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ACCESSION NBR: 8707200418 DOC. DATE: 87/07/13 NOTARIZED: NO DOCKET #
FACIL: STN-50-528 Palo Verde Nuclear Station, Unit 1, Arizona Publi 05000528
STN-50-529 Palo Verde Nuclear Station, Unit 2, Arizona Publi 05000529
STN-50-530 Palo Verde Nuclear Station, Unit 3, Arizona Publi 05000530
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CRUTCHFIELD, D. Associate Director for Projects (Post 870411)

SUBJECT: Forwards steam generator tube vibration evaluation program progress rept, per GW Knighton 870327 ltr & author 870410 commitment. Rept provides general description of program, results to date & anticipated direction of future efforts.

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COMBUSTION ENGINEERING

July 13, 1987
LD-87-038

Docket No. STN 50-470F

Mr. Dennis M. Crutchfield
Director, Division of Reactor Projects
Attention: Document Control Desk
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Subject: Palo Verde Steam Generator Tube Vibration

References: (A) NRC Letter, George W. Knighton to A. E. Scherer, March 27, 1987
(B) A. E. Scherer to G. W. Knighton, LD-87-017, April 10, 1987

Enclosure: Palo Verde Steam Generator Tube Vibration Evaluation Program Progress Report

Dear Mr. Crutchfield:

The NRC letter, Reference (A), posed a number of questions concerning the steam generator tube vibration observed at Palo Verde. As promised in our response, Reference (B), this transmittal provides a general discription of Combustion Engineering's ongoing evaluation program, our results to date as well as the anticipated direction of our future efforts.

Thus far, Combustion Engineering has utilized analytical codes and emperical methods to more accurately model steam generator flow patterns in the tube lane and tube bundle annulus regions of the steam generator cold side. We have confirmed that high velocity flow streaming in and about the open tube lane above the economizer divider plate appears to be the root cause of the tube vibration. (Secondary fluid velocities on the order of 25 feet per second are calculated to exist in the open lane.)

Our next step will be to model the complex nature of the flow at the boundaries of the tube bundle corner region. We are also considering a test program to determine the velocity threshold at which flow induced vibration could cause tube damage during the life of the plant.
It should be noted, however, that Combustion Engineering has not identified any changes to the Palo Verde steam generator design to date which would be necessary to assure its continued safe operation.

E003
1/1

Power Systems
Combustion Engineering, Inc.
1000 Prospect Hill Road
Post Office Box 500
Windsor, Connecticut 06095-0500
(203) 688-1911
Telex: 99297

We have enclosed for your review, information which briefly outlines our current results and provides additional information on our anticipated efforts. Once you have had a chance to review the enclosed material, we suggest a meeting with members of the NRC staff so that we may more fully respond to your questions and gain your input before finalizing our plans.

If I can be of any additional assistance in this matter, please do not hesitate to call me or T. L. Cameron of my staff at (203) 285-5217.

Very truly yours,

COMBUSTION ENGINEERING, INC.

A. E. Scherer
Director
Nuclear Licensing

AES:ss
Enclosure

ENCLOSURE
PALO VERDE STEAM GENERATOR TUBE VIBRATION EVALUATION
PROGRAM PROGRESS REPORT

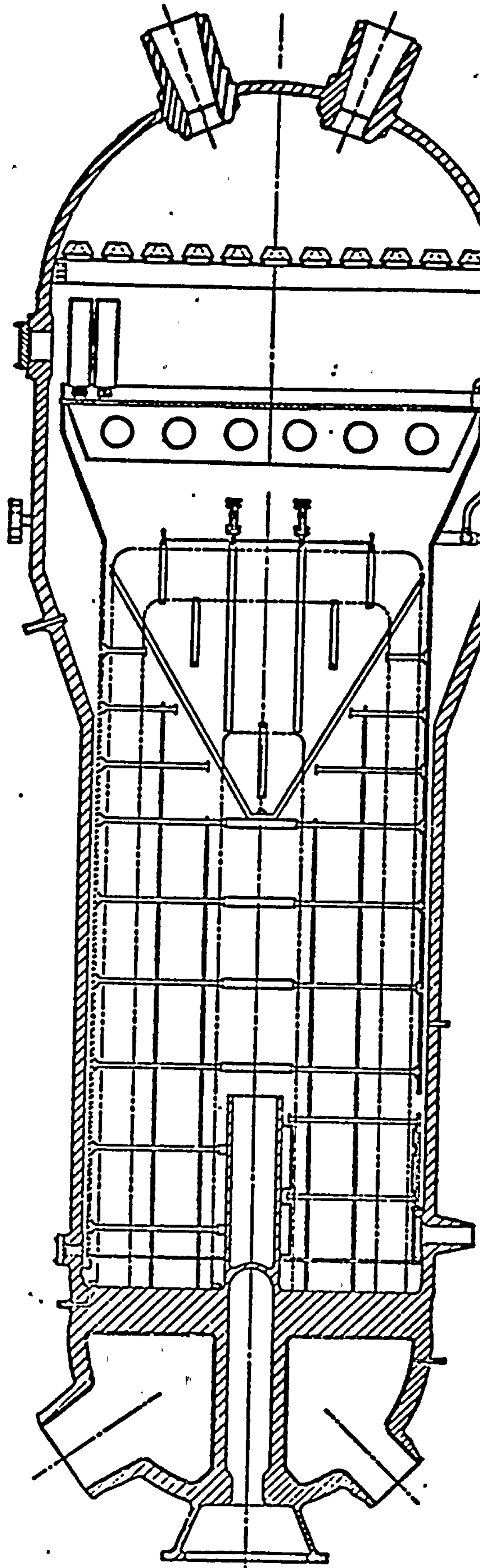
I. Introduction

C-E has performed an in-house review of all available information pertinent to the Palo Verde Steam generator tube vibration. To date, we have made substantial progress in evaluating the steam generator secondary side flow paths and flow velocities in this localized area for the Palo Verde steam generator geometry. This has been accomplished primarily through the use of more detailed flow distribution analyses methods.

