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CORE SUPPORT BLOCK THERMAL MIXING TEST ANALYSIS REPORT

**by
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ABSTRACT

The extent of gas mixing and pressure drop within the core support block was experimentally investigated for various geometric and height configurations. These tests were conducted by the Experimental Engineering Branch of General Atomic Company. As a result of this investigation, the core support block thermal mixing and pressure drop has been quantified. Thermal mixing and the temperature sensor accuracy can be substantially improved at the cost of higher pressure drop.

A 70-degree miter angle configuration is recommended for the reference design of the HTGR core support block (CSB). The recommended CSB height will depend on further evaluation of the possible range of variations in fuel region reactor conditions to be determined by the Systems Engineering Department. The average temperature in a rodded region (a region with control rods in the lowered position) can be measured by the temperature sensor to within a 45°F accuracy, a big improvement from an early CSB design tested by the Commissariat a La Energie Atomique at Saclay, France in 1974, 75.

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LIST OF SYMBOLS

A	flow area
BRB	bottom reflector block
CEA	Commissariat a La Energie Atomique, Saclay, France
CSB	core support block
d	diameter of channel
HTGR	high temperature gas-cooled reactor
HTGR-SC	steam cycle version of the HTGR
K	pressure loss coefficient
$\dot{m}$	flow rate
p	pressure
Δp	pressure differential
Re	Reynolds No., $Re = \rho u d / \mu$
RPF	region peaking factor
T	temperature
$\bar{T}$, T_m	mixed mean temperature
u	velocity
$u/\bar{u}$	velocity ratio referenced to mean velocity
μ	absolute viscosity
v	Cu-Co thermocouple millivolt reading
ρ	density
θ	influence coefficient $\theta = A_{ij} = (T_j - T_m) / (T_1 - T_m)$
θ'	influence coefficient $\theta' = C_{ij} = (T_j - T_c) / (T_1 - T_c)$
$\Sigma \theta'$	summation of θ' influence coefficients at a given point to simulate uniformly heated region.

Subscripts

CSB exit	CSB exit plane location
over-all	refers to CSB overall pressure drop (exit loss excluded)
sensor	CSB thermocouple spacer block (refer to Fig. 5)
sleeve	cylindrical housing in CSB for the spacer block
total	refers to CSB overall pressure drop with $K_{\text{exit}} = 0.8$ assumed
c	cold column value
$\bar{c}$	centerline value
i	hot column value
j	local value
m	mixed mean value
spacer A	data from spacer block A position (see Fig. 5)
spacer B	data from spacer block B position (see Fig. 5)

1. INTRODUCTION

1.1. GENERAL

In the HTGR core, the gas flow within the coolant holes of each fuel region is collected in larger flow channels in the bottom reflector blocks (BRB) as shown in Figure 1. The central control rod BRB flow channel is then fed horizontally to the surrounding six flow channels which coincides with the six flow channels in the upper core support block (CSB). A temperature sensor (thermocouple) is located within the CSB to measure the average exit temperature of the region coolant. The temperature sensor located at the outlet of each region in the core is used for control of the region inlet gas flow orifices. Reference 1 specifies that "the indicated temperature shall not deviate by more than 45°F from the actual region average gas exit temperature during plant power operation." Test results on a previous CSB design (Ref. 2) indicated that the design would not satisfy the criteria for the sensing error. The sensing error is presumed to result from poor thermal mixing of the column streams within the core support block (gas mixing error) and the averaging capability of the sensor itself. No analytical means are available to predict the sensor performance, necessitating this test program.

1.2. OBJECTIVE

The primary objective of this test is to optimize the CSB performance by determining the gas mixing error and CSB pressure loss of various alternative CSB designs using a scale model air flow testing technique. The test is to provide a measure of the temperature distribution at the CSB exit and on the surface of the temperature sensor sleeve. The mixing results from each alternative design are to be compared in order to determine their order of merit in flow stream mixing and pressure loss penalty.

The sensor data is to be used by the Systems Dynamics Branch of the General Atomic Company to aid in developing a computer simulation of the sensor performance at reactor conditions.

1.3. SCOPE

The tests were grouped into two distinct phases. The first phase consisted of a series of preliminary screening tests in which four basic CSB configurations were tested to determine the effects of CSB height and miter angle of converging jet streams on pressure drop and gas mixing. A final phase consisted of a more comprehensive series of tests using two of the four configurations tested in the preliminary phase. The specific objective of this CSB thermal mixing test were as follows:

1. Establish the feasibility of predicting gas mixing at the core support block (CSB) exit plane by deriving temperature influence coefficients from measured gas temperatures.
2. Determine the gas mixing characteristics of the CSB configuration for a partial fuel region (which occurs at the periphery of the core).
3. Obtain distributed temperature data for a simulated CSB temperature sensor sleeve to be used as a boundary condition to calculate sensor temperatures by the General Atomic Company Systems Dynamics Branch.

To achieve these objectives the major test data to be measured were:

1. To measure the fluid temperature distribution on the surface of the temperature sensor housing for various temperature-flow arrangements.

2. To measure temperature and flow distributions at the exit of the core support block.
3. To measure the pressure drop across the core support block and selected locations in the reflector block assembly.

During both the preliminary screening and final thermal mixing tests, a series of runs were made in which only one inlet flow was heated at a time. The results of this series were used to determine the temperature influence coefficients of the separately heated inlets upon various areas of the sensor and the CSB exit rake. (Refer to Sections 3.2 and 3.3.2. for definitions and use of these influence coefficients.)

A partial reactor power tilt was simulated during the final thermal mixing tests where three inlet streams to the model were heated simultaneously to several different temperatures. These multiple heated column tests were used to determine the extent of predictability of simulating multiple heated column conditions by superimposing the influence coefficients determined from single heated column tests.

2. DESCRIPTION OF APPARATUS

2.1. TEST MODEL

The test model consists of a one-half scale simulated core support block configuration and the lower part of the bottom reflector blocks. The six horizontal crossduct channels, which divert the central (control rod) bottom reflector block channel flow to the outer six surrounding channels, is included in the test model.

A composite sketch of the CSB test model is shown in Figure 2. The bottom reflector block (BRB) horizontal crossduct channel is shown at two different vertical positions above the CSB. The individual fuel coolant channels upstream of the horizontal crossduct channel are not simulated in this test model.

The core support block is simulated with several interchangeable sections. The upper CSB includes the six miter angle channels which merge into a single larger cavity above the temperature sensor.

The lower portion of the lower CSB includes the temperature sensor and the slightly divergent cavity which simulates the exit region of the CSB. Above the temperature sensor is a lower CSB insert. Inserts of various heights are installed here to simulate CSB's of different heights. (The relative distance between the temperature sensor and the CSB exit plane is fixed and is compatible with items such as spring packs, the peripheral seal, and lower plenum crossducts.)

There are fourteen variations of the four basic CSB test assemblies tested in the preliminary screening test phase. These variations are illustrated in Figure 3. The test parameters include four miter angle CSB

configurations (35, 52, 70, and 90-degrees), as many as three CSB heights (35, 41, and 53-in. full scale height), and, for certain CSB configurations, three positions above the CSB where the central fuel column/reflector block flow is redistributed horizontally to the outer six peripheral fuel/reflector column flows.

For the final thermal mixing test series, two CSB miter angle configurations (52 and 70-degrees) were more thoroughly tested at three different CSB heights (41, 48.8 and 53 in. full scale height).

The temperature sensor used in the preliminary screening test phase is shown in Fig. 4. It consists of 56 thermocouples on a uniform grid array where the thermocouple wires are routed through the inside of the hollow wood cylinder and maneuvered through an array of holes such that the thermocouple bead barely protrudes above the surface of the wooden sensor. This cylindrical sensor model was originally intended to be used for the final test series also, but it was discovered that much more accurate results could be obtained by using a specially designed simulated reactor CSB temperature sensor shown in Fig. 5 (which was originally designed to be used on a limited number of special tests). Due to other delays in the test program, this special sensor was fabricated in time to be compatible with the entire final test phase. The use of this sensor was to provide data to aid in determining the accuracy of the temperature sensor. The corresponding thermocouple test results were to be used by the Systems Engineering Department of General Atomic to verify their model of the reactor temperature sensor and to check the sensor error.

The final thermal mixing tests use a sensor as illustrated in Fig. 5. The sensor contains a sleeve and spacer geometrically similar to the latest proposed design sensor. The sleeve is instrumented with 28 thermocouples and the spacer is instrumented with 6 thermocouples. The thermal conductivity of the sleeve and spacer material should be as close as practical to 4.0 and 1.0 Btu/hr ft²F, respectively. This ensures the same ratio of solid conductance to gap and outer surface conductance between reactor and test conditions.

In an effort to maintain reasonable costs some sensor reactor design features are not duplicated. The thermo-well tubes in the actual sensor are not included in the test sensor. Some compromise is also made on duplicating the ratio of gas-to-solid conductances because the test will be run in air and materials with a thermal conductivity of 1-3 Btu/hr-ft-°F do not exist. (A commercially available 90% titanium-6% aluminum 4% vanadium alloy (MIL-9046 Type 3) with a thermal conductivity of about 4 Btu/hr-ft-°F is used.) Because of these compromises, the test results may not give directly the sensor error for reactor conditions. The test results will be indicative of the actual sensor error and they will be used to verify the analytical model for calculating the actual temperature sensor error.

The entire model as shown in Fig. 2 is installed on a lower plenum unit which is in turn connected to a blower system. The blower system draws air into the seven inlets (suction mode) so the pressure throughout the model and ducting are below atmospheric pressure. It had been intended to individually adjust the flow rate through the seven inlets by means of the butterfly valves indicated in Fig. 2. However, it was found that a better means of control was to partially block the inlets. This method was used during all the final phase testing. The butterfly valves were locked in position parallel to the tubes axes. The total flow rate is controlled by a single valve which is part of the permanent facility equipment.

Heated air is drawn through any of the seven inlets by connecting an inlet to an electrical heater unit by means of flexible ducting. For the preliminary test phase, only four out of the seven inlets were individually heated to obtain the necessary data during the preliminary screening tests because of symmetry considerations. For the final mixing tests, up to three inlets are heated simultaneously with two inlets heated to one temperature ($\sim 130^{\circ}\text{F}$) and the third heated to a different temperature ($\sim 150^{\circ}\text{F}$). For these multiple heated tests, a special manifold is employed to connect two inlets to one electrical heater unit and a second heater

is used for the third heated inlet. For the final mixing tests, each single column was generally heated individually so that the assumption of symmetry was not required for the major test configurations.

2.2. MODEL INSTALLATION

The test arrangement is depicted in Fig. 6. The model is shown installed on a work stand with a plenum located under the work platform. The ducting which connects the model to the blower system includes two venturis and a flow control valve. The 18 in. Simplex venturi is permanently installed in the facility ducting as is the pneumatically operated butterfly valve. Because of the size of the Simplex venturi, it can only be used with reasonable accuracy at the maximum flow rate called for in the Test Specification (Ref. 3). For all other flows, the smaller 12" BIF venturi was used to indicate total flow rate. During testing at the maximum flow rate, the BIF venturi was replaced with a straight section of pipe in order to avoid the pressure loss associated with this venturi.

Also depicted in Fig. 6 is a 100 kw electrical heater system which was used to supply heated air to selected inlets of the model. The heater blower, which is part of the system, was used when required to overcome the flow resistance of the heater and ducting. Also, depicted in Fig. 6 is the 15 kw auxiliary heater which was used when multiple inlet heated tests were specified for the final test phase. The auxiliary heater was used to supply the maximum temperature column hot streak while the 100 kw heater and blower units were used to supply the two adjacent column moderate hot streaks.

2.3. FACILITY EQUIPMENT

2.3.1. General

The experimental program was conducted in the General Atomic Company Experimental Engineering Airflow Building (Bldg 36). The model was located at the east end of the building close to the electrical heater system, which is permanent facility equipment, and also close to the inlet of the 18 in. ducts. The model was connected to the lower duct of the dual 18 in. ducts. The location of the model also allowed use of the overhead crane for installation and for making configuration changes when necessary.

The data acquisition system which is installed in the Airflow Building was used for this test program and a description of the data acquisition system is given in a following section.

2.3.2. Blowers

The primary air supply system consisted of three 250 hp Buffalo Forge blowers connected to a manifold, ducting, valves, and a venturi flowmeter. The specifications for the CSB Thermal Mixing Test (Ref. 3) require that two of the facility blowers be used in a series configuration. Each blower was rated at 14,000 scfm at 12.5 psia inlet pressure. The line from the manifold to the model consisted of an 18 in. duct containing a venturi flow meter and a butterfly valve for flow measurement and control, respectively. This manually operated valve was the primary flow control used to vary the total mass flow rate through the test model.

2.3.3. Hot Air Supply System

The main facility hot air supply system consisted of a 3 hp blower, a 100 kw heater bank, a manifold and ducting. The heater blower was rated at 5000 scfm with 2 in. H₂O pressure rise. Ambient air was inducted through the blower and discharged through the heater to the manifold. The inlet flow was controlled by a valve arrangement at the blower inlet.

The heater bank mounted directly downstream of the blower is divided into five separate sections of 5, 10, 10, 25 and 50 kw power. It was thus possible to add heat in 5 kw steps over the entire range from 0 to 100 kw.

The auxiliary heater is quite similar to the main heater system except it is smaller and does not have a booster blower mounted on its inlet.

2.4. INSTRUMENTATION AND MEASUREMENTS

2.4.1. Flow Measurements

The total model flow was measured using either the 18 in. Simplex venturi located in the facility ducting or the 12 in. BIF venturi which was connected to the outlet of the model plenum (Fig. 6). The mass flow rate is found from the equations

$$\dot{m} = c \frac{\pi}{4} d^2 \frac{Y}{\sqrt{1 - \beta^4}} \sqrt{\frac{2p_1 \Delta p}{RT_1}} \quad (1)$$

where

$$Y = \sqrt{\frac{\gamma}{\gamma - 1} r^{2/\gamma} \left(\frac{1 - r^{\gamma-1/\gamma}}{1 - r} \right) \left(\frac{1 - \beta^4}{1 - \beta^4 r^{2/\gamma}} \right)}$$

$$r = \frac{p_2}{p_1}$$

$$\beta = \frac{d}{D}$$

where values of d , D and C are given in the following Table.

In deriving the equation, it has been assumed that air is a perfect gas with $R = 53.34 \text{ ft-lb/lbm-R}$ the gas constant for air and $\gamma = 1.4$ the ratio of specific heat capacities for air.

The measured quantities are the upstream pressure and temperature p_1 and T_1 and the venturi differential pressure $\Delta p = p_1 - p_2$.

The venturi units used in the test program have the following parameters.

