Thermal Design, Analysis, and Testing of the Quench Module Insert Bread Board

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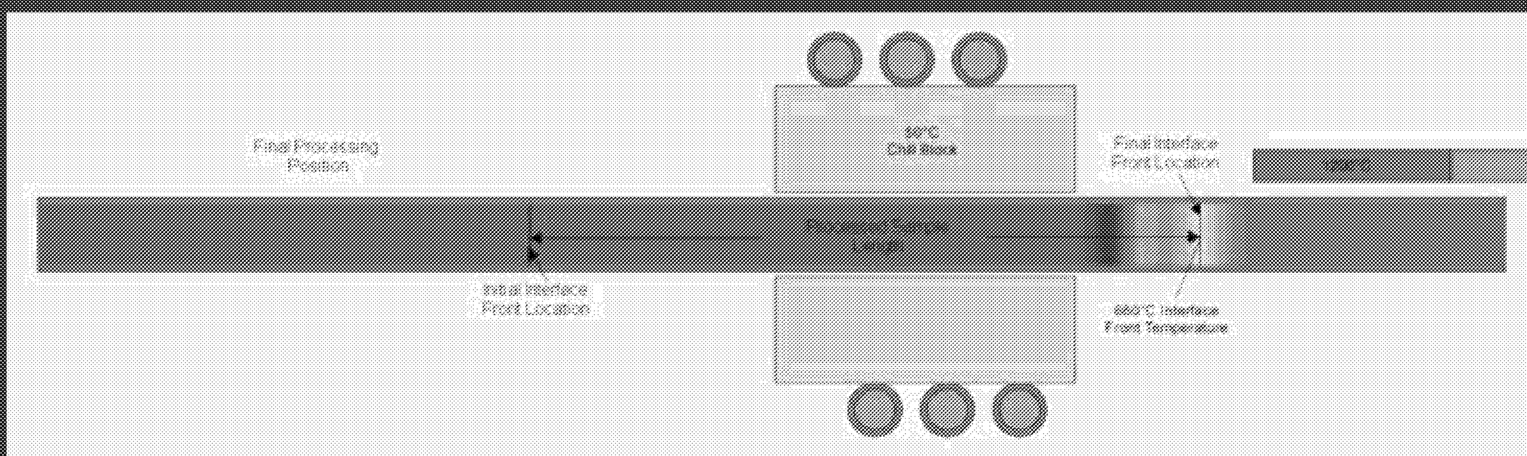
ED25/ NASA/MSFC

Quench Module Insert (QMI) Microgravity Materials Processing

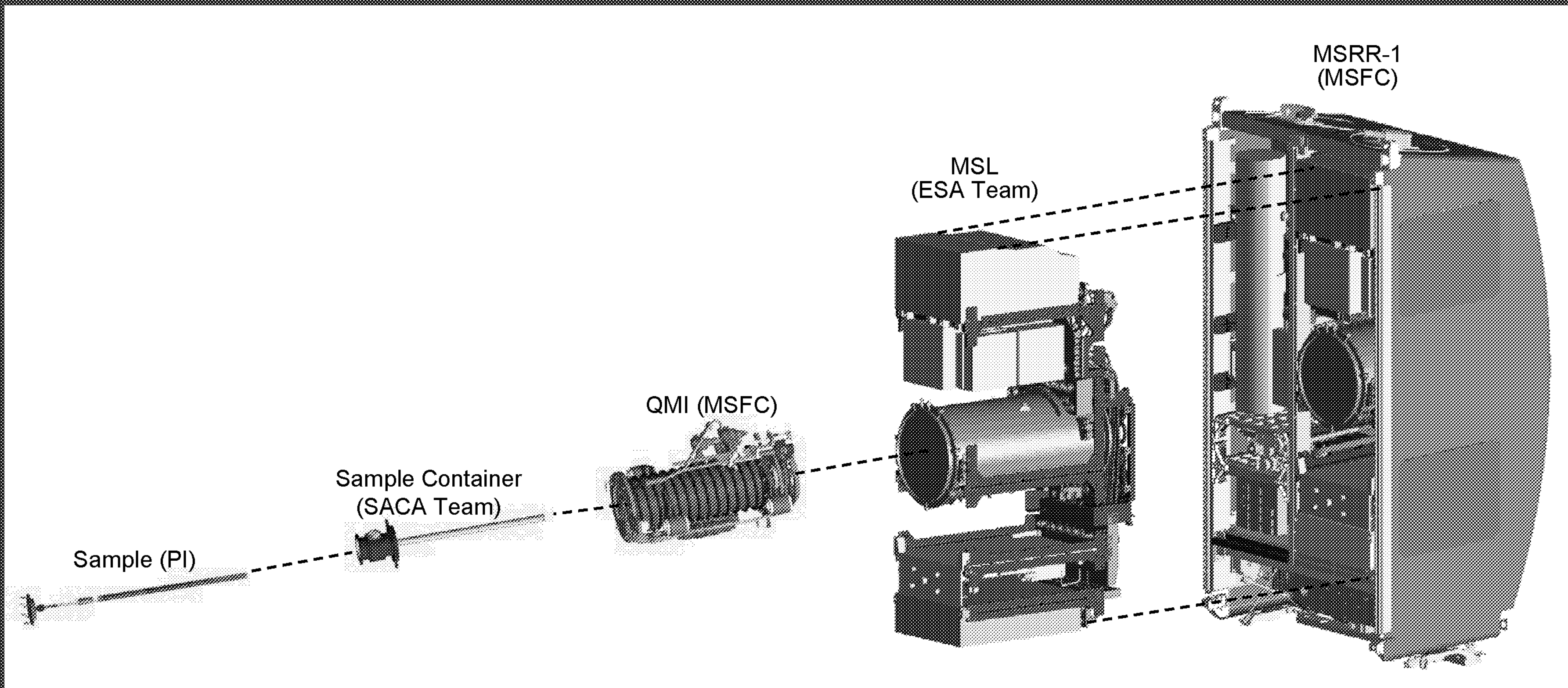
- *What is microgravity materials processing?*
  - *Creating desired thermal gradient and solid/liquid interface front movement for a given processing temperature in a microgravity environment*



Quench Module Insert (QMI) Science Requirements

- *Metals and Alloys Processing*
  - *Currently Supporting Two Investigators*
  - *Sample Processing from 600°C to 1400°C*
  - *Various Sample Materials up to 1cm diameter*
  - *Sample Gradients up to 150°C/cm for a 1cm aluminum sample at 1100°C processing*
  - *Sample Isothermality of ±10°C over a 10cm length of a 1cm dia. aluminum sample*
  - *20cm hot zone; four independently controlled zones; 20cm of translation; approximately 18cm of sample processing*
  - *Sample Quench rates providing solidification of a 2cm length of a 1cm diameter aluminum sample in 2seconds*

