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BWR Refill-Reflood Program Task 4.2 — Core Spray Distribution Final Report

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Prepared by
T. Eckert

Nuclear Engineering Division
General Electric Company
San Jose, CA 95125

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Division of Reactor Safety Research
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
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and
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

and
Nuclear Engineering Division
General Electric Company
San Jose, CA 95125

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ABSTRACT

This test program has provided core spray distribution data in a steam environment for a 30-deg sector of the BWR/4&5-218 design. The data demonstrate the applicability of the core spray methodology in this design, which uses different nozzle types and different sparger elevations than the BWR/6-218 design previously used to confirm the methodology. The effects of sparger flow rate and sparger-to-sparger interaction were also studied during this test program.

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Section 1

INTRODUCTION

1.1 BACKGROUND

Single nozzle tests performed in steam and air have shown different spray distributions between the two environments.[1] A methodology incorporating air and steam testing was developed for predicting full core spray distributions in a steam environment. The methodology was confirmed with the BWR/6 design described in NEDO-24712.[2]

The current test program has demonstrated the application of the methodology to an alternate BWR design (i.e., BWR/4&5). This design has different core spray sparger locations and different nozzle types than the BWR/6 design.

This test program is identified as Task 4.2, Core Spray Distribution, of the BWR Refill-Reflood Program. This program is jointly sponsored by the Electric Power Research Institute (EPRI), the United States Nuclear Regulatory Commission (USNRC), and the Nuclear Engineering Division (NED) of the General Electric Company (GE).

1.2 OBJECTIVES

The overall objectives of Task 4.2 of the BWR Refill-Reflood Program were to (1) provide core spray distribution data from steam environment tests for best estimate model qualification; (2) provide additional confirmation of the existing methodology; and (3) identify any further model requirements.

The effects of sparger flow rate and sparger-to-sparger interaction on core spray distribution were also studied during this test program.

This document presents the test data of Task 4.2 and the conclusions derived therefrom.

1.3 TEST PLAN APPROACH

The hardware design basis for the BWR/4&5 core spray program is the BWR/4-218 core spray system (BWR/5-218 is identical). The lower sparger was tested in a 30-deg sector. Sparger-to-sparger interaction effects were investigated using a double sparger segment with one nozzle on each sparger. Testing of the upper sparger was not a part of this program[3] because of hardware limitations [it would mechanically interfere with the BWR/6-218 spargers at the 30-deg Sector Steam Test Facility (SSTF)].

Section 2

GENERAL DESCRIPTION OF THE TEST FACILITIES

The steam tests were performed in the Horizontal Spray Facility (HSF) in San Jose, California, and in the 30-deg SSTF in Lynn, Massachusetts. The simulator tests were performed in both the Vallecitos Spray Facility (VSF) at the Vallecitos Nuclear Center (VNC) and in the HSF. A description of these test facilities is given in subsections 2.1 through 2.3.

2.1 HORIZONTAL SPRAY FACILITY

The HSF facility was designed to mock up a portion of the top of the reactor core for testing a single nozzle in a pressurized steam environment. The facility is used to determine the spray characteristics of the core spray nozzles (see Figure 2-1).

The mock-up consists of several mechanisms and structures. One mechanism (header mechanism) positions and holds a short section of the sparger containing one nozzle. Another mechanism (movable grid) holds and positions the collection tanks used in place of the fuel bundles. The grid mover mechanism can linearly position the grid over a 30-in. span. Thus, the system can sample the spray with a relatively small number of collection tanks and produce a large number of collection points. A baffle behind the header mechanism simulates the shroud wall. The core mock-up does not include the fuel bundle handles or shroud head.

The mock-up is contained in an unfired pressure vessel measuring 6-ft i.d. x 21-ft long. The supporting systems consist of a water recirculation loop for the spray, three heat exchangers to subcool the spray, and a 7000 lbm/hr boiler to produce the steam.

2.2 30-DEG SECTOR STEAM TEST FACILITY

The 30-deg sector internals provide accurate representation of the BWR/6-218 (624 bundle) reactor through the use of prototypical hardware and geometry. A schematic representation of the test section components is given in Figure 2-2.

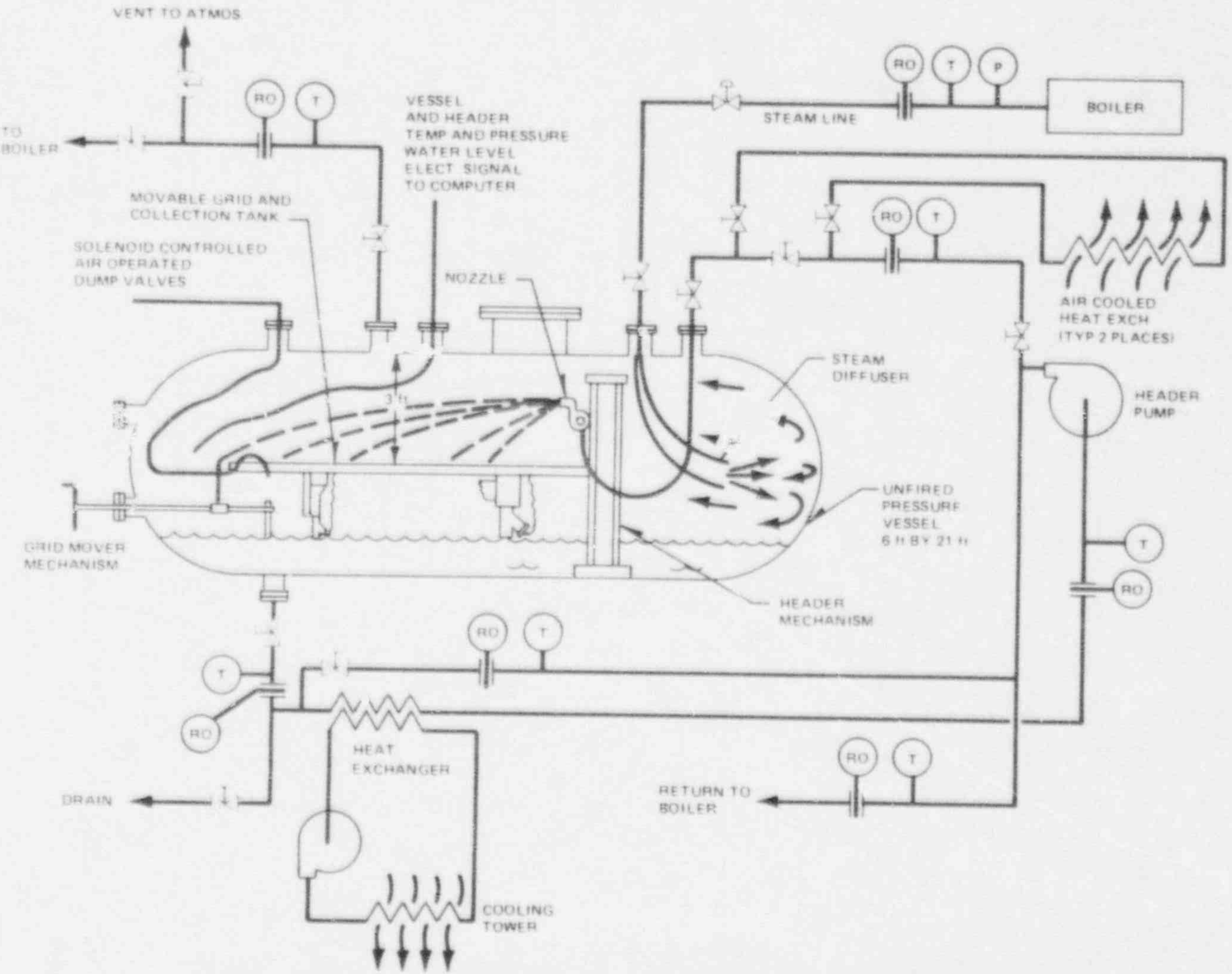

Figure 2-1. Horizontal Spray Facility

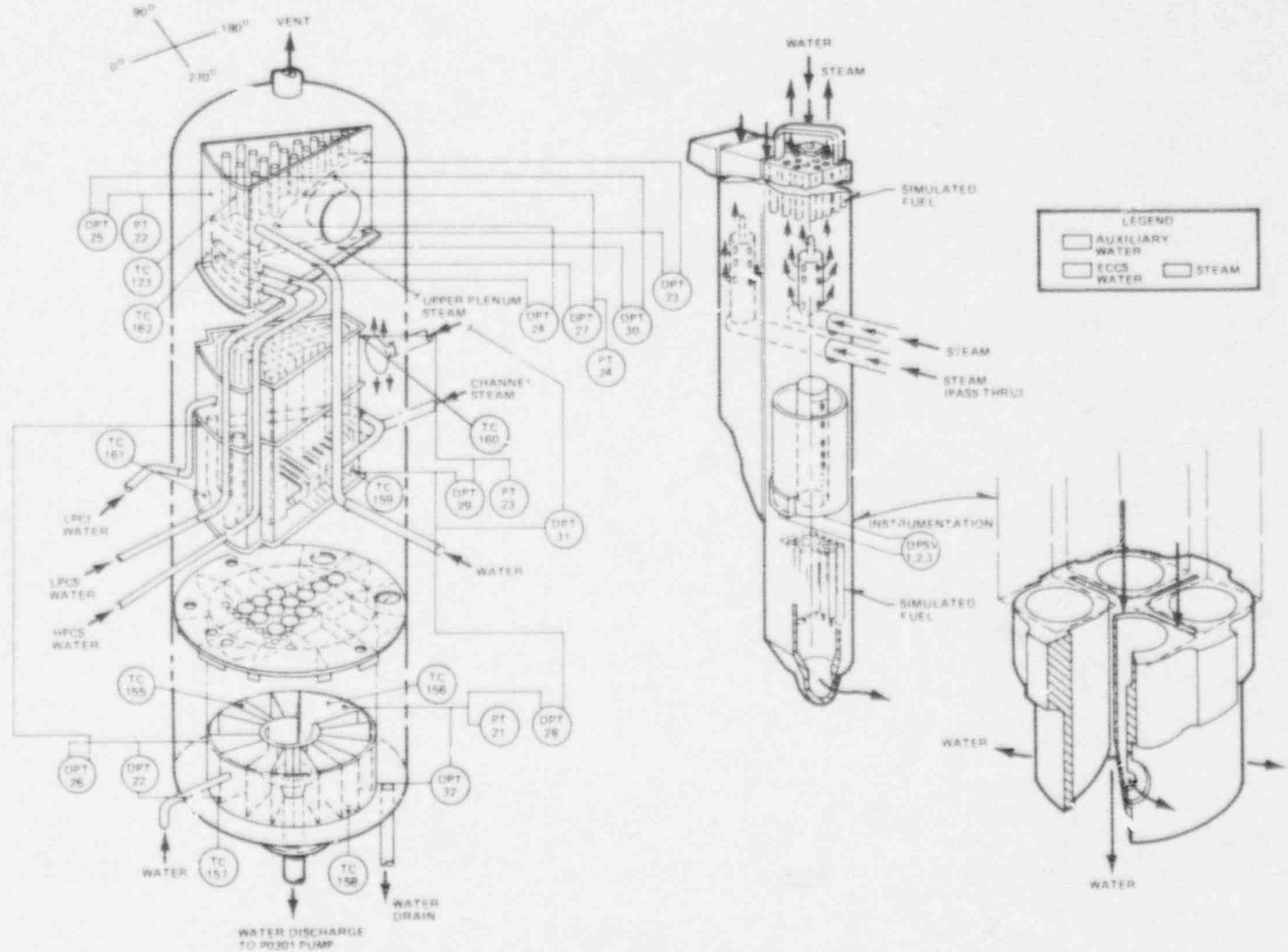

Figure 2-2. 30-Deg Steam Sector Test Section

POOR ORIGINAL

The upper plenum is a full-scale mock-up of a 30-deg sector of the BWR/6-218 upper plenum with accurate simulation of geometric shape and shroud head curvature and height. Standpipes simulating the steam separators extend up from the shroud head. The lower core spray sparger for the BWR/4-218 is a full-scale mock-up of the 30-deg sector of the reference low pressure core spray (LPCS) sparger with regard to size, curvature and location, but has a reduced number of nozzles (7 versus 8-2/3). The core region simulation includes both mock fuel bundles and the bypass region. The core region is full-scale in cross section, but is approximately 5 feet shorter than the BWR reference because of overall facility height limitations. Fifty-eight mock fuel bundles are included in the 30-deg sector (42 complete bundles and 16 partial bundles having removable cover plates and baffles to simulate the 30-deg boundary within the partial bundle); however, the first row of eight bundles had their upper tie plates and handles removed, as these bundles do not exist in the BWR/4-218 reactor. The bundles utilize production version hardware for channel, channel fasteners and spacer, upper tie plate, lower tie plate, and finger springs. Simulated fuel rods are included in both the upper and lower tie plate regions. Upper fuel rod simulation includes production version expansion springs, end pins, locking tab washers, hexagon nuts, and one fuel rod spacer. A steam injector tube is provided in each bundle below the upper rods to deliver the channel steam from the steam distribution manifold located outside the 30-deg shroud wall. A weir-tube measuring device[4] is provided in each bundle above the lower rods to measure the liquid flow. The bypass region flow area is simulated and includes dummy control rods mounted on production version fuel support castings. Leakage and flow path simulation between bundle, bypass, upper plenum, and guide tube is assured by using production version hardware in conjunction with accurate representations of the top fuel guide and core plate. Twelve volume-scaled guide tube regions are provided (one for each of the twelve centrally located side-entry fuel supports). The lower plenum volume represents the scaled volume of the reference lower plenum region outside the guide tubes.

The SSTF pressure vessel (14-ft i.d. and 27-ft inside height) serves as a pressure envelope for the 30-deg sector internals. The vessel is designed with numerous nozzles and penetrations to permit attaching the various process lines which service the internals and provide routing for the various instrumentation lines and cables.

An air-conditioned control room houses the process control equipment and data acquisition system (DAS). Process instrumentation and valves are provided to monitor and control temperature, pressure and flow in the steam supply headers, water recirculation lines, emergency core cooling system (ECCS) lines, and vent system (as indicated in Figure 2-3).

Test instrumentation and signal conditioning include pressure and differential pressure transducers, and thermocouples as shown in Figures 2-2 and 2-3. The ECCS spray distribution is determined from individual bundle flow measurements provided by weir flow elements internal to each mock fuel bundle.

A schematic of facility and external loop hardware is shown in Figure 2-3. A steam supply of 110,000 lbm/hr at 150 psia and 388°F is available. Steam is routed to the pressure vessel through a 10-in. header to an upper plenum supply nozzle and to a mock fuel bundle supply nozzle. Water is supplied to the facility from a condensate tank and retained in a supply tank which is part of the ECCS water supply and recirculation loop. The temperature of the water in the tank can be controlled by recirculation through a heat exchanger loop. The ECCS supply system provides flows representative of the reference BWR/4-218 reactor.

2.3 VALLECITOS SPRAY FACILITY

The VSF facility was designed to mock up the top of the reactor core for testing a 360-deg spray sparger and nozzles in air atmosphere. A full complement of mock fuel bundles makes up the core, with each bundle having a weir type flow measuring device attached to the bottom. Different pumps in the water recirculation loop provide the spray water for any desired flow from a single nozzle test to a 360-deg full sparger test. Used primarily for full sparger testing in air, the facility can also be used to perform single nozzle spray distribution tests by using a single nozzle sparger pipe mounted in front of a portion of the core mock-up. In this configuration, simulator nozzle development testing can be performed at this facility.

POOR ORIGINAL

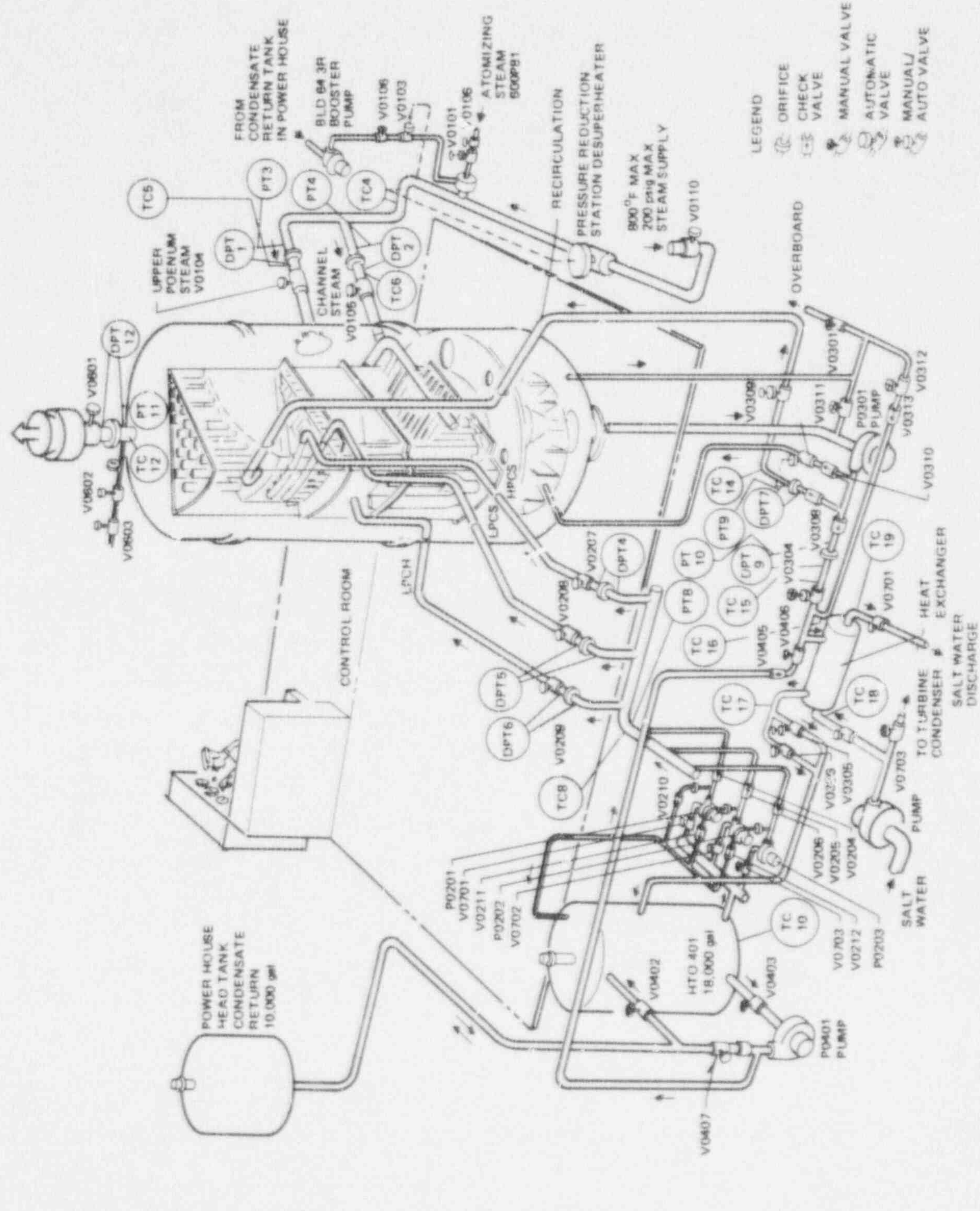

Figure 2-3. 30-Deg SSTF - Loop Control

Section 3

BWR/4&5-218 CORE SPRAY HARDWARE DESCRIPTION

3.1 30-DEG SECTOR CONFIGURATION

The SSTF accurately mocks up a 30-deg sector of a BWR/6-218 upper plenum and top of the core. For BWR/4&5-218 testing, the facility was modified by the addition of a BWR/4&5-218 sparger (lower only) and by the removal of the fuel bundle handles from the edge row of bundles (which are not present in BWR/4-218 reactors). The BWR/4 mock-up allowed only seven of the expected nine nozzles to be installed.* Hence, the BWR/4 configuration is not a direct simulation of a reactor sector, but is sufficient for model evaluation and qualification. The 30-deg lower sparger with seven nozzle assemblies was installed in the 30-deg sector as shown in Figure 3-1. The nozzle positions relative to the core mockup are shown in Figure 3-2. The nozzle assembly details and configurations are shown in Figure 3-3; nozzle aiming specifications are shown in Figure 3-4.