Venturi	TEC No.	d (in.)	D (in.)	C
18 in. Simplex	---	10.383	17.5	$0.951 + 1.9 \times 10^{-8} \text{ Re}$
12 in. BIF	73099	5.800	11.973	0.9797
3 in. BIF	73104	1.795	2.994	0.9797

The 3 in. BIF venturi was used for calibration purposes. Both BIF venturi units have the same flow coefficient, valid over the range of flows for which they were used. The Simplex venturi flow coefficient is a weak function of the throat Reynolds number.

The uncertainty factors for the venturis are estimated to be 0.25% for the 12 in. BIF, 0.75% for the 3 in. BIF and 1% for the Simplex. These are one standard deviation estimates.

The remaining flow measuring devices were located in the model inlet ducts. An orifice plate was inserted in each inlet, and these orifices were calibrated against appropriately sized venturis. (Refer to Fig. 2) The flow is found from the expression

$$\dot{m} = K \frac{\pi}{4} d^2 \sqrt{\frac{2p_1 \Delta p}{RT_1}} \quad (2)$$

with K the flow coefficient found from calibration. The measured quantities are the upstream pressure and temperature, p_1 and T_1 , and the orifice differential pressure Δp .

2.4.2. Static Pressure Measurements

The Test Specification (Ref. 3) calls for static pressure measurements at several axial planes and circumferential orientations; see Figs. 2.1-3 and 2.3-1 of Ref. 3. The locations of static taps in the model are shown in Fig. 7. The overall CSB pressure drop reported herein is measured between static tap locations 3 to 5 in Fig. 7. Note that the CSB exit expansion loss is not included since the lower plenum and other flow regions are not modeled.

All static pressure taps were 0.040 in. diameter with a depth greater than twice the diameter. The static taps were all inspected and adjusted if necessary to insure a clean, round, burr-free hole.

The estimated static pressure measurement uncertainty due to the static tap itself is the order of 0.3% of the true reading.

2.4.3. Velocity Measurements

The velocity surveys called for in the Test Specification (Ref. 3) were done with a Prandtl type pitot-static probe. The probe, a United Sensor model PDC-24-G-22-K1, has a 1/8 in. diameter sensor end which will cause a negligible blockage error at the exit of the Core Support Block and an error of about 0.1% in the inlets.

The velocity was evaluated from the equation

$$u = \sqrt{\frac{2\gamma}{\gamma - 1} RT \left[1 - \left(1 - \frac{p_t - p_s}{p_t} \right)^{\gamma-1/\gamma} \right]} \quad (3)$$

which is for compressible fluids. Measurements were: air temperature, T , total pressure, p_t , and the difference between total and static pressure, $p_t - p_s$.

2.4.4. Temperature Measurements

Thermocouples were used to measure air temperature. Seven thermocouples were inserted into the seven inlets to monitor inlet air conditions. The temperature sensor for the preliminary tests had 56 thermocouples arranged in 7 longitudinal stations and 8 circumferential locations; see Fig. 4. A thermocouple rake with 25 thermocouples was installed at the exit plane of the Core Support Block; see Fig. 8. The special simulated reactor sensor used in the final thermal mixing series, Fig. 5, had 34 thermocouples installed to measure the temperature distribution throughout the sensor. In addition to the above, thermocouples were used to measure air temperature at the venturi units.

Type T (copper-constantan) thermocouples were used for all measurements. These thermocouples were assembled by Experimental Engineering from a single batch of 24 gage, teflon insulated thermocouple wire. All thermocouples were connected to a 150°F Pace reference junction, TEC No. 67064. The air temperature was calculated from

$$T = 32.0873 + 46.6266 v - 1.31251 v^2 + 0.0573506 v^3 \quad (4)$$

which is a cubic equation fitted to the standard data over the temperature range of 60° to 220°F by the method of least squares. The equation fits the data with a standard error of 0.01°F. The limit of error for this thermocouple wire is stated to be $\pm 1-1/2^\circ\text{F}$ which is assumed to be two standard deviations.

In the above equation

$$v = v_R + v_{OR} \quad (5)$$

where v_R is the millivolt reading of a thermocouple when the reference junction is at the temperature T_R and v_{OR} is the millivolt reading of the same thermocouple sensing the temperature T_R while the reference junction is at 0°C (32°F). For example, the Pace reference junction calibration

gives $T_R=151.75^\circ\text{F}$ so $v_{OR}=2.754$ mv for type T thermocouples. The voltage was measured by the data acquisition system when the thermocouples were hooked up to the Pace reference junction. Prior to the second phase of testing, the reference junction was adjusted to give $T_R=150.0^\circ\text{F}$ and $v_{OR}=2.711$ mv.

2.4.5. Data Acquisition System

The data acquisition system (DAS) used on this test program is an integrated system which is permanently installed in the Airflow Building. A block diagram of the DAS is shown in Fig. 9.

The S-9 data logger and computer of the Non-Linear System Company is the heart of the data acquisition system. This sub-system consists of the following units:

1. NOVA model 1200 mini-computer with 8K words of memory augmented by a Plessey model PM-1216 memory board giving an additional 16K words of memory.
2. 33ASR teletype terminal (TTY) which is used for programming input and data output.
3. Multi-range A/D converter with 0.04, 0.4, 4 and 40 volt ranges.
4. Two multiplexers (cross-bar scanners) with 200 3-wire inputs of which only one was used in this test.
5. Associated displays and power supplies.

The NOVA computer is programmed using a form of the BASIC language called NLS Basic III by the manufacturer. Special programming has been built into the software to integrate the Scanivalve system into the data logging capability. Programs are maintained on paper tape. The mini-computer provides the capability for on-line data reduction but not sophisticated data analysis requiring extensive memory.

The Scanivalve sub-system consists of 5 model 64CBM-048 Scanivalves housed in a cabinet. Each Scanivalve is basically an ultra precision valve with 64 ports and extremely low leakage between ports. The valves are simultaneously actuated by a single stepping motor which drives the valves through timing pulleys. A channel coder identifies the position (port) for the stepping motor and receives its signal from the NOVA computer. Only two of the valves were used, numbers 5 and 6, and the pressure transducers were connected to these two valves in such a way that differential pressures could be measured. The differential pressures may either be the difference between two static taps on the model or one static tap and ambient pressure. The pressure taps were interconnected from the model to fittings on the exterior of the Scanivalve cabinet by means of 1/8 in. I.D. vinyl tubing.

The Druck ± 1 psid and the Statham ± 5 psid transducers were connected in parallel between Scanivalves #5 and 6. Therefore, both transducers have the same pressure signal input applied but the Statham output was used whenever the pressure was over 1 psi and the Druck output when the pressure was less than 1 psi. The Druck output signal becomes non-linear above 1 psi and eventually saturates, however, the mechanical action is not harmed with pressures up to 5 psi. By connecting the transducers in this manner, the most accurate measurement can be made over the full pressure range that can be generated by the blowers in the Airflow Building.

The signal conditioning units for the Druck and Statham transducers provide accurately regulated power to the transducers and amplification for the signal.

All thermocouples were connected to the Pace unit which provides a constant 150°F thermocouple reference junction. From the Pace, the thermocouple output voltage was fed to the S-9 data logger through regular 2-wire connectors.

3. TEST RESULTS AND DISCUSSION

3.1. GENERAL

The core support block thermal mixing test program was divided into two separate phases; (1) the preliminary screening test phase, and (2) the final thermal mixing test phase. The preliminary screening test phase cover four basic design configurations which were tested at a QAL-III level. Hence, these data should not be used directly for design purposes. For this reason, the preliminary screening test data has been placed in Appendix I. The final core support block thermal mixing test was a QAL-I level test where a more extensive test series was conducted on two basic design configurations.

3.2. PRELIMINARY SCREENING TEST PHASE

The objective of the preliminary screening test phase was to test a relatively wide range of possible CSB configurations with unheated test conditions and with relatively few, simple, single heated column tests. From these results, two CSB miter angle configurations would be re-tested thoroughly in the final thermal mixing test phase.

3.2.1. Preliminary Results and Discussion

In the preliminary screening test phase, overall CSB pressure loss coefficients

$$K_{\text{overall}} = \Delta P_{\text{overall}} \left[\frac{\dot{m}_{\text{total}}^2}{2\rho g A_{\text{CSB exit}}^2} \right] \quad (6)$$

were determined for the various CSB configurations over a range of unheated flow conditions from 1.7 lb/sec to about 6.0 lb/sec (15% reactor Re No. to 53% reactor Re No.*). Some of the tests went up to about 10 lb/sec (140% reactor Re No., or 100% reactor Re No. in a region with a region peaking factor (RPF)=1.4). As indicated in Section 2.4.2, Eq. 6 does not include the CSB exit loss. These data are shown in Tables A.1 and A.2 of the Appendix of this report. Note that the preliminary screening test data are not QAL-I level and should not be used directly for design purposes.

All of the seven column region heated tests in this preliminary screening phase were conducted at about 3.2 lbs/sec (about 28% reactor Re No.) with only one column heated. Multiple heated column tests were not conducted in this test phase. The CSB pressure loss coefficients for the heated single column tests are also shown in Tables A.2 and A.3. Corresponding pressure loss coefficients for a four-column region (assuming such regions could exist) are shown in Table A.4. For these four-column regions, three outer adjacent flow columns were blocked while the CSB was kept in an identical configuration as used in the seven-column region tests.

* Reynolds Number

A summary of selected influence coefficients on the wooden sensor model and at the CSB exit plane are shown in Tables A.5 and A.6 for the seven-column region tests, and in Table A.7 for the four-column region tests where the influence coefficient using the ambient temperature T_c , as the reference temperature is defined as

$$\theta' = C_{ij} = \frac{T_j - T_c}{T_i - T_c} \quad (7)$$

while the influence coefficient using the mixed mean temperature, T_m , as a reference is defined as

$$\theta = A_{ij} = \frac{T_j - T_m}{T_i - T_m} \quad (8)$$

The extent of thermal mixing within the CSB can be judged by noting the maximum temperature influence coefficient determined from the CSB exit plane thermocouples. Note that relatively large variations exist for the θ_c sensor for the four-column region data shown in Table A.7. The expected sensor errors resulting from these large variations are unacceptable. Also, note that in Fig. 10 the CSB exit velocity maldistribution is large for the four-column region test. One might speculate that if the CSB cavity cross-sectional area were changed from a circular shape to a truncated circle (truncated next to the flow columns that are blocked), that the sensor error might be substantially improved.

3.2.2. Adequacy of Thermal Mixing and Reactor Internals Cost Estimate

A detailed discussion of the preliminary test data is given in Ref. 4. A summary of the seven-column preliminary screening test data from A.5 is given in Table A.8, with the assumed cost information taken from Ref. 5. The data are tabulated in a generally decreasing order of thermal mixing as determined by the CSB exit plane influence coefficients. Starting from the bottom of Table A.8, the AIG influence coefficients are probably very

similar to the 35-in. high CSB tested by the CEA and reported in Ref. 2 as having insufficient thermal mixing. Test A2G is only slightly better.

As the CSB miter angle is increased to 52° for the 35 and 41-in. high CSB, the thermal mixing (as evidenced by the smaller CSB exit influence coefficients) is improved, but it is doubtful that the temperature sensor inaccuracies discussed in Ref. 2 could be reduced by a factor of at least 2. On the other hand, by moving the control rod fuel column crossduct channel upwards (further away from the CSB), the thermal mixing seems to be further improved. Also, based on a limited number of test results the B2G 52° CSB with a 53-in. high CSB appears to rate fairly high for the test configurations tested. It appears that all of the 70° and 90° miter angle CSB configurations give reasonable thermal mixing, although the 35-in.-high CSB with a 70° miter angle has less thermal mixing and higher CSB pressure drop than the 41-in.-high CSB.

Shown in the far right column of Table A.8 is the total estimated cost increase of the reactor internals (per cost estimate information in Ref. 5) compared to a 35-in.-high CSB with a 35° miter angle (similar to an old 3000 MW(t) HTGR reference design). This cost information from Table A.8 is also shown in Fig. 11 as a function of CSB pressure drop (with CSB exit loss excluded). The numbers from 1 to 14 in Fig. 11 represent the order of decreasing thermal mixing indicated in column 1 of Table A.8. For each CSB miter angle, there is a representative small range for the CSB pressure drop as indicated along the abscissa reference axis. The diagonal straight dotted lines indicate lines of constant CSB height. The test configurations (indicated by the thermal mixing order from 1 to 14) at or above the curved solid line represent configurations which appear to have good thermal mixing. The configurations below the curved dotted line have very questionable or poor thermal mixing. From Fig. 11, it is possible that a 48.8-in. high CSB with a 52° miter angle (representing the low point on the good-mixing curve) may provide adequate thermal mixing and also be approximately \$400,000 cheaper than the B2G configuration (No. 4 thermal mixing order).

The present HTGR designs already allow for a CSB height of approximately 41-in. and a maximum reactor CSB pressure drop of 1.5 psi. This associated cost of \$2.5 million is shown in Fig. 11 (data pts. 5, 6, and 7). Thus, any adjusted total costs falling below this value represents a potential cost savings.

There are three other factors involved in the selection of the optimum core support block configuration in addition to pressure drop, CSB height and thermal mixing considerations. These are: (1) the feasibility (and possibility of increased costs) to manufacture a 70-degree miter angle core support block, (2) the probability for increased erosion (if any) in the block as the miter angle is increased, and (3) the uncertainty of whether a further increase in CSB height is practical.

The present 40.94-in. CSB height would be acceptable from the thermal mixing point of view if the reference reactor CSB design were changed to include 70-degree miter angle flow channels in the CSB. In prior estimates of CSB pressure drop, it was assumed that the maximum pressure drop is $\Delta p_{\max} = 1.5$ psi (Ref. 5). Test uncertainties could raise the actual maximum CSB pressure drop to 1.8 psi.

It is anticipated that a 52-degree miter angle CSB with a 48.8-in. height is acceptable with respect to mixing and at a reduced CSB pressure drop of close to 1.0 psi. If the Change Request listed in Ref. 6 is approved, then it may be possible to achieve this CSB increase without needing an additional core cavity height increase if the radiation shielding immediately above the CSB can be moved upwards by 1/4 of a standard fuel block height. A substantial cost savings of over \$0.8 million could result from decreased pressure drop by using the 52-degree miter angle/48.8-in. high CSB.

3.2.3. Summary of Results from the Preliminary Screening Test Data

The results of the preliminary screening tests show the following:

1. The CSB pressure loss coefficients range from $1.2 < \bar{K}_{\text{overall}} < 5.5$ for CSB miter angle configurations ranging from 35 to 90-degrees, respectively. (Note that $\bar{K}_{\text{overall}}$ does not include the CSB exit loss to the lower plenum.) Otherwise, the CSB pressure loss coefficients presented herein are conservative, in that they actually include part of the reflector block.
2. The influence coefficients indicate several CSB configurations give acceptable mixing for seven-column regions (refer to Fig. 11).
3. Relatively large variations in temperature sensor influence coefficients were measured for the four-column regions when the same CSB was used as for the seven-column regions (3 flow passages blocked).
4. Increased mixing resulted from the following:
 - a. Increased CSB height.
 - b. Increased miter angle within the CSB.
 - c. Increased height between the temperature sensor and the reflector block horizontal cross-over channel.

