THERMAL
ANALYSIS METHODS FOR
LMFBR WIRE WRAPPED BUNDLES

by

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PURPOSE

This note is written to stimulate an awareness and discussion of the fundamental differences in the formulation of certain existing analysis codes for LMFBR wire wrap bundles. The contention of this note is that for those array types where data exists (one wire per pin, equal start angles), the ENERGY^{1,2} method results for coolant temperature under forced convection conditions provide benchmarks of reliability equal to the results of codes COBRA³ and TH1-3D.⁴

INTRODUCTION

Within the hierarchy of solution procedures (among others Ref.5) all of these methods are slug flow models. The key distinction between the ENERGY method and the COBRA/TH1-3D methods is in the treatment of the flow field and the need for coupling of the associated momentum equations to the energy equation. The COBRA/TH1-3D methods are subchannel methods in which these conservation equations are coupled. Historically such an approach was essential in reactor thermal analysis since the goal of early subchannel methods development was the analysis of gridded LWR bundles operating in subcooled and bulk boiling. For such bundles, significant energy exchange occurs through the mechanism of diversion crossflows. The subchannel has traditionally been chosen as the lumped region and different shapes have been chosen by different code developers.

Transport processes have been formulated in terms of proportionality parameters multiplied by differences between nodal values of velocity and enthalpy. In LWR's the cross-flows are a key transport process for momentum and energy and the establishment of these crossflows and their associated radial pressure gradients requires simultaneous solution of the conservation equations which was accomplished by the early COBRA and THINC developments.

KEY FEATURES OF COBRA/TH1-3D METHODS VERSUS ENERGY METHOD

1) COBRA/TH1-3D Methods

The current COBRA and TH1-3D methods used for LMFBR bundle analysis are outgrowths of the early COBRA and THINC developments. Therefore, the conservation equations including particularly a transverse momentum equation are written and solved for lumped regions, i.e., subchannels. Results obtained therefore characterize an average temperature or velocity over the lumped region, the subchannel. Wire mixing models are introduced which require at least one and generally more than one empirically adjustable constant.

If local temperatures within the lumped region are desired, distributed parameter techniques must be used in place of these lumped parameters.

2) ENERGY -I Method

In the ENERGY-I Method the axial flow field is characterized as a slug flow of different magnitudes in each of two zones (the bundle interior and the bundle periphery where.

the edge and corner subchannels have independent axial velocities). With axial flow so specified and by further neglect of transverse momentum coupling, the problem is formulated and solved only in terms of an energy equation which includes this flow field characterization. Such a step is highly beneficial in terms of the simplicity which it returns to bundle analysis methods and the computation storage and time savings it yields.

The characteristic size of the lumped coolant region in the ENERGY method can be the subchannel but is not restricted to the subchannel. It can be larger or smaller. The question has been discussed of whether the COBRA code could be utilized with increasing larger lumped regions sufficient to reduce the running and storage time to that of ENERGY. Consideration of this question points out the benefit of the physical model upon which ENERGY is based. Since the wire model in COBRA is that for a single wire on a subchannel basis, any steps toward coarser coolant lumps will destroy the correspondence between the wire in the model and the wire around the fuel pin. The wire input coefficients could of course be calibrated, but each sized lump would require individual calibration. Therefore in the general case the answer to the question is yes, COBRA can be run in a homogenized manner but with computation time and storage which in principal should be greater than that

required by ENERGY. Further extensive calibration to obtain input coefficients would be required. These coefficients would have lost their physical link to individual wires but could be interpreted as in ENERGY to an eddy diffusivity.

On the other hand since ENERGY characterizes the interior flow field as an effective diffusivity and the peripheral flow field as an average swirl flow, each of the regions can be aggregated as desired. The resulting temperature predicted for the lump would in fact represent the average temperature for the lump -- a temperature which may or may not be measurable depending on whether coolant thermocouples effectively integrate over the selected lump size. It should be noted that in reality the swirl flow has a periodicity circumferentially. The outer zone model in ENERGY could in the future be adjusted to include this effect.