3.2 DOUBLE SPARGER CONFIGURATION, 30-DEG SECTOR STEAM TEST FACILITY

The double sparger test assembly was installed into the core mock-up for the Phase 3 tests (after the upper plenum and the 30-deg spargers attached to it were removed). The installation is shown in Figure 3-5. Each sparger of the double sparger test rig can accommodate a maximum of three nozzle assemblies with the nozzle centerline of the middle assembly corresponding to the collection grid centerline. The single nozzle and two nozzle tests described in the Phase 3 test matrix used only the middle nozzle position of each sparger. The test rig has a backing plate which simulates the shroud wall and encourages typical reactor steam currents to the spray nozzle.

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*A BWR/4&5-218 360-deg sparger has 104 spray nozzles. Therefore a 30-deg sector should have 8-2/3 nozzles. In Phase 4 testing of reactor nozzles in air, it was possible to use eight nozzles (position L1 was used). However, for simulator nozzle tests and steam tests, position L1 was blanked off as this nozzle was too close to the sector wall, leaving only seven nozzles. A sector with seven nozzles will produce spray distributions similar to, but not identical to, the actual reactor performance (somewhat less flow density).

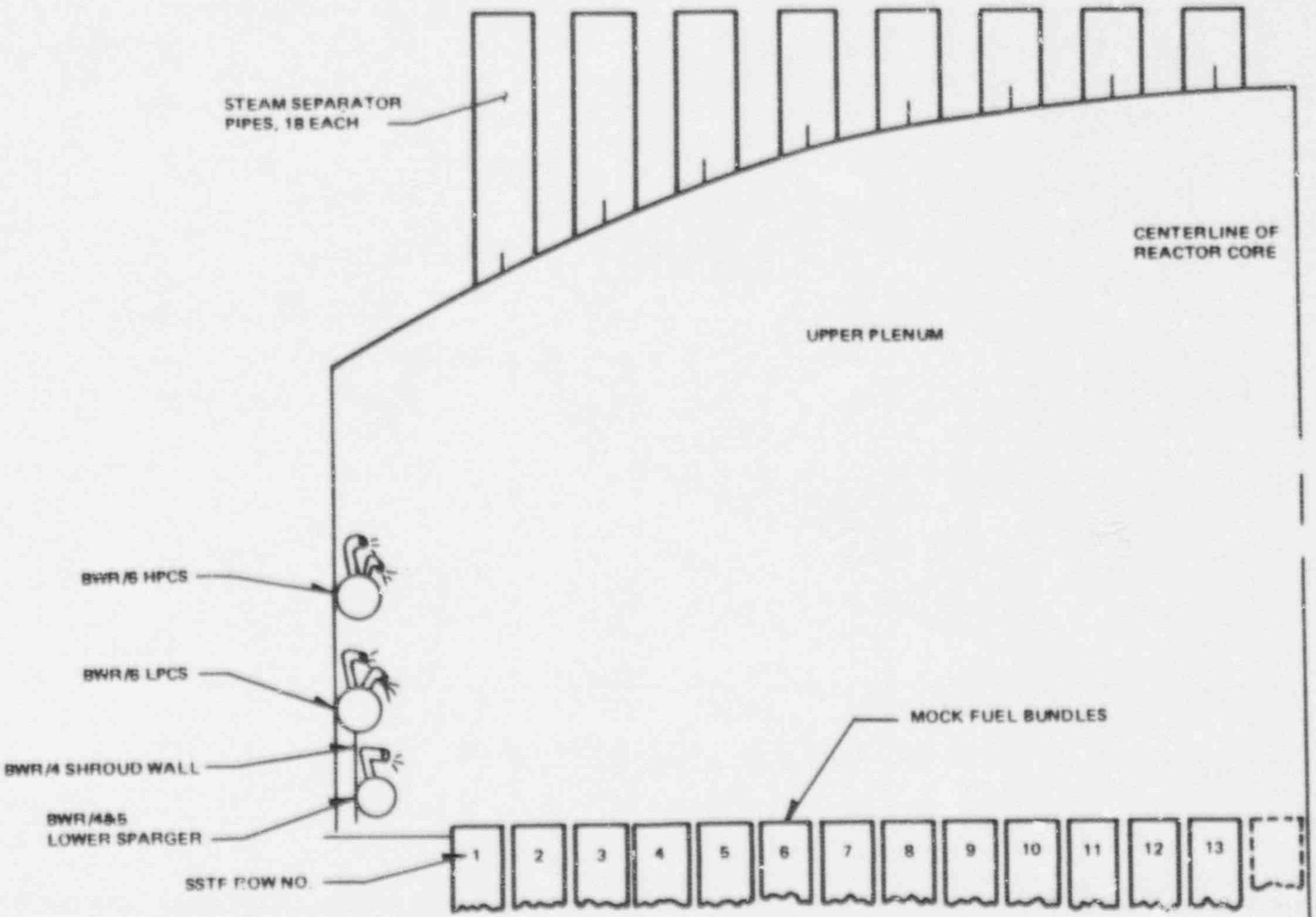


Figure 3-1. Placement of BWR/4&5 Lower Sparger Into 30° SSTF

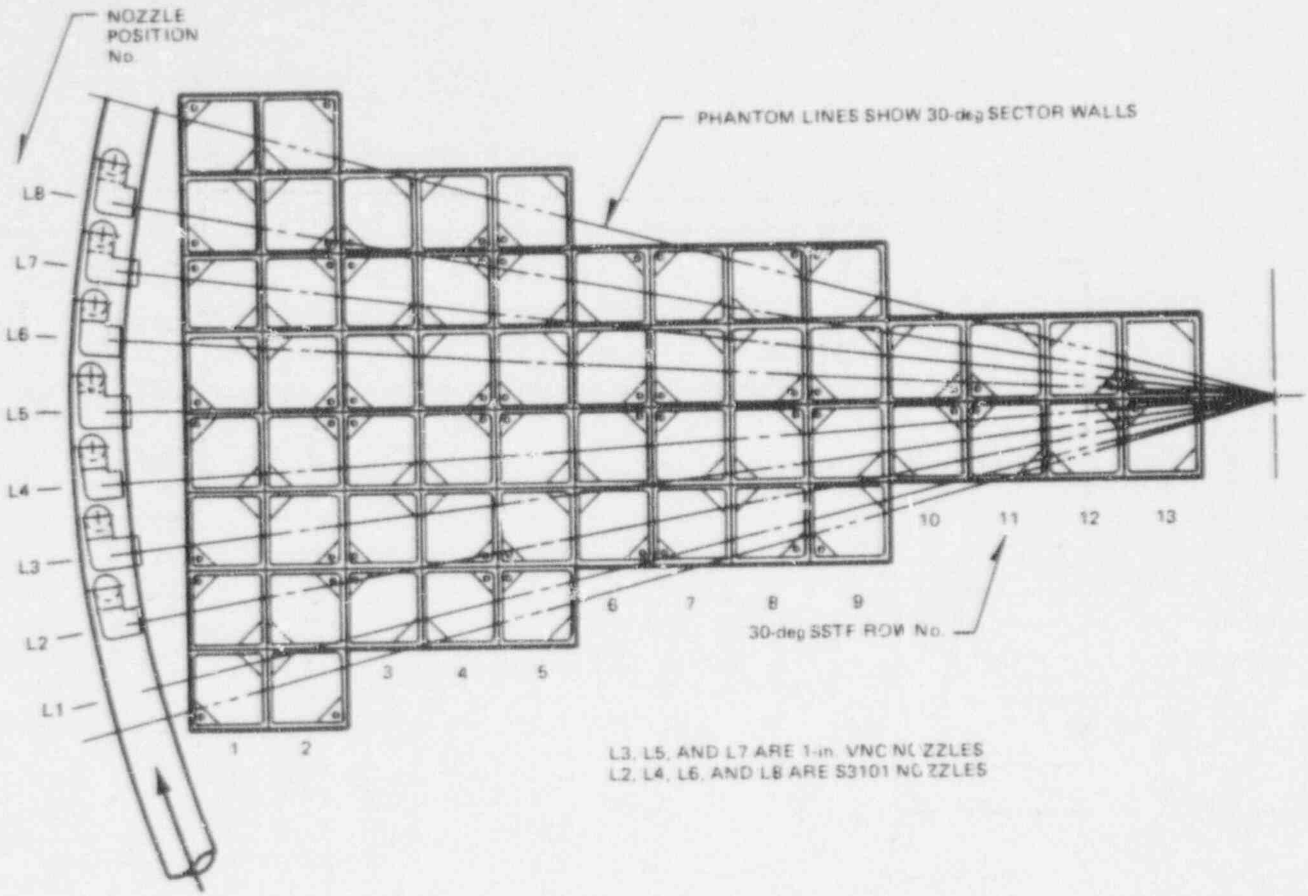
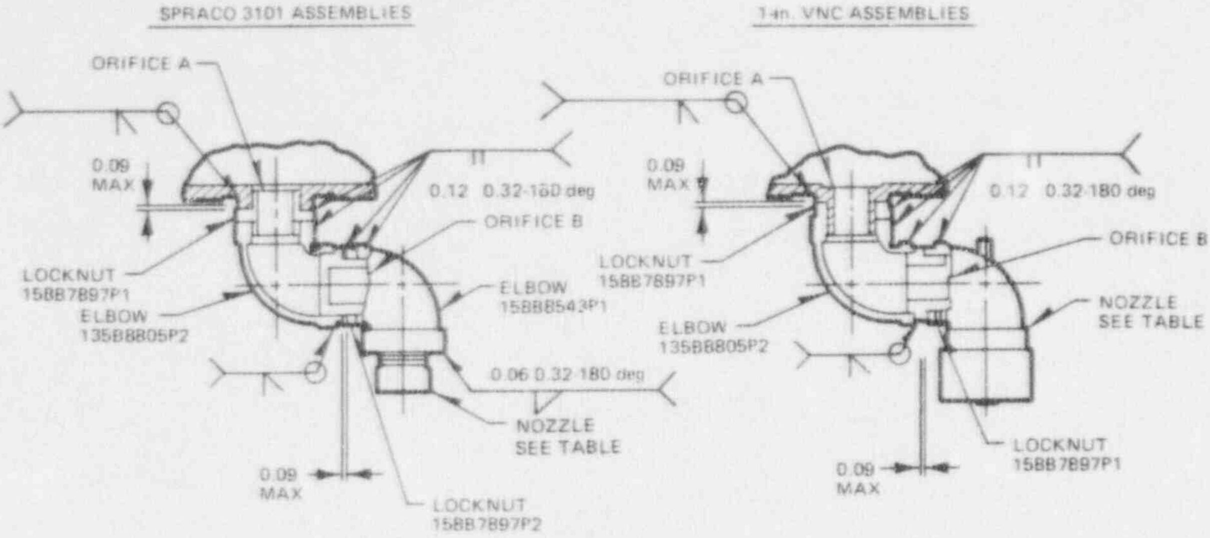


Figure 3-2. 30-Deg Lower Sparger Nozzle Positions (BWR/4-218 at 30-Deg SSTF)

The nozzle assembly details and nozzle aiming specifications used are shown in Figures 3-3 and 3-4, respectively.

3.3 SINGLE NOZZLE TESTING - VALLECITOS SPRAY FACILITY

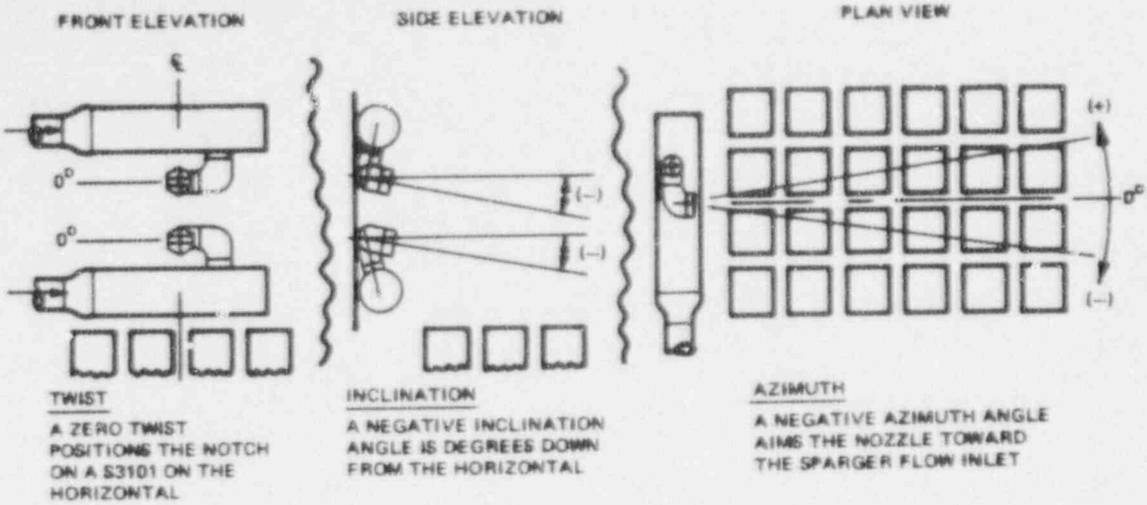
A single nozzle sparger (drawing TE082579) was used at the VSF for simulator nozzle development. The sparger was installed according to Figure 3-6. The handles were removed from the channels for comparison with HSF geometry. The nozzle assembly details and nozzle aiming specifications used are shown in Figures 3-3 and 3-4, respectively.



SPARGER	NOZZLE CONFIGURATION NUMBER	ORIFICE A (BORE SIZE)	ORIFICE B (BORE SIZE)	NOZZLE (NAME)
UPPER	3	158B7896P2 (0.620)	158B7896P6 (0.560)	158B8566P1 (SPRACO 3101)
LOWER	5	158B7896P3 (0.750)	158B7896P6 (0.560)	158B8566P1 (SPRACO 3101)
LOWER (SIMULATOR NOZZLE)	5S	158B7896P2 (0.620)	158B7896P6 (0.560)	TEOB2379P004 (2-in. EXTENSION 0.824 BORE)

SPARGER	NOZZLE CONFIGURATION NUMBER	ORIFICE A (BORE SIZE)	ORIFICE B (BORE SIZE)	NOZZLE (NAME)
UPPER	11	158B7896P3 (0.750)	158B7896P3 (0.750)	158B7896G2 (1-in. VNC 14/16)
LOWER	8	158B7896P3 (0.750)	158B7896P4 (0.880)	158B7896G1 (1-in. VNC 9/16)
LOWER (SIMULATOR NOZZLE)	8S	158B7896P3 (0.750)	158B7896P4 (0.880)	TEOB2479G1 (1-in. VNC 9/16-S 12-4)

Figure 3-3. Nozzle Assemblies for BWR/4&5-218 Core Spray



NOZZLE	NOZZLE CONFIGURATION NUMBER	SPARGER	INCLINATION ANGLE (°)	AZIMUTH ANGLE (°)	TWIST ANGLE (°)
SPRACO 3101	3	UPPER	–14	0	0
SPRACO 3101	5	LOWER	–11	0	0
SPRACO 3101 SIMULATOR	5S	LOWER	–12	+4.6	N/A
1-in. VNC 14/16	11	UPPER	–9	0	N/A
1-in. VNC 9/16	8	LOWER	–3	0	N/A
1-in. VNC 9/16 (S 12-4) (SIMULATOR)	8S	LOWER	–11	–9.2	N/A

Figure 3-4. Nozzle Aiming Specifications for BWR/4&5-218 Core Spray

3.4 SINGLE NOZZLE TESTING - HORIZONTAL SPRAY FACILITY

Two single nozzle spargers (drawing TE080679) were used at the HSF for steam tests and simulator design verification.

The spargers were installed and the grid was positioned as shown in Figure 3-7. The nozzle assembly details and nozzle aiming specifications used are shown in Figures 3-3 and 3-4, respectively.