3.2.4. Summary of Conclusions From Preliminary Screening Test Data

1. Conservatively assuming that the exit loss is $K_{\text{exit}} = 0.8$, the CSB pressure drop, ΔP , (excluding the bottom reflector block ΔP) will probably be a maximum of 1.0 to 1.8 psi (based on a maximum HTGR-SC region flow rate, $\dot{m} \approx 50$ lbs/sec), depending on whether a 52 or a 70-degree miter angle CSB is finally selected.

2. Influence coefficients which are comparable to or better than the values suggested by G. Niblock in Ref. 7 were measured for the first 10 CSB/Reflector Block configurations listed in Table 2. However, they may not all be acceptable since no guideline exists for reducing hot streaks within the CSB.
3. To avoid large potential errors in sensor measurement, the partial fuel regions must have a special CSB with a reduced cavity size or modified shape to help guide flow uniformly over the temperature sensor.
4. The best cost optimized configuration with good mixing appears to be the 53-in. high CSB with a 52-degree miter angle. A close second choice is the 41-in. high CSB with a 70-degree miter angle.
5. There is reason to hope that the most optimized version could be a 48.8-in. high CSB with a 52-degree miter angle.

3.2.5. Recommendations for Final Thermal Mixing Test Phase

It was recommended that the following be implemented into the final thermal mixing test phase of the test program:

1. The 48.8-in. high CSB with a 52-degree miter angle be thoroughly tested along with several other promising candidates (both 52 and 70-degree miter angle CSB's only).
2. To avoid fabricating new parts, rearrange the sequence of the tests so that the tests with the largest insert blocks are run first, then the inserts can be cut down to a different size for the remainder of the tests.
3. The lower CSB cavity must be redesigned for partial fuel regions to reduce large potential sensor errors.

3.3 FINAL CSB THERMAL MIXING TEST PHASE

3.3.1. General

For the final thermal mixing test phase the designation used for the CSB Configuration/Test No. is demonstrated in the following example:

7AX53(1) - 20

7 - No. of active fuel columns in a region.

A - CSB miter angle configuration;

A = 52 degree miter angle,

B = 70 degree miter angle.

X - Reflector block horizontal crossduct channel location (full scale); X = 12.69-in. above CSB, Z = 18.58-in. above CSB.

53 - Approximate full-scale CSB height, in.

(1) - Heated column no.

-20 - Sequential test run no.

Note that the simulated temperature sensor model shown in Fig. 5 was used for all of these final phase tests.

3.3.2. Temperature Sensor Test Model

The sensor temperature data from the preliminary screening test was originally to be given to the Systems Dynamics Branch to help develop a computer model for predicting sensor accuracy. Influence coefficients were not originally expected to be useful on the sensor surface since Ref. 2 reported difficulty in trying to apply the CEA test data. More recently, however, the Systems Dynamics Branch has gone back to the original CEA test data and found that superposition of single heated column results on the sensor were fairly good, e.g., $\sum_i \theta'_{i,j} \approx 1.0 \pm 0.12$ for each sensor thermocouple location. A check of the preliminary screening test data (assuming symmetry for the unheated single columns) showed that superposition of this data give values of $\sum \theta'$ as low as 0.28.

At this point (between the preliminary screening and the final test phases) some checks were made to ascertain whether or not the large discrepancies in the current summation of influence coefficients could be due to not reaching steady state conditions. Figure 12 shows the rapid increase and leveling-off of the region inlet temperature and the corresponding response in several selected sensor locations at the sensor surface. Several modifications were made to expose the thermocouples by lifting them about 1/16 in. to improve the response of this wooden sensor. This attempt made only a slight improvement.

Meanwhile, as the preliminary screening test phase was being completed, the Systems Dynamics Branch had a detailed simulated temperature sensor block fabricated from a special titanium alloy (as shown in Fig. 5). This sensor was designed to be used on a relatively few tests to help gather data to verify a computer model of the sensor.

Since this latter simulated sensor (Fig. 5) was already fabricated, it was also tested to determine its response to a rapid increase in temperature. The results are shown in Fig. 13. A large improvement is noted when compared to the wooden sensor response of Fig. 12. Within 30 minutes of turning on the heater, the upper centerline temperature appears to have reached a steady state (about 6°F below the heated air inlet temperature) while the lower centerline temperature is only 2°F below the upper centerline temperature. (Note that for the wooden sensor in Fig. 12, after 60 minutes (twice as long) the upper centerline temperature, T_{72} , was still increasing and was 10°F below the heated air temperature, while the lower centerline temperature was 8°F below T_{72} .)

These two sensor response tests were conducted using the permanent auxiliary heater/blower and thus the flow rates involved were lower than the flow rates used for most of the preliminary screening and final test runs. The temperature response shown in Fig. 13 for the titanium simulated sensor merely indicates that it is superior to the wooden sensor response (Fig. 12) in reaching a steady state condition in about 30 minutes for a relatively low flow rate. At higher flow rates, the response time should be even shorter.

The decision was then made to use the titanium simulated sensor for all of the final thermal mixing tests. As a result of using this sensor the superposition of the single heated columns was greatly improved and the accuracy was comparable to the CEA results which the Systems Dynamics Branch reviewed.

A summary of the summation of selected influence coefficients from the final thermal mixing test phase is tabulated in Table 1. These influence coefficient summations are based on unmodified test data. Note that the seven column region test data, $\Sigma\theta'$, for the spacer block locations (last two columns of Table 1) are consistently close to the ideal value of 1.0. The five column region data is not as close to 1.0 for the spacer block largely because of more difficulties encountered in trying to get a steady state condition. The spacer block data was not originally intended to be used for superposition of individual heated jet data, but the data in Table 1 implies that the method can be used (with some modifications described below) for the seven-column region test data and with less accurate results for the five-column region test data.

Under reactor conditions, for the same CSB configuration tested herein, the temperature sensor sleeve and CSB exit plane influence coefficients should be the same as the test results reported herein. This is largely due to the fact that the convective heat transfer coefficient in both the test and reactor conditions on the outer surface of the temperature sensor sleeve is large. Thus, differences in gas and surface temperatures will be small since the thermal resistance between the gas and the surface is small.

For the test, the cylindrical spacer block rests essentially along a line contact at the bottom inside surface of the sleeve as indicated in Fig. 5. An air gap exists between the sleeve and the spacer at all other boundaries of the spacer block. This air gap serves as a relatively large thermal resistance in the test model. Under reactor conditions, this gap will be filled with helium which will have a much higher thermal conductivity (than ambient air) and hence a smaller thermal resistance. This factor is

accounted for in the selection of the simulated sensor sleeve and spacer block material by the Systems Dynamics Branch of General Atomic Company. For test and reactor similarity, the thermal conductivity of the sleeve and spacer material should be as close as practical to 2.7 and 1.3 Btu/hr ft°F, respectively. This ensures the same ratio of solid conductance to gap and outer surface conductance between reactor and test conditions. The material selected for the simulated sensor sleeve and spacer block has a thermal conductivity of about 4 Btu/hr ft°F. Therefore, the air test results on the sensor spacer block can not be used directly for predicting exact reactor sensor results, but should prove valuable in checking out the computer thermal model of the sensor.

A typical distribution of the summation of influence coefficients $\Sigma\theta'$, is shown in Fig. 14. The maximum $\Delta\theta'$ on the sensor sleeve occurs at the centermost upstream position, while the minimum values are located on the downstream side of the end-most locations. In the immediate vicinity of the sensor sleeve (the three center-most columns on Fig. 14), the $\Sigma\theta'$ values are in good agreement with a range of $0.94 \leq \Sigma\theta' \leq 1.18$. At the CSB exit plane, $0.92 \leq \Sigma\theta' \leq 1.14$. In general, the range of values of $\Sigma\theta'$ at the CSB exit plane is smaller (more predictable) than the values of $\Sigma\theta'$ at the temperature sensor sleeve and spacer blocks as indicated in Table 1.

3.3.3. Seven-Column Region - Single Heated Columns

A summary of important temperature influence coefficients and overall CSB pressure loss coefficients for the single heated column is given in Tables 2 through 5 for the final test phase. Some of the test runs (e.g., shown in Table 5) represent not-quite steady state conditions, especially in the thermocouples mounted in the spacer. The objectives of this part of the test program (the single heated column tests) did not include obtaining spacer thermal data. Since the sensor data were recorded anyhow the results are tabulated even though the spacer block may not always have reached steady state.

A summary of some selected maximum influence coefficients for the 52-degree miter angle CSB is tabulated in Table 2. The maximum θ' influence coefficient (refer to Eq. 7 where θ' is referenced to the cold column temperature) is shown for the sensor and CSB exit plane positions. The maximum value of $\theta'_{\text{CSB exit}}$ is indicative of the amount of thermal mixing taking place within the CSB. A comparison of $\theta'_{\text{sens max}}$ to $\theta'_{\text{CSB exit}}$ gives an indication of which flow column most directly impinges onto the sensor sleeve. From Table 2, hot streaks originating from columns 2, 3, 5, and 6 (see Fig. 2 for relative location) apparently do not impinge directly onto the sensor sleeve as evidenced by the significantly lower values of θ' at the sensor location as compared to that for the CSB exit plane. Also to be noted in Table 2 is that in general the maximum values of $\theta'_{\text{CSB exit}}$ get smaller (indicating greater mixing) as the CSB height is increased.

Maximum and minimum values of $\theta_{\text{E sleeve}}$ (θ is defined in Eq. 8 and is referenced to the mixed mean temperature) are also shown in Table 2. (These values are at or near steady state, since the test procedure included monitoring the sensor sleeve temperatures to ensure steady state values.) Test No. 7AX53(7)-15 indicates that $\theta_{\text{E sleeve/max}} = 0.266$. This means that if column 7 initially had a hot streak of 100°F above the mixed mean average and all of the other columns were uniform in temperature, then the maximum centerline sleeve surface temperature would be 26.6°F above the mixed mean temperature. The simulated sensor spacer block indicates that from $\theta_{\text{E spacer A}} = 0.226$ there could be a 22.6°F sensing error for an initial 100°F column 7 hot streak. Refer to station 1 Fig. 5 for the location of this reading. This is a relatively large sensing error which should be carefully considered.

Similar data is shown in Table 3 for the 70-degree miter angle CSB. Here, single heated column tests were conducted for each individual flow column for each of three CSB heights. Because of the steeper convergence angle which causes opposite jets to impinge more directly than for the 52-degree miter angle CSB, the temperatures of the flows from columns 2 and 5 can be seen to be more readily sensed by the sensor sleeve. The thermal mixing within the 70-degree CSB is better than that for the 52-degree CSB,

with the mixing improving as the CSB height is increased (as evidenced by values of $\theta'_{\text{CSB exit/max}}$).

Because of some relatively large differences in $\theta'_{\text{sens max}}$ and $\theta'_{\text{CSB exit max}}$, one might draw the conclusion that relatively large errors might exit when the hot streak is concentrated in columns 2, 3, 5 or 6. However, when one examines the values at $\theta_{\text{E sleeve max/min}}$ or $\theta_{\text{E spacer A/B}}$ in Tables 2 and 3, the error is less than 13 percent of the difference between the maximum CSB inlet and the true mixed mean temperatures. Thus, an original column 2, 3, 5 or 6 hot streak of $(T_{\text{max CSB inlet}} - \bar{T}) = 100^\circ\text{F}$ would result in an error of less than 13°F (no uncertainties included in this estimate). Generally, from these four columns, the measured temperature will be lower than the true mixed mean temperature. The opposite is generally true for hot streaks emanating from columns 4 and 7 where the indicated mixed mean temperature is higher than the true mixed mean temperature.

When one compares the 52-degree and the 70-degree miter angle CSB results for $\theta_{\text{E spacer}}$, errors up to 30% may occur in the $T_{\text{max}} - \bar{T}$ readings for the tests tabulated in Table 2 (52-degree CSB) while the maximum error shown in Table 3 (70-degree CSB) is 14 percent.

The influence coefficients along the centerline of the sleeve and spacer block are all generally smaller than the θ_{E} 's for the 52-degree CSB. Thus, the temperature sensor should be more accurate for the 70-degree CSB. From the test data in Table 3 the largest sensor error due to a single column hot streak of 100°F above the mixed mean temperature is 13.2°F for test 7BX48(4)-113. Similarly, if the initial column hot streak was 200°F above the mixed mean temperature, then the expected error could be 26.4°F . From past experience in looking at column temperatures, a hot streak in one column is generally followed by a relatively cold column on the opposite side of the same region; hence, some of the sensing error tends to negate itself. This observation should be confirmed by the Systems Engineering Department when the CSB influence coefficient data is used in the COLUMN and PLENUM computer codes.

Influence coefficient test data for the 70-degree miter angle CSB are shown in Figs. 15a through 15g for the 41-in. high CSB, and in Figs. 16a through 16g for the 48.8-in. high CSB.

The discussions have been concentrated around the maximum values of influence coefficients either in the temperature sleeve and block or at the CSB exit plane. Furthermore, only single heated column flows have been discussed in this section thus far. The reader is reminded here that the location of the maximum influence coefficient is different for each heated column. As the mixing improves, the maximum influence coefficient gets smaller, but the presence of the hot streak is also more broad. Thus for a given location which originally was affected only by one particular heated column for a CSB with poor mixing, better mixing may cause that same location to be affected by other heated columns. It may be possible that the combined effect of multiple heated columns is not significantly different between a CSB configuration which promotes poor mixing, and one which promotes good mixing. This will not be determined until the data is actually used by the Systems Engineering Department for various realistic reactor conditions.

Other miscellaneous seven-column region test results are shown in Table 4. Some of these test results were conducted while the spacer block temperatures were still changing, some were conducted at different total flow rates, and some were taken where the heated column flow rate was either increased or decreased from the nominal specified flow rate. These results indicate that

1. There is no obvious Reynolds Number (Re No.) effect on the influence coefficients or pressure loss coefficient due to flow rate variation for a fuel region in the range of 15 to 44 percent reactor Re No.
2. As a single column heated flow increases relative to the remaining column flow rates, the maximum influence coefficients also increases. This effect is more prominent on the sensor sleeve than at the CSB exit plane

3. The sensor sleeve temperatures reach a steady state value much faster than the spacer block located inside the sleeve.

3.3.4. 5-Column Region - Single Heated Columns

Comparable selected influence coefficients are summarized in Table 5 for five-column regions representative of some peripheral core regions in an HTGR. Note that the CSB cavity shape for these regions has been changed from a circular cross-sectional area to the shape shown in Fig. 17. This change in shape for the five-column tests was a result of poor sensing accuracy indicated by the four-column tests conducted in the preliminary screening test phase of this program. With the circular cross-sectional area used in the preliminary test phase, large velocity maldistributions occurred as indicated in Fig. 10. A velocity ratio of $u/\bar{u} = 1.0$ would represent a local velocity equal to the average velocity through the CSB cavity. Note that the velocity distribution varies from 0.05 to 2.39 for this configuration.