DOES ADEQUATE ANALYSIS OF WIRE BUNDLES REQUIRE SIMULTANEOUS SOLUTION OF CONSERVATION EQUATIONS?

The wire wrap in these bundles so dominates the flow field that it is reasonable to consider whether in fact, for the desired engineering results, it is necessary to solve the system as a coupled equation problem. Application of LWR methods as COBRA and THINC to wire wrapped bundle analysis, should not be viewed as the logical extension of

such developments. The word "necessary" above identifies the key issue. Obviously the formulation of this problem in terms of couple conservation equations cannot be wrong. Rather, I conclude that the use of methods formulated to solve coupled conservation equations for wire wrap bundle analysis are only necessary if such methods yield predictions (1) in better agreement with test results or (2) covering a wider range of conditions of design interest than alternative methods.

COMPARISON OF PREDICTION TO EXISTING COOLANT TEMPERATURE TEST RESULTS

Coolant test results to date exist primarily for forced convection conditions. ENERGY-I has been extensively calibrated against such published data.⁶ This data has been used to establish recommended correlations for the empirical coefficients ϵ^* and C over a wide range of geometric variables.⁷ Uncertainty in predictions of 217 pin fuel bundles exists because the available HEDL data does not appear internally consistent. For those published cases where COBRA and THI-3D predictions have been compared to available coolant temperature data, ENERGY predictions give equally accurate results.

There is however a difference in the spatial variation in coolant temperatures predicted by codes which model the effect of each wire (COBRA and THI-3D) and by ENERGY which models the integrated effect of the wire wrap in each region. This difference is shown in figures 1 through 4 which represent the following ORNL FFM-Bundle 2A cases (see Table I for input

conditions for calculations):

Figures	P O W E R S K E W			
	U n i f o r m		3:1 T i l t	
	Interior Channel	Peripheral Channels	Interior Channel	Peripheral Channels
1		✓		
2	✓			
3			✓	
4				✓

If a designer wishes to predict the locally fluctuating spatial shape, the codes modeling each wire will yield such a representation. ENERGY, by virtue of its homogenization by region of the flow field, in fact achieves its simplicity by eliminating these local fluctuations. A spatial variation in the channels can be introduced, however, in the ENERGY model with no complication when sufficient bundle data exists upon which to formulate the spatially varying flow field. These figures also include the reported ORNL temperature measurements and illustrate that these data at any given position are as closely predicted by ENERGY as by COBRA.

Additionally there are cases where these methods are equally unsuccessful. For example the case of only three adjacent, peripheral heated pins is one where ENERGY predictions, using parameters determined by calibration against other data,

are not good. However, other methods are not any more successful in matching the data. Also, predictions of blanket temperatures⁸ differ widely between COBRA and TH1-3D even though both are reported to predict existing fuel assembly data equally well.

Based on published comparisons of predictions to date, I observe no systematic evidence that either of these three codes yields predictions any closer to test results than the others. The results of the Westinghouse 11:1 Scale Bundle Air Flow Tests which indicated lack of geometric symmetry in velocity measurements and the observation of John Wantland from ORNL tests that real heated bundles do not conform to normal specified geometry may be significant in this respect. This geometric variability plus uncertainties in thermocouple readings through calibration error, location uncertainty, and corrections for imbedded locations as well as heat balance losses, yield a net uncertainty in coolant thermocouple readings which investigators should strive to establish. This minimum variability in test data characteristic of the wire wrapped bundles themselves will effectively limit the precision to which any prediction method can match test results.

COMPARISON OF CAPABILITY TO HANDLE A WIDER RANGE OF CONDITIONS OF DESIGN INTEREST

Differences among the methods exist relative to this capability. These differences are discussed individually.