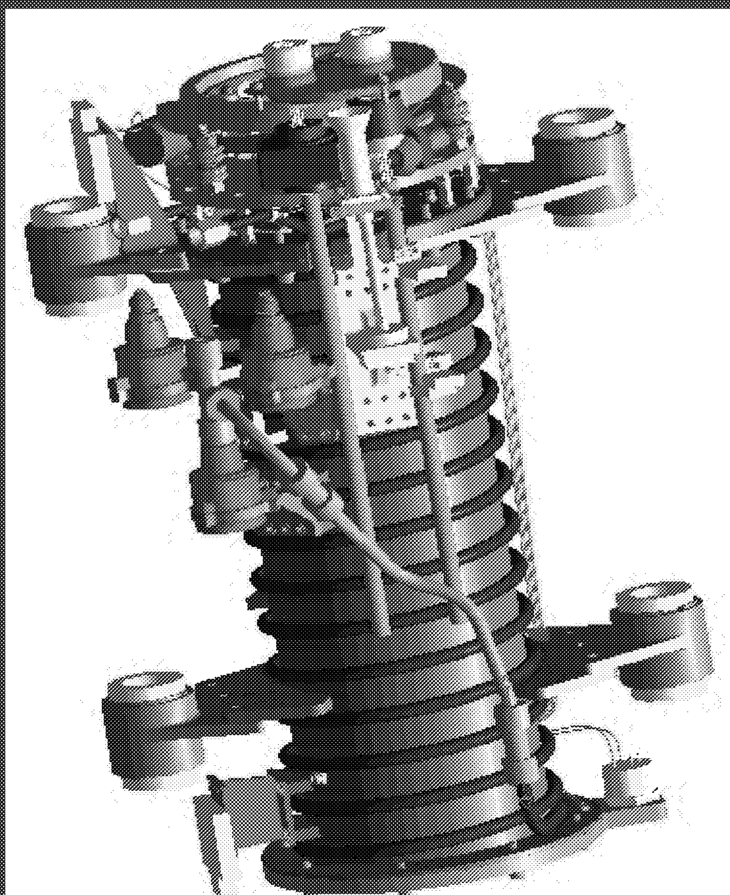
Quench Module Insert (QMI) Interfaces



Quench Module Insert (QMI) Interface Requirements

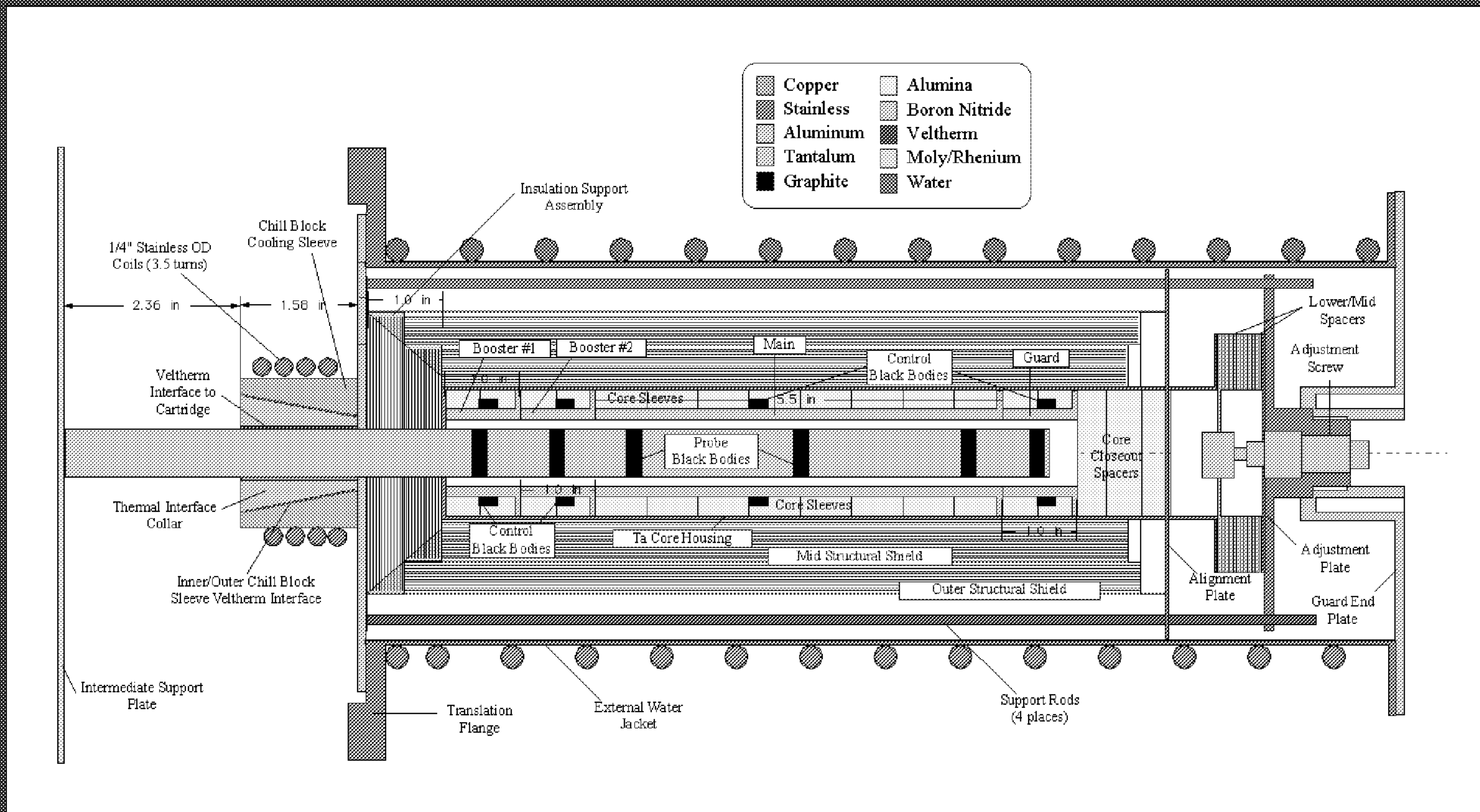
- *Integration in the ESA's Materials Science Laboratory*
  - *3kW Max. Power/Cooling Allocation (currently showing a max. power requirement of less than 450W at 1400°C)*
  - *Fail Safe Loss of Cooling (max. 600ml of expelled volume)*
  - *Touch Temperature (>49°C) during all phases of processing*
  - *Limits on waste heat losses to the ESA thermal chamber (100W)*
  - *Max. Shell temperatures*
  - *Max. Coolant return temperatures*
  - *190mbar pressure drop at max. coolant flow conditions*

Quench Module Insert (QMI) Design Layout



- *Bridgman-type, Vacuum Furnace*
- *Four heated zones*
- *One interchangeable cold zone*
- *Phase Change Quench System*
- *Highly Efficient Insulation Design*

