside diameter.

Comparisons between experiments and predictions by FIDAS on dryout power is summarized in Fig.9. The prediction accuracy by FIDAS on dryout power could be estimated to be ±5%, since almost all of the predictions within ±5% error band which is indicated by broken lines in the figure.

Finally, comparisons between FIDAS predictions and similar subchannel predictions using the COBRA-IV[6] code are shown in Fig.10. As shown in the figure, the prediction by FIDAS traces well dryout power decrease with the enlargement of inner diameter of the pressure tube. On the other hand, COBRA-IV[6] failed to simulate the measurement, although COBRA had been carefully fine-tuned for the 36-rod bundle geometry in advance of this analysis. This is attributable to the fact that the inter-subchannel mixing including void drift is not taken into account adequately in COBRA, which formulates two-phase flow on the basis of the homogeneous mixture model.

5. CONCLUSIONS

FIDAS was found to be generally successful in predicting flow quality in subchannels, under actual reactor operating conditions. Comparison between FIDAS prediction and the full-scale dryout experiment shows that FIDAS provides sufficient prediction capability of dryout power for the rod bundle geometry, a capability that exceeds that of COBRA-IV. It is concluded that the FIDAS code is a powerful tool for nuclear reactor design and safety evaluation.

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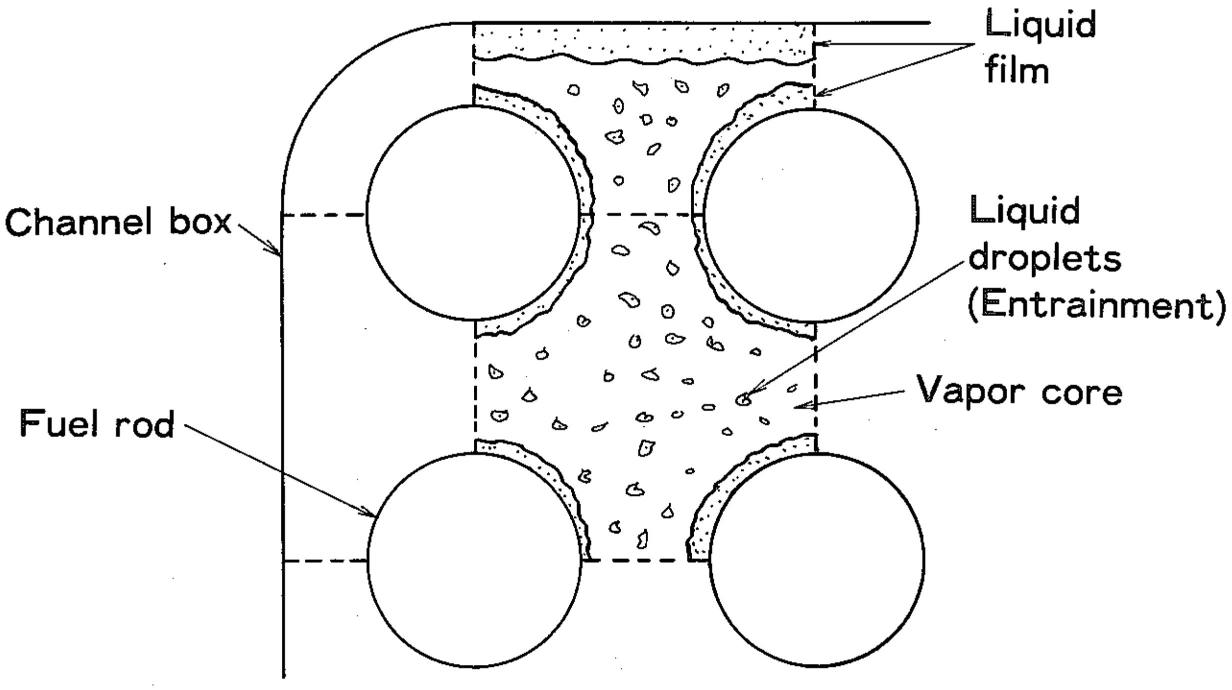
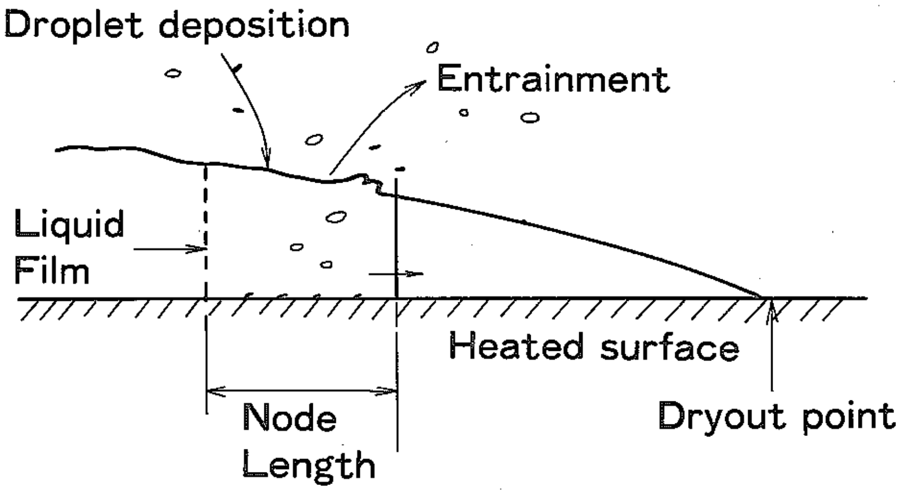
Table 1: Experimental conditions for GE and ISPRA tests