II. Flow Analysis

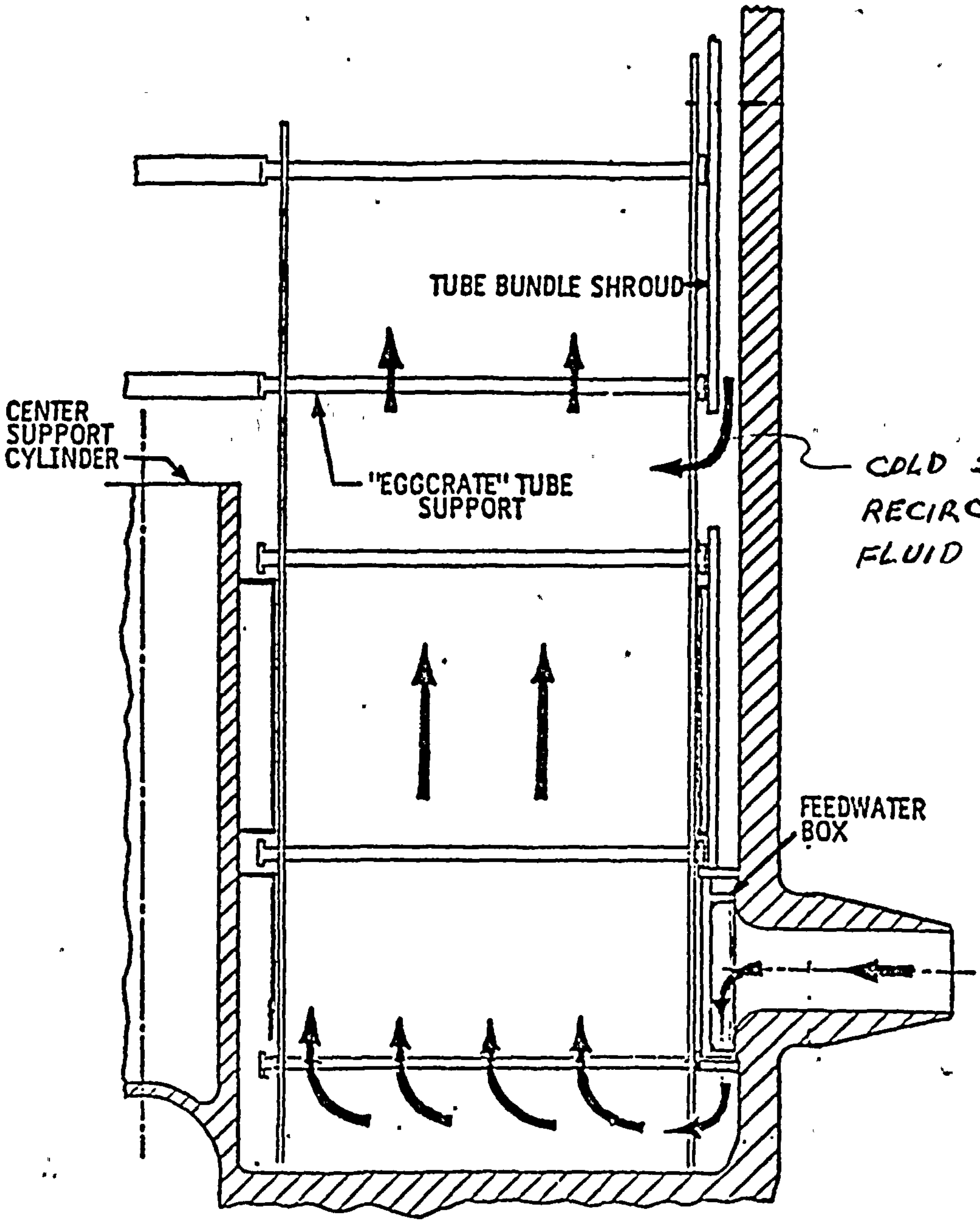
In the Palo Verde steam generators, (Figure 1), the downcomer recirculating flow enters the cold leg side tube bundle above the integral economizer between the second and third tube supports (Figure 2). At the intersection of the recirculating water entrance window and the tube lane, a unique condition exists wherein the downcomer recirculating water preferentially seeks the low flow resistance open tube lane (Figure 3). This results in high local radial cross flow velocities. These velocities may be of sufficient magnitude to cause tubes along the tube lane near the recirculating water entrance window to vibrate within the eggcrate supports, resulting in tube damage.