Quench Module Insert (QMI) Design Layout



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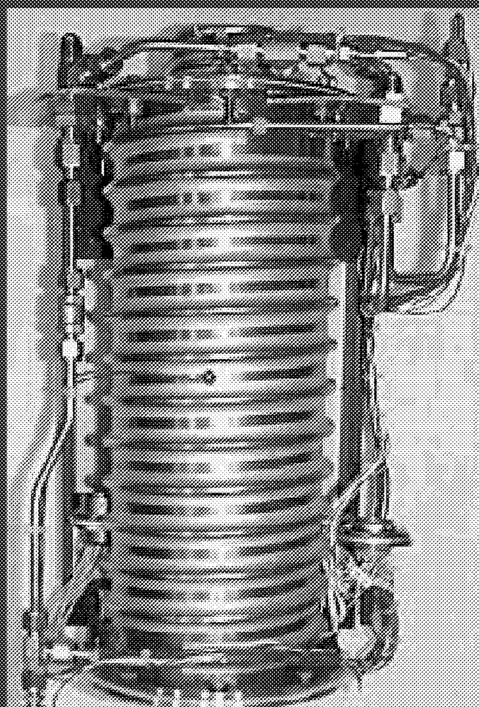
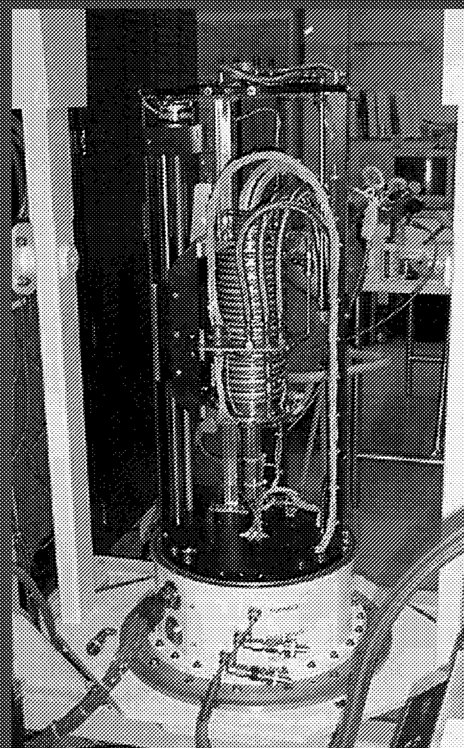
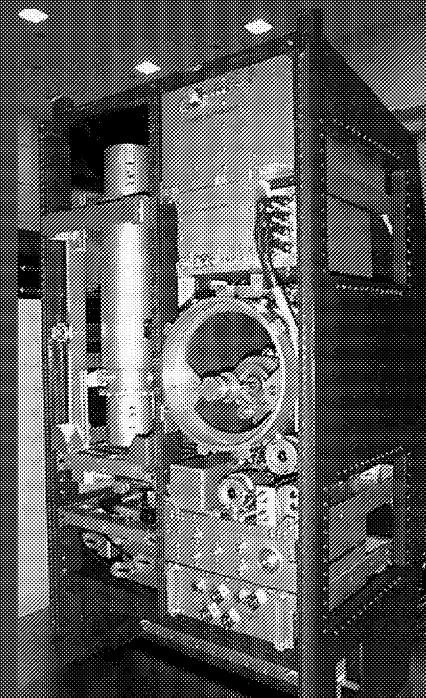


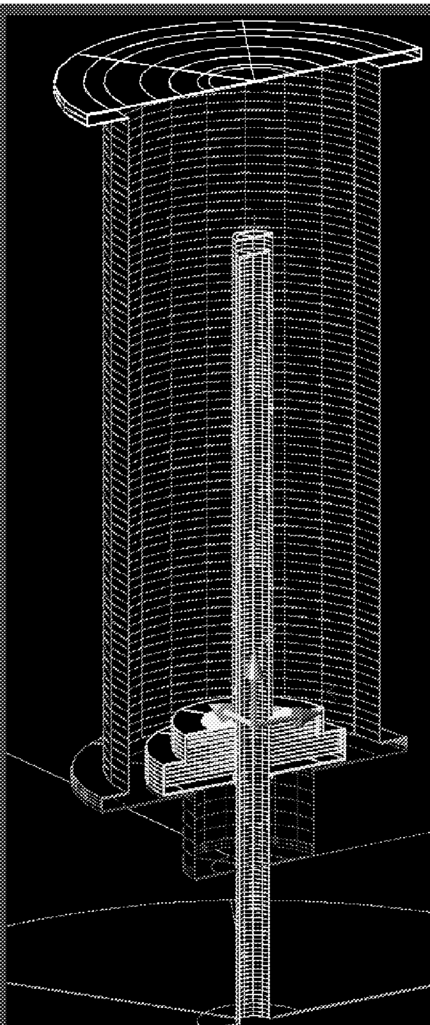


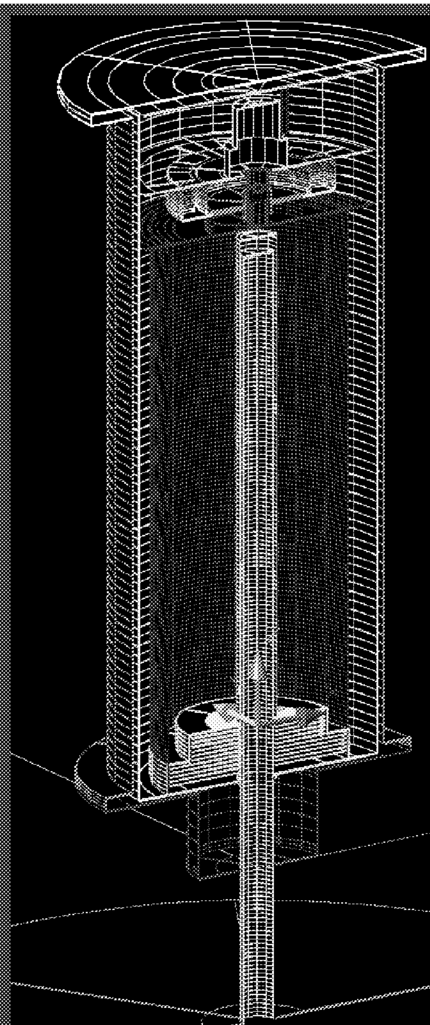


QMI Thermal Analysis and Design Methodology

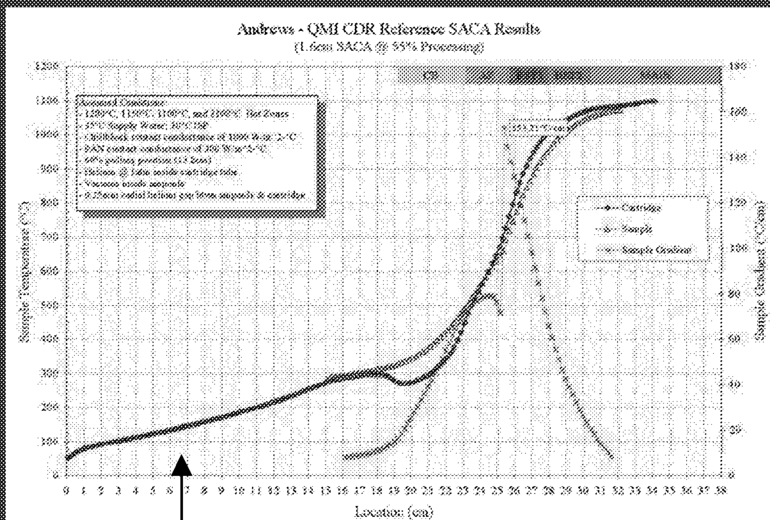
- *Modeling via TRASYS II, SINDA/G, and SINDA85*
  - *One overall axi-symmetric SINDA/G model (>5000 nodes) per Unit*
    - *Easily reconfigured for any translation position via user constants*
    - *Detailed component level temperature summary tables and plots generated for each case*
    - *User defined sinroutines for helical heat transfer coefficient, uniform power distribution, summary tables, plot files*
  - *Three TRASYS II models (translatable bore, jacket, and PCD)*
    - *Easily reconfigured for any translation position or SACA geometry/surface properties via users constants*
- *Preliminary Hot Zone Test Article to verify insulation and thermal performance in a static test condition (heavily instrumented)*
- *Hot Zone Test Article model correlation results and lessons learned are applied to Bread Board and Flight models*
- *Bread Board model correlation results and lessons learned are applied to both the Bread Board and Flight models*