	GE 9-rod bundle (uniform heating)	ISPRA 16-rod bundle (uniform heating)
Pressure (MPa)	7.0	7.0
Mass flux (kg/ m²s)	725 1450	1000 1500 2000
Bundle power (kW)	530 - 1600	320 - 1600
Subcooling (kJ/kg)	70 - 600	40 - 110
Average exit quality(%)	2.9 - 31.8	2.0 - 31.0

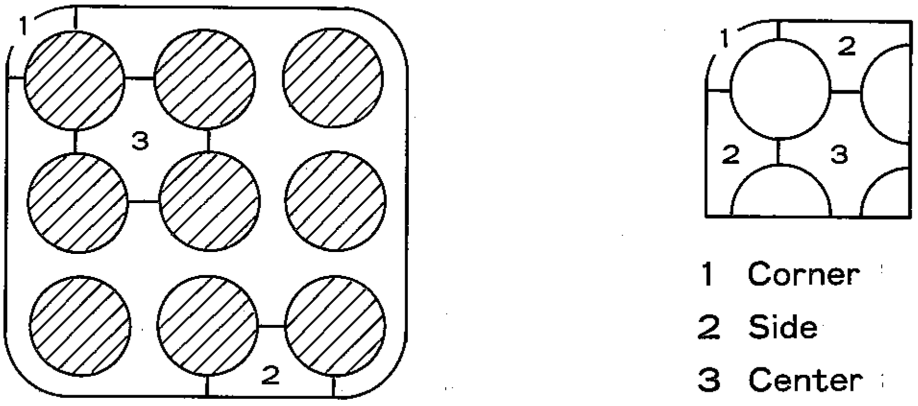


(a) Three-fluid model for rod bundle



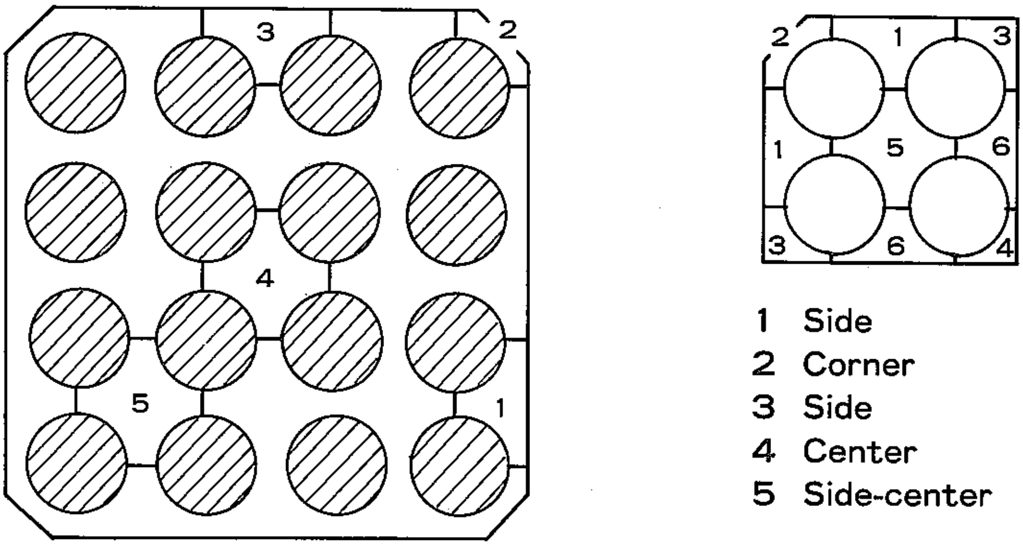
(b) Film dryout model

Fig. 1 Three-fluid and film dryout modeling in FIDAS



GE 9-rod bundle

configuration for code analysis