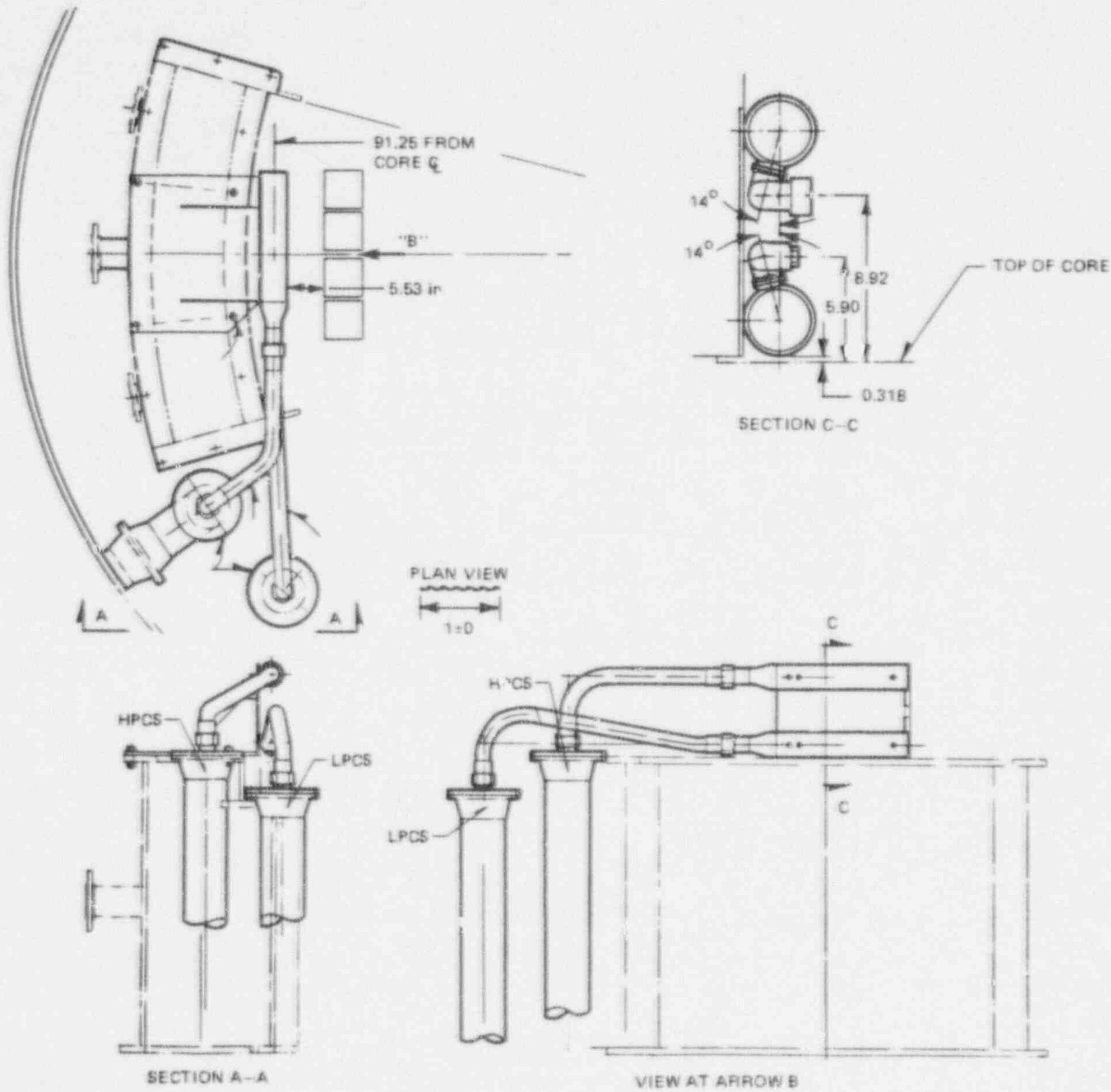


Figure 3-5. Double Sparger Test Rig Installation at 30-Deg SSTF

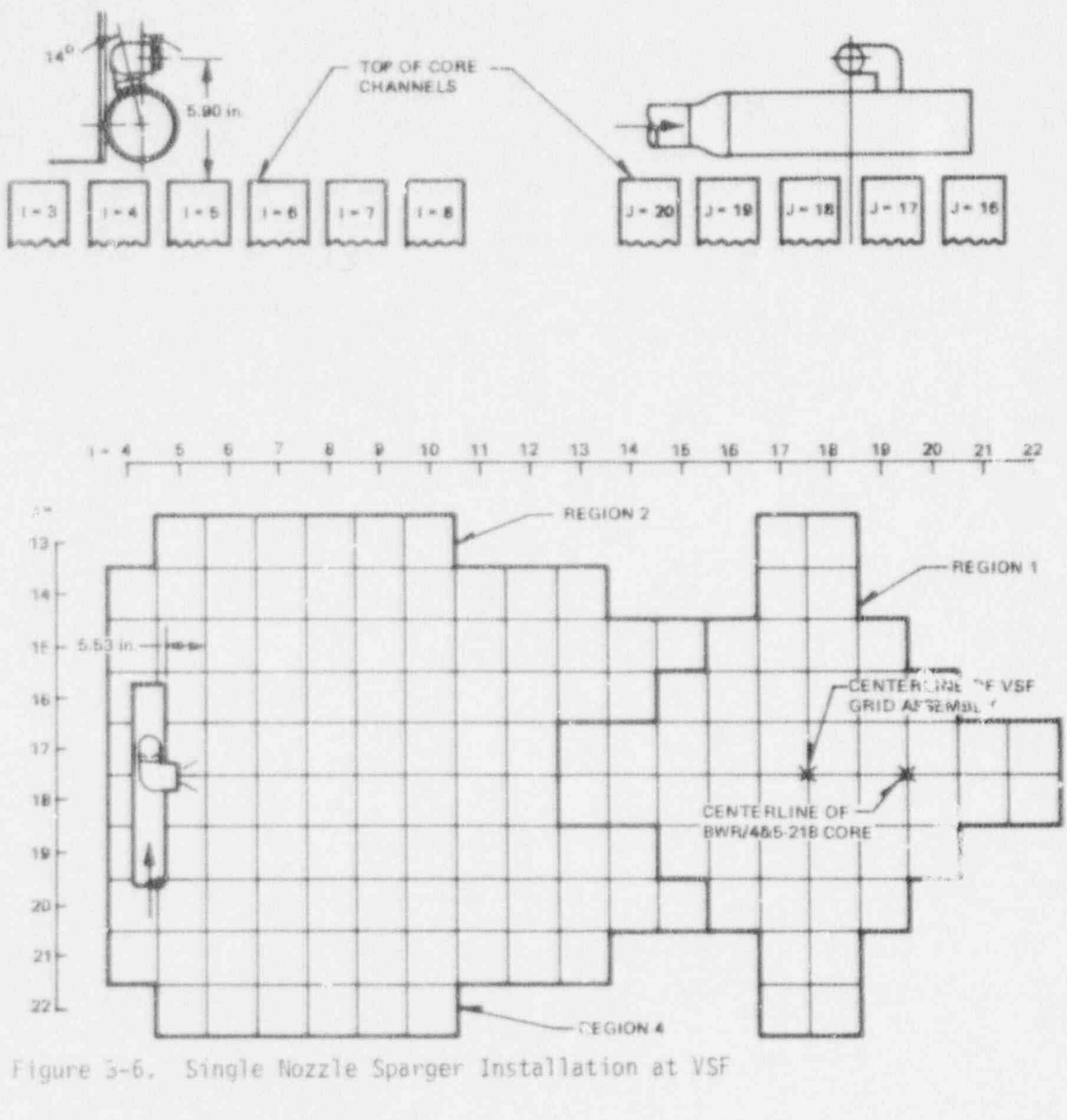


Figure 3-6. Single Nozzle Sparger Installation at VSF

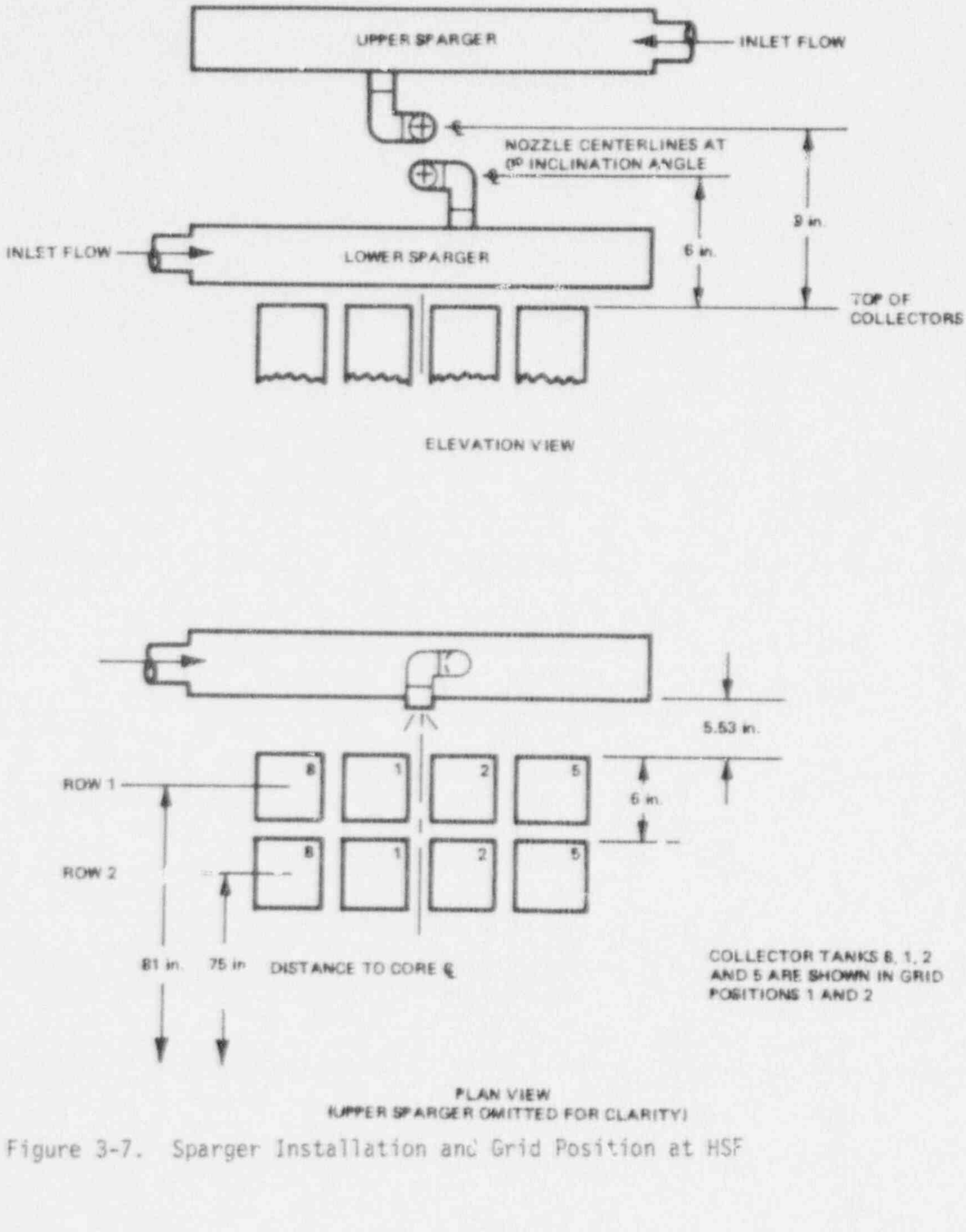


Figure 3-7. Sparger Installation and Grid Position at HSF

Section 4

TEST RESULTS

4.1 CONFIRMATION OF THE METHODOLOGY

The core spray methodology was reconfirmed by the spray distribution results in the 30-deg sector of the BWR/4-218 lower sparger in steam comparing very well with predicted values.

4.1.1 Confirmation Test Conditions

For the purpose of methodology confirmation, a specific set of typical operating conditions was selected. These conditions were:

System Pressure:	29.5 psia
ECCS Flow Rate:	375 gpm
ECCS Water Temperature:	145°F

The tests were conducted with the 30-deg sector walls in place. This configuration provides the correct flow areas so that vapor velocities are typical. In the present tests, one-half of the steam condensing on the spray is supplied by the core steam injectors. The remainder of the steam condensing on the spray is drawn down into the upper plenum through the steam separators. Enough steam is supplied to the steam dome above the separators to accommodate the spray condensation needs and maintain a constant system pressure. Prediction of the radial spray flow distribution is made for bundles adjacent to the sector centerline to allow comparison for the greatest radial distance. However, because wall effects become significant near the apex of the sector, no prediction is made in this region (c.f., Figure 4-1).[5]

4.1.2 Core Spray Methodology and Prediction

Core spray flow rate at a particular fuel bundle location is calculated as follows:

Predicted Spray flow in SSTF in steam	=	Superposition of single nozzle spray flows in steam	+	Multiple nozzle Interaction factor (MIF)

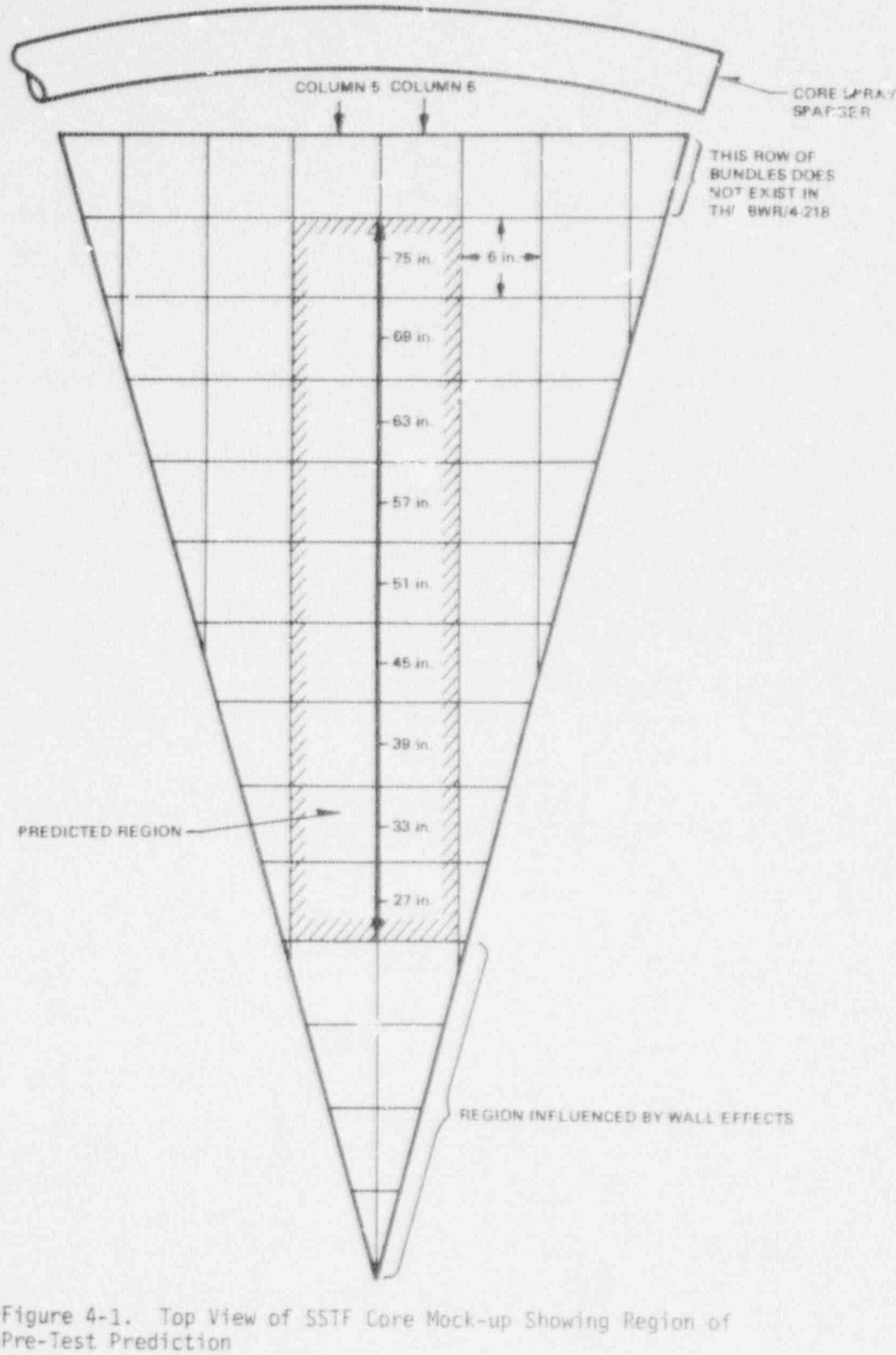


Figure 4-1. Top View of SSTF Core Mock-up Showing Region of Pre-Test Prediction

where

Multiple nozzle Interaction factor (MIE)	=	Measured spray flow for SSTF in air with simulator nozzles	-	Superposition of single nozzle spray flows for simulators in air

This relationship can be expressed algebraically:

$$F = \sum_{i=1}^{N} f_i + G - \sum_{i=1}^{N} g_i \tag{1}$$

and

$$MIE = G - \sum_{L=1}^{N} g_i \tag{2}$$

This combination of steam and air results is based upon the assumption that the thermodynamic (i.e., condensation) and hydrodynamic (interaction) effects are separable. That is, interaction effects obtained from air tests are directly applicable to a steam environment.

The nomenclature is described below:

Symbol	Description
F	Predicted flow density at a particular location in SSTF for the 30-deg sector steam test.
f_i	Flow density at a particular location from nozzle i, measured in a single nozzle steam test. [Data is shown in Figures 4-15 and 4-16 (see subsection 4.4.1).]
G	Flow density at a particular location in SSTF, measured during a 30-deg sector air test using simulator nozzles. (Data is shown in Figure 4-20, Test 20.)
g_i	Flow density at a particular location from simulator nozzle i, measured in a single nozzle air test. [Data is shown in Figure 4-19 (Test 7903-7) and Figure 4-20 (Test 7903-14A) presented in subsection 4.4.2.]
i	Index indicating specific nozzle location in SSTF.
N	Total number of nozzles.

The terms G and $\sum_{i=1}^{N} g_i$ are obtained from multiple and single nozzle tests with simulators in air. Comparison of the two terms for each bundle location provides quantification of the hydrodynamic effects of multiple nozzles [i.e., the multiple nozzle interaction factor (MIE)], according to Equation (2). The MIE was calculated on both a centerline average and an individual bundle basis to allow evaluation of bundle-to-bundle variations. The resultant MIE values are shown in Figures 4-2 and 4-3 for the centerline average and individual bundle basis, respectively.

Using the MIE values from either Figure 4-2 or Figure 4-3, and the single nozzle steam tests results (i.e., $\sum_{i=1}^{N} f_i$), the predicted bundle flows for the SSTF steam test can be obtained from Equations (1) and (2). The predicted flows for the individual bundles in columns 5 and 6 (see Figure 4-1 for location of columns) are shown in Table 4-1.