QMI Thermal Analysis and Design Methodology

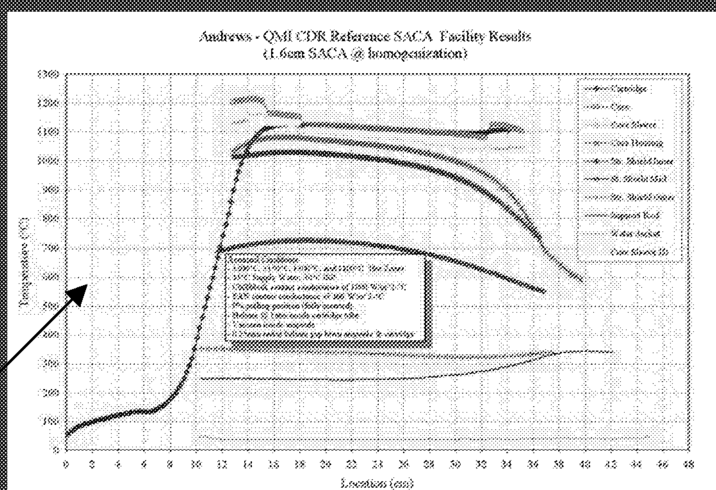




QMI Thermal Analysis and Design Methodology



Science Requirements Temperature Plots



Component Level Temperature Plots

Updated Thermal Model Results for Heater Control Temperatures at 1200 °C, 1150 °C,1100 °C, 1100 °C

BOUNDARY CONDITIONS

Cartridge Position: 0.00cm (fully inserted; Refrence SACA with pure Aluminum Sample)

Hot Zone Settings:			**Coolant Water Settings:**		
Booster #1 Temp :	1200	°C	Chill Block Inlet:	35	°C
Booster #2 Temp:	1150	°C	Chill Block flow Rate:	50	kg/hr
Main Temperature:	1100	°C	Pan Conductance:	300	W/m^2-°C
Guard Temperature:	1100	°C	Water Jacket Inlet:	35	°C
			Water Jacket flow rate:	40	kg/hr

Temperature Results

Components	Max. (°C)	Min. (°C)	Avg. (°C)
Quench Zone			
Housing	N/A	N/A	N/A
Shoe	N/A	N/A	N/A
Chill Block:			
Bore Temp	56.5	50.2	52.6
Inner Sleeve	56.5	49.6	52.2
Outer Sleeve	40.0	39.0	39.6
Water	36.6	35.0	35.9
Chill Block Plate			
Plate	61.4	60.4	60.8
Bore	61.4	N/A	N/A
Chill Block Interface	61.3	N/A	N/A
AZ Interface	61.3	N/A	N/A
Rod Interface	60.4	N/A	N/A
Adiabatic Zone			
Disks	785.5	299.8	566.2
Ints Support Structure	609.3	121.7	406.9
Shield #2	700.2	687.6	693.4
Shield #3	352.3	351.1	351.9
Core Housing	1013.9	N/A	N/A
Guard Zone Closeout			
Adjustment Plate	448.1	397.8	427.5
Adjustment Screw	438.3	426.2	433.8
Lower Spacer	506.6	483.7	495.2
Mid. Spacer	468.3	457.8	463.6
Top Plate Closeout	61.9	59.4	60.6
Inner Closeout Spacer	1032.9	896.4	915.4
Mid Closeout Spacer	749.7	738.3	743.9
Outer Closeout Spacer	600.8	591.5	596.9
Devo Plate	459.4	422.3	449.5
Core housing Intf.	556.9	N/A	N/A
Ext Water Jacket			
Cylinder	55.9	36.3	38.9
Flange, CB side	59.1	59.1	59.1
Flange, Guard side	59.3	59.2	59.3
Water	38.6	35.2	36.8
CB Plate Intf	59.1	N/A	N/A

Components	Max. (°C)	Min. (°C)	Avg. (°C)
Hot Zone			
Booster #1 Overall	1213.3	1184.4	1203.8
Booster #1 Bore	1202.8	1184.4	1196.5
Booter #1 Lead	1191.4	107.6	922.0
Booter #1 Solder	95.8	62.0	71.0
Booster #2 Overall	1164.4	1145.8	1156.7
Booster #2 Bore	1160.2	1148.1	1155.5
Booter #2 Lead	1142.9	104.8	893.5
Booter #2 Solder	93.6	61.6	70.2
Main Overall	1124.3	1073.3	1105.9
Main Bore	1124.3	1080.4	1106.5
Main Lead	1071.5	105.4	618.8
Main Solder	94.1	61.7	70.4
Guard Overall	1127.1	1081.6	1113.5
Guard Bore	1125.0	1096.1	1115.1
Guard Lead	1068.7	106.9	473.7
Guard Solder	95.2	61.8	70.7
Core Sleeves			
Booster #1	1199	1128	1156
Booster #2	1150	1125	1130
Main	1107	1045	1079
Guard	1099	1038	1051
Core Housing			
Overall	1081	557	966
Booster #1 Area	1078	1034	1060
Booster #2 Area	1081	1080	1081
Main Arrea	1078	949	1034
Guard Area/Flange	937	557	671
Structural Shields			
Layer #1 (inner)	1030	737	964
Layer #2	725	550	678
Layer #3 (outer)	352	322	336
Support Rods			
Rod #1	343	244	273
Rod #2	343	244	273
Rod #3	343	244	273
Rod #4	343	244	273