Figure 18 shows the velocity distribution for a five-column region using the CSB cavity cross-sectional area shown in Fig. 17. The flow distribution is seen to be much more uniform than in Fig. 10 with a minimum and maximum velocity ratio of 0.62 and 1.16, respectively in the free flow area. The baffle plate used in the simulated CSB cavity was intended to provide a simple modification which would cause a minimal effect on the flow paths of the active flow columns (compared to a seven-column region), e.g. one-third of the flow area is removed from the CSB cavity region by the baffle to conform with two blocked flow passages out of six in a normal full CSB region.

Because the baffle was inserted in an attempt to make the flow pattern for the five-column CSB similar to the flow pattern for the seven-column region, the influence coefficients are expected to be much closer to that for the seven-column region test results than for the four-column region test results shown in Table A.5 in the Appendix. The summary of selected influence coefficients given in Table 5 verifies this expectation. Note,

however, that the influence coefficients for the spacer are also higher (a maximum of $\theta_{\text{spacer A}} = 0.215$) thus the greatest sensor inaccuracies may be expected to occur in partial regions. Since there are only six such regions in a medium size HTGR it may be beneficial to lower the average temperature from these regions by slightly over-cooling them. The sensor accuracies under reactor conditions will have to be checked out with actual expected reactor conditions by the Systems Engineering Department.

The pressure loss coefficients given in Table 5 for the 5-column region are approximately 30 percent higher than those for the 7-column region given in Tables 2 and 3. This fact must be accounted for in the design and operation of the HTGR. The additional pressure drop in these 5-column regions may hinder the ability to always over-cool these regions.

3.3.5. Multiple-Heated Column Tests

In addition to having an extensive single heated column test series in the final thermal mixing test phase, a number of multiple heated column tests were also conducted. The purpose of these tests was to provide experimental data for some simulated region power tilts and to see how close superimposed single heated column results would match with these data. It should be pointed out here that the only influence coefficients which can be superimposed and satisfy the boundary conditions for superposition are the θ' values defined in Eq. 7.

Selected values of influence coefficients determined from the multiple-heated 7-column tests are shown in Table 6. The predicted values of θ' are also shown based on the superposition of the corresponding single heated column results. The predicted results are based on the actual test data, i.e., the data has not been made symmetric (e.g., $\theta'_6 = \theta'_3$) nor normalized (e.g., $\sum \theta'_i = 1.0$).

The most accurate values of θ' in Table 6 should be $\theta'_{\text{sens. max.}}$ and $\theta'_{\text{CSB exit max.}}$. Some of the predicted values of $\theta'_{\text{E spacer}}$ may be lower than experimentally measured due to the possibility that steady state for the sensor spacer may not have reached for each single heated column test. (Note that the original objectives of this test program did not include measurement of this data.) Nevertheless, in many cases the agreement between experimental and predicted results is good. Not only are the maximum values well predicted, but Figs. 19 through 22 show that the distributions are well predicted. In Figs. 19 through 22, the experimental multiple heated test results for several 5 and 7-column regions are shown on a computer printout with the superimposed single hot streak predictions written above the test data. Other predictions are contained in the calculation file for this report. In all cases the predicted distributions are similar to the experimental values.

An indication of the temperature sensor error may be deduced by studying the "max" and "min" values of $\theta_{\text{E sleeve}}$ in Tables 6 and 7. In general, the 7A-series (52-degree miter angle CSB) has a larger mixed mean temperature error than the 7B-series (70-degree miter angle, as evidenced by the values of $\theta_{\text{E sleeve}}$ of $|\theta_{\text{E sleeve}}| \approx 0.22$ (an error of 22°F for an initial hot streak of $T_{\text{max}} - \bar{T} = 100^\circ\text{F}$). Although the value of $\theta_{\text{E spacer}}$ in the last two columns of Tables 6 and 7 indicate better agreement with the true mixed mean temperature, it should be remembered that the test material used for the simulated sleeve and spacer block could not exactly duplicate the reactor thermal sensor thermal conductivity in a helium environment so that the test model $\theta_{\text{E spacer}}$ data should not be used directly. These values of $\theta_{\text{E spacer}}$ are mainly useful in checking out the computer code model used to simulate the temperature sensor.

The reader is reminded at this point that as discussed in Section 3.3.3, cold streaks usually exist in the opposite side of the 7-column fuel region. The multiple heated 7-column tests described herein only contain half of the normal region power tilt. If the "cold" streaks were also included, the tendency would be to improve the accuracy of the temperature sensor.

Based on the relatively good agreement in the summation of all single heated column flow results and the multi-heated column test predictions with experimental results, one may conclude that this superposition technique could be applied satisfactorily to a computer program to predict the reactor CSB temperature sensor sleeve and spacer block temperatures. One may want to make the data symmetrical and perhaps normalized, but this is not done in this report.

4. CONCLUSIONS

Conclusions which can be drawn from the final test phase results are as follows:

1. The multiple heated columns test results can be reasonably predicted from the single column heated jet test data. This good correlation occurs both at the CSB exit plane and along the temperature sensor sleeve.
2. The thermal mixing and the CSB pressure drop for the 52 and 70-degree miter angle CSB configurations have been quantified. The thermal mixing data for the 52-degree miter angle CSB was not as good as indicated by the preliminary screening test phase.
3. The accuracy of the temperature sensor for a five-column region can be greatly improved when the 19 in. diameter circular cross-sectional area is modified to the truncated circular shape as shown in Fig. 17. With this cavity shape modification, the sensor accuracy for these peripheral fuel regions is expected to meet the design criteria specified in Ref. 1.

5. RECOMMENDATIONS

As a result of the CSB thermal mixing test program, the following recommendations are made:

1. The recommended CSB configuration should have a 70-degree miter angle to ensure good thermal mixing and adequate temperature sensor accuracy. Although the 48.8-in. high CSB has better mixing than the 41 in. high CSB, further application of the test data may show that both designs will satisfy the temperature sensing accuracy requirements. If so, the 41 in. CSB will be less expensive.
2. General use of the influence coefficients and pressure loss coefficients should have an uncertainty of ± 10 percent added to the test data. The temperature sensor sleeve data should prove extremely useful for current and subsequent sensor spacer block designs by providing good estimates of reactor boundary conditions for a thermal model of the temperature sensor.
3. A pressure loss coefficient of $K=3.8$ should be used for the 70-degree miter angle CSB, excluding the CSB exit loss, or $K = 4.6$ if one assumes an exit loss of $K_{\text{exit}}=0.8$. These loss coefficients are based on the CSB exit flow area and should be used in design analyses.

6. REFERENCES

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3. Hussmann, C., and E. Chin, "Specification for Core Support Block Thermal Mixing Test, General Atomic Company, unpublished data, May 13, 1977.
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5. Brown, S. J., "Core Cavity Redesign Study - Final Report," General Atomic Company, unpublished data, July 5, 1977.
6. Brown, S. J., "Increase in Core Cavity Height," General Atomic Company, unpublished data, February 9, 1977.
7. Niblock, G. A., "Lead Plant Core Support/Reflector Block Estimated Influence Coefficients for Gas Mixing," General Atomic Company, unpublished data, September 3, 1976.

Figure 1. Typical Core Support Block and Bottom Reflector Block Assembly

Figure 2. Core Support Block Mixing Test Model

A, B, C & D indicate different upper CSB miter angles.
 G indicates the lower CSB which includes the temp. sensor
 1 & 2 indicate different heights of the insert block in the CSB
 3 & 4 indicate different heights of the BRB crossduct channel

FIGURE 3
Test Configuration Schematic

FIGURE 4 - Thermocouple Layout for Temperature Sensor

Figure 5. Simulated Reactor Temperature Sensor Model

Figure 6. Test Arrangement

No. Static Pressure TAP

- ① Orifice upstream
- ② Orifice downstream
- ③ Crossover upstream
- ④ Crossover downstream
- ⑤ CSB outlet

Figure 7. CSB Static Pressure TAP Locations

PRELIMINARY TEST
PHASE ORIENTATION
OF PRINTED OUTPUT

FINAL TEST PHASE
ORIENTATION OF
PRINTED OUTPUT

Figure 8. CSB Exit Plane Thermocouple Rake

FIGURE 9- Data Acquisition System (DAS) Block Diagram

Preliminary Test No. 127
 CSB Configuration: B1G
 Columns 5, 6 & 7 blocked
 Flow Rate: 4.3 lbs/sec

Figure 10. Normalized Velocity Traverse at a 4-Column Region
 CSB Exit Plane with Circular Flow Area

Figure 11. Estimated Cost Optimization of CSB Configurations

Figure 12. Transient Response of Wooden Sensor

Figure 13. Transient Response of Titanium Simulated Sensor

Sleeve	{	.878	.946	.996	.950	.843	 Bottom
		.935	1.006	1.054	.998	.887	
		1.045	1.127	1.179	1.124	.998	 Top
		.916	1.013	1.066	1.012	.891	
		.878	.946	.996	.950	.843	 Bottom

Spacer Block	{			.954		
				.972	 Top of Spacer	
				.959		
		.938	.971	.934	 Spacer axis	

Temperature Sensor Sleeve and Spacer Block

				.953		
	.952					.964
				1.005		
		.989			.997	
				1.078		<u>CSB Exit Plane</u>
			1.074		1.077	
.971	1.011	1.069	1.140	1.046	.990	.971
			1.075		1.040	
				1.094		
		.995			.949	Test Configuration 7B x 48
				.988		
	.931					.923
				.934		

Figure 14. Example of Summation of Influence Coefficients

TEST NO.: INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

.0735	.1054	.109	.0836	.0443
.0863	.1203	.1294	.1035	.0553
.1049	.1398	.1488	.1276	.0795
.0817	.1194	.1289	.1076	.0667
.0735	.1054	.109	.0836	.0443

SENSOR

			.1067			
			.1081			
			.1076			
		.0967	.1103	.1054		
			.0663			
	.0745				.0507	
			.0758			
		.0799		.0626		
			.0976			
		.0999	.0876			
.0749	.0881	.1035	.1117	.0781	.0571	.0489
			.099	.0804		
			.0967			
	.0813			.0599		
			.0745			
.0635				.0544		
			.0635			

Figure 15a. θ' Influence Coefficients for Run 7BZ41(1) - 36

TEST NO.:

INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

.0074	.0849	.1723	.2047	.153
.0013	.0478	.1213	.1144	.0817
.0167	.0673	.1883	.2056	.1443
.0046	.0664	.2229	.2761	.2311
.0074	.0849	.1723	.2047	.153

SENSOR

			.125			
			.1466			
			.1393			
		.1043	.1264	.1622		
			.0204			
	.0162				.0534	
			.0325			
	.0246			.0798		
			.0817			
		.0706		.1494		
.0209	.0372	.0798	.2443	.2847	.2334	.1865
		.1112	.4015			
			.2525			
	.0622			.4403		
		.2248				
.0353				.4354		
		.1887				

Figure 15b. 0' Influence Coefficients for Run 7BZ41(2) - 37
60

TEST NO.: INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

.052	.0843	.0664	.0187	-.0089
.0205	.0538	.0516	.0119	-.0048
.0421	.0942	.1009	.0439	.0146
.0475	.1201	.1201	.0417	.0002
.052	.0843	.0664	.0187	-.0089

SENSOR

			.048			
			.0498			
			.0615			
		.0489	.0597	.0385		
			.0151			
	.0394				.0146	
			.0205			
	.0349			.02		
			.0448			
		.0597	.0493			
.1206	.1228	.1513	.1655	.0861	.0412	.025
		.3069	.2323			
			.3722			
	.3383			.1872		
		.4616				
.3418				.1411		
		.5143				

Figure 15c. θ' Influence Coefficients for Run 7BZ41(3) - 38

TEST NO.:

INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

.5202	.3066	.1368	.0198	-.0157
.4859	.3146	.0958	.0115	-.0087
.6097	.4053	.1278	.0289	.008
.6289	.4257	.1265	.0171	-.0074
.5202	.3066	.1368	.0198	-.0157

SENSOR

			.2226			
			.2106			
			.2123			
	.2765	.2421	.145			
			.0359			
.3159			.0402		.0045	
	.2097		.0585		.008	
		.1386	.0228			
.4793	.3994	.2918	.0915	.0163	.0049	.0023
		.2922	.0359			
		.1429				
	.3622		.0167			
		.1265				
.381					.0119	
		.1144				

Figure 15d. θ' Influence Coefficients for Run 7BZ41(4) - 39

TEST NO.: INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

.1653	.1775	.0892	.0147	-.0159
.2606	.2761	.1278	.0231	-.0075
.174	.223	.1204	.0342	.0081
.1033	.1322	.0752	.0121	-.0088
.1653	.1775	.0892	.0147	-.0159

SENSOR

			.1287			
			.1103			
			.1116			
		.1361	.1169	.0831		
			.2993			
	.4308				.0571	
			.2761			
		.4544		.0633		
			.2438			
		.3744		.0774		
.1979	.2554	.2666	.1199	.0298	.016	.0147
		.123		.0227		
			.0545			
	.0813			.0085		
		.024				
.0474				.0098		
			.0147			

Figure 15e. θ' Influence Coefficients for Run 7BZ41(5) - 40

TEST NO.: INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

.0007	.0589	.0867	.0649	.0378
.002	.064	.1469	.0991	.0352
.0132	.0558	.1128	.0704	.0317
-.0037	.0309	.0631	.0322	.0084
.0007	.0589	.0867	.0649	.0378

SENSOR

			.0769			
			.0717			
			.0704			
	.0627	.07		.0709		
			.425			
.0692					.406	
			.4205			
	.1473			.3763		
			.3593			
		.2298		.3107		
.0218	.0503	.0991	.1601	.1414	.1431	.1533
		.0533		.0391		
			.0365			
	.0218			.0227		
			.0097			
.0058					.0296	
			.0045			

Figure 15f. θ' Influence Coefficients for Run 7BZ41(6) - 41

-.0098	.0655	.2106	.3774	.5421
-.0085	.0379	.2363	.4623	.6534
.0074	.0446	.2286	.444	.6282
-.0077	.0317	.1844	.3448	.4896
-.0098	.0655	.2106	.3774	.5421

SENSOR

			.1684			
			.2061			
			.168			
	.1218	.1622	.2607			
			.0638			
.0129					.3384	
		.0978				
	.025			.3299		
		.1478				
	.0767	.3118				
.0099	.0208	.0496	.177	.3328	.4404	.5007
		.048	.1717			
		.0783				
	.0216		.2257			
		.04				
.0074				.3005		
		.0258				