4.1.3 Comparison With SSTF Data

The data from the SSTF confirmation tests are compared with the predicted flows of Table 4-1 on an individual bundle basis. The comparisons are shown in Figures 4-4 and 4-5 for both types of predictions. Both predictions agree very well with the data. The comparison is better using the individual bundle MIEs for those bundles at 57-, 63- and 75-in. core radius. Note that comparisons with predicted flows at 69 inches are not meaningful since the data are limited by the 20 gpm/bundle capacity of the flow measurement devices.

The excellent comparisons further confirm the basic assumptions of the core spray design methodology and demonstrate that they are also applicable with changes in spray nozzle type and sparger location. This is as-expected, since the important assumption of separability of thermodynamics (i.e., condensing) and hydrodynamic effects should not be affected by such changes.

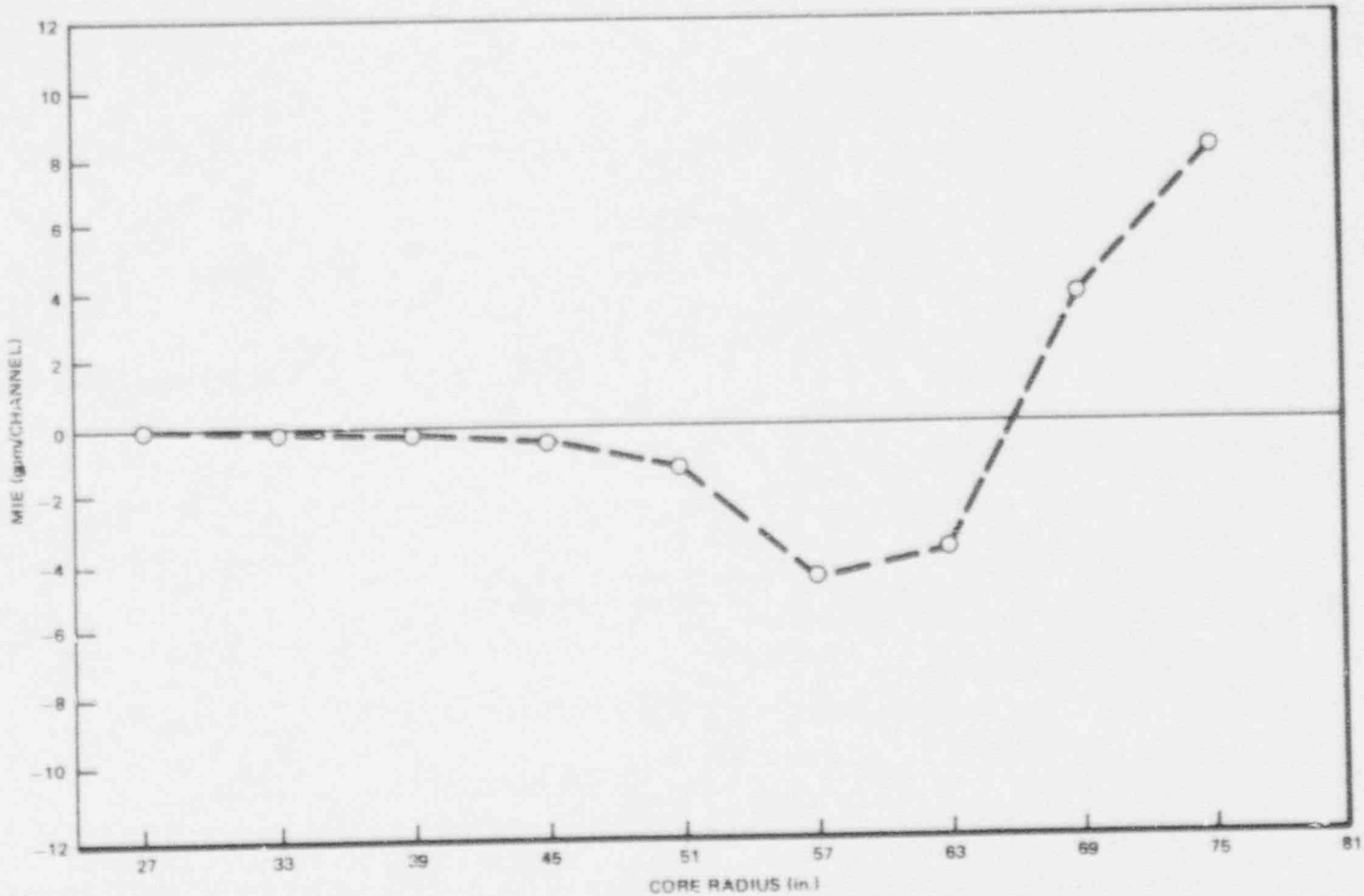


Figure 4-2. Centerline Average Interaction Effect (MIE) in SSTF (BWR/4-218)

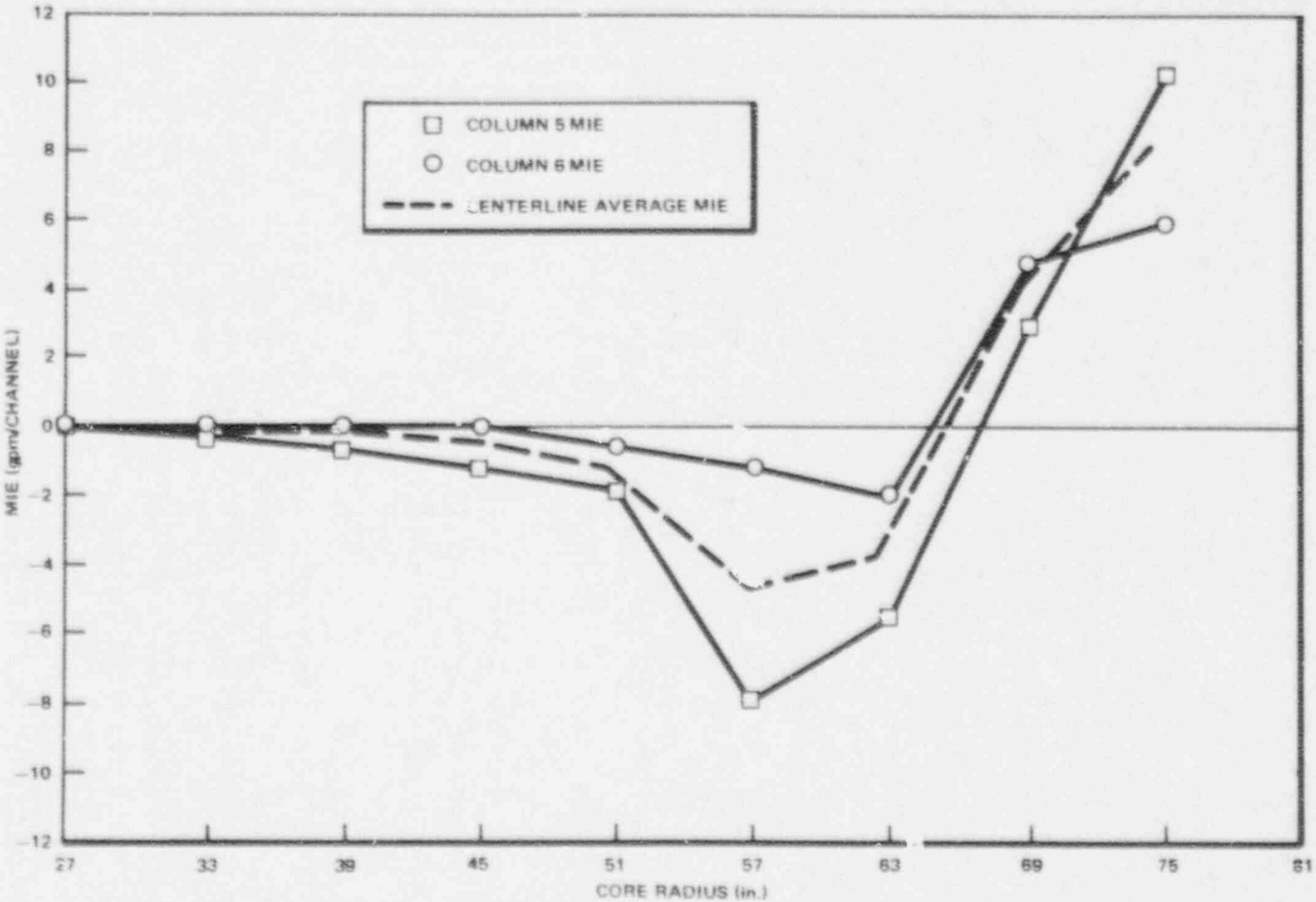


Figure 4-3. Individual Bundle Interaction Effect (MIE) in SSTF (BWR/4-218)

BWR/4-218 SSTF PREDICTION

Distance From Apex to Bundle Centerline (in.)	Lower Sparger Prediction (gpm/bundle)			
	Using Average MIE		Using Individual Bundle MIEs	
	Column 5	Column 6	Column 5	Column 6
27	0.48	0.70	0.38	0.79
33	0.70	0.84	0.58	0.99
39	1.47	1.43	1.14	1.75
45	3.32	2.68	2.75	3.25
51	7.31	6.01	6.59	6.69
57	11.06	8.74	7.75	12.21
63	18.34	15.98	16.58	17.82
69	23.24	21.02	22.40	22.04
75	16.28	15.02	18.44	12.93

4.2 THE EFFECT OF SPRAY FLOW RATE ON SPRAY DISTRIBUTION

The design basis flow (DBF) for this test program is 375 gpm for seven spray nozzles.* This provides individual nozzle flows equivalent to 5900 gpm per 360-deg sparger, which is typical of BWR/4 design.

For a parameter effect study, the sparger flow was varied from 33% DBF to 130% DBF. These test cases have 124, 251, and 488 gpm. The centerline average bundle flow versus radius for these tests is compared in Figure 4-6; the core

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*On a 360-deg sparger there are

50 Spraco 3101 nozzles at 39 gpm	=	1950 gpm
54 1-in. VNC nozzles at 73 gpm	=	3942 gpm
		5892 gpm total

On the seven-nozzle SSTF sparger there are

4 Spraco 3101s at 39 gpm	=	156
3 1-in. VNCs at 73 gpm	=	219
		375 gpm

Hence, the flow is less than that expected in a 30-deg sector of the reactor.

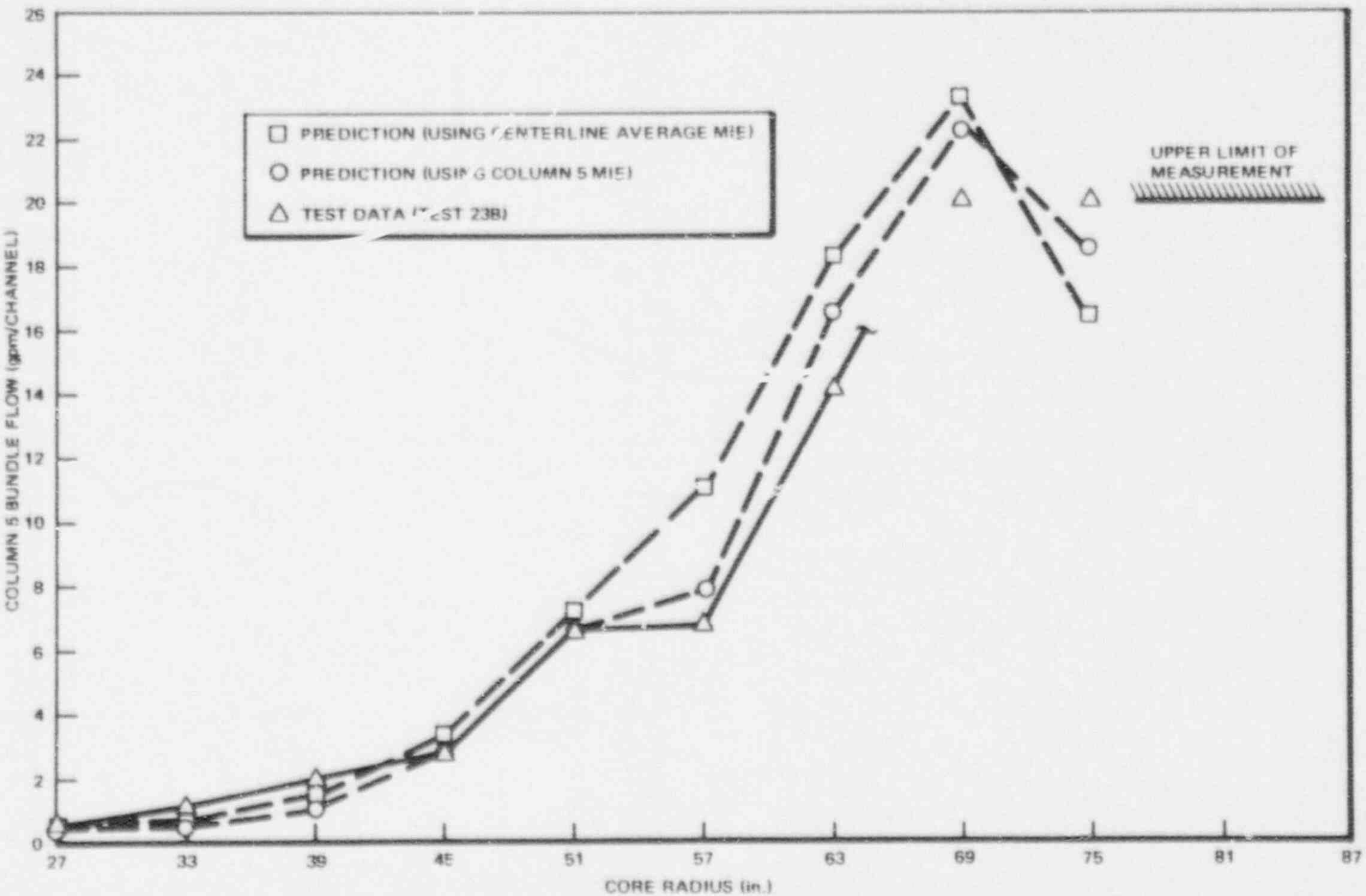


Figure 4-4. Comparison of Predicted Spray Distribution with Flow Measured in SSTF for Column 5 Bundles

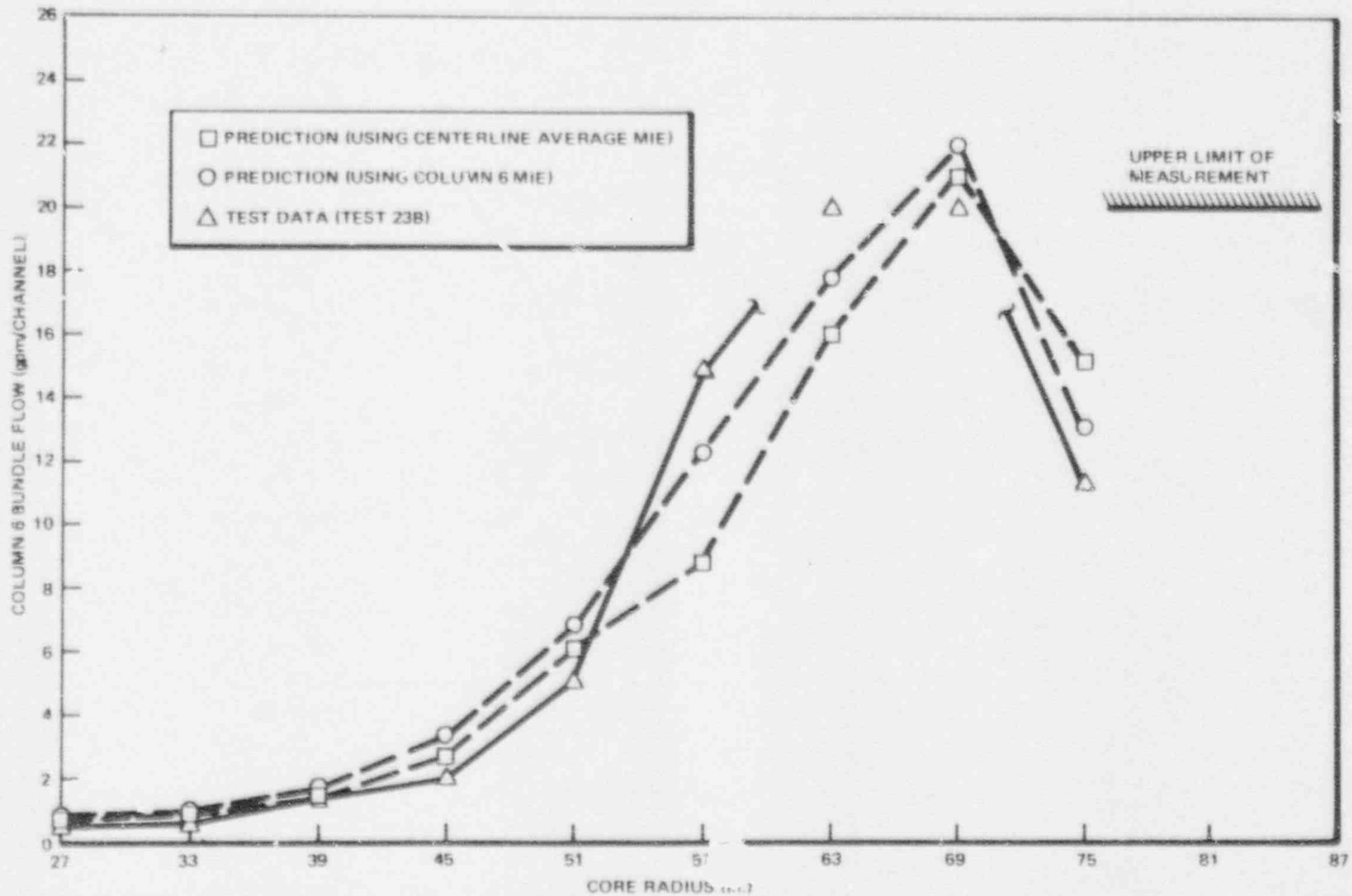


Figure 4-5. Comparison of Predicted Spray Distribution with Flow Measured in SSTF For Column 6 Bundles