1. Predictions within the axial distance of the first wire lead length.

The wire wrap geometry only sets up a field which can be characterized by an effective eddy diffusivity when a sufficient number of wire passes have been made through a subchannel. This requires about $3/4$ of a lead length based on count of the number of wire passes through a subchannel which occur over this length. Attempts to confirm this estimate through analysis of the Westinghouse 11:1 scale data⁹ have established that $\frac{32''}{129.4''} \approx \frac{1}{4}$ of a lead length is an insufficient length. A positive estimate of the required length cannot be made from 11:1 scale data since these test results could only be obtained over one quarter of a lead. The ENERGY method also inputs a fully developed flow split into the bundle at the inlet.

Both these factors will cause inaccuracies in the ENERGY results over the first $3/4$ of a lead. The axial length this involves is 9 of 36 inches in a fuel assembly and 3 of 36 inches in a blanket assembly. The significance of this error is small since these are not the zones where temperature predictions are generally desired and since transverse temperature gradients in this entrance region are small.

Nevertheless this error in the inlet bundle region is one introduced by the ENERGY assumptions. To understand its origin is to understand the fundamental formulation of the ENERGY method. In fact this error is a price paid for savings in computation time and storage obtained in ENERGY by decoupling the conservation equations.

2. Predictions at Low Reynolds Numbers (in mixed forced/free convective region)

The formulations of the COBRA and TH1-3D methods will cover the range of Reynolds number conditions from turbulent through laminar with the use of appropriate flow resistance factors and in some code versions to conditions of flow reversal. However, the empirical coefficients in the wire wrap model must be recalibrated in the transition and laminar regions with test data just as is required for the parameters ϵ^* and C in the ENERGY method. The ENERGY method was expanded as ENERGY II and III to cover conditions of mixed free and forced convection since the ENERGY I method did not include means for lateral energy transport by convective flow as required for cases where free convection effects are important. Further, a Grashof number criterion was developed to identify the conditions under which free convection effects must be considered. Use of this criteria permits a designer to use ENERGY I with confidence and achieve computation time and storage savings for cases in which free convection effects are determined to be negligible.

It is true that in the low Reynolds number region, the computation time of the ENERGY II and III methods does increase significantly as compared to ENERGY-I although it should in principal be considerably less than the required COBRA/TH1-3D times. However, use of ENERGY does permit time reductions in these cases by aggregating regions, a step which can be done

without change in empirical constants by virtue of the physical model upon which ENERGY is based.

Finally it should be recognized that below some Reynolds number, wire effects will be secondary to molecular effects. In this regime, radial temperature gradients will exist principally in the vicinity of edge subchannels. These temperature gradients will also change with axial position from the inlet. If accurate local temperature predictions are required in this flow regime, the lumped parameter methods discussed here will have to be replaced by distribution parameter approaches, probably with 3D capability.

3. Predictions for New Geometries of the Same Array Type.

Prediction of the effects of p/d and h/d are desirable. The physical basis of the ENERGY parameters ϵ^* and C appear to offer the opportunity to prepredict their behavior with these geometric parameters but this has not been done to date. Rather ϵ^* and C have been calibrated against available data over a range of these geometric variables. Since the input parameters of COBRA and TH1-3D characterizing the wire wrap are independent of these geometric parameters, these codes proprot to allow preprediction of temperature fields in bundles of changing geometry. Assessment of this claim requires publication of a comprehensive comparison of predictions versus data, publication which has not appeared to date for either code. However, the substantial differences in predictions in blanket temperatures⁸ between COBRA and TH1-3D

when both codes have been claimed to predict ORNL fuel assembly data equally well offer reason to speculate whether the input to these methods is in fact independent of array geometry.

4. Fuel and Clad Temperature Predictions

Both COBRA and TH1-3D have the capability to make such predictions. The ENERGY codes as written predict only the coolant temperature field. The ENERGY codes can be expanded to make such temperature predictions utilizing the same level of approximation (i.e., utilize a heat transfer coefficient) as in the COBRA and TH1-3D codes. This is being done as part of the expansion of the ENERGY method to include transient capability.