Figure 15g. θ' Influence Coefficients for Run 7BZ41(7) - 42

TEST NO.:

INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

.0654	.0894	.1061	.0948	.0649
.0742	.108	.1257	.1134	.0791
.0938	.1286	.1452	.1315	.0924
.0781	.1105	.1257	.1115	.0737
.0654	.0894	.1061	.0948	.0649

SENSOR

			.0997			
			.1002			
			.1012			
	.0889	.1027	.0987			
			.0732			
.0708					.0747	
		.0845				
.0811				.085		
		.1022				
		.1002	.1051			
.0806	.088	.1002	.1129	.0933	.0821	.0757
		.1036	.088			
		.1041				
	.0884			.0683		
		.0845				
.0772					.0649	
			.0762			

Figure 16a. θ' Influence Coefficients for Run 7B x 48(1) - 106

TEST NO.:

INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

.0007	.0327	.1151	.1828	.202
.003	.034	.1168	.1635	.1637
.0194	.0552	.1623	.2401	.2397
.0052	.0464	.1689	.2537	.2699
.0007	.0327	.1151	.1828	.202

SENSOR

.0786

.0913

.0883

.0552 .0817 .1221

.0172

.0083

.068

.03

.0172

.0883

.0663

.046

.1405

.0189

.0296

.0539

.1702

.2665

.2527

.2224

.1142

.3643

.2509

.0777

.4043

.2704

.0495

.3972

.2721

Figure 16b. θ' Influence Coefficients for Run 7B x 48 (2) - 111

TEST NO.: INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

.0816	.1017	.1075	.0713	.0214
.0461	.0794	.1004	.0637	.0214
.0699	.116	.1397	.0906	.038
.0365	.1339	.1463	.0897	.0236
.0816	.1017	.1075	.0713	.0214

SENSOR

			.087			
			.0861			
			.0986			
		.0794	.0977	.0356		
			.0164			
	.0362				.0227	
			.0281			
		.0416		.0353		
			.061			
			.0807	.0704		
.1512	.1645	.181	.181	.0964	.0565	.0376
			.3282	.1898		
			.3352			
	.3704			.1574		
			.3951			
.3387				.1196		
			.4172			

Figure 16c. θ' Influence Coefficients for Run 7B x 48(3) - 112
68

TEST NO.: INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

.4222	.3589	.2263	.0998	.0127
.3998	.3269	.1876	.0723	.0132
.4547	.3798	.2147	.082	.0238
.4689	.3933	.2039	.0769	.0123
.4222	.3589	.2263	.0998	.0127

SENSOR

			.2434			
			.2293			
			.2463			
		.2703	.2612	.1721		
			.0345			
	.2084				.0149	
			.0523			
	.1813			.0294		
			.0964			
		.1909	.0642			
.4157	.388	.3302	.1834	.0515	.023	.0132
		.3075	.0612			
		.1704				
	.3466		.0243			
		.1203				
.381				.0136		
		.0993				

Figure 16d. θ' Influence Coefficients for Run 7B x 48(4) - 113

TEST NO.:

INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

.2934	.2925	.2209	.1182	.0189
.3877	.364	.2498	.1129	.0233
.3584	.3355	.2363	.1072	.0296
.2603	.259	.1854	.0323	.0126
.2934	.2925	.2209	.1182	.0189

SENSOR

			.2253			
			.2003			
			.2161			
	.2332	.2201	.1519			
			.2594			
.4534					.0694	
		.2895				
	.4457			.1005		
		.313				
	.4015	.1563				
.2695	.2312	.2943	.2319	.0336	.043	.03
		.1336	.056			
		.0841				
	.0787		.0121			
		.0251				
.0639				.0053		
		.0076				

Figure 16e. Influence Coefficients for Run 7B x 48(5) - 114

TEST NO.: INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

.0142	.0359	.077	.0934	.0844
.022	.0563	.1124	.1253	.1003
.0307	.0539	.1042	.1098	.0779
.0133	.0337	.0706	.0736	.0506
.0142	.0359	.077	.0934	.0844

SENSOR

			.0783			
			.0809			
			.0719			
		.0654	.0727	.0779		
			.4352			
	.1592				.3489	
			.3973			
	.195			.325		
			.3115			
		.1935		.2643		
.0281	.0446	.0744	.1233	.1382	.1412	.1523
			.0359	.0553		
			.0433			
	.0111			.0355		
			.0172			
.0046					.0407	
			.0107			

Figure 16f. θ' Influence Coefficients for Run 7B x 48(6) - 115

TEST NO.: INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

-.0015	.0346	.1432	.2895	.4386
.0024	.0377	.1614	.342	.4852
.0179	.0527	.1766	.3628	.497
.0033	.0364	.1601	.3194	.4436
-.0015	.0346	.1432	.2895	.4386

SENSOR

.1419

.1831

.1362

.1257 .1345 .2255

.117

.0152

.3658

.1232

.0272

.3335

.1275

.0566 .2762

.0069 .0152 .0346 .1327 .3164 .3917 .4394

.047 .225

.1057

.0219

.247

.0751

.0103

.2809

.0566

Figure 16g. θ' Influence Coefficients for Run 7B x 48(7) - 119

Note: The blocked-off section of the cavity may also be in other positions relative to the temperature sensor, e.g., columns 3 and 4 may be blocked in one section of the reactor core.

Figure 17. 5 Column Region CSB Mixing Cavity

Figure 18. Normalized Velocity Traverse at 5-Column Region CSB Exit Plane with Modified Flow Area

TEST NO.: INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)
 7BX48(3,2,4)-110

(.330)	(.331)	(.308)	(.237)	(.147)
.3255	.3305	.3021	.2377	.1492
(.282)	(.291)	(.279)	(.205)	(.125)
.2808	.2914	.2741	.2011	.1254
(.348)	(.371)	(.361)	(.279)	(.193)
.3377	.3567	.3361	.2556	.1797
(.364)	(.392)	(.368)	(.286)	(.194)
.3639	.385	.3483	.2724	.191
(.330)	(.331)	(.308)	(.237)	(.147)
.3255	.3305	.3021	.2377	.1492

SENSOR

(.276)

.273

(.274)

.2707

(.295)

.2898

(.270)

.2629

(.299)

.2943

(.258)

.2534

(xxx)

predicted values

xxxx

test data values

(.047)

.0486

(.163)

.1565

(.076)

.0754

(.071)

.0726

(.158)

.1514

(.156)

.1469

(.104)

.1061

(.220)

.2067

(.190)

.187

(.406)

.4082

(.409)

.4077

(.406)

.3966

(.388)

.3678

(.283)

.2763

(.218)

.2191

(.176)

.1786

(.575)

.565

(.439)

.4375

(.619)

.6293

(.582)

.5704

(.409)

.4232

(.591)

.6195

(.624)

.6439

(.360)

.3778

(.635)

.6721

Figure 19. Multiple Heated Column Test Results and Predictions / 7B x 48(3,2,4) - 110

TEST NO.:
7BX48(7,2,6)-109

INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)

(.010)	(.079)	(.269)	(.470)	(.626)
.0182	.1049	.3039	.5162	.6674
(.019)	(.097)	(.311)	(.534)	(.658)
.023	.1097	.3364	.5607	.6917
(.051)	(.127)	(.351)	(.591)	(.704)
.0396	.1191	.348	.5858	.7131
(.015)	(.089)	(.317)	(.536)	(.653)
.0206	.099	.3242	.5402	.6714
(.010)	(.079)	(.269)	(.470)	(.626)
.0182	.1049	.3039	.5162	.6674

SENSOR

	(.244)	
	.2455	
	(.296)	
	.2835	
	(.241)	
	.2496	
(.185)	(.235)	(.356)
.181	.2426	.3637

(xxx) predicted values
xxxx test data values

(.412)
.3868

(.125)
.1262

(.402)
.3903

(.638)
.6623

(.166)
.1681

(.374)
.3827

(.603)
.6335

(.216)
.2186

(.541)
.5698

(.038)
.0444

(.064)
.0658

(.118)
.1197

(.328)
.3352

(.581)
.6085

(.649)
.6832

(.684)
.7193

(.145)
.1386

(.499)
.4967

(.080)
.0747

(.298)
.2736

(.526)
.5407

(.046)
.0474

(.263)
.2461

(.567)
.5806

(.241)
.2356

Figure 20. Multiple Heated Column Test Results and Predictions/7B x 48(7,2,6) - 109

TEST NO.: INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)
 58X48(2,3,7)-129

(.288)	(.404)	(.440)	(.451)
.289	.4047	.456	.4794
(.302)	(.394)	(.429)	(.435)
.2906	.3763	.4272	.4565
(.399)	(.480)	(.525)	(.525)
.3704	.4464	.507	.5409
(.377)	(.472)	(.515)	(.522)
.365	.4556	.5197	.5499
(.288)	(.404)	(.440)	(.451)
.289	.4047	.456	.4794

SENSOR

	(.328)	
	.3457	
	(.344)	
	.3618	
	(.348)	
	.3629	
(.321)	(.335)	(.305)
.3392	.3489	.3274

(xxx) predicted values
 xxxxx test data values

(.211)
 .2054

(.256) (.283)
 .2462 .2982

(.331) (.314)
 .3123 .3236
 (.405) (.390)
 .3768 .33

(.515) (.495) (.475) (.468)
 .5006 .5012 .4911 .4889

(.540) (.606)
 .5271 .6131

(.532) (.598) (.618)
 .524 .5995 .6452

(.600) (.597)
 .6173 .6362

(.583)
 .6105

TEST NO.: INFLUENCE COEFFICIENTS (AMB. TEMP. REF.)
 58X48(7,2,6)-127

(.301)	(.485)	(.597)	(.635)
.3115	.506	.6311	.6816
(.324)	(.515)	(.634)	(.676)
.3292	.513	.6531	.7178
(.344)	(.543)	(.675)	(.702)
.3524	.5355	.6737	.7402
(.282)	(.482)	(.605)	(.641)
.2999	.4946	.6275	.6875
(.301)	(.485)	(.597)	(.635)
.3115	.506	.6311	.6816

SENSOR

	(.414)	
	.4343	
	(.434)	
	.4543	
	(.410)	
	.4313	
(.390)	(.389)	(.395)
.4076	.4082	.4161

(xxx) predicted values
 xxxxx test data values

(.585)
 .6055

(.578) (637)
 .5923 .6911

(.566) (.644)
 .5774 .6875
 (.490) (.643)
 .4934 .6614

(.520) (.650) (.673) (.690)
 .5239 .6703 .7112 .7331

(.312) (.535)
 .3177 .5714

(.399)
 (.247) .4107 (.552)
 .2583 .578

(.329)
 .3299 (.575)
 .6132

(.289)
 .2816

Figure 22. Multiple Heated Column Test Results and Predictions/5B x 48(7,2,6) - 127

TABLE 1
SUMMARY OF SELECTED INFLUENCE COEFFICIENT SUMMATION, $\sum \theta_i$

CSB Config	Flow Rate (lb/sec)	Press. Loss Coeff. $K_{overall}$	θ'_{sens} max/min (C_{ij})	$\theta'_{CSBexit}$ max/min (C_{ij})	$\theta'_{\bar{E}}$ sleeve max (A_{ij})	$\theta'_{\bar{E}}$ sleeve min (A_{ij})	$\theta'_{\bar{E}}$ spacer A* (A_{ij})	$\theta'_{\bar{E}}$ spacer B* (A_{ij})
7AX53	5.	2.34 $\pm$ 0.05	1.141/0.920	1.093/0.917	1.141	1.037	1.073	1.074
7BX53	5.	3.56 $\pm$ 0.09	1.130/0.869	1.076/0.884	1.130	1.011	0.953	0.970
7AZ41	5.	2.29 $\pm$ 0.06	1.129/0.857	1.158/0.908	1.129	0.997	1.045	1.080
7BZ41	5.	3.69 $\pm$ 0.09	1.028/0.777	1.070/0.882	1.028	0.871	0.871	0.888
7AX48	5.	2.13 $\pm$ 0.12	1.119/0.834	1.101/0.941	1.119	1.012	1.003	1.009
7BX48	5.	3.57 $\pm$ 0.08	1.179/0.843	1.140/0.923	1.179	0.996	0.959	0.971
5AX53	3.5	2.89 $\pm$ 0.03	0.989/0.874	1.033/0.954	0.988	0.905	0.840	0.838
5BX53	3.5	4.39 $\pm$ 0.07	1.046/0.882	1.031/0.888	1.046	0.920	0.825	0.819
5BZ41	3.5	4.81 $\pm$ 0.17	1.095/0.831	1.097/0.935	1.043	0.907	0.840	0.847
5AX48	3.5	2.76 $\pm$ 0.06	1.023/0.867	1.052/0.928	1.023	0.897	0.766	0.759
5BX48	3.5	4.35 $\pm$ 0.11	1.082/0.742	1.072/0.934	1.082	0.882	0.740	0.720

*Refer to Figure 5 for locations A and B.