FIGURE 1



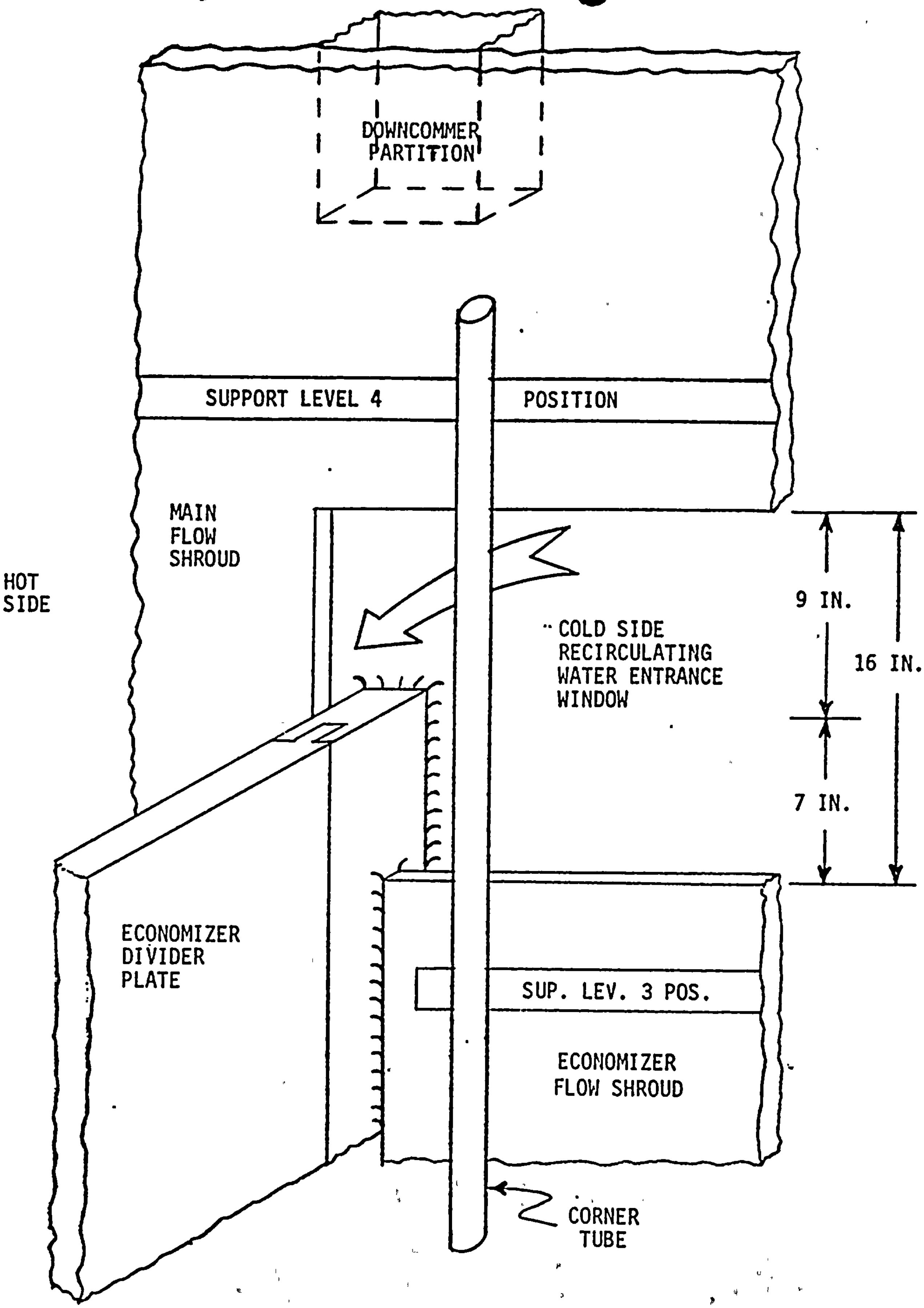
PALO VERDE STEAM GENERATOR

FIGURE 2



INTEGRAL AXIAL FLOW ECONOMIZER

FIGURE 3



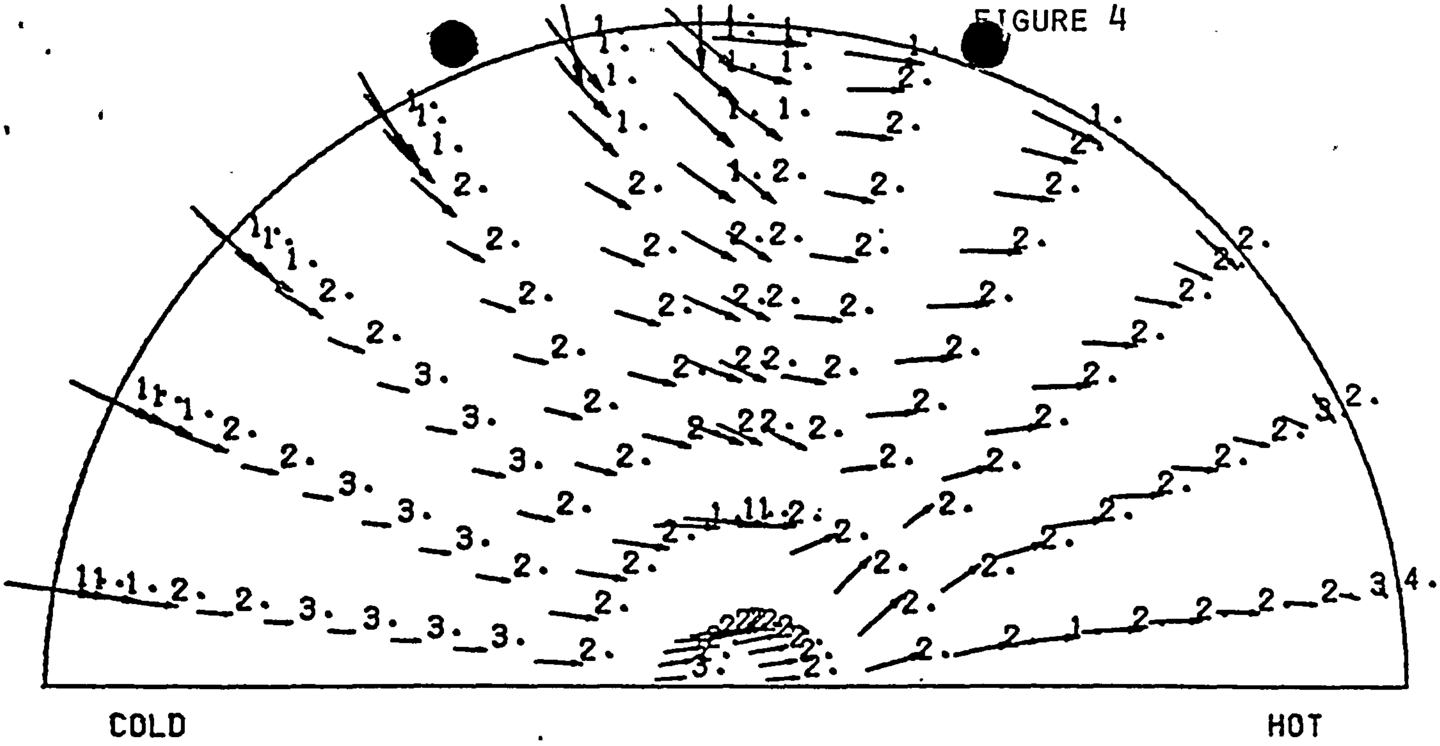
PALO VERDE STEAM GENERATOR COLD SIDE RECIRCULATING FLUID ENTRANCE REGION

Eddy current test inspection results at Units 1 and 2 demonstrated that this damage is isolated to the small number of tubes at the intersection of the tube lane and the downcomer window. Previous thermal hydraulic design analysis used a coarse mesh model to simulate steam generator flow characteristics. In the tube lane/ recirculating window region, the coarse mesh model did not simulate the peak local velocities in sufficient detail. As such, this localized region of high velocity was not initially predicted. In order to better understand the flow characteristics, C-E has recently performed further analysis in this region of interest using a much more detailed approach.