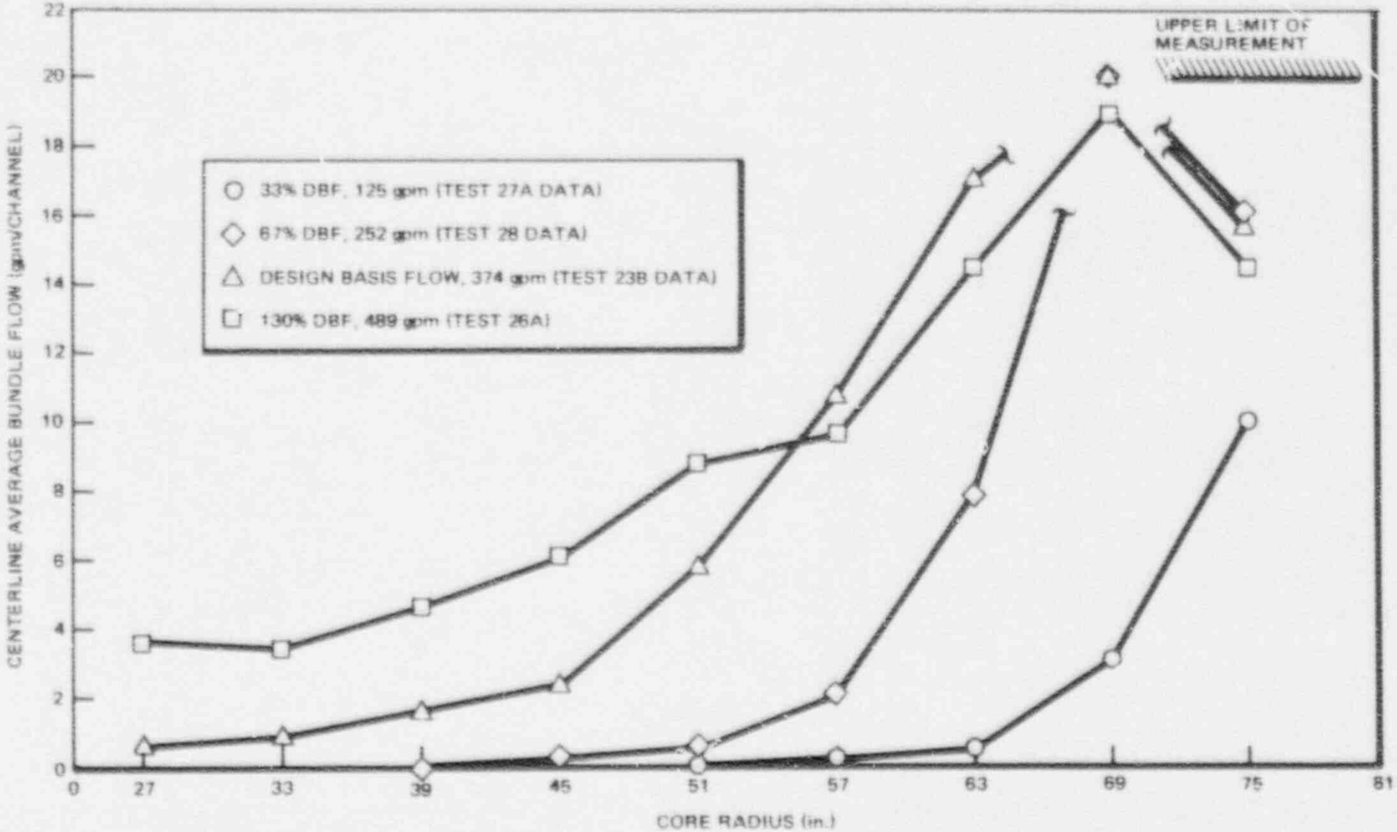
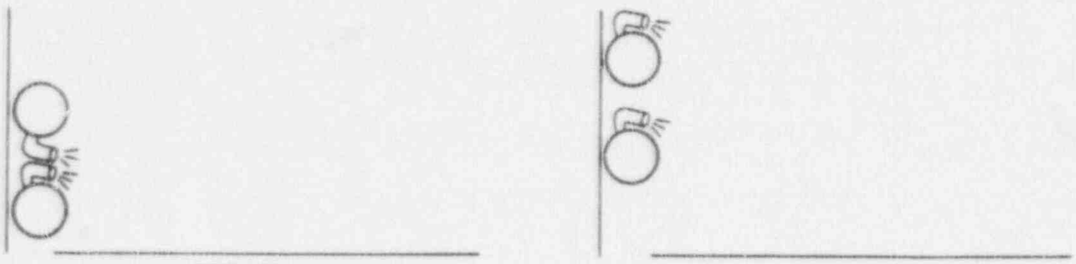


Figure 4-6. Effect of Spray Flow Rate on Spray Distribution in SSTF (BWR/4-218)

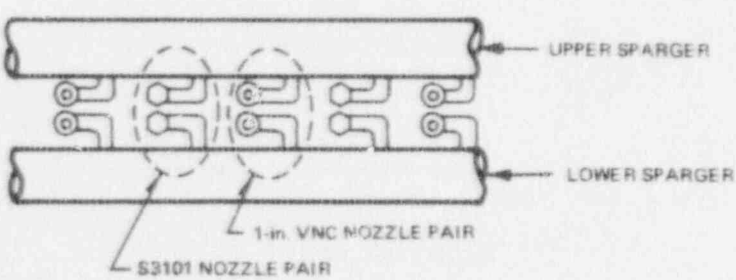
maps of the spray distribution data are presented in Figures 4-7 and 4-8. As shown on these figures, increasing the flow from the DBF greatly increases the spray density at 27, 33, 39, 45, and 51-in. radii. At 33% and 67% DBF, the spray covers only the periphery of the core, reaching 57-in. and 45-in. core radii, respectively.

4.3 SPARGER-TO-SPARGER INTERACTION EFFECTS

The nozzle placement configuration of the BWR/4&5 design is significantly different from that of the BWR/6, as illustrated below. Because of the closeness of the upper and lower sparger nozzles of the BWR/4&5 design, there was significant interest about sparger-to-sparger interaction effects.



Since there was no BWR/4-30-deg upper sparger installed at the SSTF, sparger-to-sparger interaction effects were investigated using the double sparger test assembly while the upper plenum and all of the 30-deg spargers were removed (see subsection 3.2 and Figure 3-5). As shown below, the BWR/4&5-218 design uses Spraco 3101 nozzles and 1-in. VNC nozzles on both the upper and lower spargers. Hence, the local interaction alternately involves pairs of Spraco 3101 nozzles and pairs of 1-in. VNC nozzles.



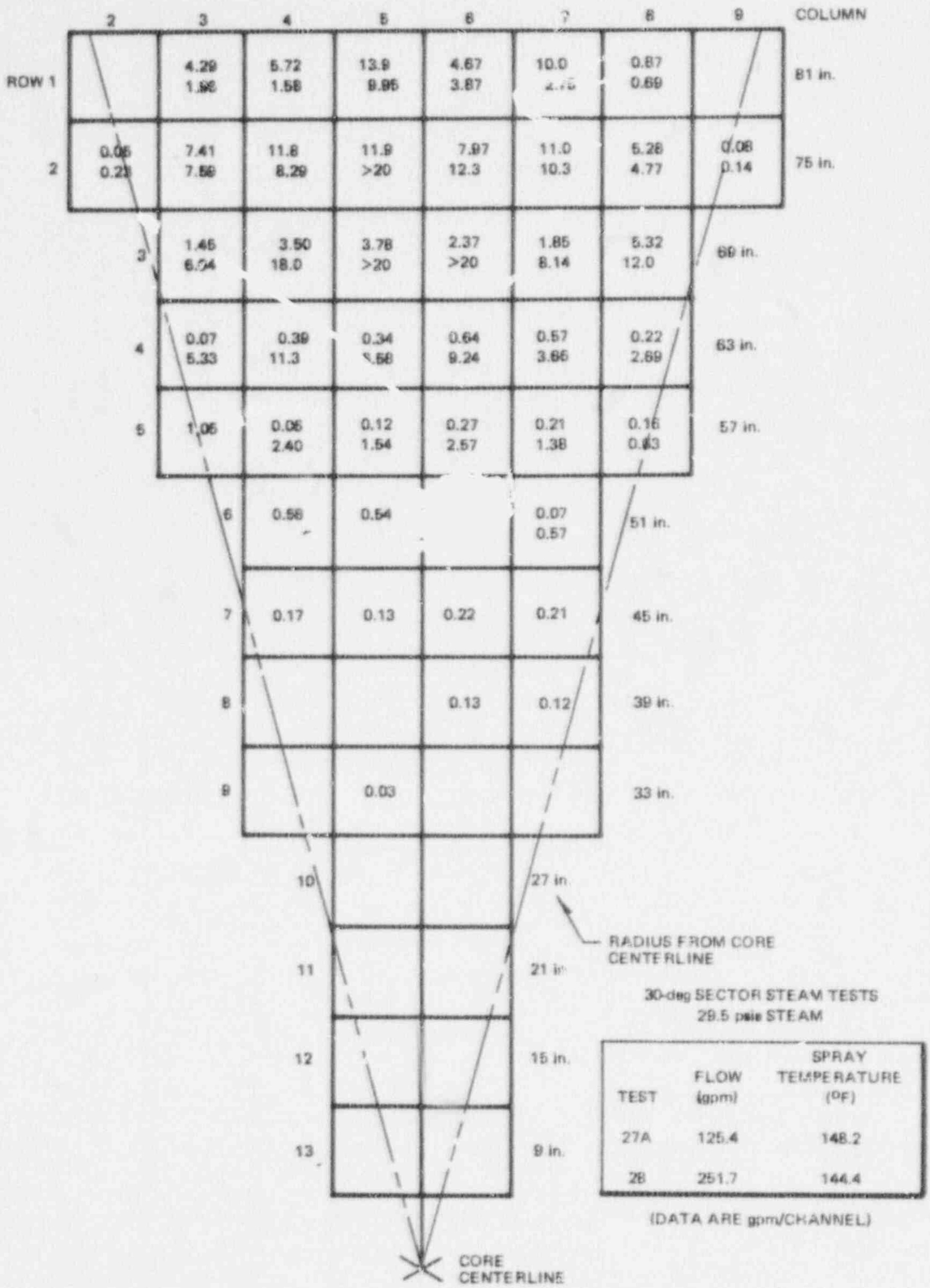


Figure 4-7. Core Map of Spray Distribution Data, SSTF (BWR/4-218)

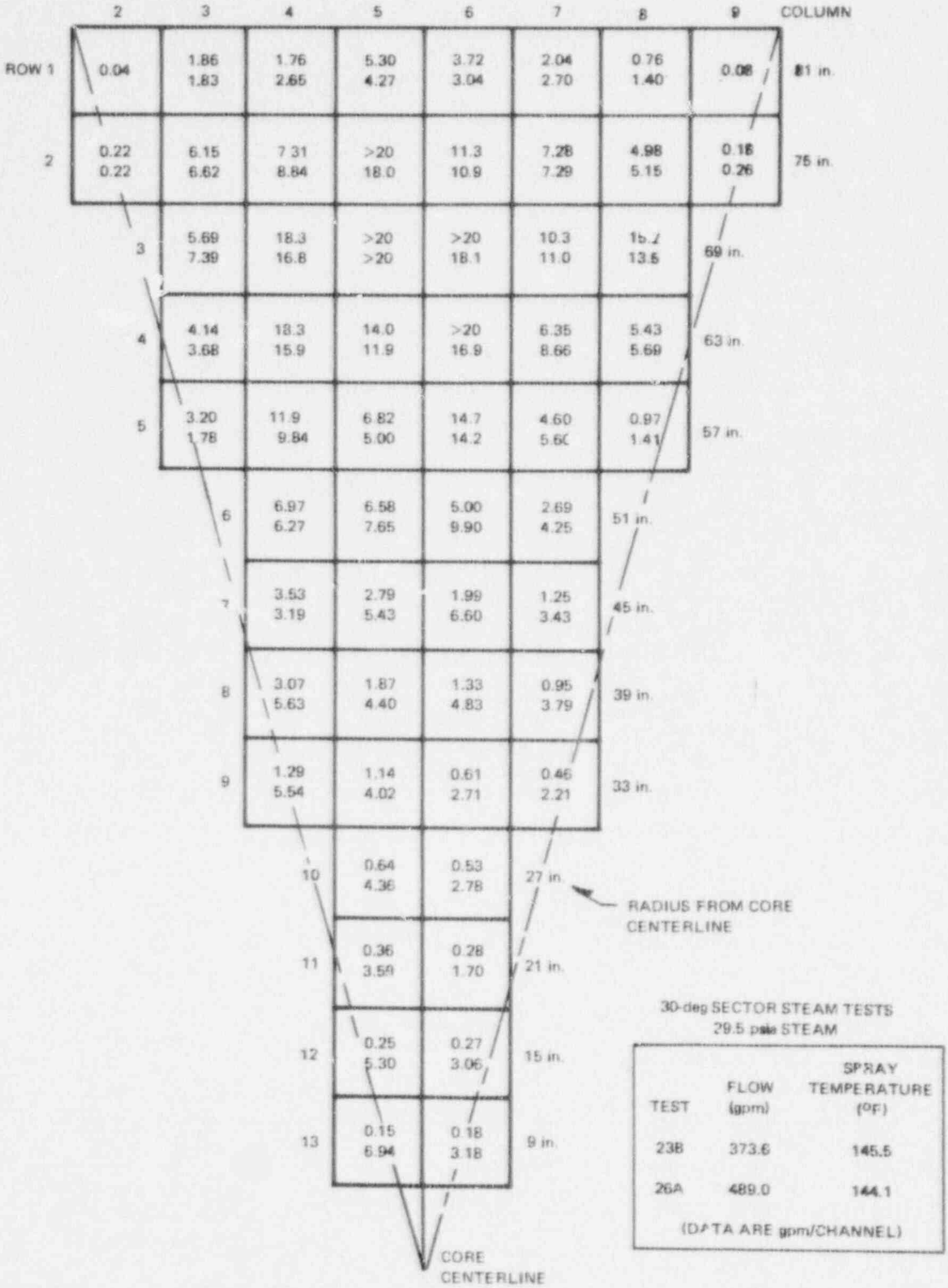


Figure 4-8. Core Map of Spray Distribution Data, SSTF (BWR/4-218)

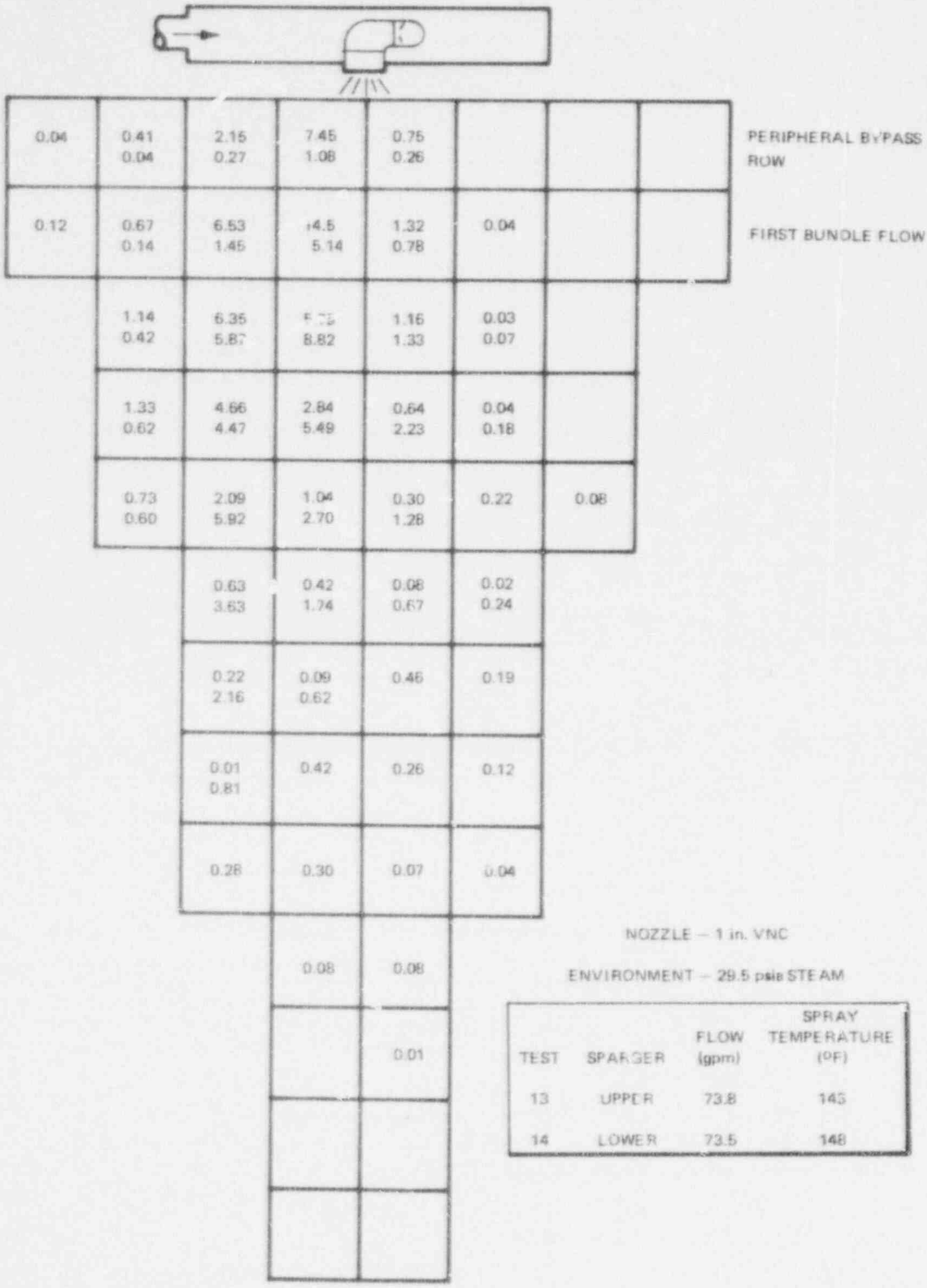
For each of the two types of nozzle pairs, nozzle-pair testing was performed at the SSTF wherein each nozzle was tested individually and then both nozzles of the pair were tested simultaneously as shown in the Phase 3 test matrix below.