Heater Wire Informations

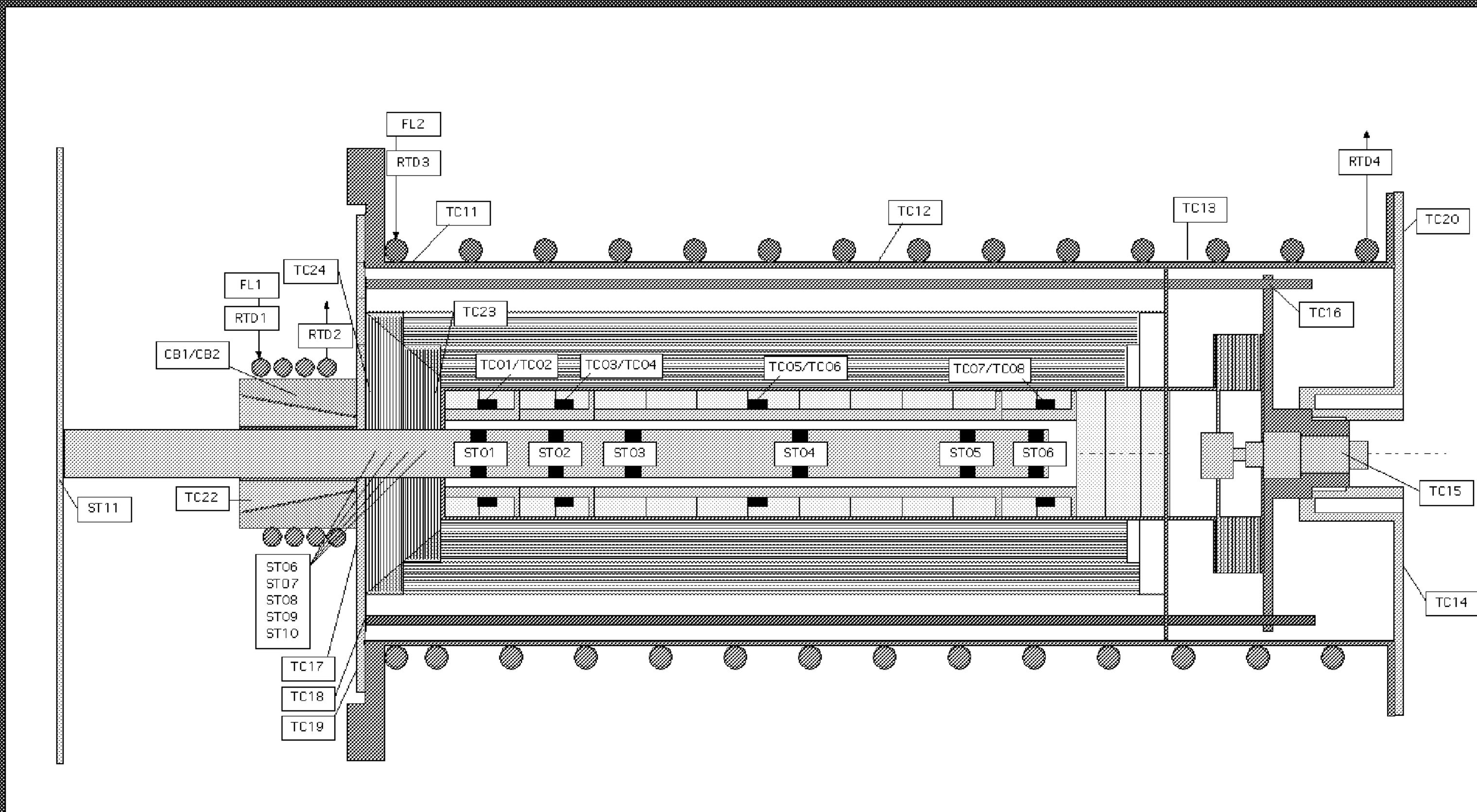
Heater Wire Losses (W)		**Heater Wire Currents (Amp)**	
Booster #1	1.1	Booster #1	3.37
Booster #2	0.2	Booster #2	1.62
Main	0.2	Main	2.11
Guard	0.1	Guard	2.16

Component Level & Housekeeping Summary Tables

QMI Bread Board Testing and Instrumentation Approach

- *HZTA Testing focused on determination of insulation performance and verification of heat flow mapping (losses, contact coefficients)*
- *Bread Board focused on overall insert performance, chill block performance, hot zone control, and heat flow mapping*
  - *Furnace instrumentation placed to map the flow of heat from the heaters at various areas to obtain a total energy balance and evaluation of the system performance*
  - *Overall energy balance was obtained real-time by adding calculations to the data system for coolant loops to compare to power draw*
  - *Heat flow between components was verified by measuring temperature at the components know conductive heat flow paths*
  - *Detailed understanding of zone-to-zone interaction as a function of set points was required. Needed to assess what actual average bore temperature was obtained for a given zone's set point*
  - *Assess the ability to maximize the booster#1 set point temperature and maintain control of booster#2 to maximize gradient capability*

QMI Bread Board Testing and Instrumentation Approach

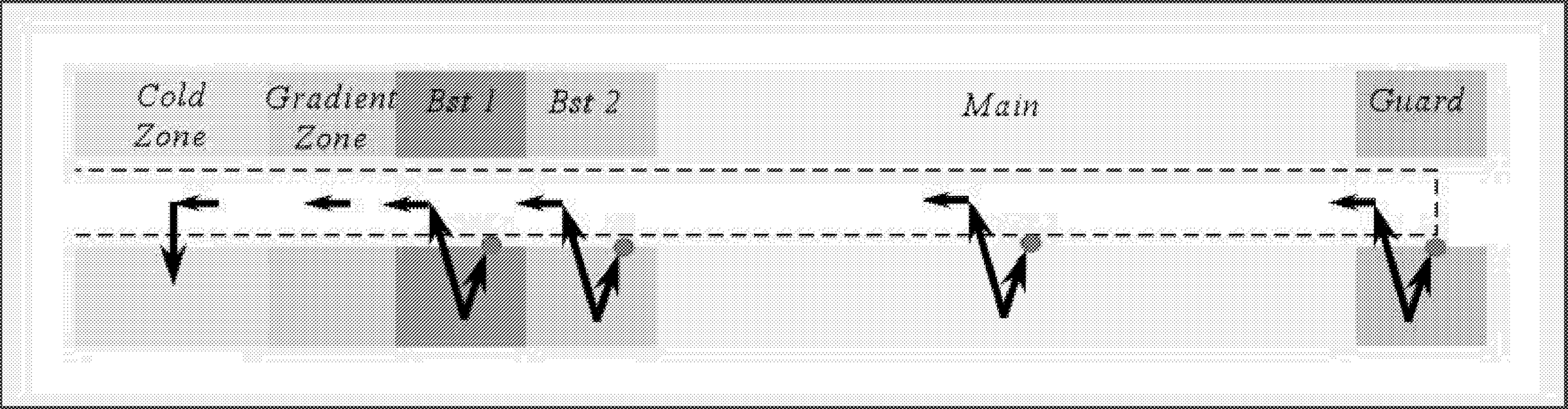


QMI Breadboard Thermal Probe Requirements

- *Provide repeatable and accurate measurements of furnace performance*
  - *Thermal gradient measurement*
    - *Surface properties*
    - *Material thermal conductivity*
    - *Gradient zone instrumentation location and spacing*
  - *Heated zone measurements*
    - *Surface properties*
    - *Heated zone instrumentation location*
    - *Instrumentation isolation*
- *Provide performance measurements while simulating a science sample*
  - *Heater power*
  - *Cold zone heat load*

QMI Thermal Probe Design Parameters

- *Surface properties*
  - *High emissivity preferred*
  - *Stable under vacuum*
- *Materials selection*
  - *Low thermal conductivity*
  - *1400°C processing temperature*
- *Instrumentation*
  - *Location and spacing in the gradient zone*
  - *Location and isolation in the heated zone*
- *Science sample loading*