C-E's detailed analysis utilizes a combination of two flow models: ATHOS 2 and FLOW 3. The ATHOS code analyzes steady-state flow distributions within the secondary side of PWR steam generators and can be used to model one, two, and three-dimensional geometries. FLOW 3, on the other hand, is a general purpose flow distribution model which is limited to steady-state thermal and hydraulic analyses of two phase flows.

In order to obtain values for flow velocities in this region, the ATHOS flow distribution code was used to model the entire steam generator secondary side. Figure 4

FIGURE 4



VELOCITY VECTORS (R,θ) AT HEIGHT= 8.83 FEET

RANGE	MAX VEL (FT/SEC.)
1.	3.450
2.	1.725
3.	.862
4.	.431
5.	.215
6.	.107
7.	.053
8.	.026
9.	.013
10.	.006

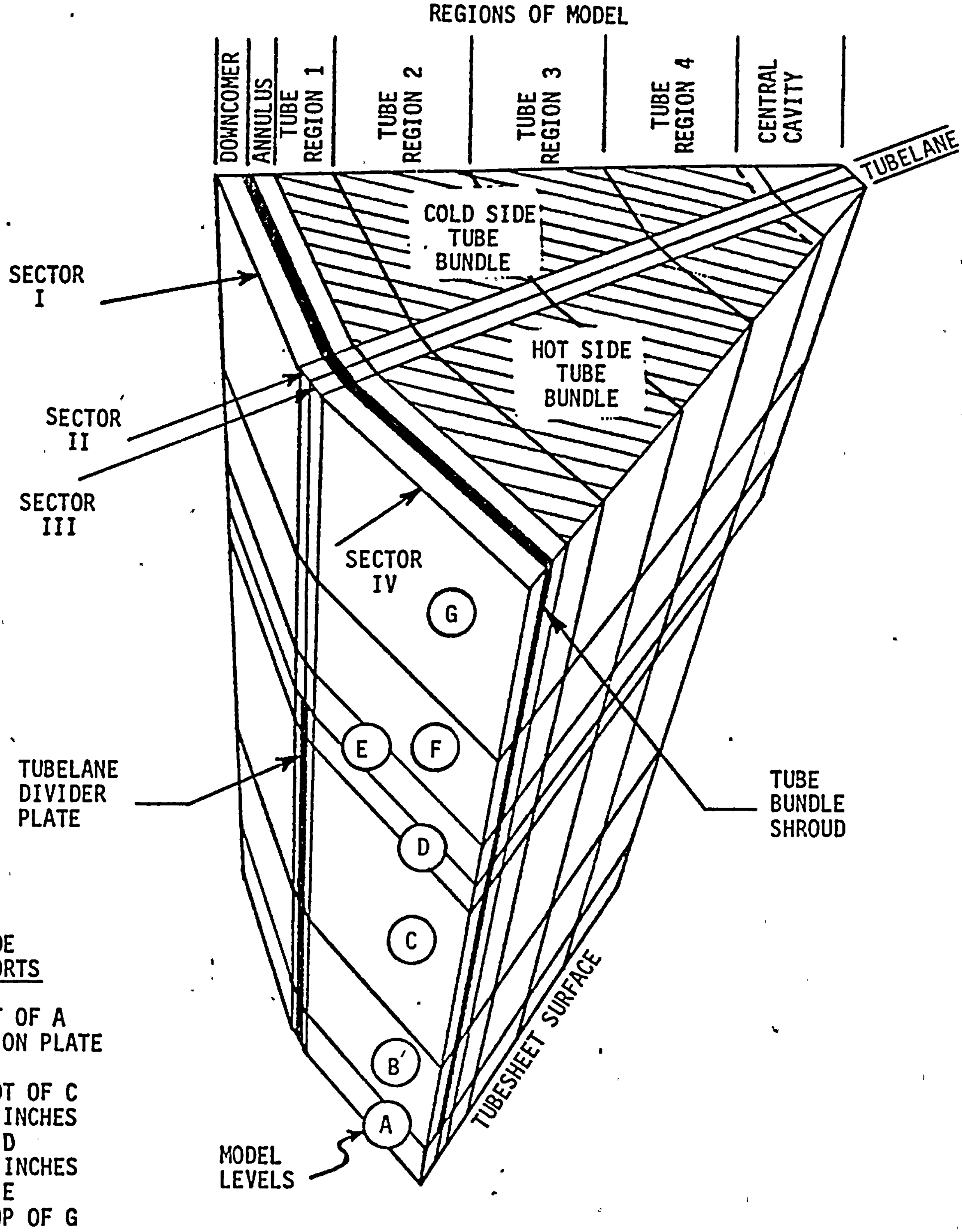
ATHOS ANALYSIS

ARIZONA SYSTEM 80 (100 PCT)

represents typical results which were obtained from ATHOS for one of the steam generator elevations. The boundary conditions generated by ATHOS for the region of interest were then applied to the FLOW 3 local flow distribution model. Figure 5 diagrams the methodology for segmenting a portion of the steam generators into nodes. The FLOW 3 model was then run and relative fluid velocities were obtained into and out of each node. Figure 6 provides an indication of the velocities predicted for the tube lane at level E which is directly above the point at which the economizer divider plate ends. These results indicate that high velocities exist in both the tube lane and the tube bundle annulus. This figure also shows a relative dropoff in velocity for fluid which flows through the tube gaps. In other words, as the path through the tube gap from the tube bundle annulus to the tube lane lengthens, a corresponding reduction in tube lane velocity is noted. Also, Figure 6 indicates the tubes which were found to have experienced damage in any one of the two quadrants within each of the four steam generators. The number within each tube represents the maximum wear which was found in tubes at that location. The key identifies how to interpret the percentage of tube wall wear.