PHASE 3 TEST MATRIX

Test Number		13	14	15	16	17	18
Nozzle Type		1-in. VNC			S3101		
Nozzle Assembly-Figure Number (and Serial Number)	Upper Sparger	11 (11-1)	-	11 (11-1)	3 (3-1)	-	3 (3-1)
	Lower Sparger	-	8 (8-1)	8 (8-1)	-	5 (5-1)	5 (5-1)
Spray Flow (gpm) ±0.5		73	73	73 ea	39	39	39 ea
Spray Temperature (°F)		145 ± 3.0					
System Pressure (psia)		29.5 ± 0.5					

Tests 13 through 15 comprise the data set to evaluate the magnitude of any interaction effects with a 1-in. VNC nozzle on each sparger. The distributions for each sparger operating separately are given in Figure 4-9. This figure indicates that the flow from the upper sparger nozzle mainly falls within the first 3 or 4 rows of bundles and to the right of the sector centerline (viewing from behind the nozzle). The lower sparger flow is also skewed to the right, but generally falls further out in the sector (bundle rows 1 through 6). The summation of the lower and upper sparger results compared with the data of simultaneous operation is presented in Figure 4-10. This comparison shows that the downward momentum of the upper sparger flow tends to dominate the lower sparger flow. That is, the simultaneous operation pattern is concentrated more toward the periphery of the sector than indicated by a direct summation of the individual sparger results. This shift is shown on a plot of flow versus core radius in Figure 4-11.

The interaction effects using Spraco 3101 nozzles were investigated in tests 16 through 18. Individual sparger spray distribution patterns are given in Figure 4-12. The upper sparger spray is slightly skewed to the left of the sector centerline and mainly falls in bundle rows 2 through 5. The lower sparger spray is also slightly skewed to the left and mainly falls in bundle rows 1 through 3. A comparison between the summation of the two individual sparger



TEST	SPARGER	FLOW (gpm)	SPRAY TEMPERATURE (°F)
13	UPPER	73.8	143
14	LOWER	73.5	148

Figure 4-[illegible]. 1-in. VNC Nozzle Upper and Lower Sparger Distributions - SSTF

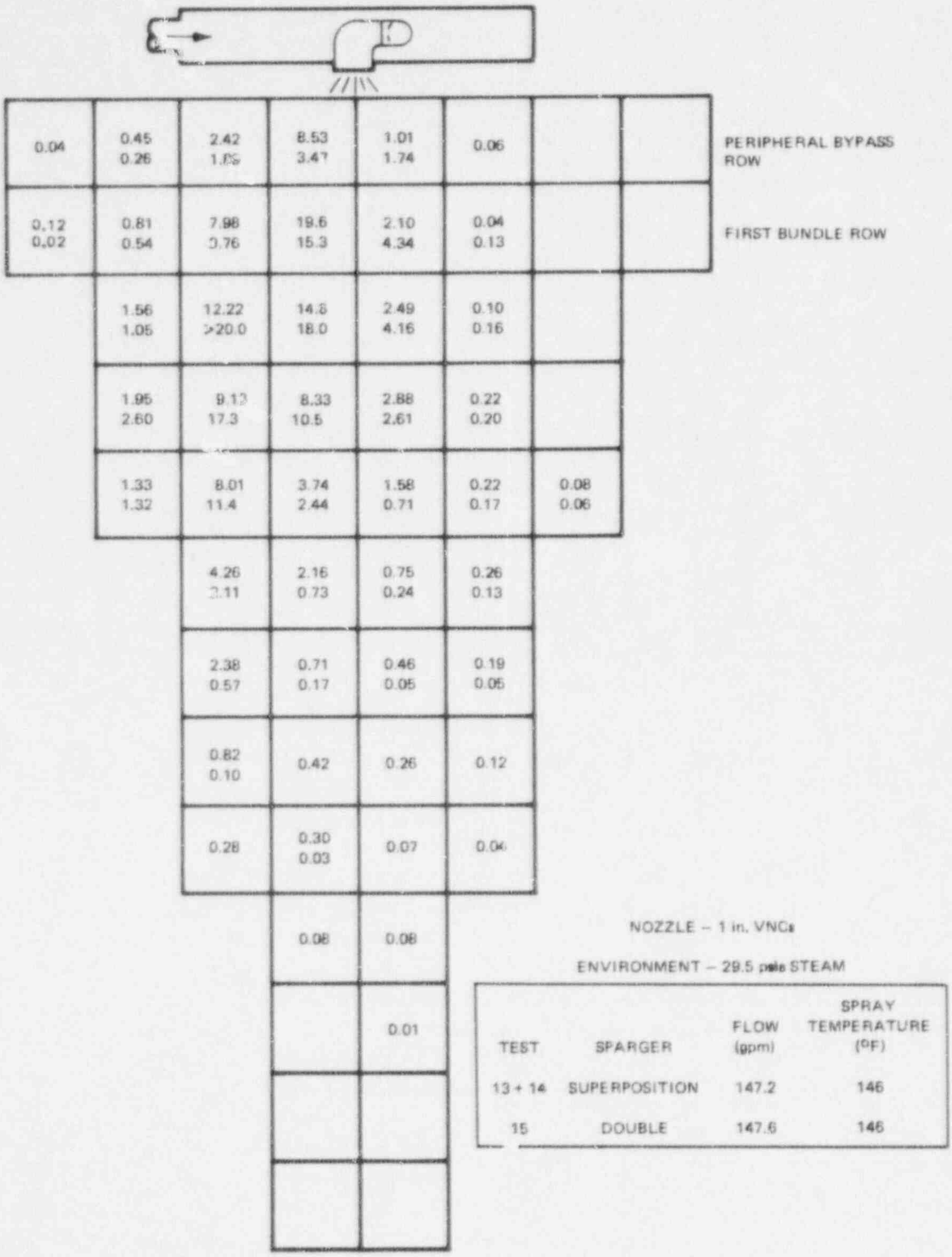


Figure 4-10. 1-in. VNC Nozzle Superposition and Double Sparger - Distributions - SSTF

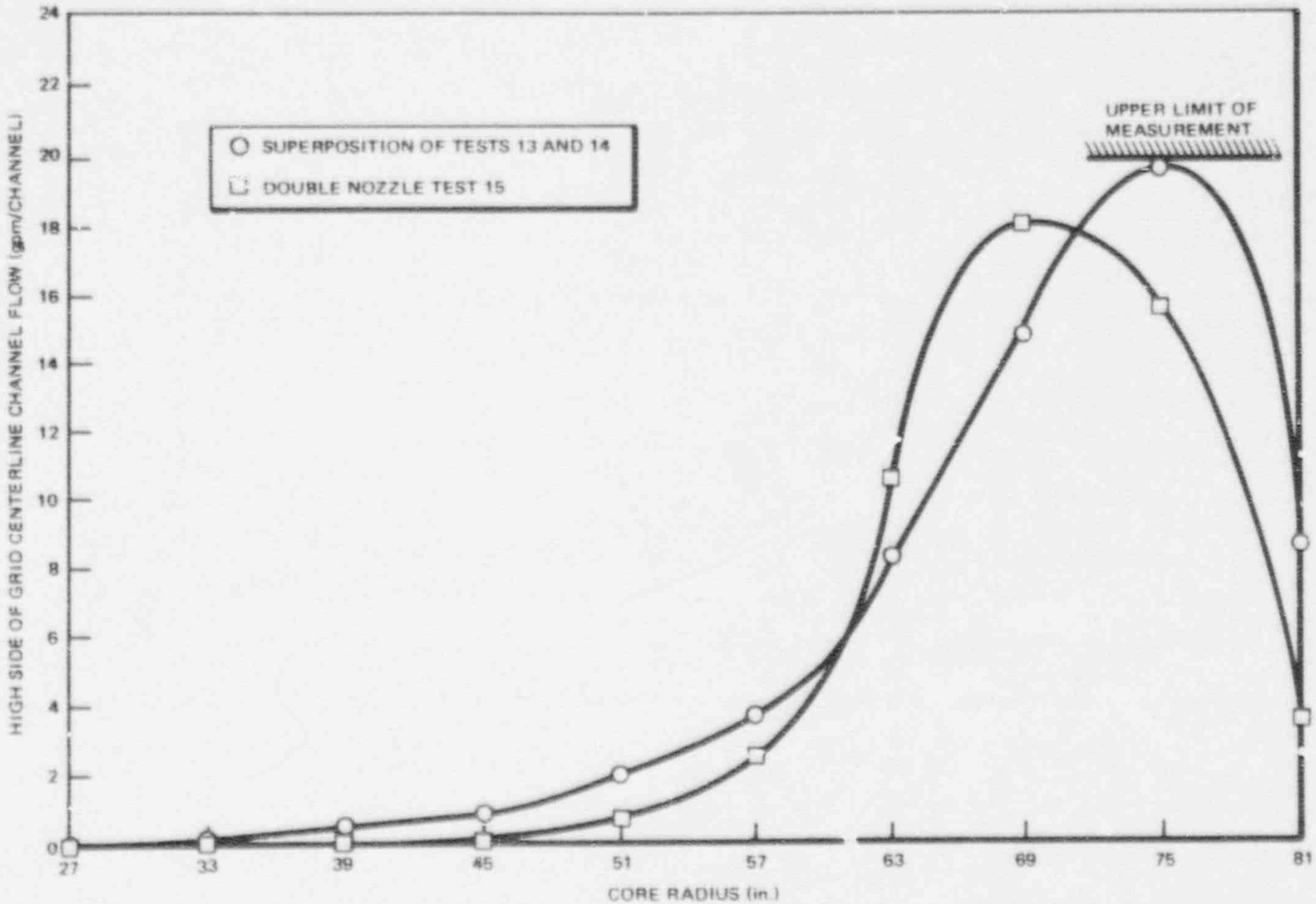
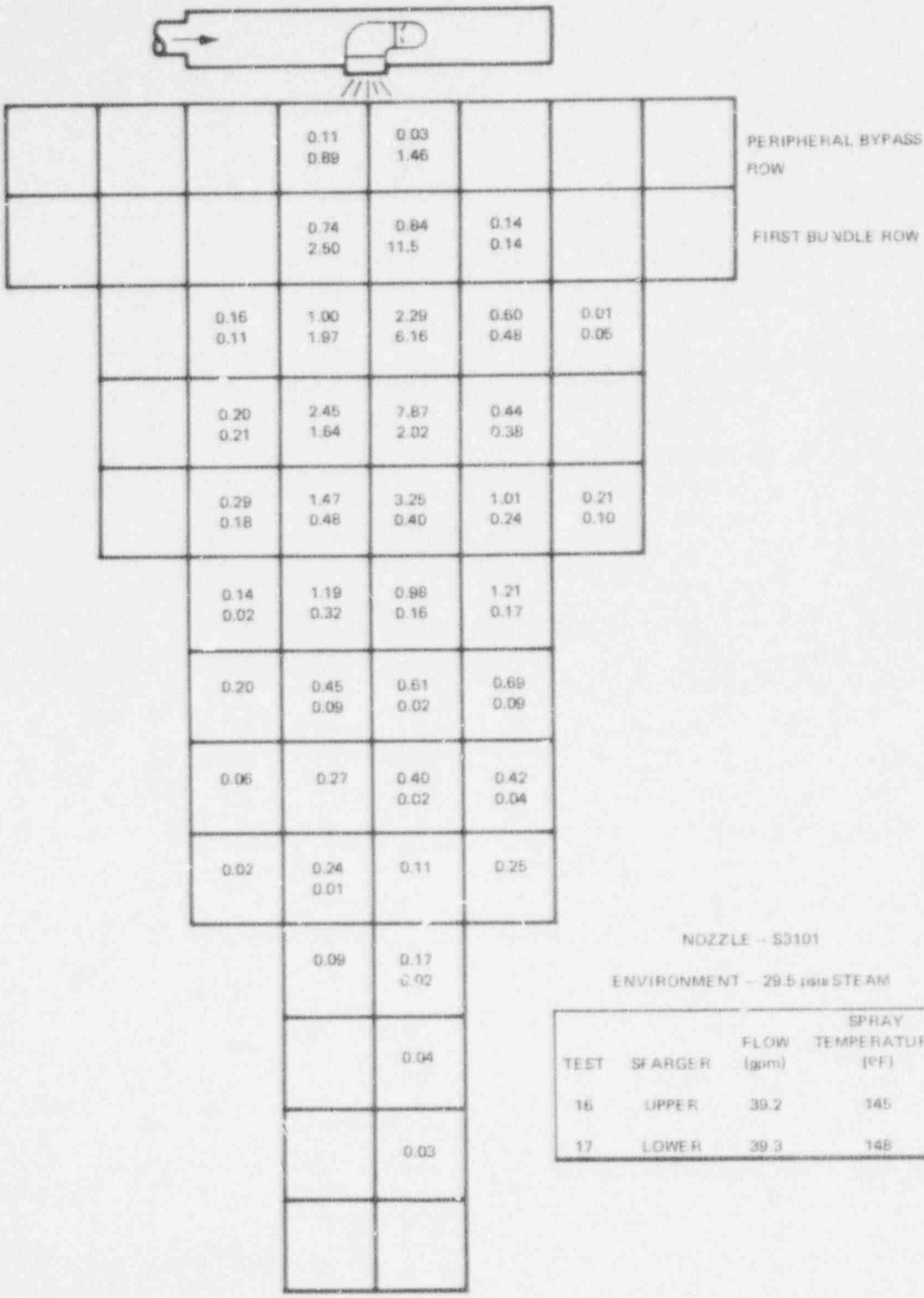


Figure 4-11. Comparison of Superposition and Double Nozzle Spray Distributions for 1-in. VNC Nozzles for High Side Bundles



NOZZLE – S3101

ENVIRONMENT – 29.5 psia STEAM

TEST	SPARGER	FLOW (gpm)	SPRAY TEMPERATURE (°F)
16	UPPER	39.2	145
17	LOWER	39.3	148

Figure 4-12. S3101 Nozzle Upper and Lower Sparger Distributions - SSTF

distributions and the simultaneous operation distribution shows essentially no interaction effect for the Spraco 3101 nozzles, as shown in Figure 4-13. This lack of interaction is also shown on a plot of flow versus core radius in Figure 4-14.

4.4 REACTOR NOZZLE DATA AND SIMULATOR NOZZLE DESIGN

Each of the two nozzle types for each of the two spargers were tested in the HSF in a steam atmosphere. Simulator nozzles were developed at the VSF for the lower sparger. The simulators, as developed at VSF, were then retested at HSF for more accurate low flow collector readings.

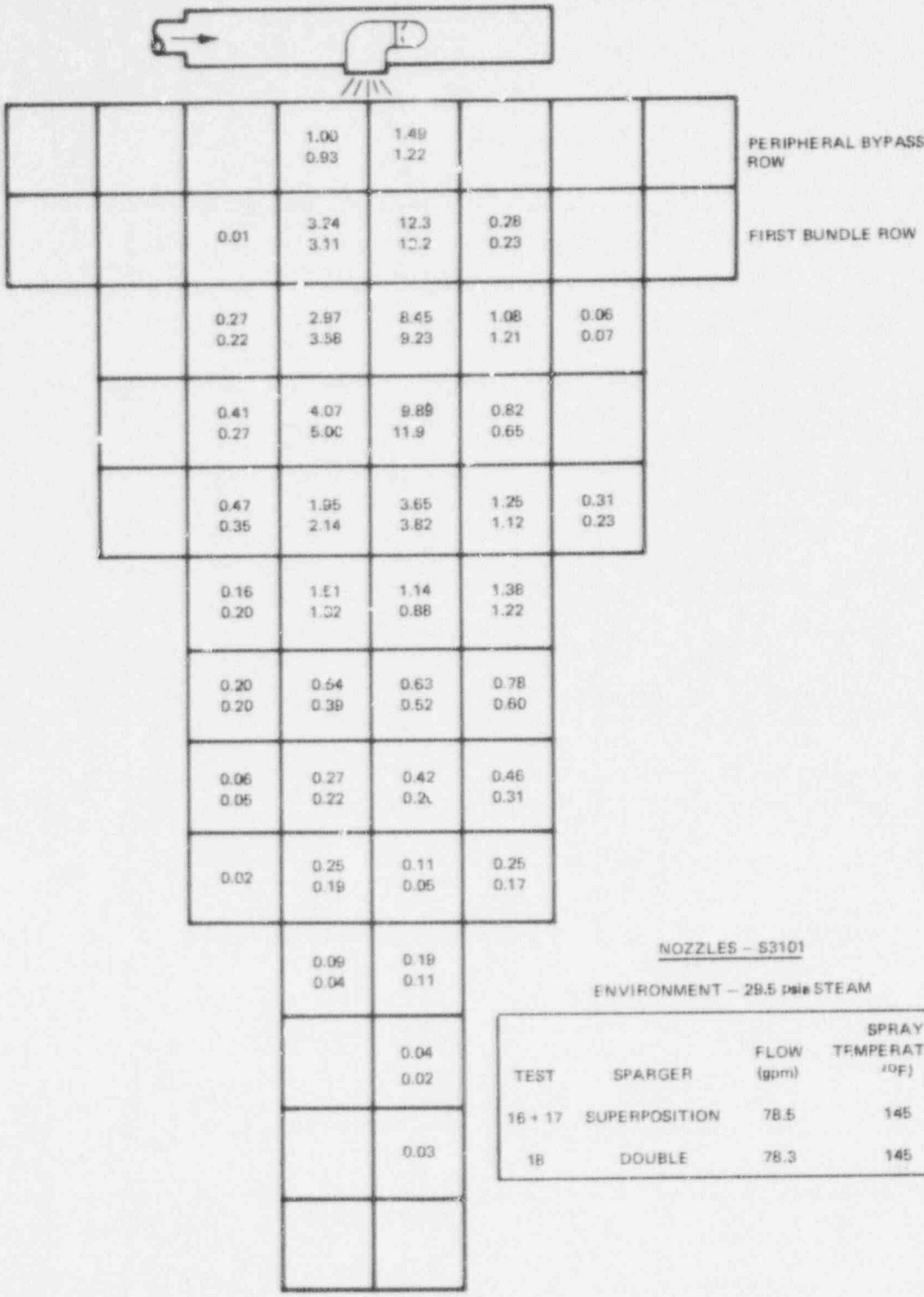
4.4.1 Single Nozzle Spray Distributions In Steam - (HSF)

The single nozzle steam tests were performed in the HSF for the four BWR/4-218 core spray nozzles, as shown in the Phase 1 test matrix below.

PHASE 1 TEST MATRIX

Test Number	1	3	5	7
HSF Test Number	7902-31	7902-29	7903-1,2,3	7903-9,10,31
Nozzle Type	1-in. VNC 14/16	S3101	1-in. VNC 9/16	S3101
Nozzle Assembly Configuration Number	11	3	8	5
Sparger	Upper	Upper	Lower	Lower
Spray Flow (gpm)	73	39	73	39
Spray Temperature (°F)	145	145	145	145
System Pressure (psia)	29.5	29.5	29.5	29.5

The spray distribution of the 1-in. VNC 14/16 on the upper sparger is presented in Figure 4-15. The spray is skewed to the right (when observed from behind the nozzle) with distribution covering the core from a 15- to 81-in. radius.