TABLE 2
SUMMARY OF SELECTED INFLUENCE COEFFICIENTS/52° MITER ANGLE

CSB Config/ Test No.	Flow Rate (lb/sec)	Press. Loss Coeff. Koverall	θ'_{sens} max (Cij)	$\theta_{CSBexit}$ max (Cij)	θ_E sleeve max (Aij)	θ_E sleeve min (Aij)	θ_E spacer A (Aij)	θ_E spacer B (Aij)
7AX53(1)-20	5.11	2.39	0.162	0.133	0.082	0.042	0.046	0.045
7AX53(2)-24	5.09	2.41	0.276	0.577	-0.026	-0.074	-0.042	-0.045
7AX53(3)-18	5.15	2.27	0.163	0.570	-0.021	-0.072	-0.069	-0.067
7AX53(4)-12	5.15	2.39	0.548	0.513	-0.041	-0.064	-0.031	-0.005
7AX53(5)-13	5.12	2.27	0.218	0.518	-0.050	-0.079	-0.052	-0.046
7AX53(6)-10	5.11	2.34	0.117	0.502	-0.037	-0.073	-0.078	-0.081
7AX53(7)-15	5.12	2.33	0.656	0.501	0.266	0.225	0.226	0.204
7AX48(1)-86	4.86	2.22	0.163	0.131	0.084	0.047	0.037	0.037
7AX48(2)-87	4.84	2.32	0.205	0.551	-0.008	-0.054	-0.059	-0.067
7AX48(3)-88	4.81	2.18	0.129	0.544	-0.025	-0.077	-0.072	-0.077
7AX48(4)-91	4.98	2.01	0.624	0.549	0.103	0.048	0.135	0.165
7AX48(5)-92	5.00	2.00	0.258	0.552	0.027	-0.031	-0.021	-0.021
7AX48(6)-93	4.94	1.97	0.120	0.560	-0.033	-0.083	-0.096	-0.101
7AX48(7)-90	4.97	2.18	0.627	0.526	0.079	0.055	0.092	0.087
7AZ41(1)-121	4.99	2.40	0.163	0.150	0.085	0.044	0.005	0.007
7AZ41(2)-122	4.90	2.28	0.173	0.522	-0.057	-0.115	-0.121	-0.127
7AZ41(3)-123	4.91	2.26	0.146	0.504	-0.008	-0.102	-0.103	-0.114
7AZ41(4)-124	4.92	2.23	0.771	0.663	0.162	0.069	0.262	0.292

TABLE 3
SUMMARY OF SELECTED INFLUENCE COEFFICIENTS/70° MITER ANGLE

CSB Config/ Test No.	Flow Rate (lb/sec)	Press. Loss Coeff. Koverall	θ'_{sens} max (Cij)	$\theta'_{CSBexit}$ max (Cij)	θ_{ϵ} sleeve max (Aij)	θ_{ϵ} sleeve min (Aij)	θ_{ϵ} spacer A (Aij)	θ_{ϵ} spacer B (Aij)
7BX53(1)-26	5.03	3.76	0.150	0.123	0.069	0.029	0.019	0.022
7BX53(2)-27	4.99	3.45	0.308	0.396	0.073	0.011	-0.019	-0.029
7BX53(3)-28	4.96	3.49	0.112	0.414	-0.062	-0.105	-0.095	-0.091
7BX53(4)-29	4.99	3.54	0.449	0.417	0.019	-0.021	0.055	0.075
7BX53(5)-30	5.02	3.57	0.311	0.413	0.023	-0.026	0.021	0.031
7BX53(6)-31	4.96	3.60	0.154	0.391	-0.001	-0.063	-0.068	-0.067
7BX53(7)-32	4.94	3.52	0.454	0.384	0.090	0.069	0.023	0.015
		3.56 ± 0.09						
7BX48(1)-106	4.96	3.48	0.145	0.113	0.064	0.021	0.016	0.018
7BX48(2)-111	5.06	3.53	0.270	0.405	0.016	-0.048	-0.080	-0.088
7BX48(3)-112	4.95	3.53	0.146	0.417	-0.006	-0.061	-0.063	-0.064
7BX48(4)-113	4.92	3.60	0.469	0.416	0.091	0.045	0.114	0.132
7BX48(5)-114	4.92	3.56	0.388	0.453	0.113	0.036	0.073	0.077
7BX48(6)-115	4.92	3.74	0.125	0.435	-0.043	-0.092	-0.090	-0.089
7BX48(7)-119	4.81	3.58	0.497	0.439	0.029	-0.011	-0.019	-0.021
		3.57 ± 0.08						
7BZ41(1)-36	5.15	3.86	0.149	0.112	0.067	0.024	0.022	0.025
7BZ41(2)-37	5.05	3.56	0.276	0.440	0.082	-0.038	-0.017	-0.032
7BZ41(3)-38	5.05	3.68	0.120	0.514	-0.042	-0.123	-0.111	-0.113
7BZ41(4)-39	5.06	3.64	0.629	0.479	-0.014	-0.062	0.075	0.110
7BZ41(5)-40	5.06	3.76	0.276	0.454	-0.025	-0.086	-0.044	-0.037
7BZ41(6)-41	5.07	3.69	0.147	0.425	-0.003	-0.102	-0.093	-0.094
7BZ41(7)-42	5.03	3.62	0.653	0.501	0.103	0.042	0.023	0.016
		3.69 ± 0.09						

TABLE 4
SUMMARY OF MISCELLANEOUS SELECTED INFLUENCE COEFFICIENTS

CSB Config/ Test No.	Heated Column Flow Ratio $\dot{m}_i/\dot{m}_{total}$	Flow Rate (lb/sec)	Press. Loss Coeff. Koverall	θ'_{sens} max (Cij)	$\theta'_{CSBexit}$ max (Cij)	θ_E sleeve max (Aij)	θ_E sleeve min (Aij)	θ_E spacer A (Aij)	θ_E spacer B (Aij)
7AX53(1)-6	0.085	6.28	2.35	0.150	0.129	0.072	0.023	0.011	0.010
7AX53(2)-7	0.155	6.23	2.23	0.324	0.564	-0.047	-0.090	-0.059	-0.066
7AX53(3)-9	0.150	6.46	2.24	0.103	0.543	-0.080	-0.118	-0.114	-0.112
7AX53(2)-16	0.155	5.13	2.38	0.283	0.566	0.019	-0.031	0.054	0.046
7AX53(2)-25	0.152	5.07	2.40	0.281	0.518	-0.004	-0.053	-0.002	-0.007
7AX53(4)-11	0.154	5.18	2.42	0.571	0.568	-0.050	-0.081	-0.082	-0.050
7AX53(7)-14	0.154	5.11	2.29	0.653	0.521	0.220	0.191	0.090	0.067
7AX48(7)-89	0.164	5.15	2.08	0.659	0.514	0.195	0.156	0.151	0.134
7AX48(1)-99	0.086	1.75	2.20	0.162	0.144	0.082	0.061	0.054	0.055
7AX48(2)-100	0.152	1.74	2.21	0.187	0.525	-0.018	-0.060	-0.060	-0.067
7AX48(3)-102	0.149	1.74	2.14	0.128	0.545	-0.024	-0.066	-0.045	-0.049
7AX48(4)-101	0.153	1.74	2.19	0.609	0.526	0.138	0.089	0.161	0.188
7BZ41(1)-48	0.086	1.71	3.75	0.148	0.130	0.068	0.046	0.032	0.034
7BZ41(2)-49	0.151	1.70	3.52	0.301	0.429	0.078	-0.008	0.001	-0.014
7BZ41(3)-50	0.154	1.75	3.64	0.134	0.478	-0.023	-0.101	-0.071	-0.073
7BZ41(4)-51	0.155	1.75	3.77	0.630	0.495	0.021	-0.023	0.061	0.095
7BZ41(4)-52	0.172	1.76	3.76	0.676	0.514	0.073	0.013	0.094	0.129
7BZ41(4)-53	0.142	1.77	3.53	0.575	0.462	-0.025	-0.060	0.026	0.057
7BZ41(1)-143	0.076	4.81	4.05	0.119	0.098	0.047	0.005	-0.003	-0.004
7BZ41(1)-144	0.094	4.86	4.09	0.147	0.129	0.058	0.014	0.003	0.002
7BZ41(2)-147	0.133	5.03	3.64	0.190	0.429	-0.032	-0.087	-0.075	-0.080
7BZ41(2)-148	0.175	5.12	3.66	0.372	0.452	0.140	0.007	-0.044	-0.066
7BZ41(3)-149	0.174	5.07	3.60	0.197	0.505	0.029	-0.093	-0.059	-0.071

TABLE 5
SUMMARY OF SELECTED INFLUENCE COEFFICIENTS/5-COLUMN REGIONS

CSB Config/ Test No.	Flow Rate (lb/sec)	Press. Loss Coeff. Koverall	θ_{sens}^{max} (Cij)	$\theta_{CSBexit}^{max}$ (Cij)	$\theta_{\epsilon}^{sleeve max}$ (Aij)	$\theta_{\epsilon}^{sleeve min}$ (Aij)	$\theta_{\epsilon}^{spacer A}$ (Aij)	$\theta_{\epsilon}^{spacer B}$ (Aij)
5AX53(1)-65	3.42	2.92	0.184	0.170	0.058	0.012	-0.013	-0.012
5AX53(2)-66	3.44	2.87	0.266	0.516	-0.021	-0.094	-0.037	-0.042
5AX53(3)-67	3.39	2.92	0.234	0.630	-0.109	-0.169	-0.176	-0.166
5AX53(6)-68	3.39	2.90	0.217	0.523	0.0	-0.098	-0.134	-0.131
5AX53(7)-69	3.42	2.83	0.576	0.431	0.169	0.110	0.165	0.153
		2.89 $\pm$ 0.03						
5AX48(1)-135	3.51	2.88	0.194	0.195	0.079	0.027	-0.001	-0.004
5AX48(2)-136	3.51	2.77	0.181	0.493	-0.057	-0.151	-0.118	-0.127
5AX48(3)-137	3.46	2.72	0.301	0.601	-0.010	-0.121	-0.143	-0.140
5AX48(6)-139	3.51	2.71	0.196	0.504	-0.027	-0.141	-0.163	-0.164
5AX48(7)-138	3.53	2.74	0.642	0.498	0.175	0.110	0.149	0.136
		2.76 $\pm$ 0.06						
5BX53(1)-57	3.46	4.53	0.177	0.154	0.062	0.016	-0.006	-0.005
5BX53(2)-58	3.46	4.37	0.336	0.389	0.061	-0.003	0.014	-0.001
5BX53(3)-60	3.46	4.33	0.286	0.461	-0.039	-0.115	-0.156	-0.146
5BX53(6)-61	3.48	4.36	0.281	0.549	0.012	-0.084	-0.118	-0.112
5BX53(7)-62	3.50	4.37	0.424	0.370	0.033	-0.023	0.038	0.029
		4.39 $\pm$ 0.07						
5BX48(1)-130	3.60	4.50	0.181	0.155	0.064	0.013	-0.004	-0.007
5BX48(2)-131	3.58	4.27	0.259	0.386	-0.027	-0.101	-0.102	-0.114
5BX48(3)-132	3.56	4.26	0.363	0.554	0.004	-0.091	-0.129	-0.118
5BX48(6)-133	3.49	4.26	0.234	0.552	0.021	-0.100	-0.132	-0.136
5BX48(7)-134	3.49	4.46	0.493	0.421	0.088	0.063	0.029	0.013
		4.35 $\pm$ 0.11						
5BZ41(1)-72	3.50	4.99	0.168	0.149	0.044	-0.011	-0.036	-0.035
5BZ41(2)-73	3.49	4.91	0.265	0.467	0.015	-0.037	-0.036	-0.053
5BZ41(3)-74	3.42	4.84	0.374	0.476	-0.124	-0.197	-0.188	-0.149
5BZ41(6)-75	3.45	4.81	0.292	0.645	0.022	-0.158	-0.166	-0.159
5BZ41(7)-77	3.47	4.48	0.667	0.441	0.202	0.122	0.215	0.200
		4.81 $\pm$ 0.17						

TABLE 6
SUMMARY OF MULTIPLE-HEATED COL. INFLUENCE COEFFICIENTS/7-COLUMN REGIONS

CSB Config./ Test No.	Flow Rate (lb/sec)	Press. Loss Coeff. Koverall	θ_{sens}^{max} (Cij)	$\theta_{CSBexit}^{max}$ (Cij)	$\theta_{\epsilon}^{spacer}$ A (Cij)	$\theta_{\epsilon}^{spacer}$ B (Cij)	$\theta_{\epsilon}^{sleeve}$ max (Aij)	$\theta_{\epsilon}^{sleeve}$ min (Aij)	$\theta_{\epsilon}^{spacer}$ A (Aij)	$\theta_{\epsilon}^{spacer}$ B (Aij)
7AX53(2,7,6)-23	4.74	2.33	0.819	0.784	0.492	0.466	0.283	0.235	0.195	0.152
	Prediction		(0.852)	(0.773)	(0.540)	(0.515)				
7BX53(7,2,6)-33	4.77	3.52	0.776	0.733	0.399	0.382	0.226	0.191	0.068	0.042
	Prediction		(0.704)	(0.655)	(0.325)	(0.313)				
7BX53(3,2,4)-34	4.79	3.49	0.369	0.666	0.251	0.261	-0.068	-0.166	-0.121	-0.107
	Prediction		(0.369)	(0.614)	(0.272)	(0.280)				
7BX53(3,2,4)-35	4.82	3.51	0.370	0.664	0.230	0.239	-0.103	-0.200	-0.144	-0.131
7AX48(7,2,6)-95	5.01	2.06	0.787	0.781	0.351	0.340	0.057	0.006	0.011	-0.005
	Prediction		(0.750)	(0.728)	(0.336)	(0.325)				
7AX48(7,2,6)-103	1.52	2.18	0.713	0.707	0.265	0.256	0.048	-0.015	-0.052	-0.065
	Prediction		(0.719)	(0.678)	(0.312)	(0.302)				
7AX48(3,2,4)-98	4.94	2.08	0.424	0.749	0.271	0.276	-0.044	-0.161	-0.101	-0.094
	Prediction		(0.433)	(0.762)	(0.319)	(0.327)				
7BX48(7,2,6)-109	4.87	3.49	0.713	0.719	0.250	0.243	-0.006	-0.074	-0.158	-0.169
	Prediction		(0.704)	(0.684)	(0.241)	(0.235)				
7BX48(3,2,4)-110	4.89	3.52	0.385	0.672	0.290	0.295	0.032	-0.078	-0.055	-0.047
	Prediction		(0.392)	(0.635)	(0.295)	(0.299)				
7BX48(6,2,7)-107	4.87	3.51	0.522	0.654	0.216	0.212	-0.051	-0.111	-0.176	-0.184
	Prediction		(0.558)	(0.614)	(0.208)	(0.204)				

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TABLE 6 (Continued)

CSB Config./ Test No.	Flow Rate (lb/sec)	Press. Loss Coeff. Koverall	$\theta'_{\text{sens max}}$ (Cij)	$\theta'_{\text{CSBexit max}}$ (Cij)	$\theta'_{\text{E spacer A}}$ (Cij)	$\theta'_{\text{E spacer B}}$ (Aij)	$\theta_{\text{E sleeve max}}$ (Aij)	$\theta_{\text{E sleeve min}}$ (Aij)	$\theta_{\text{E spacer A}}$ (Aij)	$\theta_{\text{E spacer B}}$ (Aij)
7AZ41(7,2,6)-125	5.02	2.37	0.817	0.801	0.255	0.251	-0.079	-0.151	-0.146	-0.151
	Prediction (Modified)		(0.822)	(0.809)	(0.447)	(0.460)				
7BZ41(3,2,4)-43	4.85	3.76	0.445	0.717	0.263	0.273	-0.034	-0.223	-0.100	-0.086
	Prediction		(0.440)	(0.694)	(0.273)	(0.283)				
7BZ41(7,2,6)-44	4.85	3.56	0.821	0.753	0.403	0.383	0.223	0.149	0.106	0.076
	Prediction		(0.731)	(0.702)	(0.292)	(0.278)				
7BZ41(7,2,6)-46	1.55	3.47	0.820	0.767	0.406	0.387	0.212	0.149	0.100	0.072