The analysis has also demonstrated that the conditions necessary to induce the vibrational damage are not present in the hot side tube region. The conditions for

FIGURE 5



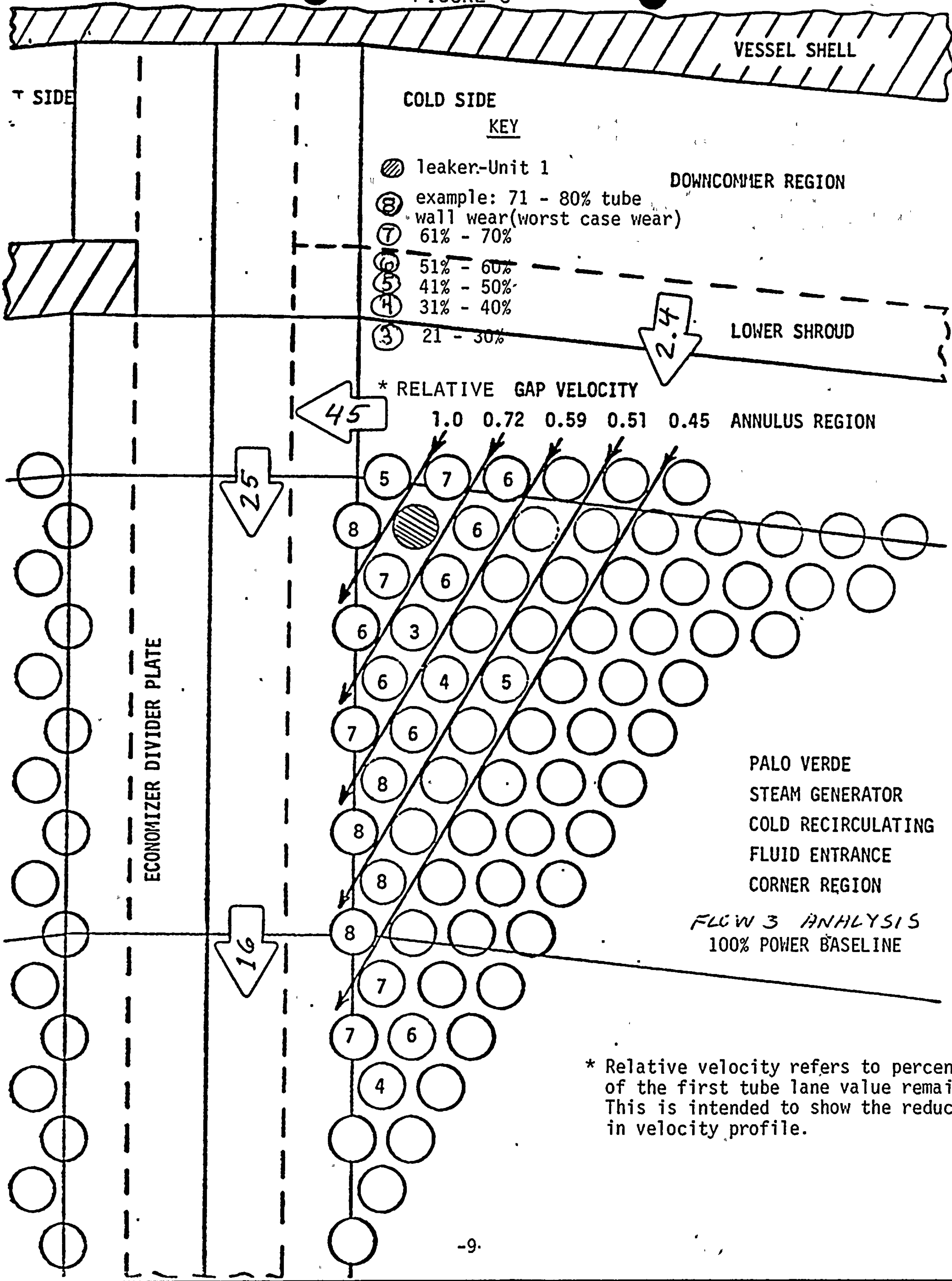
COLD SIDE
TUBE SUPPORTS

TUBESHEET - BOT OF A
FLOW DISTRIBUTION PLATE
 - BOT OF B
EGGCRATE 1 - BOT OF C
EGGCRATE 2 - 4 INCHES
 BELOW BOT OF D
EGGCRATE 3 - 4 INCHES
 ABOVE TOP OF E
EGGCRATE 4 - TOP OF G

FLOW3 MODEL

FLOW DISTRIBUTION ANALYSIS MODEL
ECONOMIZER LOCAL CORNER REGION
OF PALO VERDE STEAM GENERATOR

FIGURE 6



* Relative velocity refers to percent of the first tube lane value remainin This is intended to show the reductio in velocity profile.

damage were not expected since the hot side recirculating fluid enters the tube bundle region immediately above the tube sheet where the tubes are much stiffer and the hot side does not have the recirculating water entrance window higher in the bundle. The analysis has shown that while some fluid from the cold side recirculation entrance window does pass to the hot side, the velocities are much less.

III. Test Verification

In order to quantify the extent that tube wear can be anticipated over the plant life, C-E must be able to determine velocities in the tube gap regions shown on Figure 6. Since analytical means alone may not be sufficient to determine tube gap velocities with sufficient confidence, C-E is considering a test which would model steam generator flow conditions in the local tube lane region. We anticipate that this test would enable us to determine the threshold at which flow induced vibration is able to inflict tube damage via excessive wear over the life of the plant.

Once the threshold is determined, a comparative analysis can be performed to determine the tube regions which may be subjected to flow velocities in excess of the threshold value. It should then be possible to determine the extent

of wear which can be anticipated during Palo Verde's operating life and what, if any, further corrective actions need to be performed. (Also, the results could serve as a basis for substantiating any modifications, if any, which may be considered for future System 80 steam generator designs.)

We have included, as part of this enclosure, exerpts from an EPRI study which was performed to verify the ATHOS and FLOW 3 codes against experimental data obtained from the Swedish FRIGG Heated Rod Bundle Experiment.