ISPRA 16-rod bundle

configuration for code analysis

Fig.2 GE and ISPRA rod-bundles

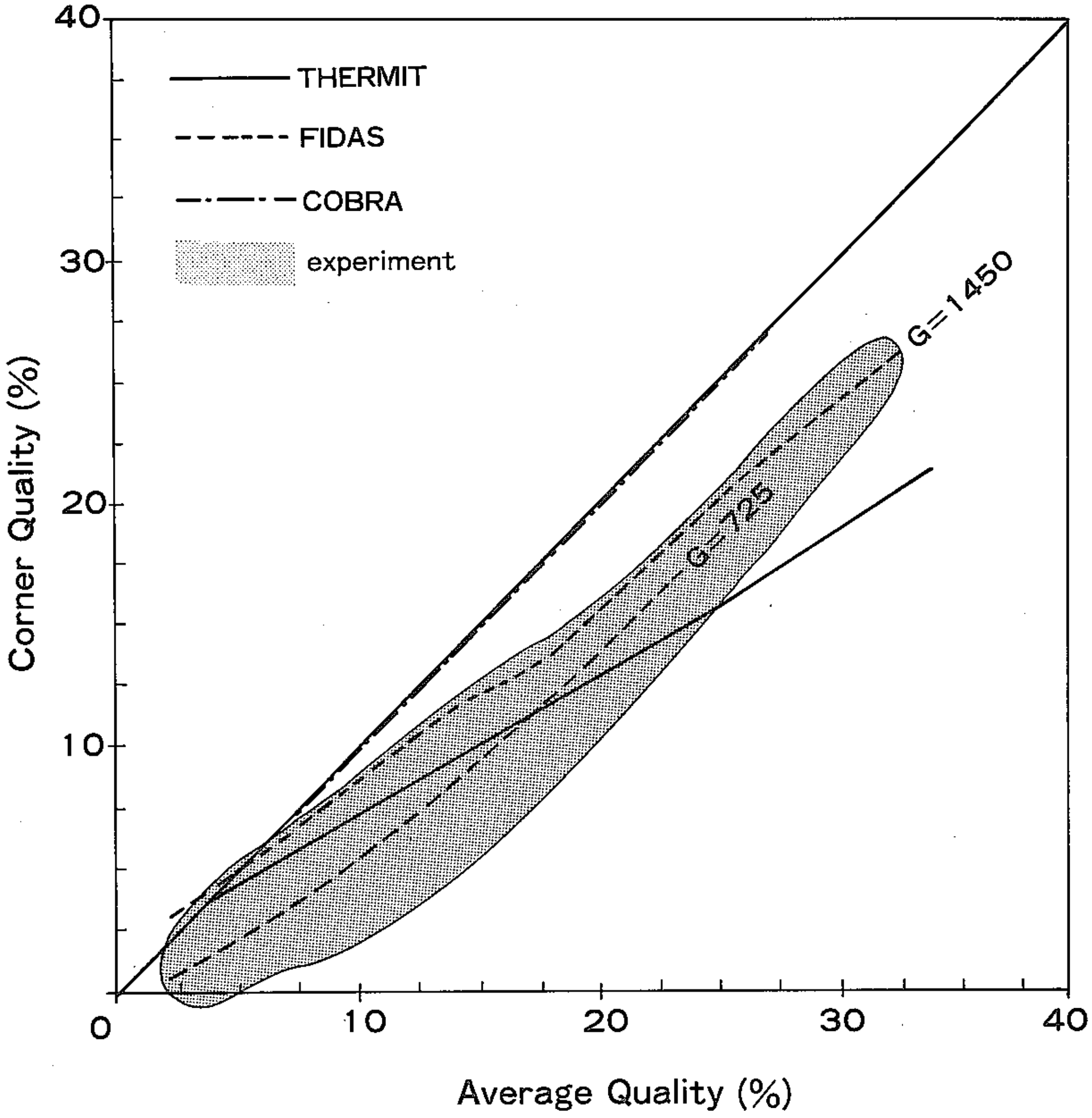


Fig. 3 Predicted and measured qualities for GE corner subchannel

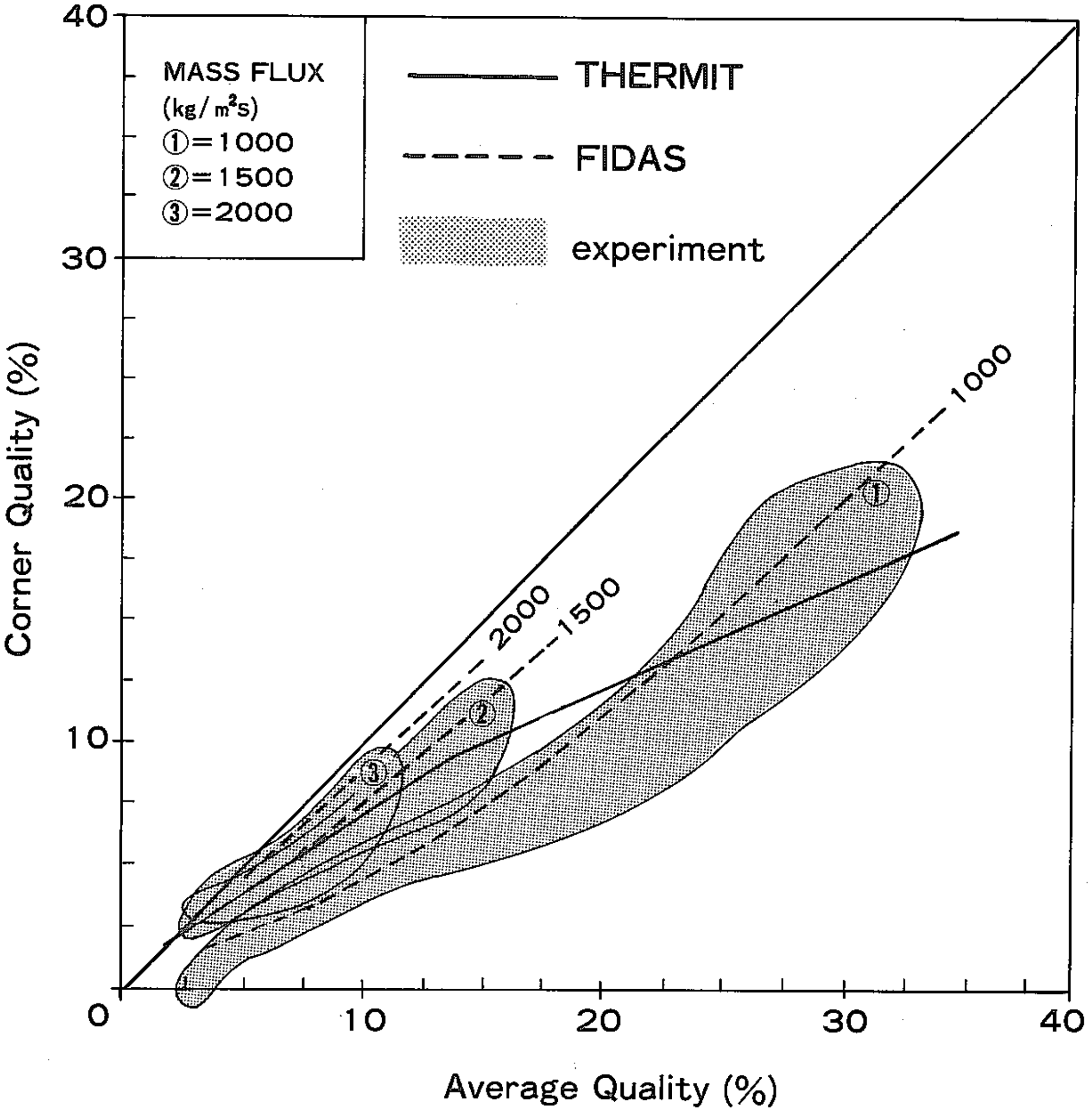