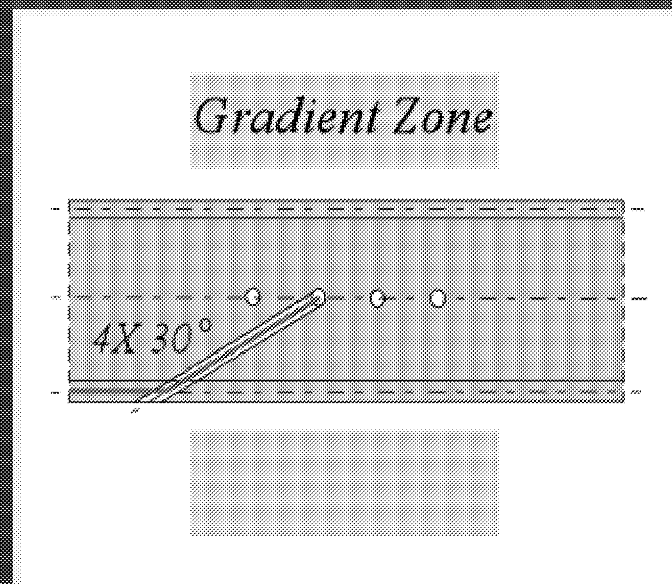


Preliminary Thermal Probe Designs

- High Gradient Furnace with Quench (HGFQ)
  - 1.6cm OD stainless steel probe
  - Performance at 1100 °C processing
    - 169 - 218 °C/cm gradient
    - 1100W steady state heater power (inert gas furnace)
- Hot Zone Test Article (HZTA)
  - 1.6cm OD stainless steel probe
  - Performance at 1200/1150/1100/1100°C processing
    - 182°C/cm gradient
    - 342W steady state heater power
- QMI PDR Probe Design
  - 1.3cm OD aluminum nitride probe
  - Performance at 1200/1150/1100/1100°C processing
    - 132°C/cm gradient
    - 298W steady state heater power

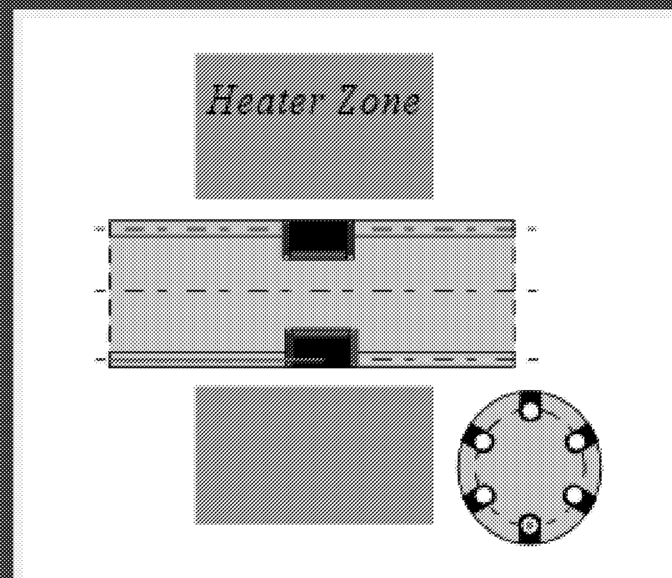
Design Features for Gradient Measurement

- 1.6cm solid tantalum thermal probe
  - Surface emissivity of 0.2
  - Low thermal conductivity of 2.8 Btu/hr in °F
- Four Type C tantalum sheath thermocouples
  - Thermocouple spacing of 0.3 in
  - Sheaths run along surface grooves
  - Beads positioned at probe centerline with a 30° entry angle
  - Beads potted into position with epoxy