Although C-E has not reviewed the specific details, EPRI has sponsored several other studies in which the ATHOS code has been qualified. ATHOS and FLOW 3 have been previously used within the industry for modeling steam generators flow patterns. Predictions for the circulation ratio, primary inlet and outlet temperatures and secondary fluid temperatures just above the tube sheet have compared well with data measured by Electricite de France (EdF) at their plants. That study included steady-state simulations at full power and several reduced power levels, as well as a transient load rejection from full power. ATHOS predictions have shown good agreement with a theoretical solution for flow in the upper plenum of a BWR. Comparisons with measured data have also been made of the flow field in the Westinghouse Model Boiler No. 2 experiment.

IV. DESIGN CHANGES

The Palo Verde steam generators have very limited access to the economizer region. This makes any further modifications, including installation of instrumentation extremely difficult. In addition, C-E believes that with the variations in tube to tube support clearance, data obtained on a small scale could be misleading and not necessarily helpful. Finally, a tube removal from Palo Verde's steam generators for inspection purposes will not yield any new information since the multi-frequency eddy current testing already performed, has enabled us to define the wear scar.

The corrective actions which have been implemented at the Palo Verde units have significantly reduced the potential for further tube damage. The results which we have obtained to date and the future analysis and testing which we are considering should be adequate to demonstrate whether any further tube damage at the Palo Verde units will be significant and whether major modifications will be required.

A number of design improvements for our future System 80 steam generator designs are currently under consideration at this time. The modifications could include modifying the

downcomer region, reducing the size of the cold side flow entrance window, and/or raising the tube lane economizer divider plate.

V. SUMMARY

The flow modeling and analysis which has been performed to date has increased our knowledge and understanding of the vibration phenomena in the cold side tube lane and tube bundle annulus region of Palo Verde's steam generator. To date, Combustion Engineering has not identified any new changes to the Palo Verde steam generator design which are necessary to assure its continued safe operation. Further analysis and possible flow testing is expected to demonstrate the anticipated wear pattern over the life of Palo Verde. Finally, C-E intends to review possible improvements to our System 80 steam generator design.

APPENDIX

EPRI

Electric Power Research Institute

Topics:
Steam generators
Thermal hydraulics
Code validation
ATHOS code

EPRI NP-3514
Project 1066-2
Final Report
May 1984

ATHOS and FLOW3 Simulation of the FRIGG Heated Rod Bundle Experiment

Prepared by
Combustion Engineering, Inc.
Chattanooga, Tennessee

EPRI PERSPECTIVE

PROJECT DESCRIPTION

The ATHOS code, described in EPRI report NP-2698-CCM, analyzes steady-state and transient flow distributions within PWR steam generators. ATHOS is applicable to one-, two-, and three-dimensional geometries. FLOW3, a similar program, is limited to steady-state thermal and hydraulic analyses of two-phase flows in one- and two-dimensional geometries. In this current study, the two codes simulated the small-scale Swedish experiment, FRIGG, as the first step in the ATHOS verification process.

The ATHOS verification and validation program calls for selected small-, medium-, and large-scale simulations of steam generator experiments. In this initial verification step, ATHOS simulated the FRIGG heated rod bundle experiments in order to calculate void-fraction distributions at different inlet conditions. Investigators compared the results of the ATHOS simulations with the FRIGG data. FLOW3 results for the same steady-state calculations provided researchers with a second verification criterion and enabled them to compare the two codes' abilities.

PROJECT OBJECTIVE

The objective of this project, RP1066-2, is to complete a preliminary verification of the thermal-hydraulic code ATHOS by validating it against FRIGG and FLOW3 results.

PROJECT RESULTS

The results demonstrate the capability of the ATHOS code to three-dimensionally predict thermal-hydraulic parameters. In most steady-state cases, there is good agreement between the ATHOS calculations and the FRIGG rod bundle experimental data.

In a 6.5% power reduction transient simulation, the exit void fraction predicted by ATHOS agrees well with the measured data. In addition, ATHOS produced physically consistent results when such factors as axial friction, cross-flow friction, spacer blockage factors, and void model were varied. There were slightly better agreements between ATHOS results and the experiment than between FLOW3 results and the

experiment, and ATHOS required less computer time. The essentially two-dimensional FRIGG experiment did not, however, exercise the full three-dimensional capability of ATHOS.

The ultimate purpose of this research is to produce a verified and validated thermal-hydraulic code for the nuclear industry to use in analyzing and solving operational problems associated with PWR steam generators. It will also help the industry address material degradation problems caused by tube vibration, corrosion, sludge buildup, and so on. Data comparisons such as those documented in this report will lead to checks of all parts of ATHOS, error corrections, and an improved predictive tool. The degree of agreement between the data and code predictions has enhanced the reliability of the code methodology in calculating void distributions and related thermal-hydraulic variables.

Intermediate- and full-scale comparisons of ATHOS are discussed in EPRI reports NP-2887 and NP-2872, respectively.

G. S. Srikantiah, Project Manager
Nuclear Power Division

ABSTRACT

Void fractions within the Swedish FRIGG experiment were computed with the ATHOS and FLOW3 codes and compared with each other and against measured data. The experimental model consisted of 36 electrically heated rods, each with a heated length of 4.365 m (14.32 ft) and a 13.8 mm (0.54 in) outer diameter. Heat flux in the simulations ranged from 4.52×10^5 to 8.15×10^5 w/m^2.

One transient and four steady state cases were simulated. Resistance factors, inlet geometry, computational grid, and code options were varied in additional base case simulations with ATHOS, while different void fraction correlations were used with the base case model with FLOW3. The ATHOS simulation was three-dimensional, the FLOW3 simulation two-dimensional.

Numerous plots comparing the measured and calculated results are provided. In general, agreement between the simulations and the measured results was good, with ATHOS results slightly better. Parametric variation also produced expected qualitative changes. Variations among the results in different cross section zones made trends hard to establish. Experimental data on regional flow rate would have been helpful in interpreting results.