TABLE 7
SUMMARY OF MULTIPLE-HEATED COL. INFLUENCE COEFFICIENTS/5-COLUMN REGIONS

CSB Config./ Test No.	Flow Rate (lb/sec)	Press. Loss Coeff. Koverall	θ_{sens}^{max} (Cij)	$\theta_{CSBexit}^{max}$ (Cij)	θ_{E}^{spacer} A (Cij)	θ_{E}^{spacer} B (Cij)	θ_{E}^{sleeve} max (Aij)	θ_{E}^{sleeve} min (Aij)	θ_{E}^{spacer} A (Aij)	θ_{E}^{spacer} B (Aij)
5AX53(7,2,6)-71	3.43	2.86	0.771	0.415	0.571	0.562	0.159	0.063	0.145	0.126
	Prediction		(0.744)	(0.428)	(0.545)	(0.536)				
5AX53(2,3,7)-70	3.43	2.81	0.714	0.844	0.576	0.569	0.081	-0.101	0.047	0.031
	Prediction		(0.682)	(0.795)	(0.528)	(0.523)				
5BX53(7,2,6)-64	3.48	4.37	0.725	0.722	0.534	0.523	0.081	0.003	0.040	0.016
	Prediction		(0.696)	(0.677)	(0.496)	(0.484)				
5BX53(2,3,7)-63	3.48	4.39	0.696	0.767	0.550	0.539	0.072	-0.081	-0.014	-0.040
	Prediction		(0.664)	(0.669)	(0.503)	(0.490)				
5AX48(7,2,6)-142	3.55	2.76	0.803	0.783	0.492	0.477	0.124	0.001	-0.003	-0.032
	Prediction		(0.756)	(0.732)	(0.472)	(0.457)				
5AX48(2,3,7)-141	3.43	2.76	0.514	0.701	0.362	0.346	0.015	-0.105	-0.179	-0.208
	Prediction		(0.503)	(0.682)	(0.369)	(0.358)				
5BX48(7,2,6)-127	3.42	4.23	0.740	0.733	0.431	0.408	0.063	-0.020	-0.148	-0.194
	Prediction		(0.702)	(0.690)	(0.410)	(0.389)				
5BX48(2,3,7)-129	3.53	4.21	0.550	0.645	0.363	0.349	-0.007	-0.159	-0.185	-0.211
	Prediction		(0.525)	(0.618)	(0.348)	(0.335)				
5BZ41(7,2,6)-81	3.47	4.39	0.827	0.772	0.610	0.588	0.227	0.094	0.179	0.133
	Prediction		(0.771)	(0.730)	(0.588)	(0.572)				
5BZ41(2,3,7)-79	3.45	4.32	0.625	0.725	0.500	0.491	0.087	-0.168	-0.002	-0.021
	Prediction		(0.602)	(0.769)	(0.498)	(0.496)				

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APPENDIX A
PRELIMINARY SCREENING TEST DATA
(Not QAL-I level)

This data not to be used directly for design purposes.

TABLE A-1
PRELIMINARY PRESSURE LOSS COEFFICIENTS FROM HIGH FLOW TESTS
USING LARGE VENTURI METER

Test Run No.	CSB Config.	Flow Rate (lb/sec)		K_{overall}	Comments
		$\dot{\Sigma}_{\text{minlet}}$	$\dot{m}_{\text{outlet}}$		
1.1	B1G	4.715	5.027	2.014	+ indicates questionable tests due to T/C problems
1.2		4.706	5.025	2.068	
1.3		4.734	5.011	1.971	
2.2		5.800	6.605	1.810 +	
2.3		5.789	6.581	1.855 +	
2.4		5.879	6.627	1.925 +	
3.1		7.578	7.894	2.074	
4.1		9.801	10.026	2.088	
5.	B1G	9.840	10.117	2.066	
				$\bar{K} = 1.986, \sigma = 0.097$	
7.0	C1G	4.624	4.927	3.355	
7.1		4.728	4.959	3.470	
8.0		5.698	6.036	3.290	
8.1		5.761	6.030	3.354	
9.0		7.395	7.804	3.007	
10.0		7.395	7.829	2.987	
11.0		8.960	9.332	3.051	
11.1		8.973	9.343	3.024	
12.0	C1G	8.968	9.264	3.357	
				$\bar{K} = 3.211, \sigma = 0.179$	
13.0	D1G	4.663	5.327	5.651	4.330 K based on $\dot{\Sigma}_{\text{minlet}}$
13.1		4.699	5.336	5.546	4.301
14.0		5.759	6.539	5.442	4.221
14.1		5.740	6.507	5.441	4.234
15.0		7.446	8.384	5.244	4.136
15.1		7.462	8.356	5.277	4.208
16.0		8.541	9.475	5.043	4.098
17.0	D1G	8.544	9.484	5.091	4.132
				$\bar{K} = 5.342, \sigma = 0.201$	

TABLE A-1 (Continued)

Test Run No.	CSB Config.	Flow Rate (lb/sec)		K _{overall}	Comments
		Σ _{m_{inlet}} [•]	m _{outlet} [•]		
19.0	A2G	4.847	5.098	1.416	K based on Σ _{m_{inlet}} [•] ↓
20.0	↓	5.880	6.158	1.392	
21.0	↓	7.602	7.910	1.394	
22.0	↓	9.842	10.014	1.433	
23.0	↓	9.830	9.972	1.416	
24.0	A2G	10.297	10.376	1.381	
				1.360	
K̄ = 1.405, σ = 0.018					

TABLE A-2
PRELIMINARY PRESSURE LOSS COEFFICIENTS FOR LOW FLOW TESTS
USING SMALL VENTURI METER

Test Run No.	CSB Config.	Flow Rate (lb/sec)		Heated Col. Temp. (°F)	T _{avg. in} (°F)	T _{avg. out} (°F)	T _{avg. Rake} (°F)	K _{overall arith. avg.}
		$\dot{m}_{inlet}$	$\dot{m}_{outlet}$					
25	B1G ↓	6.272	6.346					2.083
26		5.520	5.545					2.117
27		4.451	4.494					2.086
28		2.406	2.420					2.109
29		1.709	1.699					2.061
29.1		1.73	1.73					2.117
30.		3.145	3.200					2.037
31.		3.217	3.225					2.113
31.1		3.220	3.238					2.068
31.2		3.177	3.248	T ₁ = 200.3	84.5	83.5	84.5	2.164
32.0		3.165	3.163	T ₂ = 184.3	89.3	89.9	90.8	2.135
33.		3.165	3.173	T ₃ = 159.3	85.3	85.3	86.7	2.100
33.1		3.125	3.216					2.115
33.2		3.178	3.162	T ₃ = 180.8	89.2	89.3	90.9	2.024
34.		3.126	3.105	T ₄ = 164.1	90.1	90.4	90.8	2.041
34.1	B1G	3.142	3.146	T ₄ = 182.6	89.5	89.3	91.2	2.097
35	BG ↓	5.467	5.581					2.451
36		4.231	4.362					2.506
37		3.209	3.254					2.444
37.1		3.070	3.173					2.428
38		2.370	2.388					2.441
39		1.668	1.686					2.397
40		3.153	3.206	T ₃ = 181.1	90.4	91.8	90.1	2.460
40.1		2.768	2.802	T ₄ = 189.7	93.7	93.3	97.1	2.377
41		3.174	3.272	T ₁ = 170.4	79.7	78.0	78.2	2.505
42		3.173	3.247	T ₄ = 177.1	87.3	86.8	90.9	2.380
43	BG	3.187	3.237	T ₂ = 176.9	88.3	90.1	93.1	2.319

TABLE A-2 (Continued)

Test Run No.	CSB Config.	Flow Rate (lb/sec)		Heated Col. Temp. (°F)	T _{avg.} in (°F)	T _{avg.} out (°F)	T _{avg.} Rake (°F)	K _{overall} arith. avg.
		$\dot{m}_{inlet}$	$\dot{m}_{outlet}$					
44	B2G ↓	5.512	5.648					2.008
45		4.423	4.608					2.120
46		3.195	3.298					2.099
47		2.448	2.517					2.078
48		1.743	1.785					2.040
49		6.955	7.132					2.074
50		3.185	3.266	T ₃ = 176.3	90.4	90.9	91.4	2.091
51		3.202	3.269	T ₄ = 177.0	90.7	90.4	92.5	2.067
52		3.120	3.210	T ₂ = 183.6	88.9	90.3	93.8	2.035
53	B2G	3.110	3.210	T ₁ = 176.0	85.1	84.2	84.4	2.104
54	C1G ↓	3.143	3.246					3.583
55		2.421	2.503					3.651
56		1.707	1.749					3.580
57		4.411	4.649					3.754
58		5.552	5.783					3.753
59		6.639	6.944					3.693
60		3.119	3.226					3.646
61		3.155	3.313	T ₁ = 203.1	89.6	87.9	88.3	3.651
62		3.173	3.282	T ₂ = 191.7	97.5	98.8	101.2	3.576
63	C1G ↓	3.146	3.246	T ₃ = 197.9	104.1	105.2	107.3	3.606
64		3.119	3.256	T ₄ = 200.7	107.6	107.5	108.8	3.628
65	CG ↓	6.437	6.785					4.273
66		5.608	5.887					4.412
67		4.342	4.571					4.439
68		3.098	3.238					4.318
69		2.396	2.488					4.100
70		1.719	1.769					3.963
71		3.168	3.288	T ₁ = 179.8	87.1	86.3	85.9	4.276
72		3.151	3.258	T ₂ = 189.7	98.4	100.3	105.6	4.068
73		3.127	3.251	T ₃ = 194.9	100.6	101.3	102.0	4.293
74	CG	3.150	3.245	T ₄ = 194.0	100.3	100.3	100.3	4.047

TABLE A-2 (Continued)

Test Run No.	CSB Config.	Flow Rate (lb/sec)		Heated Col. Temp. (°F)	T _{avg. in} (°F)	T _{avg. out} (°F)	T _{avg. Rake} (°F)	K _{overall} Arith. Avg.
		$\dot{m}_{inlet}$	$\dot{m}_{outlet}$					
75	C2G	6.487	6.829					3.608
76	↓	5.322	5.651					3.741
77		4.286	4.543					3.690
78		3.122	3.273					3.572
79		2.412	2.488					3.500
80		1.658	1.721					3.559
81		3.086	3.253	T ₁ = 179.1	82.1	81.0	81.1	3.570
82		3.106	3.234	T ₂ = 186.9	91.4	92.8	97.4	3.690
83	↓	3.102	3.218	T ₃ = 202.9	95.5	96.6	99.2	3.606
84	C2G	3.073	3.201	T ₄ = 208.4	99.6	98.6	101.5	3.617
85	D1G	3.054	3.244					4.665
86	↓	6.303	6.717					4.729
87		5.295	5.678					4.787
88		4.189	4.510					4.658
89		3.004	3.214					4.617
90		2.329	2.471					4.658
91		1.649	1.740					4.563
92		3.024	3.206	T ₁ = 197.6	85.3	83.7	83.6	4.622
93		3.082	3.232	T ₂ = 201.7	93.5	95.1	100.8	4.575
94	↓	3.064	3.240	T ₃ = 196.4	92.9	94.6	97.8	4.620
95	D1G	3.009	3.212	T ₄ = 200.7	85.9	84.7	86.4	4.717
96	DG	6.143	6.579					5.506
97	↓	5.220	5.606					5.562
98		4.248	4.583					5.340
99		3.076	3.259					5.437
100		2.401	2.492					5.251
101		1.678	1.748					5.422
102		3.080	3.278	T ₁ = 180.4	78.7	76.3	77.9	5.446
103	↓	3.046	3.186	T ₂ = 201.8	99.8	101.3	108.1	5.450
104	DG	3.046	3.233	T ₃ = 200.0	103.3	103.5	104.3	5.444

TABLE A-2 (Continued)

Test Run No.	CSB Config.	Flow Rate (lb/sec)		Heated Col. Temp. (°F)	T _{avg.} in (°F)	T _{avg.} out (°F)	T _{avg.} Rake (°F)	K _{overall} Arith. Avg.
		$\dot{m}_{inlet}$	$\dot{m}_{outlet}$					
105	DG	3.063	3.211	T ₄ = 201.1	104.8	104.4	104.5	5.325
106	A2G ↓	3.060	3.290					1.295
107		6.688	7.079					1.386
108		5.284	5.655					1.361
109		4.252	4.544					1.356
110		3.060	3.239					1.329
111		2.358	2.503					1.285
112		1.670	1.752					1.332
113		3.079	3.255	T ₁ = 181.4	85.2	83.6	85.1	1.359
114		3.081	3.237	T ₂ = 189.6	92.7	94.2	98.0	1.206
115		3.071	3.237	T ₃ = 200.5	93.5	94.9	94.1	1.300
116	A2G	3.118	3.282	T ₄ = 203.1	88.7	87.3	92.2	1.250
117	A1G ↓	6.664	7.083					1.413
118		5.269	5.633					1.388
119		4.187	4.518					1.329
120		3.087	3.283					1.305
121		2.331	2.471					1.178
122		1.728	1.793					1.242
123		3.059	3.232	T ₁ = 186.0	86.7	84.8	85.4	1.396
124		3.067	3.213	T ₂ = 191.7	93.0	95.1	97.9	1.321
125		3.021	3.201	T ₃ = 205.1	95.3	96.2	95.1	1.302
126	A1G	3.072	3.246	T ₄ = 202.2	94.2	94.2	95.9	1.292

TABLE A-3
PRELIMINARY PRESSURE LOSS COEFFICIENTS
(With Increased Reflector Block Height)

Test Run No.	CSB Config.	Flow Rate (lb/sec)		Heated Col. Temp. (°F)	T _{avg. in} (°F)	T _{avg. out} (°F)	T _{avg. Rake} (°F)	K _{overall} Arith. Avg.
		$\dot{m}_{inlet}$	$\dot{m}_{outlet}$					
F1	3B1G	2.934	3.168	T ₁ = 167.2	75.1	74.1	76.5	2.799
F2	3B1G	2.973	3.104	T ₂ = 193.9	86.6	87.2	90.1	2.494
F3	3B1G	2.927	3.135	T ₃ = 183.2	89.3	88.8	88.9	2.623
F4	3B1G	2.987	3.202	T ₄ = 174.8	85.8	84.2	86.2	2.671
F5	4B1G	3.019	3.204	T ₁ = 184.8	73.7	73.3	73.7	2.677
F6	4B1G	3.034	3.133	T ₂ = 178.8	86.8	85.9	88.0	2.665
F7	4B1G	3.045	3.197	T ₃ = 177.5	90.4	88.7	89.6	2.299
F8	4B1G	3.132	3.189	T ₄ = 177.8	90.3	89.9	90.0	2.236
F9	3C1G	3.009	3.185	T ₁ = 178.0	81.7	82.0	81.8	3.884
F10	3C1G	3.126	3.174	T ₂ = 190.0	91.7	89.9	93.1	3.464
F11	3C1G	3.102	3.205	T ₃ = 180.2	89.1	87.2	87.3	3.588
F12	3C1G	3.059	3.202	T ₄ = 175.6	79.8	79.5	81.1	3.485
F13	4C1G	3.043	3.168	T ₁ = 171.7	79.5	79.3	79.2	3.712
F14	4C1G	3.077	3.168	T ₂ = 193.2	88.8	86.9	86.9	3.557
F15	4C1G	3.091	3.163	T ₃ = 182.4	85.1	83.3	84.8	3.699
F16	4C1G	3.058	3.208	T ₄ = 173.8	84.3	83.4	85.2	4.257