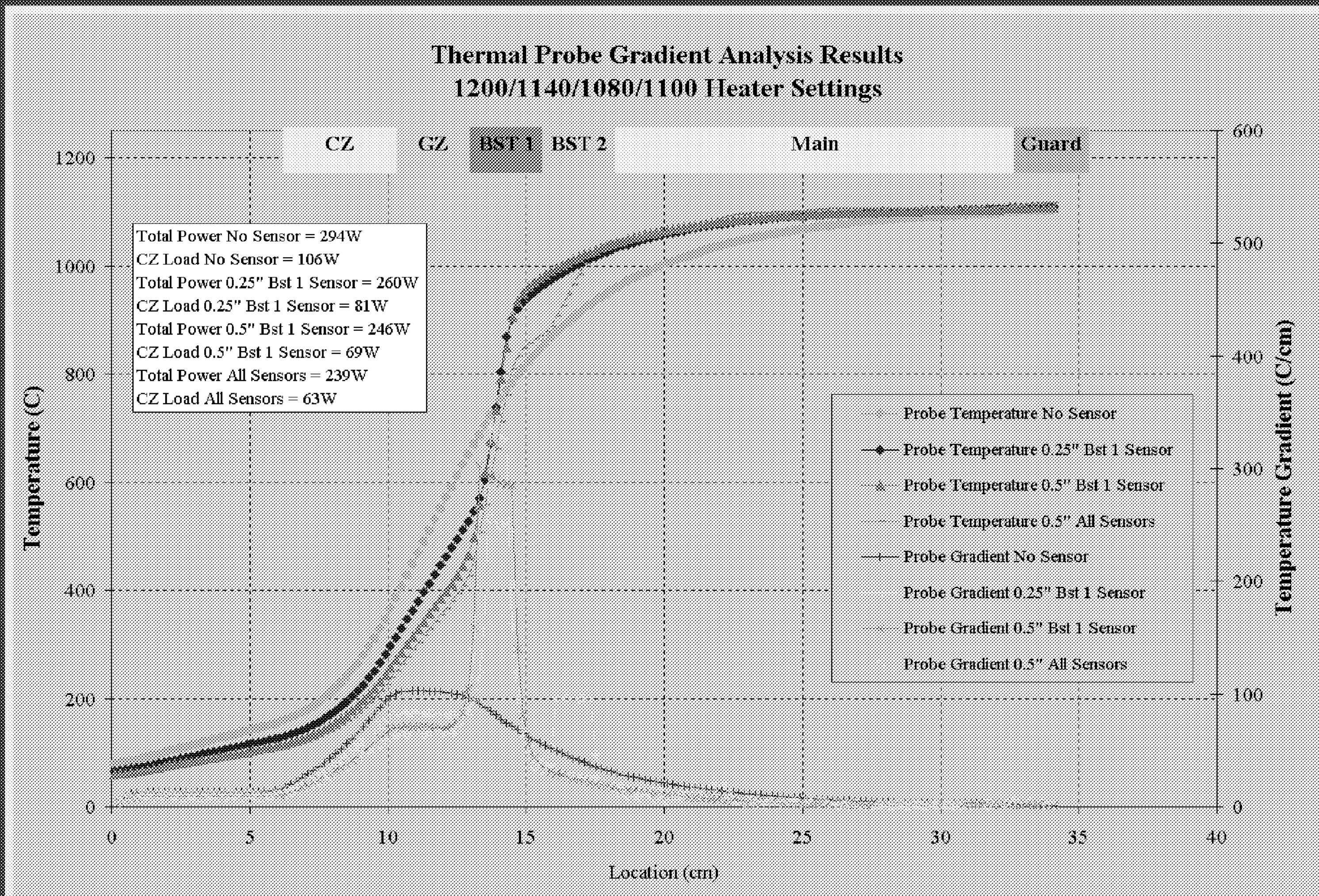


Design Features for Heated Zone Measurements

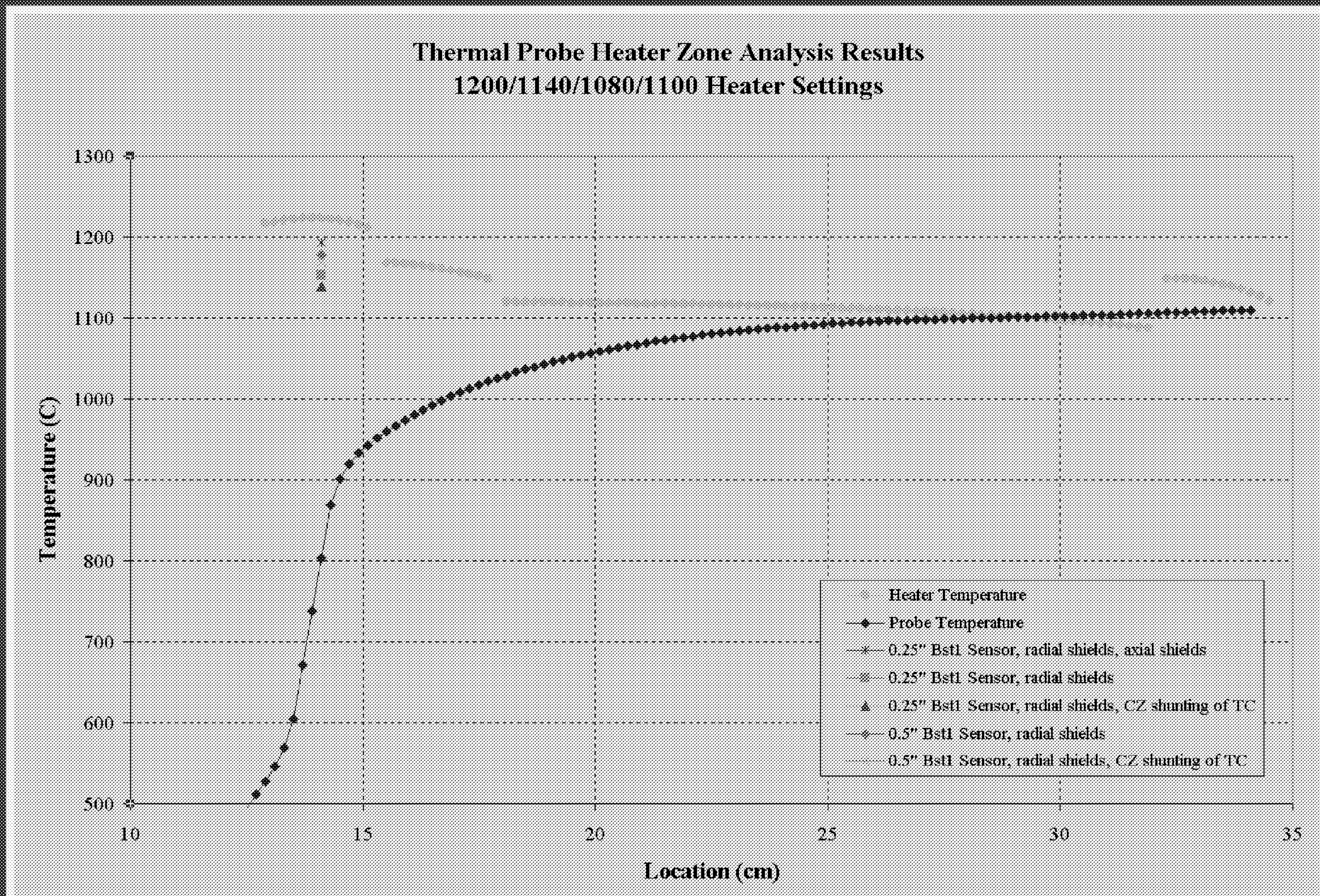
- *Graphite ring black body sensors*
  - *Surface emissivity of 0.9*
  - *Maximize heat transfer to sensors without compromising heat transfer to probe*
- *Sensors isolated from probe*
  - *Dimpled tantalum shields wrapped to cut radial losses*
  - *Multiple tantalum disks cut axial losses*
- *Type C tantalum sheath thermocouples*
  - *Sheaths run along surface grooves*
  - *Beads potted into graphite rings with epoxy*



Thermal Gradient Analysis Results

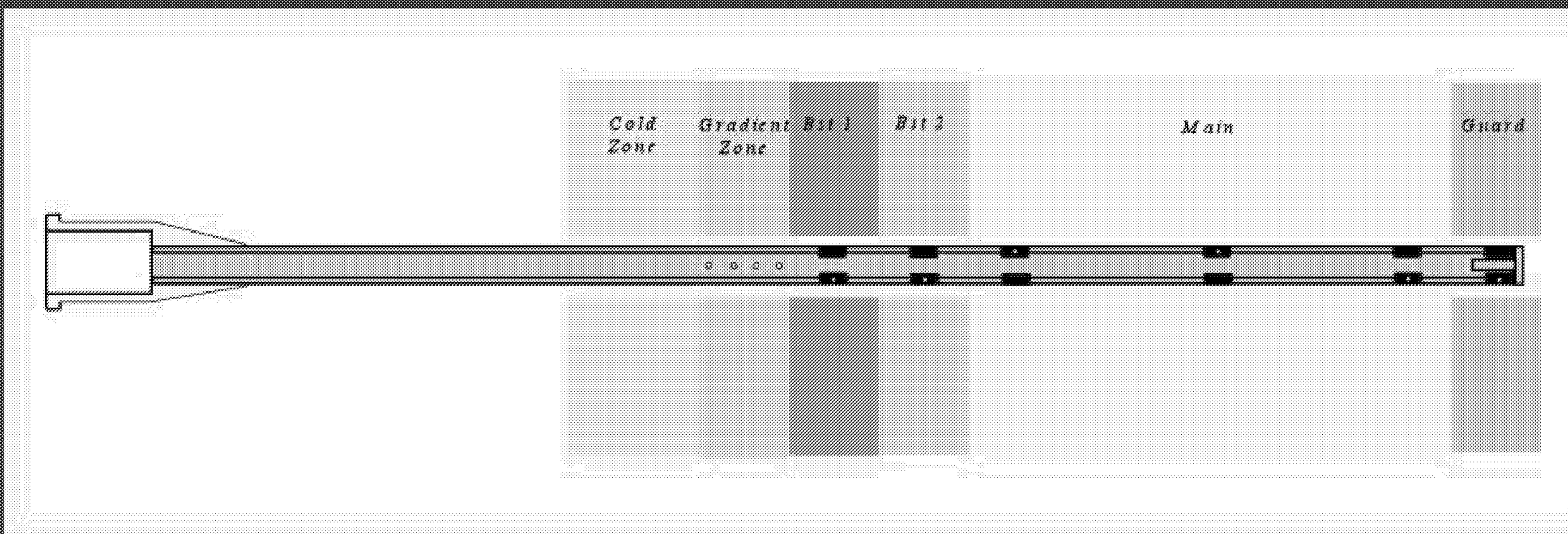


Heated Zone Analysis Results



Breadboard Thermal Probe Layout

- *Four centerline thermocouples in gradient zone*
- *Six isolated 0.25 inch blackbody sensors in heated zones*
  - *One sensor in Bst1, Bst2, and guard and three sensors in longer main*
  - *One thermocouple per sensor*