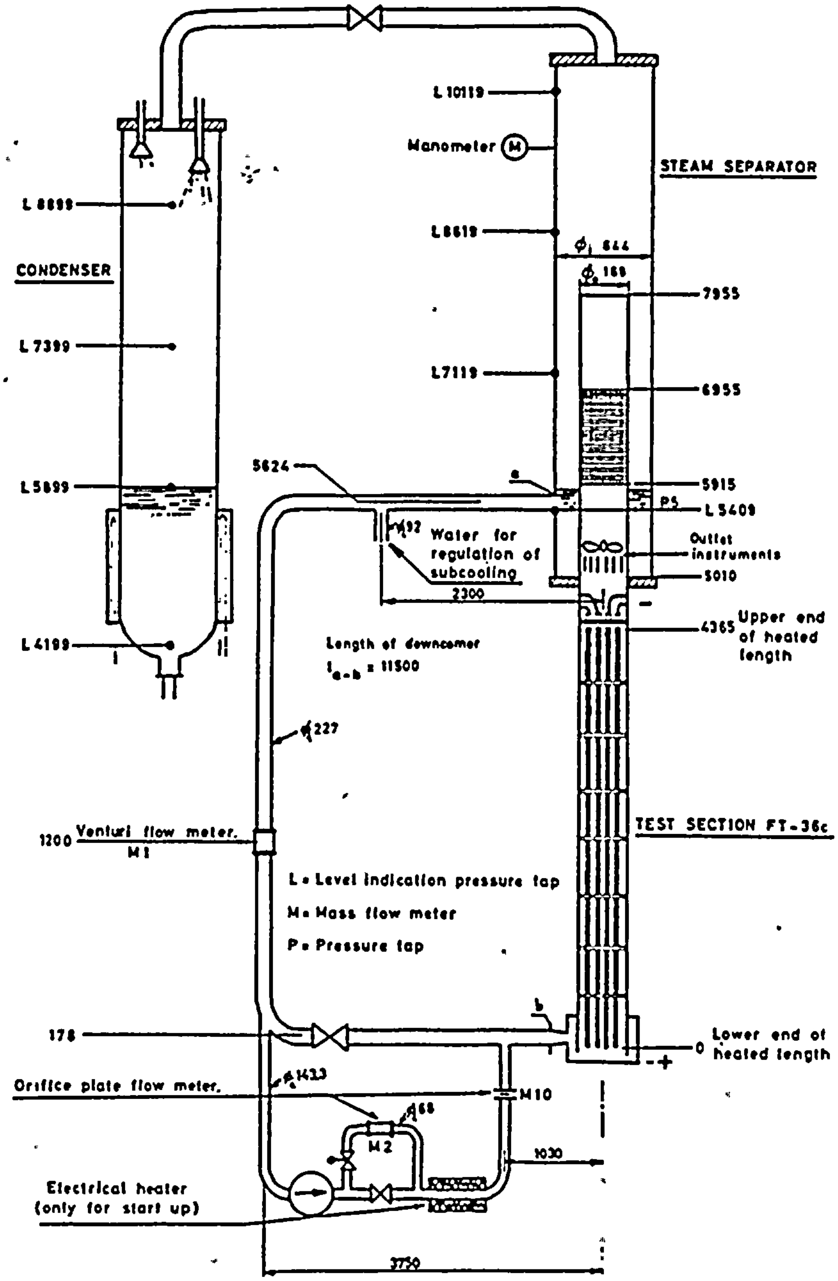


Figure 2-1. The FRIGG Experimental Loop, Data in mm.

Section 6

CONCLUSIONS

This study has been valuable in demonstrating the predictive ability of the ATHOS and FLOW3 codes. The appropriateness of different void fraction correlations under various thermal hydraulic conditions has also been tested. On an average cross-sectional basis, ATHOS and FLOW3 results have been in good agreement with the measured FRIGG data, with ATHOS results generally a little better. However, variation within the several zones made trends difficult to define. There was a tendency for calculated values to be high in Zones 1 and 3 and low in Zones 2 and 4, especially above 3.5 m. This behavior may be partially explained if the calculated inlet velocities were too low, which would not allow proper rod bundle penetration at the outer perimeter. Hence, calculated upward flow in Zone 4 would be higher than measured and void fractions lower. Calculated cross flow resistance also may have been incorrect. Data on the zonal flow in the experiment would be very helpful in this regard. It should be emphasized that the average number of rods per cell in the calculational models (1.125) was very small compared to the same quantity for an ATHOS model of the System 80 tube bundle (367). The FRIGG rod bundle was very sparse compared to tube bundles normally modeled with ATHOS. Thus, the calculations reported herein were made on a much finer scale than usual and local hydraulic effects such as tube wakes could violate the assumption explicity in ATHOS modeling of a porous continuum. The experimental void fractions also may have been in error locally. Finally, neither ATHOS nor FLOW3 can model net vapor generation in subcooled regions. This produced differences between the experimental and predicted results at low elevations.

The degree of agreement between ATHOS calculations and experiment was consistent among steady-state cases 1, 3, and 4. In Case 2, the case with higher exit flow quality, calculated and measured results diverged somewhat more, as evidenced by comparing the slab-average results for each of these cases.

The transient calculation showed ATHOS results to be independent of time step. However, the calculation did not reproduce all of the oscillation in the measured results after 4 seconds of the transient, a result which may be due to incomplete specification of the transient boundary conditions.

Except for Case 2 there was a tendency for FLOW3 void fractions to be higher than ATHOS results in Zones 1 and 2, but the reverse to be true in Zones 3 and 4. The result curves from each calculation within a zone also tended to converge at higher elevations. It would be useful to evaluate this behavior by comparing existing FLOW3 results with those to be obtained with ATHOS using an operational Zuber-Findlay void fraction correlation.

The comparison of three-dimensional ATHOS and two-dimensional FLOW3 results in this study showed ATHOS results to be only slightly more accurate when compared to the experimental results. The two-dimensional nature of the test model may have contributed to this near equality of results. Had the flow through the test model required a fully three-dimensional description, it is expected that the ATHOS results would have been superior. Furthermore, since the heat source in the model was electrically heated rods rather than a flowing primary fluid, local heat fluxes were specified rather than being calculated based on local conditions, as ATHOS, but not FLOW3, is capable of doing. Thus, the ATHOS code was designed to handle more complex thermal hydraulic situations than the small scale, two-dimensional, electrically heated FRIGG model.