NOZZLES – S3101

ENVIRONMENT – 29.5 psia STEAM

TEST	SPARGER	FLOW (gpm)	SPRAY TEMPERATURE (°F)
16 + 17	SUPERPOSITION	78.5	145
18	DOUBLE	78.3	145

Figure 4-13. S3101 Nozzle Superposition and Double Sparger Distributions - SSTF

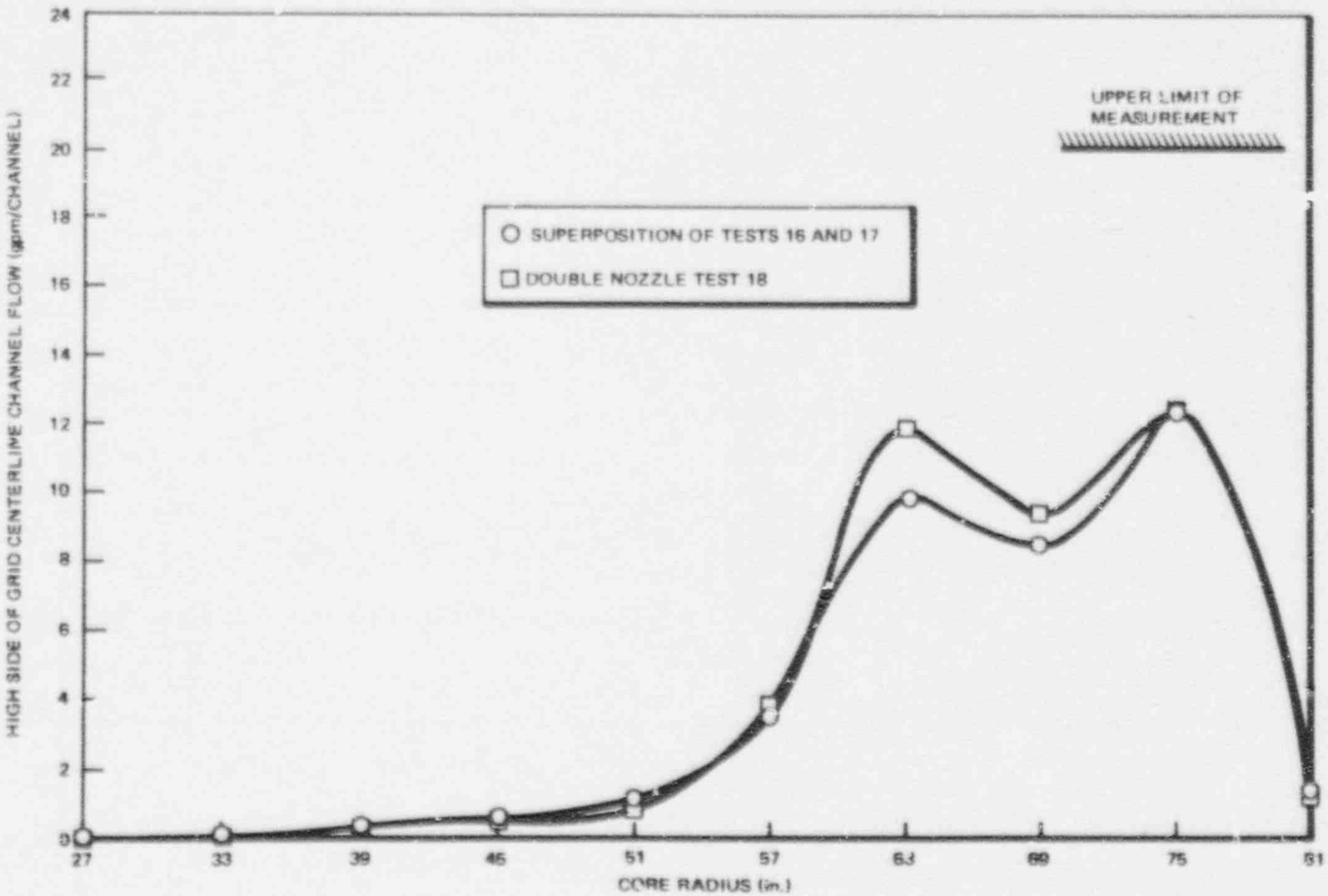


Figure 4-14. Comparison of Superposition and Double Nozzle Spray Distributions for S3101 Nozzles for High Side Bundles

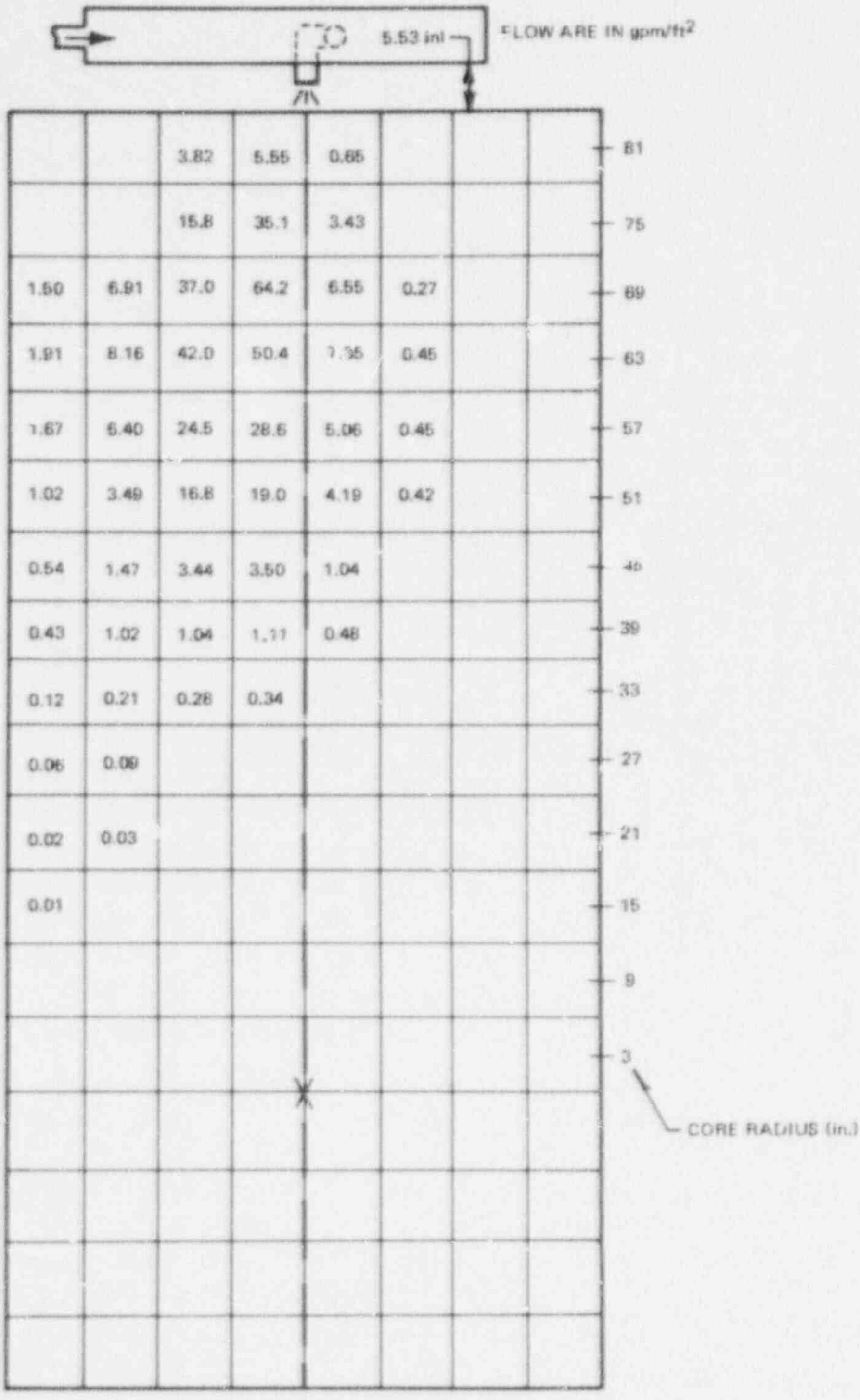


Figure 4-15. Spray Distribution of the 1-in. VNC 14/16, Upper Sparger in Steam - HSF

The spray distribution of the Spraco 3101 on the upper sparger is presented in Figure 4-16. The spray is skewed to the left (when observed from behind the nozzle) with distribution covering the core from a 21- to 75-in. radius.

The spray distribution of the 1-in. VNC 9/16 on the lower sparger is presented in Figure 4-17. The spray is skewed to the right (when observed from behind the nozzle) with distribution covering the core from a 9- to 81-in. radius. The data presented is the average of the data from Tests 7903-1, -2, and -3.

The spray distribution of the Spraco 3101 on the lower sparger is presented in Figure 4-18. The spray is skewed to the left (when observed from behind the nozzle) with distribution covering the core from a -21- to 81-in. radius. (A -21-in. radius means four bundles past the core centerline.) The data presented are the averages of the data from Tests 7903-9, -10, and -31.

4.4.2 Single Nozzle Spray Distributions In Air - (VSF, HSF)

Spray distribution data of the reactor nozzle in air and the simulator nozzle in air were obtained for each of the two lower sparger nozzles according to the Phase 2 test matrix shown below.

PHASE 2 TEST MATRIX

Nozzle Type	1-in. VNC 9/16			S3101		
Test Description	Reactor Nozzle in Air	Simulator Nozzle in Air	Simulator Nozzle in Air	Reactor Nozzle in Air	Simulator Nozzle in Air	Simulator Nozzle in Air
Test Facility, Test Matrix Number	VSF, 11-001A	VSF, 11-010A	HSF, 7903-7	VSF, 12-001A	VSF, 12-011A	HSF, 7903-14A
Nozzle Configuration Number	8	8S	8S	5	5S	5S
Sparger	Lower			Lower		
Spray Flow (gpm)	73			39		
Spray Temperature (°F)	80			80		

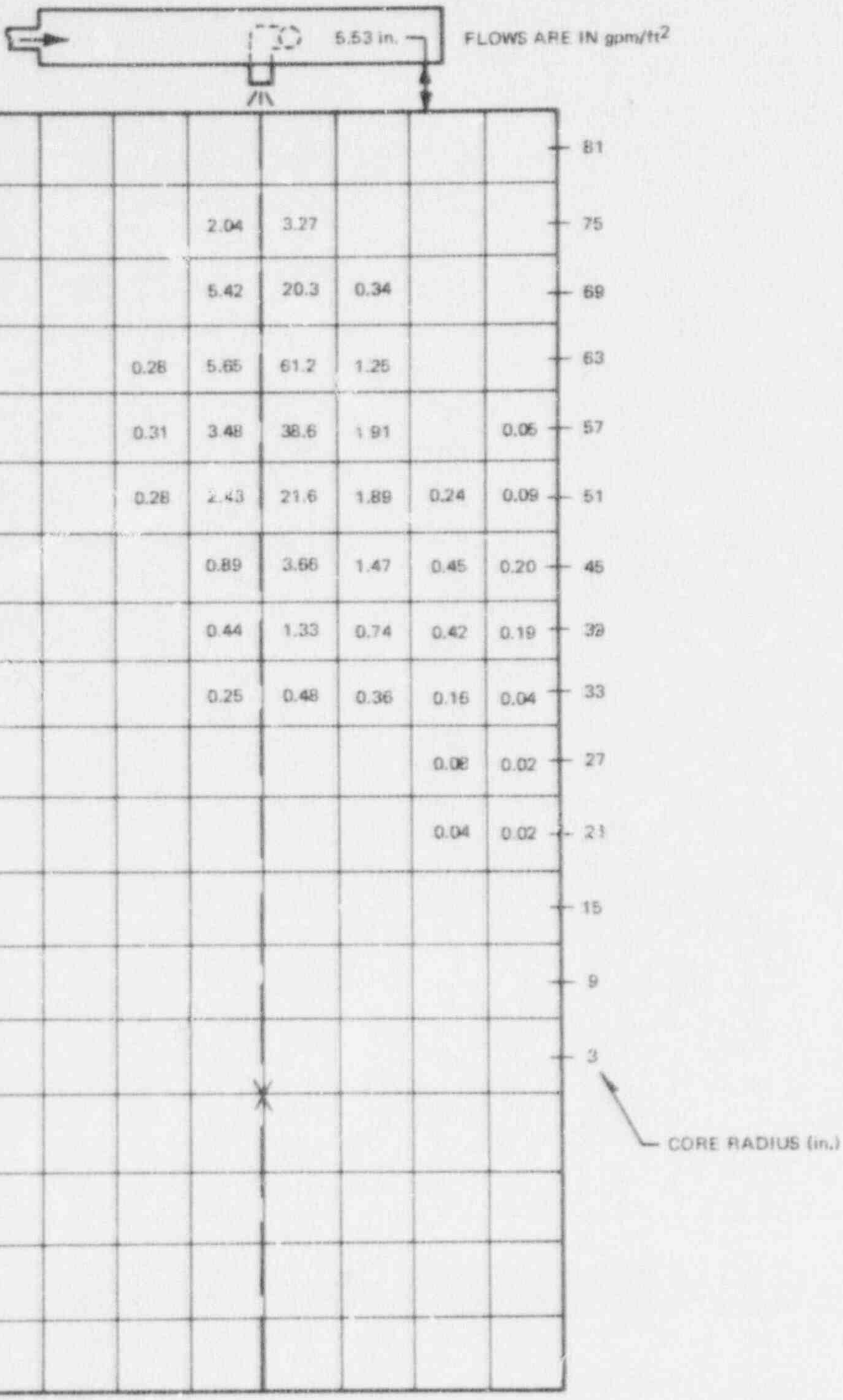


Figure 4-16. Spray Distribution of the Spraco 3101, Upper Sparger in Steam - HSF

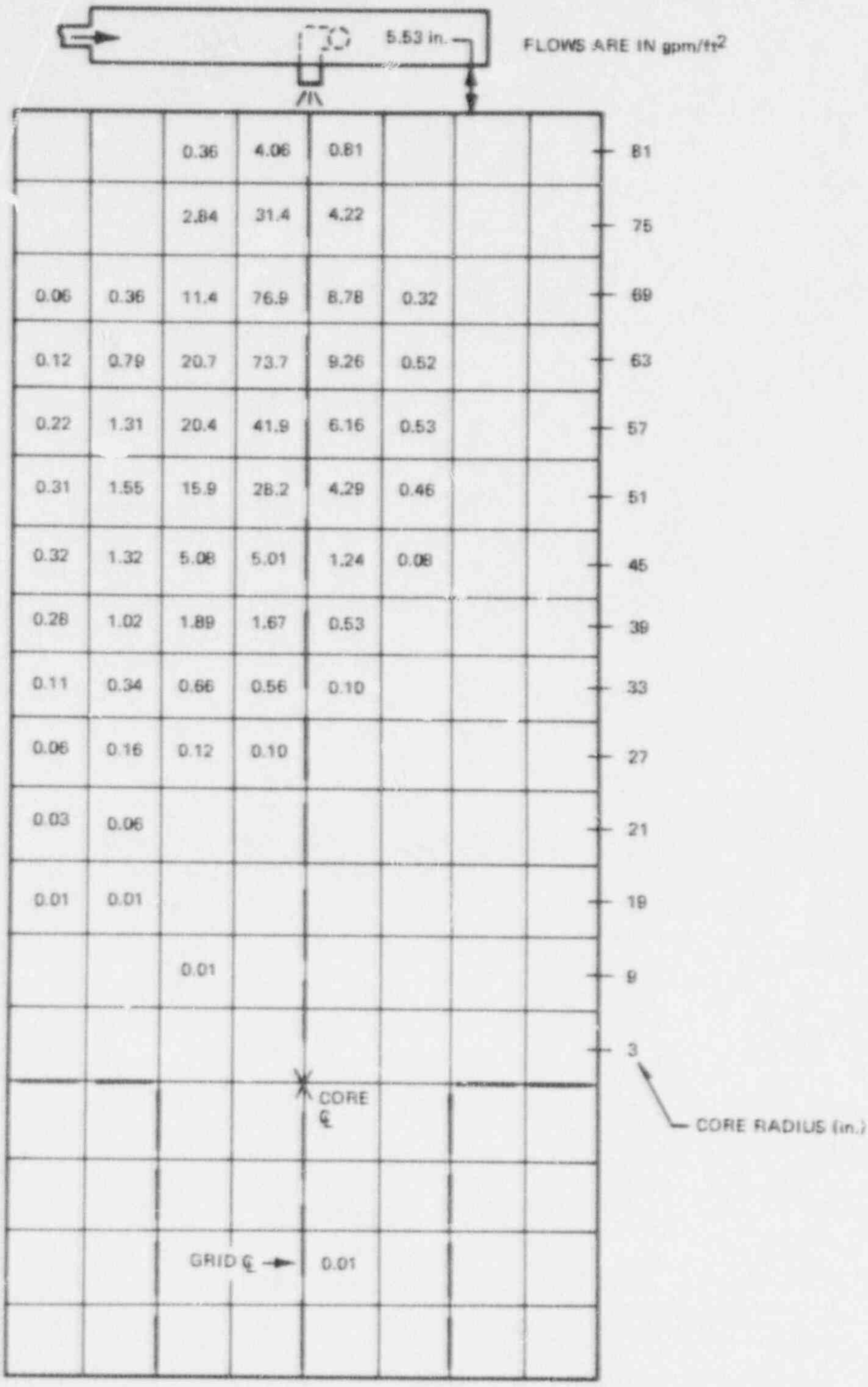
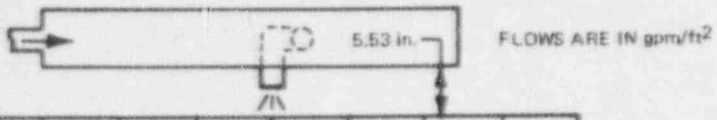


Figure 4-17. Spray Distribution of the 1-in. VNC 9/16, Lower Sparger in Steam - HSF



								Core radius (in.)
			0.69	1.56				81
			2.91	11.0	0.23			75
		0.10	3.97	37.2	1.39		0.03	69
		0.23	3.86	38.1	3.11	0.09	0.05	63
		0.30	3.03	19.0	3.97	0.30	0.10	57
0.01		0.31	2.61	13.4	3.81	0.58	0.19	51
0.02		0.30	1.37	4.47	2.23	0.62	0.23	45
0.01		0.26	1.01	2.69	1.66	0.64	0.24	39
0.01	0.05	0.20	0.70	1.72	1.26	0.46	0.14	33
0.01	0.04	0.07	0.46	1.04	1.01	0.35	0.11	27
0.01	0.03	0.05	0.29	0.64	0.66	0.23	0.08	2'
0.01	0.02		0.17	0.44	0.40	0.16	0.07	15
	0.01	0.04	0.10	0.12	0.10	0.11	0.06	9
		0.03	0.06	0.08	0.07	0.07	0.04	3
		0.02	0.04	CORE ℄ 0.06	0.04			−3
		0.01	0.01	0.04	0.02			−9
		GRID ℄ →		0.03	0.01			−15
				0.02	0.01			−21

CORE RADIUS (in.)