Fig. 4 Predicted and measured qualities for ISPRA-BWR corner subchannels

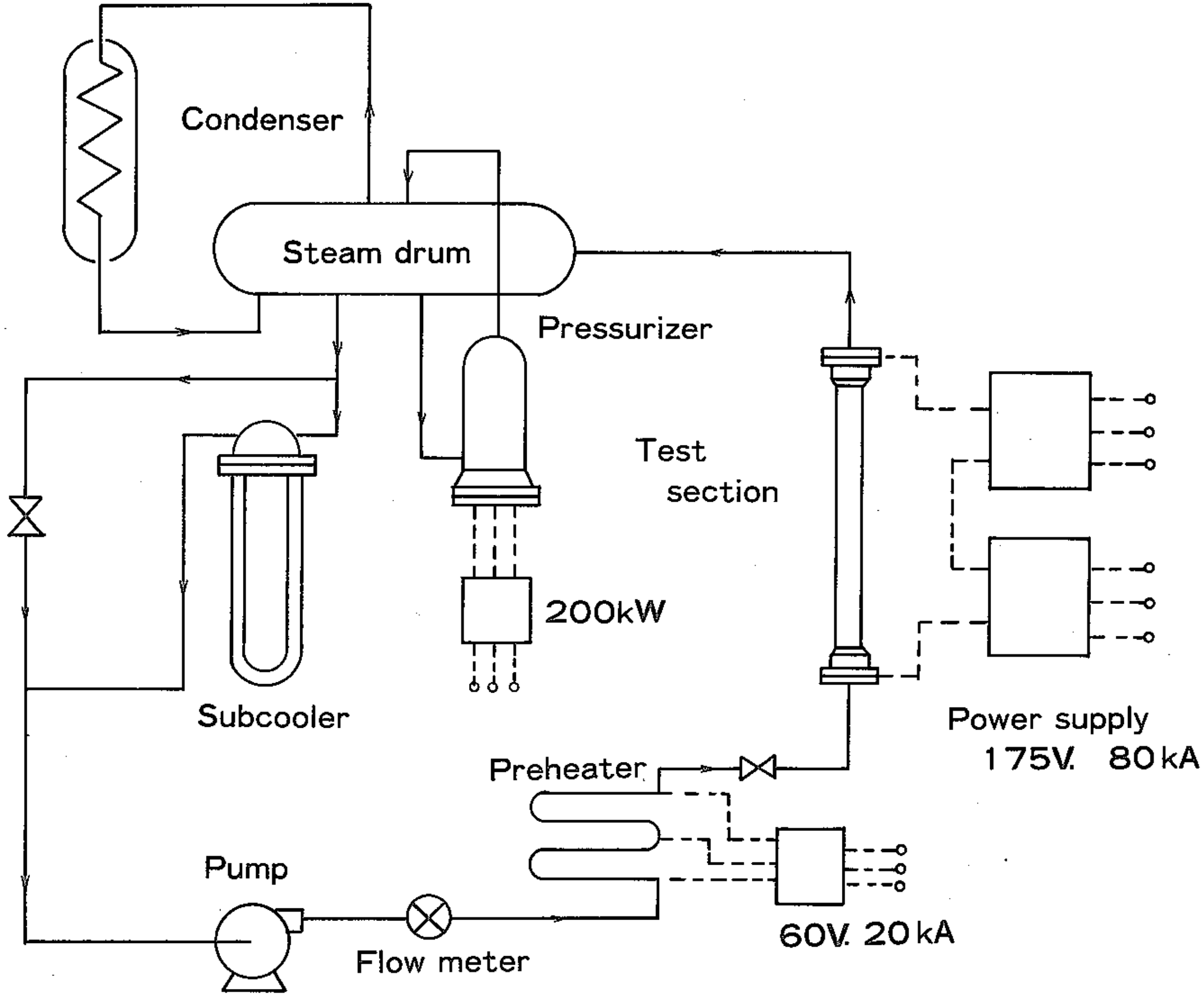
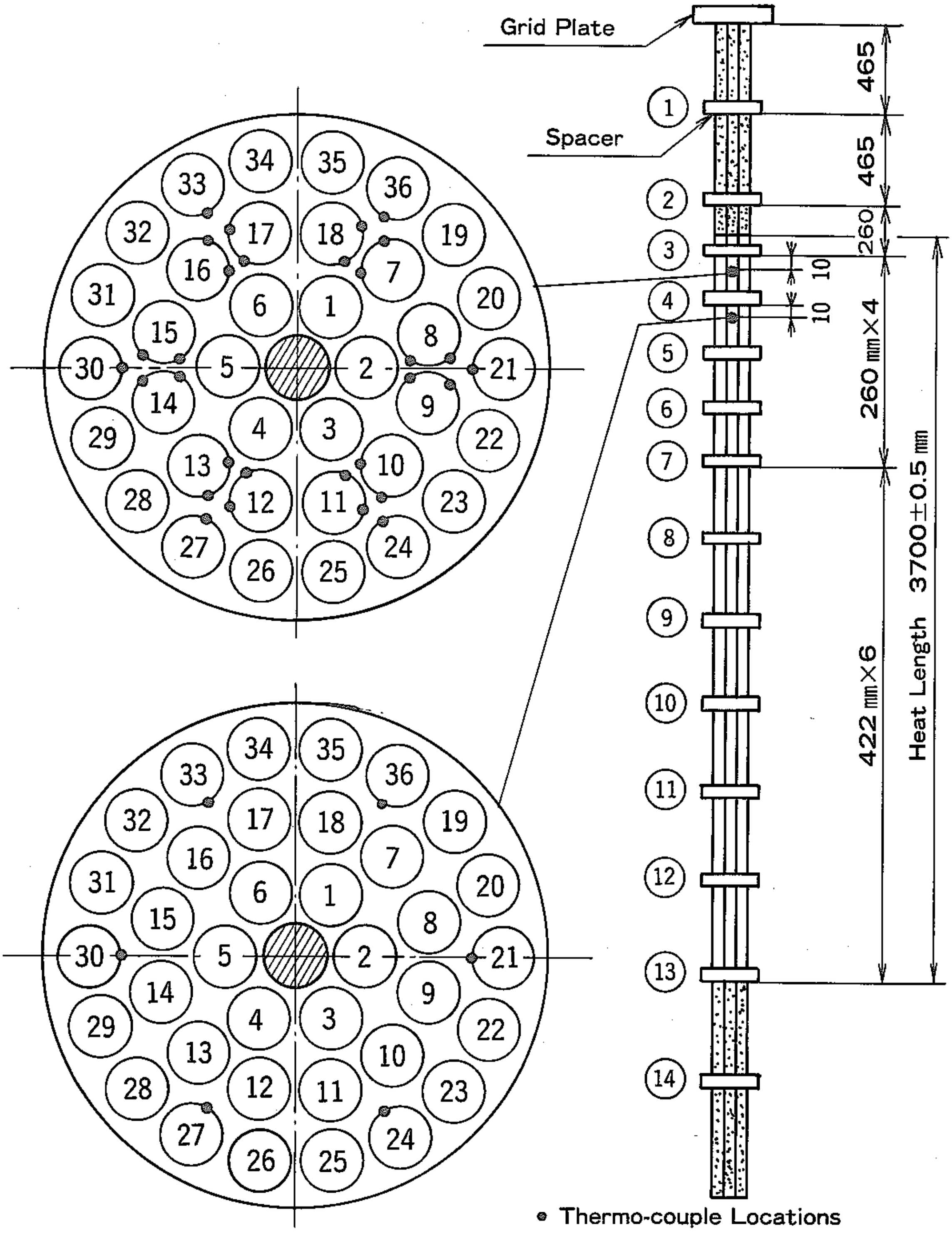


Fig. 5 Flow Diagram of 14 MW Heat Transfer Loop (HTL)

Lateral Power Distribution:
1.11/1.01/0.65 (Outer to Inner Layer)