EPRI
Electric Power
Research Institute

Topics:
Steam generators
Thermal hydraulics
Nuclear power codes—validation
ATHOS code

EPRI NP-2698-CCM
Volume 4
Project 1066-1
Computer Code Manual
August 1984

ATHOS—A Computer Program for Thermal-Hydraulic Analysis of Steam Generators

Volume 4: Applications

Prepared by
CHAM of North America Incorporated
Huntsville, Alabama

ABSTRACT

Analysis of the Thermal Hydraulics of Steam Generators (ATHOS) is a user-oriented computer code for three-dimensional steady-state and transient analysis of steam generators. Its detailed description is provided in three volumes. This report constitutes the fourth volume of the ATHOS documentation. The purpose of this volume is to consolidate the description of all code qualification and verification applications. These have been divided into five categories: code checkout studies, parametric calculations, simulations of small-scale experiments, model steam generator simulations, and full-scale operating steam generator simulations.

All applications and studies described herein are presented in sufficient detail so as to allow new users to assess the code's capabilities and limitations. The results and discussions presented in this volume will serve as a useful guide for future applications.

From these verification applications, the major overall findings can be summarized as follows:

1. Agreement with available experimental data is generally good.
2. Agreement with experimental data is always better when employing the algebraic-slip (rather than homogeneous) flow model.
3. Consistent and plausible trends are found in all parametric studies undertaken.
4. Agreement with experiment is generally not as good for low-power-level cases (less than 50%). This indicates that further study of empirical correlations is needed, particularly for low-power-level calculations.

Several model improvements and further developments have also been identified and suggested for future implementation.

Section 7

CONCLUSIONS

This report has consolidated various code check-out and verification applications of ATHOS.

The series of code check-out calculations described herein (Sections 2 and 3) have demonstrated the solution consistency and stability under a variety of steady-state and transient conditions. For absolute (i.e. mathematical) tests of convergence, two steady-state calculations were successfully continued until the residual errors of all conservation equations were reduced to the computer (CDC 7600) truncation-error level ($\approx 10^{-9}$). All parametric studies have yielded consistent and plausible solutions. Furthermore, every available feature of the code (both geometric and thermal-hydraulic) has been exercized.

The verification applications described in Sections 4 through 6 were divided into the following three categories:

Section 4 - small-scale tests: (a) single-phase flow in the upper plenum of a pressurized water reactor (PWR); and (b) steam-water flow in a cylindrical duct with heated rods (FRIGG test)

Section 5 - model generators: (a) Westinghouse's Model Boiler No. 2 (MB-2); and (b) EPRI's 1/7th scale Freon model generator

Section 6 - full-scale generators: two Westinghouse Model-51 type steam generators at the Bugey and Tricastin units of the Electricite de France (EdF).

In the small-scale tests, comparison between the exact (analytical) and ATHOS PWR upper-plenum solutions showed good agreement, both qualitatively and quantatively, thereby demonstrating the accuracy of the basic ATHOS solution scheme. The symmetric nature of this particular problem also demonstrated the ability of ATHOS to preserve symmetry for a symmetric flow problem. In the FRIGG-test problem, calculated and measured void fractions were found to be in generally good agreement in all cases. In the few instances where agreement was relatively not quite so good, the omission of turbulent diffusion (which is normally not important in full-scale steam generators due to the large number of tubes) was felt to be responsible. This problem also demonstrated the capability of the code, and the built-in Lellouche algebraic-slip

correlation, to model two-phase flow situations with velocity slip.

For the two model generator applications, both the MB-2 and Freon generator results indicated that code predictions compare reasonably well with measurements for a variety of both steady-state and transients tests. Generally, comparisons were better at higher power levels (i.e. greater than 75%), and the algebraic-slip model results always compared better than those obtained with the homogeneous model. In both model generator applications the assumption of a perfect separation of steam and water at the separators, together with the simple point model of the steam dome may have adversely affected the results. The MB-2 results may also have been influenced by the omission of friction losses due to the sudden contraction in the riser section. The generally quite good agreement with experimental data in the Freon application is particularly encouraging in view of the fact that the empirical correlations used for velocity slip and boiling heat transfer are based on steam-water experiments. The broad range of steady-state and transient tests involved in these two applications has also effectively demonstrated the versatility and stability of the ATHOS code.

In the full-scale operating steam generator simulations the overall agreement with the available measured data was generally very good. Again, as in the model generators, agreement was not so good at the lower power levels. The most probable causes for this are the possible inaccuracies of empirical correlations for velocity slip and heat transfer at lower power levels and, also, uncertainties in the separator operating characteristics (i.e. carry-under and carry-over). These require further investigation.

From these verification applications, the major overall findings are summarized as follows.

1. Agreement with the available experimental data was generally good.

2. Agreement with experimental data was always better when the algebraic-slip (rather than homogeneous) flow model was used.

3. Consistent trends were found in all parametric studies undertaken.

4. Agreement with experiment is generally not as good for low(er) power level cases, indicating that further study of empirical correlations (particularly those for slip and heat transfer coefficients) is needed for low-power applications.

Based on the experience of the above-described and other ATHOS simulations, several model improvements have been identified. At the time of publication of this report, the majority of these modifications have already been implemented in a development

version of the code (to be called ATHOS3). The major improvements of ATHOS3 over ATHOS are as follows.

- Further generalization and enhancement of the code to facilitate simulation of all major steam generator types and features (e.g. OTSG's and UTSG's with split-flow economizer and contracted riser sections (as in MB-2) etc.), extension of computational grid into the downcomer, and provision for: a turbulence model, steam outflow as boundary condition in transients, READ input data option in the thermal-hydraulics module, temperature varying density of subcooled water and primary-fluid specific heat, maintaining a fixed height of downcomer water level during transients, specification of an unequal feedwater split into the hot and cold sides of the downcomer, account of the thermal inertia effects of the metal in the dome and downcomer and specification of either fixed heat load or fixed primary-inlet temperature as the thermal boundary condition for steady-state calculations.

In addition, the following major developments are planned for the near future, viz:

- provision for modeling full (360^{0}) steam generators with asymmetric tube layout and/or grid distributions;
- provision for simulation of model steam generator tube rupture (SGTR) transients.

Data from other planned model and full-scale operating steam generator experiments are expected to become available in the future. Further ATHOS verification work will be performed as and when these (and other) data become available.