TABLE A-4
LOW FLOW PRESSURE LOSS COEFFICIENTS
FOR PRELIMINARY FOUR-COLUMN REGIONS

Test Run No.	CSB Config.	Flow Rate (lb/sec)		Heated Col. Temp. (°F)	T _{avg.} in (°F)	T _{avg.} out (°F)	T _{avg.} Rake (°F)	K _{overall} Arith. Avg.
		$\Sigma \dot{m}_{inlet}$	$\dot{m}_{outlet}$					
127	Col. BIG 1,2,3,4	4.263	4.707					>7.2
128	↓	3.993	4.487	T ₁ = 198.3	91.6	88.0	91.1	6.46
129	↓	3.999	4.346	T ₂ = 203.1	113.4	119.1	118.1	6.27
130	Col.	4.010	4.425	T ₃ = 199.7	108.6	106.8	111.0	6.21
131	BIG 1,2,3,4	4.211	4.530	T ₄ = 218.4	115.5	112.1	112.6	6.13
132	Col. BIG 1,2,6,7	4.530	4.708	T ₁ = 195.5	89.4	87.3	89.8	6.23
133	↓	4.460	4.524	T ₂ = 188.8	103.3	111.5	112.8	5.81
134	↓	4.001	4.281	T ₆ = 173.7	105.8	105.2	105.4	5.98
135	Col. BIG 1,2,6,7	3.600	4.022	T ₇ = 171.9	110.4	110.0	109.3	5.98
136	Col. BIG 1,2,3,7	3.717	4.170	T ₇ = 178.6	108.9	108.7	112.7	6.43
137	↓	3.720	4.232	T ₁ = 183.0	94.7	92.1	93.7	6.72
138	Col.	3.828	4.299	T ₂ = 156.5	88.6	93.5	90.5	6.62
139	BIG 1,2,3,7	3.692	4.222	T ₃ = 181.1	100.3	98.0	96.0	6.27

TABLE A-5
SUMMARY OF SELECTED INFLUENCE COEFFICIENTS - 7-COLUMN REGIONS

Test No.	Config.	Heated Col. No.	Flow Rate (lb/sec)	K_{overall} Arith. Avg.	$\theta'_{\text{sensor max}}$ (Cij)	$\theta'_{\text{CSBexit max}}$ (Cij)	$\theta(A_{ij})$ for Sensor Centerline		
							$\theta_{\text{E sens. max}}$	$\theta_{\text{E sens. min}}$	$\theta_{\text{E sens. avg.}}$
123	A1G	1	3.23	1.40	0.180	0.181	0.102	-0.054	0.016
113	A2G	1	3.26	1.36	0.160	0.171	0.080	-0.054	0.006
41	BG	1	3.27	2.51	0.137	0.153	0.054	-0.062	-0.010
31.2	B1G	1	3.25	2.13	0.174	0.156	0.096	-0.025	0.023
53	B2G	1	3.21	2.10	0.107	0.122	0.023	-0.073	-0.029
71	CG	1	3.29	4.28	0.105	0.128	0.020	-0.056	-0.021
61	C1G	1	3.31	3.65	0.123	0.121	0.039	-0.056	-0.010
81	C2G	1	3.25	3.57	0.112	0.113	0.027	-0.065	-0.024
102	DG	1	3.28	5.45	0.079	0.127	-0.003	-0.107	-0.057
92	D1G	1	3.21	4.62	0.103	0.103	0.017	-0.064	-0.026
124	A1G	2	3.21	1.32	0.328	0.884	0.033	-0.134	-0.059
114	A2G	2	3.24	1.21	0.296	0.798	0.054	-0.118	-0.049
43	BG	2	3.24	2.32	0.262	0.749	0.132	-0.158	-0.050
32.0	B1G	2	3.16	2.13	0.220	0.590	0.050	-0.134	-0.056
52	B2G	2	3.21	2.04	0.285	0.464	0.141	-0.115	-0.005
72	CG	2	3.28	4.07	0.413	0.609	0.157	-0.148	-0.021
62	C1G	2	3.28	3.58	0.372	0.492	0.066	-0.138	-0.051
82	C2G	2	3.23	3.69	0.325	0.478	0.092	-0.115	-0.016
103	DG	2	3.19	5.45	0.484	0.483	0.174	-0.146	-0.002
93	D1G	2	3.23	4.58	0.449	0.448	0.156	-0.074	0.031
125	A1G	3	3.20	1.30	0.259	0.790	0.127	-0.160	-0.040
115	A2G	3	3.24	1.30	0.262	0.699	0.132	-0.119	-0.015
40	BG	3	3.21	2.46	0.133	0.693	-0.018	-0.126	-0.087
33.2	B1G	3	3.16	2.02	0.139	0.536	-0.011	-0.162	-0.099
50	B2G	3	3.27	2.09	0.191	0.399	0.052	-0.135	-0.057
73	CG	3	3.25	4.29	0.082	0.530	-0.079	-0.179	-0.140
63	C1G	3	3.25	3.61	0.240	0.412	0.106	-0.171	-0.066
83	C2G	3	3.22	3.61	0.268	0.364	0.140	-0.121	-0.003
104	DG	3	3.23	5.44	0.140	0.444	-0.014	-0.194	-0.125
94	D1G	3	3.24	4.62	0.276	0.467	0.148	-0.104	0.003

TABLE A-5 (Continued)

Test No.	Config.	Heated Col. No.	Flow Rate (lb/sec)	K overall Arith. Avg.	$\theta_{\text{sensor max}}^{\text{'}}$ (Cij)	$\theta_{\text{CSBexit max}}^{\text{'}}$ (Cij)	$\theta(A_{ij})$ for Sensor Centerline		
							$\theta_{\text{L sens. max}}$	$\theta_{\text{L sens. min}}$	$\theta_{\text{L sens. avg.}}$
126	A1G	4	3.25	1.29	0.846	0.642	0.110	0.122	-0.006
116	A2G	4	3.28	1.25	0.543	0.657	0.075	-0.146	-0.031
42	BG	4	3.25	2.38	0.844	0.544	-0.006	-0.108	-0.044
34.1	B1G	4	3.15	2.10	0.866	0.689	-0.047	-0.140	-0.088
51	B2G	4	3.27	2.07	0.484	0.521	-0.060	-0.146	-0.094
74	CG	4	3.25	4.05	0.852	0.447	0.057	-0.118	-0.048
64	C1G	4	3.26	3.63	0.652	0.556	0.035	-0.143	-0.060
84	C2G	4	3.20	3.62	0.391	0.409	0.042	-0.144	-0.050
105	DG	4	3.21	5.33	0.888	0.359	0.066	-0.137	-0.044
95	D1G	4	3.21	4.72	0.555	0.471	0.026	-0.159	-0.070

TABLE A-6
SUMMARY OF SELECTED PRELIMINARY INFLUENCE COEFFICIENTS
(with Increased Reflector Block Height)

Test No.	Config.	Heated Col. No.	Flow Rate (lb/sec)	K_{overall} Arith. Avg.	$\theta_{\text{sensor max}}$ (Cij)	$\theta_{\text{CSBexit max}}$ (Cij)	$\theta(A_{ij})$ for Sensor Centerline		
							$\theta_{\text{E sens. max}}$	$\theta_{\text{E sens. min}}$	$\theta_{\text{E sens. avg.}}$
31.2	B1G	1	3.25	2.13	0.174	0.156	0.096	-0.025	0.023
F1	3B1G	1	3.17	2.80	0.110	0.143	0.027	-0.078	-0.031
F5	4B1G	1	3.20	2.68	0.102	0.111	0.019	-0.050	-0.018
32.0	B1G	2	3.16	2.13	0.220	0.590	0.050	-0.134	-0.056
F2	3B1G	2	3.10	2.49	0.270	0.568	0.038	-0.131	-0.058
F6	4B1G	2	3.13	2.66	0.302	0.541	0.011	-0.151	-0.078
33.2	B1G	3	3.16	2.02	0.139	0.536	-0.011	-0.162	-0.099
F3	3B1G	3	3.14	2.62	0.159	0.492	0.012	-0.168	-0.091
F7	4B1G	3	3.20	2.30	0.133	0.511	-0.029	-0.191	-0.123
34.1	B1G	4	3.15	2.10	0.866	0.689	-0.047	-0.140	-0.088
F4	3B1G	4	3.20	2.67	0.677	0.636	-0.011	-0.161	-0.092
F8	4B1G	4	3.19	2.24	0.658	0.578	0.027	-0.175	-0.086
61	C1G	1	3.31	3.65	0.123	0.121	0.039	-0.056	-0.010
F9	3C1G	1	3.19	3.88	0.097	0.103	0.016	-0.071	-0.028
F13	4C1G	1	3.17	3.71	0.094	0.099	0.010	-0.068	-0.033
62	C1G	2	3.28	3.58	0.372	0.492	0.066	-0.138	-0.051
F10	3C1G	2	3.17	3.46	0.294	0.450	-0.040	-0.162	-0.106
F14	4C1G	2	3.17	3.56	0.306	0.415	-0.034	-0.151	-0.095
63	C1G	3	3.25	3.61	0.240	0.412	0.106	-0.171	-0.066
F11	3C1G	3	3.21	3.56	0.092	0.419	-0.077	-0.174	-0.133
F15	4C1G	3	3.16	3.70	0.118	0.454	-0.059	-0.172	-0.124
64	C1G	4	3.26	3.63	0.652	0.556	0.035	-0.143	-0.060
F12	3C1G	4	3.20	3.49	0.567	0.521	0.032	-0.151	-0.073
F16	4C1G	4	3.21	4.26	0.528	0.511	-0.024	-0.158	-0.098

TABLE A-7
SUMMARY OF SELECTED PRELIMINARY INFLUENCE COEFFICIENTS - 4-CAL. REGION

Test No.	Config.	Heated Col. No.	Flow Rate (lb/sec)	K _{overall}	θ' (Cij) for Sensor and Exit Rake					θ (Aij) for Sensor ξ		
					$\theta'_{\text{sensor max}}$	$\theta'_{\text{CSBexit max}}$	$\theta'_{\text{sensor min}}$	$\theta'_{\text{CSBexit min}}$	$\theta'_{\text{calc. avg.}}$	$\theta_{\xi \text{ sens. max}}$	$\theta_{\xi \text{ sens. min}}$	$\theta_{\xi \text{ sens. avg.}}$
128	BIG	1	4.49	6.46	0.191	0.231	0	0.087	0.161	-0.16	-0.20	-0.17
129	BIG	2	4.35	6.27	0.834	0.663	0.043	0.115	0.278	-0.24	-0.31	-0.28
130	BIG	3	4.43	6.21	0.552	0.435	0.028	0.173	0.279	+0.38	-0.31	-0.04
131	BIG	4	4.53	6.13	0.613	0.507	0.010	0.074	0.282	-0.02	-0.32	-0.20
132	BIG	1	4.71	6.23	0.091	0.207	0.003	0.119	0.163	-0.16	-0.19	0.17
133	BIG	2	4.52	5.81	0.769	0.612	0.031	0.160	0.277	+0.60	-0.27	+0.13
134	BIG	6	4.28	5.99	0.215	0.501	0	0.074	0.279	-0.36	-0.42	-0.40
135	BIG	7	4.02	5.98	0.723	0.432	0.058	0.192	0.281	+0.28	-0.27	-0.06
136	BIG	7	4.17	6.43	0.675	0.567	0.002	0.070	0.283	-0.26	-0.39	-0.32
137	BIG	1	4.23	6.72	0.155	0.183	0.013	0.080	0.159	-0.13	-0.17	-0.16
138	BIG	2	4.30	6.62	0.802	0.561	0.046	0.205	0.280	+0.72	-0.22	+0.17
139	BIG	3	4.22	6.27	0.619	0.560	0	0.080	0.279	-0.32	-0.38	-0.35

TABLE A-8
PRELIMINARY COST OPTIMIZATION OF CORE SUPPORT BLOCK CONFIGURATIONS

Order ^(a)	Config.	H CSB Height (in.)	θ Miter Angle (°)	CSB Exit Plane Max. Influence Coeff. for Heated Jets				Press. Loss Coeff. $\bar{K}_{\text{Overall}}$ (±1 σ)	ΔH Costs (\$ million)	ΔP ^(b) Costs (\$ million)	Total Costs (\$ million)	Adjusted Total Costs (\$ million)
				θ ₁	θ ₂	θ ₃	θ ₄					
				Reasonable Mixing								
1	C2G	53	70	0.113	0.478	0.364	0.409	3.62 ± 0.07	1.5	2.7	4.2	3.2
2	D1G	41	90	0.103	0.448	0.467	0.471	4.66 ± 0.06	0.5	3.4	3.9	2.9
3	DG	35	90	0.127	0.483	0.444	0.359	5.42 ± 0.09	0	4.0	4.0	3.0
4	B2G	53	52	0.122	0.464	0.399	0.521	2.07 ± 0.03	1.5	1.5	3.0	2.0
5	4C1G	41	70	0.099	0.412	0.454	0.511	3.81 ± 0.27	0.5	3.0	3.5	2.5
6	3C1G	41	70	0.103	0.450	0.419	0.521	3.61 ± 0.17	0.5	2.8	3.3	2.3
7	C1G	41	70	0.121	0.492	0.412	0.556	3.65 ± 0.06	0.5	2.7	3.2	2.2
8	4B1G	41	52	0.111	0.541	0.511	0.578	2.47 ± 0.20	0.5	2.0	2.5	1.5
9	CG	35	70	0.128	0.609	0.530	0.447	4.22 ± 0.16	0	3.2	3.2	2.2
10	3B1G	41	52	0.143	0.568	0.492	0.636	2.65 ± 0.11	0.5	2.0	2.5	1.5
				Questionable Mixing								
11	B1G	41	52	0.156	0.590	0.536	0.689	2.09 ± 0.04	0.5	1.6	2.1	1.1
12	BG	35	52	0.153	0.749	0.693	0.544	2.43 ± 0.05	0	1.8	1.8	0.8
				Unacceptable Mixing								
13	A2G	53	35	0.171	0.798	0.699	0.657	1.31 ± 0.05	1.5	1.0	2.5	1.5
14	A1G	41	35	0.181	0.884	0.790	0.642	1.32 ± 0.07	0.5	1.0	1.5	0.5

Assumptions: 1.0 psi ΔP costs \$2 million; 1.0 ft ΔH costs \$1 million

$$\Delta P_{\text{max, reactor}} = \frac{\dot{m}^2 K}{2\rho g A^2} = 0.365 \text{ K psi}$$

- (Notes): a. 1 is best mixing; 14 is worst mixing.
b. CSB exit loss has been excluded from these estimates.