Pitch Circle: Outer Layer ϕ97.07 mm
Middle Layer ϕ64.52 mm
Inner Layer ϕ33.72 mm

Fig. 6 Thermo-couple and spacer locations

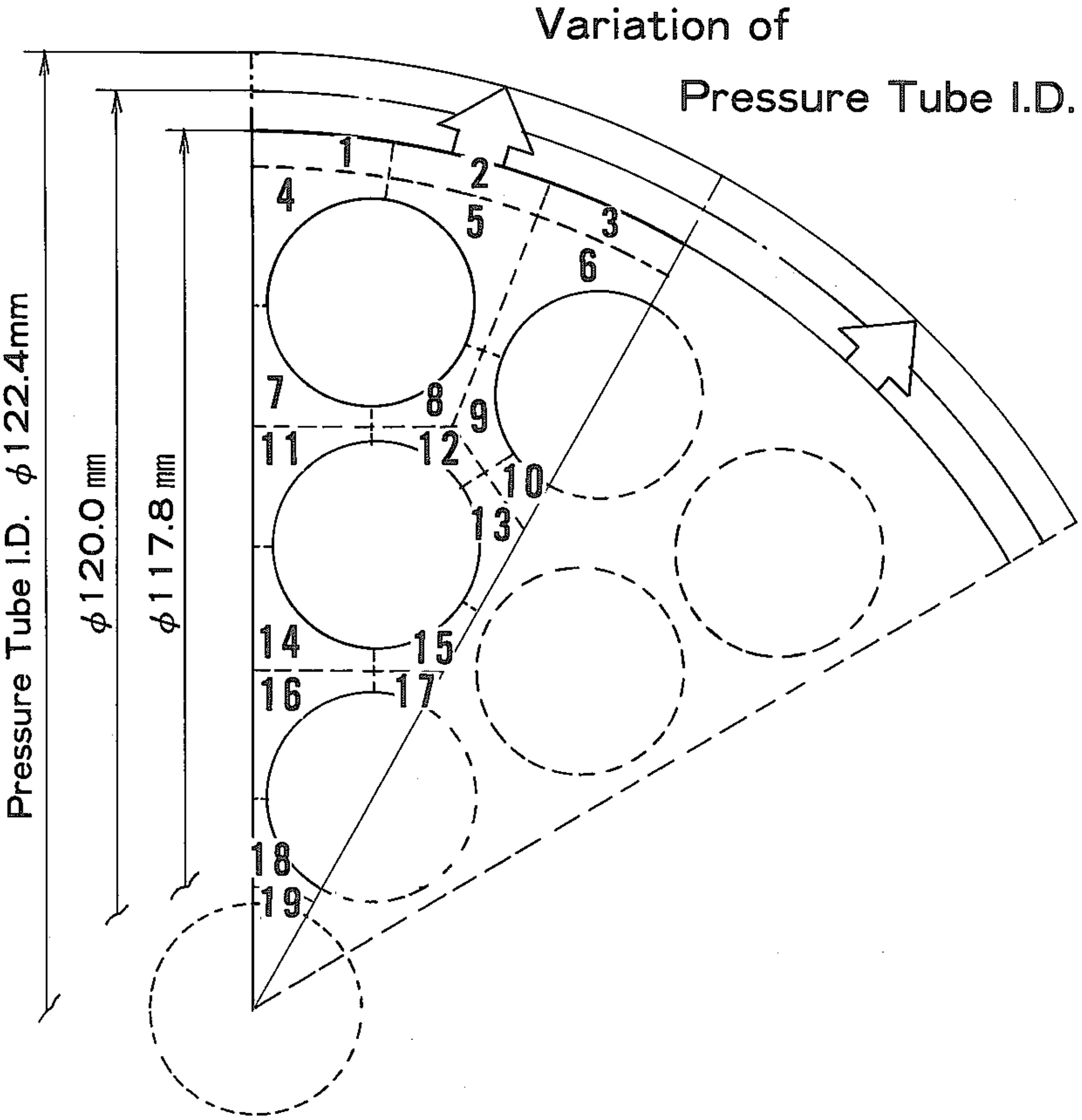