5. Off-Normal Geometry

Both COBRA and TH1-3D have the capability to make such predictions by virtue of their formulation solving the coupled conservation equations. In each case the adequacy of the transverse momentum equation must be confirmed. For such problems the ENERGY method can only be used when calibrated for stipulated configurations. Since a method is probably desired to handle an arbitrarily shaped blockage, the COBRA and TH1-3D methods are the obvious choice for such problems. COBRA IV has been formulated to specifically handle such problems.

Conclusions

Except for predictions within the first wire lead, all

methods require the same degree of calibration against heated bundle data and once calibrated, all methods yield equally reliable results for coolant temperatures under forced convection in normal geometry bundles. Presently, ENERGY predicts only coolant temperatures but the capability to predict fuel and clad temperatures is being added.

Figures 1-4 also point out we are far from the designer's stated goal of prediction accuracy within 1-5 °F (.3 to 1.6% for 300 °F ΔT) even for coolant temperatures in 19 pin bundles. I believe such a goal is unattainable in view of the uncertainties in geometry that heated bundle adopt and uncertainties in test data due to thermocouple output interpretation and heat balance errors. Rather the present state of temperature differences among prediction methods and test data of the order of 5-10 °F probably represents the attainable limit in prediction accuracy. Designers will have to develop methods for core reliability analysis which recognize the existence of this order of uncertainty in clad temperature prediction.

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TABLE 1

ORNL FFM2A Bundle Parameters as Used in Figures 1-4

	TEST BUNDLE	COBRA IIIC INPUT	SUPERENERGY INPUT
I. General			
number of pins	19	19	19
number of subchannels	42	36	42
pin diameter (in.)	0.230	0.230	0.230
wire wrap diameter (in.)	0.056	0.056	0.056
rod pitch (in.)	~ 0.286	0.286	0.286
wire wrap lead (in.)	12.0	12.0	12.0
heated length (in.)	21.0	21.0	21.0
axial steps per inch		1	15
effective eddy diffusivity			0.01948 ⁺
swirl/axial velocity ratio			0.09518 ⁺
diversion crossflow			
resistance factor		0.500 [*]	
subcooled mixing factor		0.020	
flow split		equal pressure gradient	equal pressure gradient
II. 3/1 Power Skew	Test 14 Run 101		
inlet temperature (°F)	647.02	647.0	647.0
inlet pressure (psi)	33.55	33.55	
flow	54.59 GPM	4.579 M-lb/hr-ft ²	23,810 lbm/hr
average heat flux $\frac{\text{M-Btu}}{\text{hr-ft}^2}$	0.2847	0.2847	0.2847
III. 1/1 Power Skew	Test 2 Run 105		
inlet temperature (°F)	836.18	836.2	836.2
inlet pressure (psi)	33.91	33.91	
flow	54.63 GPM	4.445 M-lbm/hr-ft ²	23,115 lbm/hr
average heat flux $\frac{\text{M-Btu}}{\text{hr-ft}^2}$	0.5498	0.5498	0.5498

⁺ Based on values recommended by empirical correlations in Ref. 7

^{*} Values from sample problem in COBRA Manual (BNWL-1695).

1 $\pm$ /1 $\pm$ POWER SKEW

CIRCUMFRENTIAL TEMPERATURE DISTRIBUTION FOR ORNL FFM-2A BUNDLE

AXIAL HEIGHT - 23"

FIGURE 1

COOLANT TEMPERATURE VS AXIAL HEIGHT
FOR ORNL FFM-2A BUNDLE $1\frac{1}{2}$ POWER SKEW
CHANNEL #3

FIGURE 2

COOLANT TEMPERATURE VS AXIAL HEIGHT
FOR ORNL FFM-2A BUNDLE $\frac{3}{1}$ POWER SKEW
CHANNEL #3

FIGURE 3

3/1 POWER SKEW

CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION
FOR ORNL FFM-2A BUNDLE
AXIAL HEIGHT - 23"

--- SUPERENERGY PREDICTION
— COBRA IIIc PREDICTION
⊗ DATA POINTS

Figure 4