Figure 4-18. Spray Distribution of the Spraco 31C1, Lower Sparger in Steam - HSF

The spray distribution data for the 1-in. VNC 9/16 reactor nozzle in air, reactor nozzle in steam, and the simulator nozzle in air are presented in Figure 4-19. Comparison of the reactor nozzle data between air and steam shows that the steam effects skew the spray down and in the direction opposite of the sparger flow [(-) negative azimuth skew] and narrow the spray cone angle. Comparison of the data from the reactor nozzle in steam and the simulator nozzle shows very good agreement (i.e., the simulator nozzle design was acceptable).

The spray distribution data for the Spraco 3101 reactor nozzle in air, reactor nozzle in steam, and the simulator nozzle in air are presented in Figure 4-20. Comparison of the reactor nozzle data between air and steam shows that the steam effects skew the spray up and in the direction of the sparger flow [(+) positive azimuth skewing] and narrow the spray cone angle. Comparison of the data from the reactor nozzle in steam and the simulator nozzle again shows very good agreement.

4.5 30-DEG SECTOR TESTS IN AIR

4.5.1 30-deg Reactor Nozzle Tests

The spray distribution for the eight-nozzle* reactor nozzle set in an air environment was determined at both the design basis flow (DBF) and at 78% DBF. The distributions for the two different flows are given in Figure 4-21.

In general, the spray pattern is essentially the same in both cases, with the measured flow difference being due to the difference in total sparger flow between the cases. The overall distribution in both cases is slightly skewed to the right, i.e., the negative azimuth direction. The low point in both distributions is at the sixth row of bundles from the periphery. The high flow at the apex, especially in the DBF case, is mostly the result of reflection from the test section walls.

---

*Nozzle position L1 (see Figure 3-2) was to be used throughout the test program, resulting in eight nozzles with the DBF at 448 gpm. However, during 30-deg simulator nozzle installation it was observed that the 1-in. VNC simulator for position L1 could not be correctly azimuthally aimed without interference with the sector wall. Thus position L1 was blanked off and the remainder of the test program (30-deg simulators and 30-deg steam) was run with only seven nozzles. [The DBF was reduced by 73 gpm (the flow of a 1-in. VNC) to 375 gpm.]

1-in. VNC 9/16, LOW'R SPARGER

REACTOR NOZZLE IN AIR

ROW	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	0.21	0.95	0.95	0.79	0.79	0.68	0.32	0.74	0.68	0.63	0.21	0.21	0.37					
	2.11	4.11	4.42	2.74	1.74	1.63	1.63	1.37	1.74	1.42	0.63	0.84	1.26	0.79	0.42			
	7.26	14.53	11.68	4.47	2.21	1.53	1.05	1.16	1.37	1.16	0.74	1.32	1.58	1.68	1.47			
	4.68	19.0	19.89	13.47	6.84	2.63	1.68	1.21	0.95	0.95	1.05	1.79	2.37	1.89	2.26			
		0.95	2.95	4.47	6.85	6.10	5.57	4.79	4.10	3.58	3.21	3.53	3.26	3.84	2.63			
				0.37	0.37	1.36	1.53	2.16	1.95	2.63	2.16	2.79	2.63	2.58				
								0.47				0.79	1.32					

TEST 11-001A

REACTOR NOZZLE IN STEAM

ROW	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
			0.28	0.45	0.46	0.40	0.07											
	0.70	3.64	7.58	7.99	5.32	3.70	1.07	0.49	0.09								0.01	
	3.50	27.1	86.4	63.6	36.2	24.3	4.32	1.44	0.48	0.09								
	0.31	2.45	9.84	17.9	17.6	13.7	6.38	1.63	0.57	0.10			0.01					
			0.31	0.68	1.13	1.34	1.14	0.88	0.29	0.14	0.05	0.01						
			0.05	0.10	0.19	0.27	0.28	0.24	0.09	0.05	0.03	0.01						

TEST 7903-1,-2,-3 (CORRECTED FOR CONDENSATION AND DENSITY)

SIMULATOR NOZZLE IN AIR

ROW	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
						0.03	0.03	0.03	0.01									
									0.02									
					0.18	0.17												
		1.74	4.50	4.73	2.85	1.86	0.78	0.47	0.31	0.24			0.03					
	1.96	21.8	[illegible]	58.1	25.4	16.9	4.39	2.29	1.19	0.84	0.38	0.21	0.07	[illegible]				
		1.04	6.29	16.4	15.1	12.5	6.50	3.91	2.39	1.81	0.87	0.48	0.14	0.05	0.03	0.02		
				0.24	0.61	1.18	1.64	1.67	1.57	1.06	0.68	0.52	0.23	0.13				
			0.03	0.05	0.13	0.28	0.48	0.53	0.57	0.44	0.33	0.31	0.16	0.10				

TEST 7903-7

ALL COLLECTOR FLOWS ARE gpm/ft^2

Figure 4-19. 1-in. VNC 9/16, Lower Sparger, Single Nozzle Spray Distributions

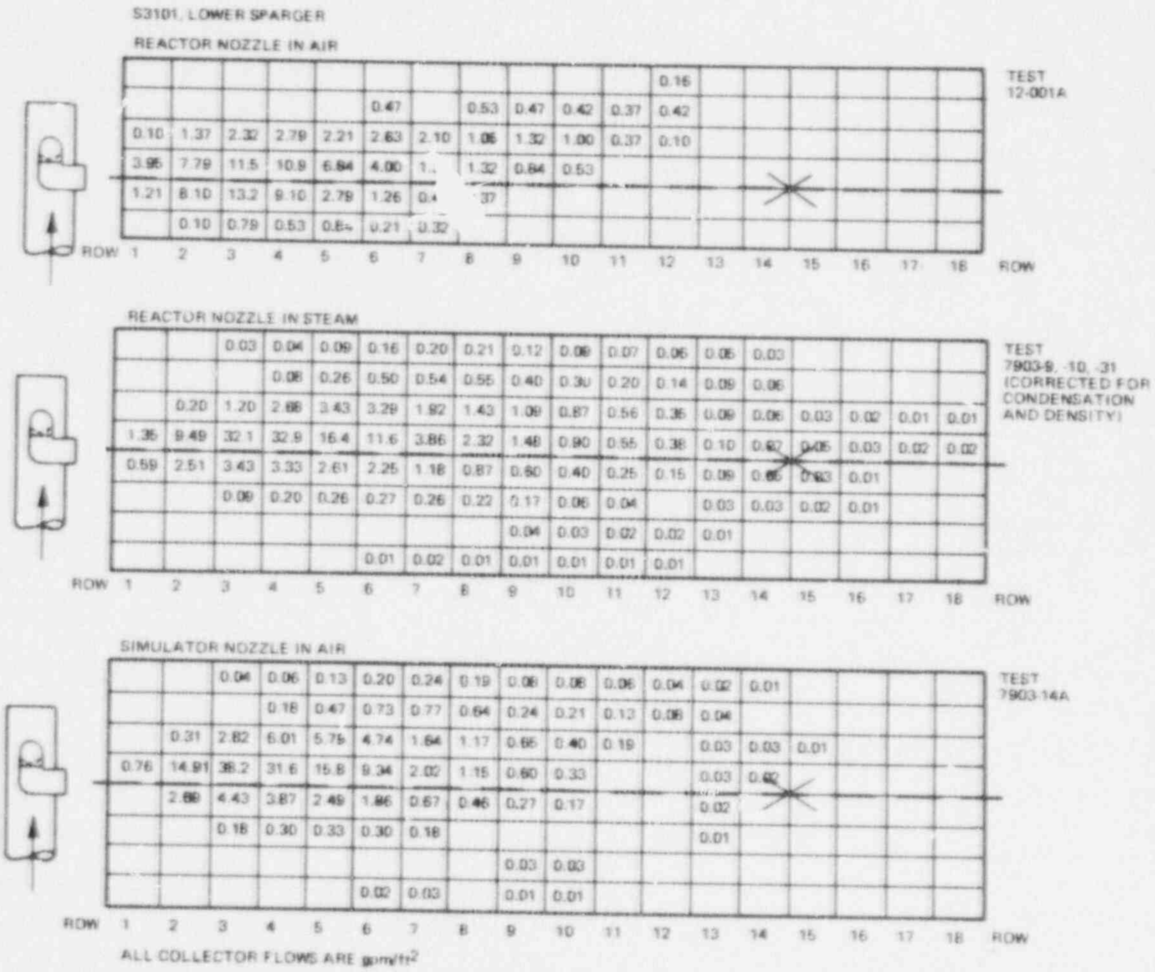


Figure 4-20. S3101, Lower Sparger, Single Nozzle Spray Distributions

[illegible] 1.83	1.70 1.54	3.88 2.84	4.70 2.08	3.87 2.61	4.14 2.85	1.75 1.43	0.30 0.25	PERIPHERAL BYPASS ROW
3.54 3.56	8.54 8.99	9.84 8.51	10.73 8.88	10.46 9.65	8.84 8.79	3.48 4.60	0.55 0.46	FIRST BUNDLE ROW
	11.77 9.17	10.56 7.41	[illegible] [illegible]	11.43 11.35	7.57 6.86	5.65 5.51		
	6.70 4.85	8.67 6.13	6.90 6.64	8.26 7.31	5.05 4.95	2.96 3.44		
	5.74 5.80	5.74 3.89	3.15 2.90	4.86 4.10	[illegible] 2.85	1.83 2.34		
		3.54 2.30	3.05 1.92	2.62 2.75	2.30 2.17			
		2.71 1.79	1.91 1.44	2.28 2.43	2.31 1.77			
		[illegible] [illegible]	2.44 1.88	2.30 2.59	3.90 2.56			
		3.97 2.15	2.66 1.97	1.76 1.77	1.59 1.26			
			3.45 2.47	2.06 1.97				
			3.29 2.19	1.94 1.87				
			5.23 2.74	3.60 2.54				
			7.25 2.42	2.77 1.63				

TEST	FLOW (gpm)	SPRAY TEMPERATURE (°F)
22	445.1	82
31	347.4	83

Figure 4-21. 30-Deg Reactor Nozzles in Air Spray Distribution

4.5.2 30-deg Simulator Nozzle Tests

The spray distributions for the simulator nozzle set at the DBF and at 78% DBF are given in Figure 4-22. In this case, only nozzles L_2 through L_8 were operating.* The distribution for both cases shows a strong flow concentration in the second row of bundles (an indicated flow of 20 gpm means the flow to that bundle exceeded the capability of the measurement device). The strong directional nature of the spray patterns is indicated by the relatively large flow differences from one bundle to the next (i.e., the center bundles in the first bundle row, or the bundles in rows 3 and 4). For both flow cases, the water mainly falls within bundle rows 1 through 7.

---

*Nozzle position L1 (see Figure 3-2) was to be used throughout the test program, resulting in eight nozzles with the DBF at 448 gpm. However, during 30-deg simulator nozzle installation it was observed that the 1-in. VNC simulator for position L1 could not be correctly azimuthally aimed without interference with the sector wall. Thus position L_1 was blanked off and the remainder of the test program (30-deg simulators and 30-deg steam) was run with only seven nozzles. [The DBF was reduced by 73 gpm (the flow of a 1-in. VNC) to 375 gpm.]

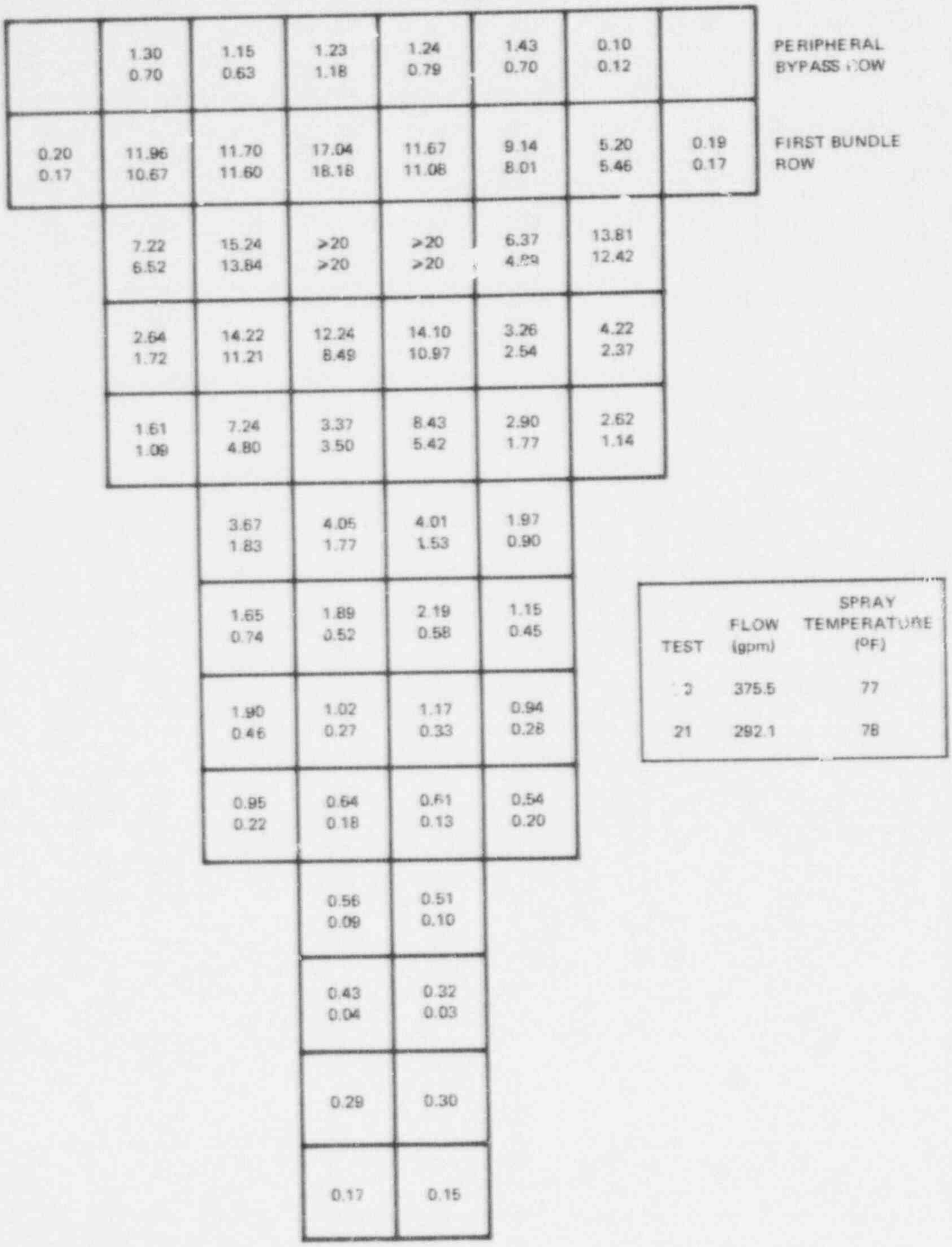


Figure 4-22. 30-Deg Simulator Nozzles in Air Spray Distribution

Section 5

CONCLUSIONS

Core spray distribution data for individual nozzles, and for arrays of nozzles, have been obtained in both air and steam environments for use in model qualification. This data has provided additional confirmation of the existing core spray methodology.[2] No further model requirements were identified as a result of these tests.

5.1 SINGLE NOZZLE TESTS

Single nozzles in steam, discussed in subsection 4.4, show significant azimuthal skewing for each nozzle type. Spraco 3101 nozzles skew about 4 or 5 degrees in a positive direction (same direction as the sparger flow), and the 1-in. VNC nozzles skew about 9 degrees in a negative direction.

5.2 DOUBLE SPARGER INTERACTION

Sparger-to-sparger interaction effects were investigated with "nozzle-pair" testing, as discussed in subsection 4.3. The two nozzles of the Spraco 3101 nozzle pair were found to have negligible effect on each other. However, for the 1-in. VNC nozzle pair, the two sprays do interact significantly. Simultaneous operation shows an increase in flow at 69- and 63-in. core radii and a reduction in flow at 51- through 27-in. core radii when compared to the superposition of independent operation. The sparger-to-sparger interaction effects can be incorporated in an evaluation of two-sparger operation using the core spray methodology by developing "nozzle pair" nozzle simulators for full size distribution tests in air.

5.3 CORE SPRAY METHODOLOGY CONFIRMATION

As discussed in subsection 4.1, the core spray methodology was successfully confirmed by the spray distribution of the 30-deg sector of the BWR/4-218 lower sparger in steam comparing very well with predicted values. The excellent comparisons further confirm the basic separability assumption of the core spray design methodology and demonstrate that it is also applicable with changes in spray nozzle type and sparger location. This confirmat .n is to be expected since the important assumption of separability of thermodynamics (i.e., condensing) and hydrodynamic effects should not be affected by such changes.

5.4 EFFECTS OF SPARGER FLOW RATE

As discussed in subsection 4.2. the 30-deg sparger flow rate was varied to identify parameter effects. Increasing the flow rate of the lower sparger from the DBF to 130% of that flow greatly increases the spray density at 27-, 33-, 39-, 34-, and 51-in. radii. Conversely, reducing the flow to 33% and 67% of the design flow reduces the spray density in that region.

Section 6

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3. Contract NRC-04-79-184, BWR Refill-Reflood Program, NRC, EPRI, GE-NED.

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*Available in the NRC Public Document Room for inspection and copying for a fee.

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16. ABSTRACT (200 words or less)

The test program has provided core spray distribution data in a steam environment for a 30° sector of the BWR/4&5-218 design. The data demonstrate the applicability of the core spray methodology in this design which uses different nozzle types and different sparger elevations than the BWR/6-218 design previously used to confirm the methodology. The effects of sparger flowrate and sparger to sparger interaction were also studied in this test program.

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