Fig. 7 Subchannels of 1/12 sector model

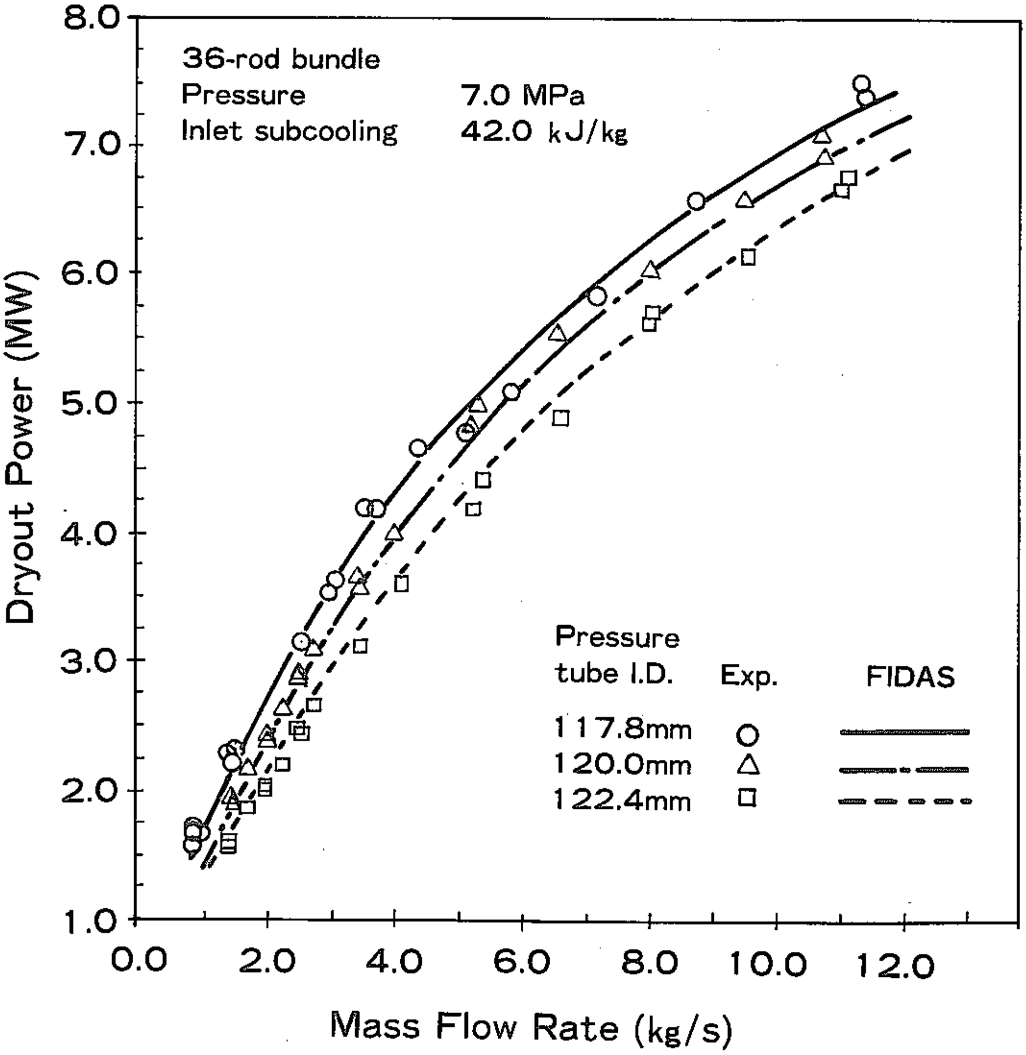


Fig. 8 Effect of pressure tube I.D. on dryout power

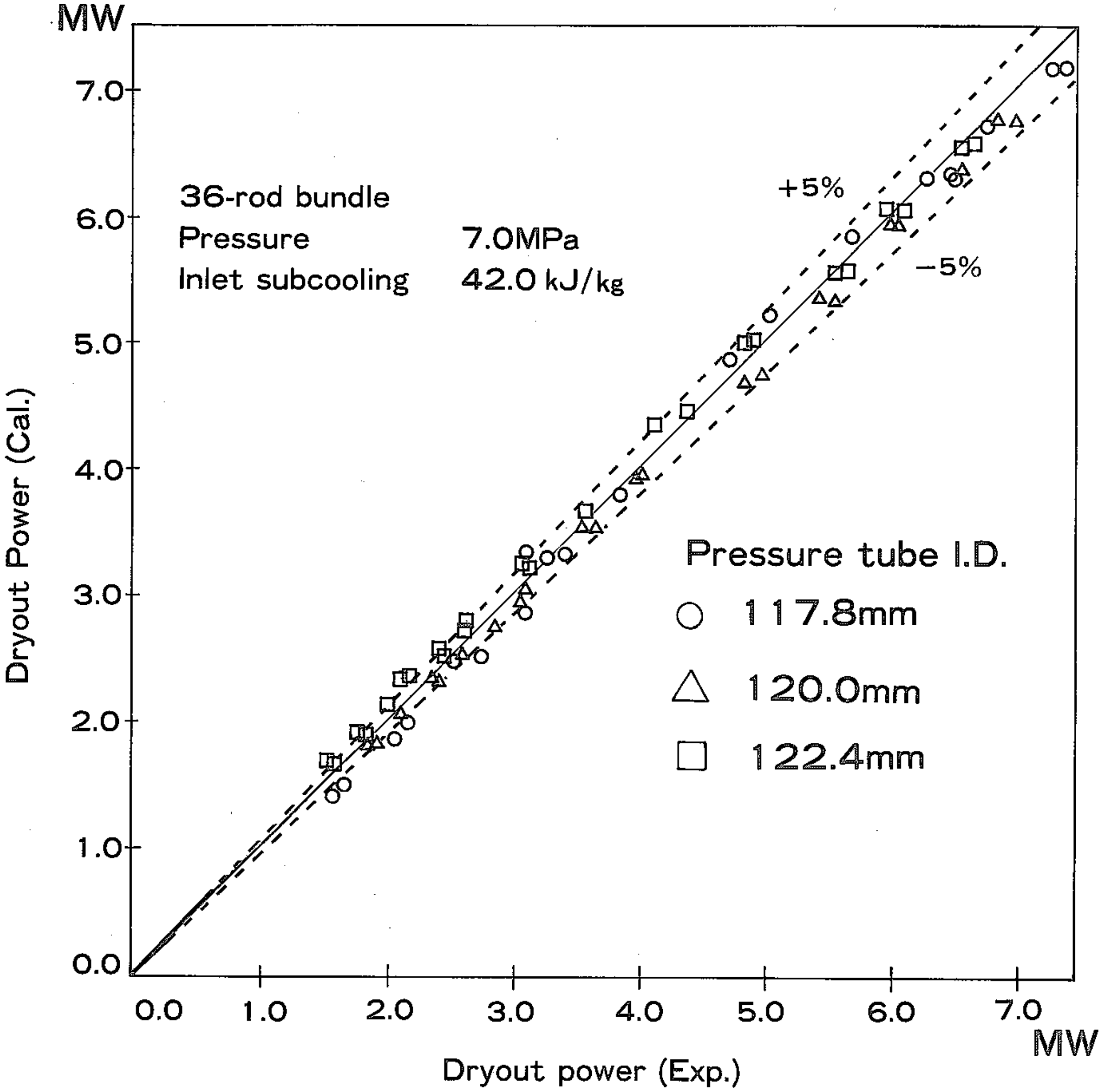


Fig. 9 Comparison between FIDAS and COBRA

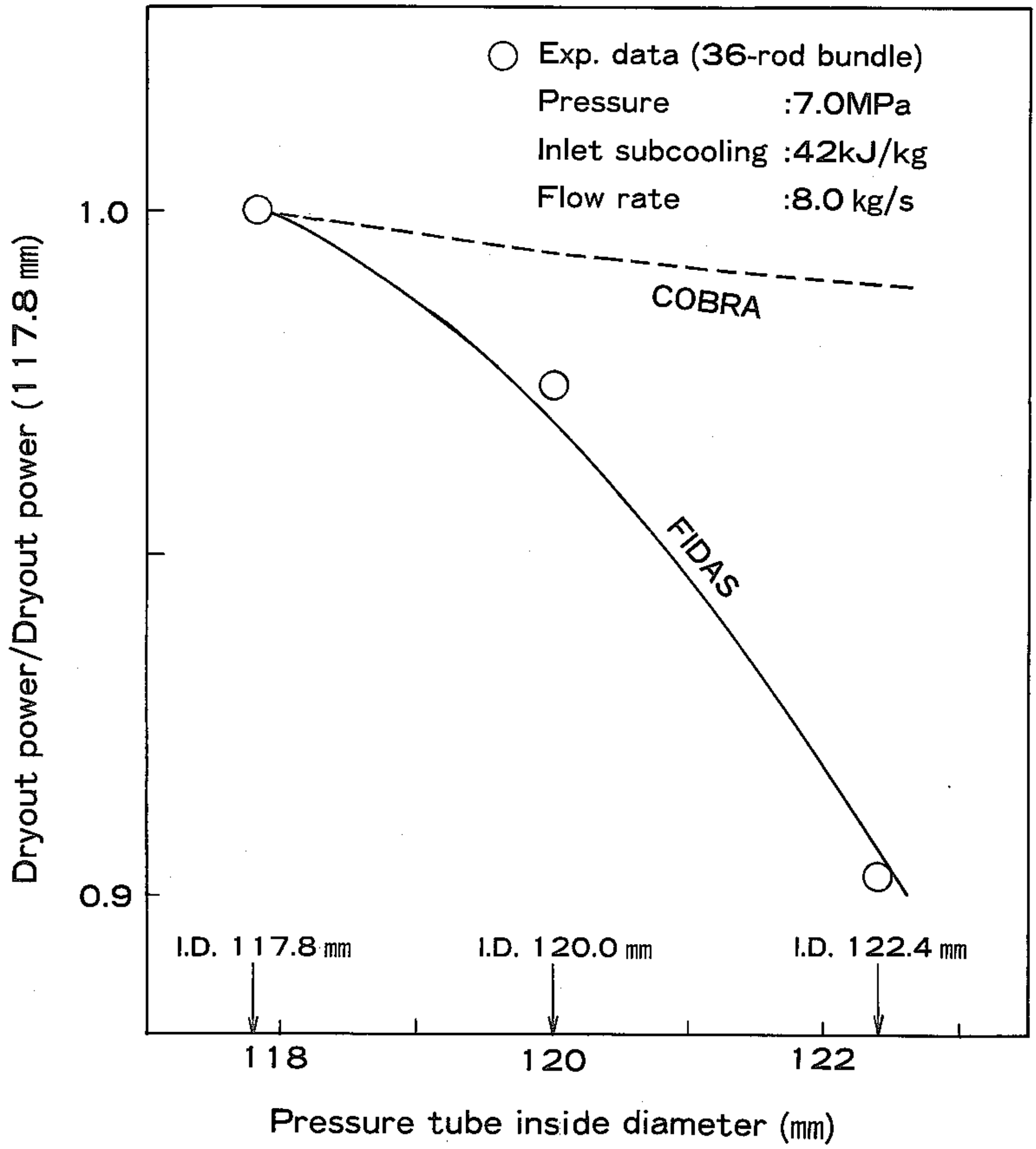


Fig.10 Prediction accuracy of FIDAS on dryout power