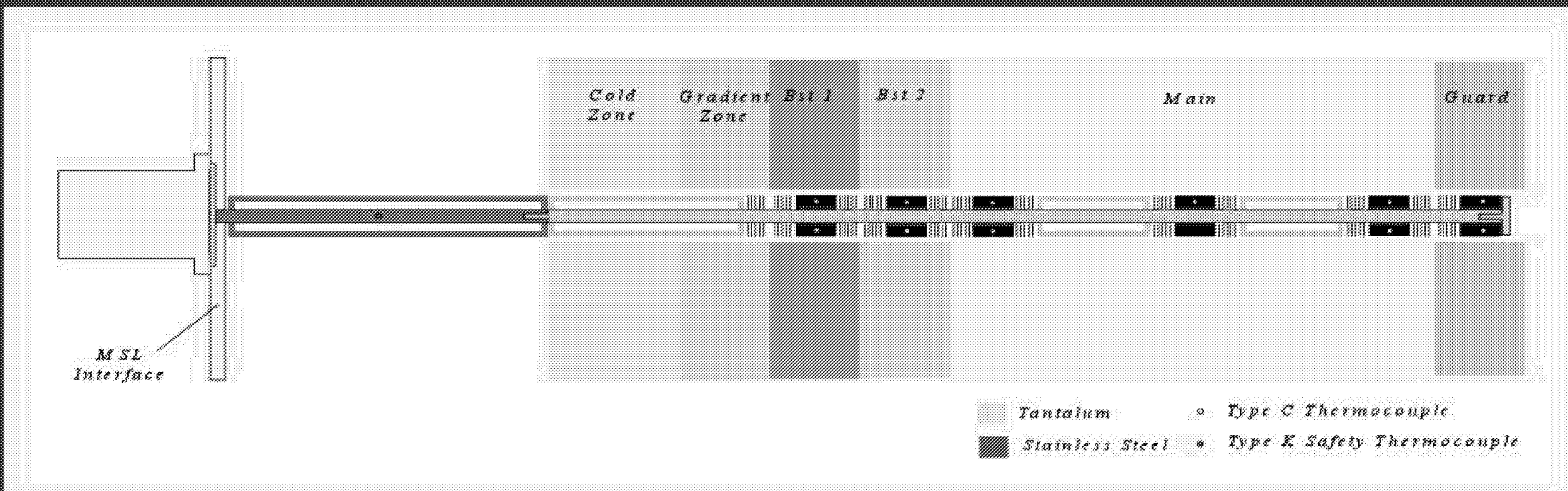


Flight Thermal Probe Requirements

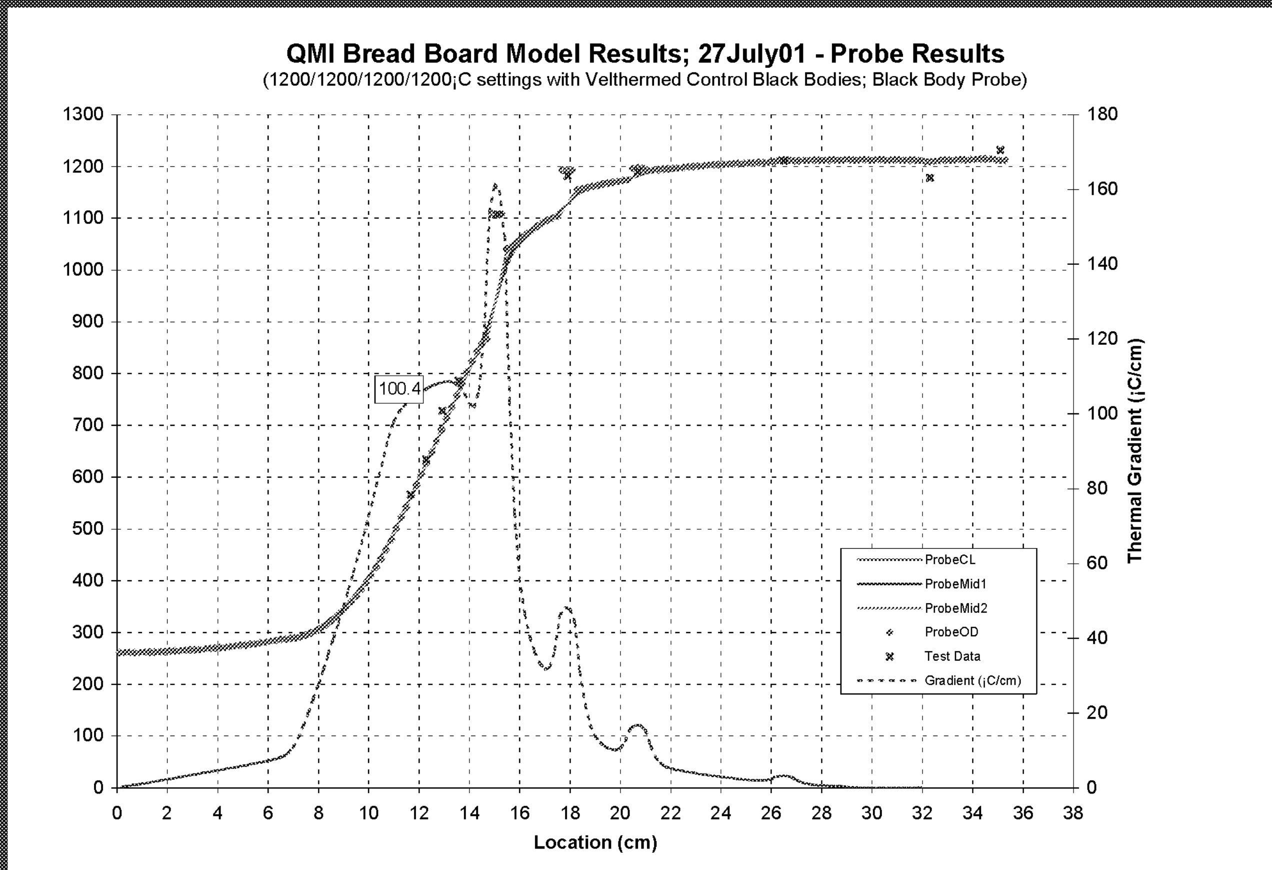
- *Provide repeatable and accurate measurements of heated zone*
  - *Blackbody sensor design concept*
  - *Limited to 12 thermocouples by MSL*
- *Incorporate MSL required safety thermocouple*
- *Maximize probe life*
  - *Eliminate gradient measurement*
  - *Cold zone performance monitored by PT1000s*
- *Minimize weight*
  - *Decrease use of tantalum material*

Flight Thermal Probe Design Features

- Six 0.5 inch blackbody sensors in heated zones
  - Graphite or silicon carbide coated boron nitride rings
  - Redundant thermocouples in each sensor except main central sensor
  - Sensors isolated from one another by axial shielding
- Weight reduction
  - Tantalum shaft with thin walled tantalum brackets
  - Substitution of stainless steel where temperatures allow



QMI Bread Board Correlation and Performance



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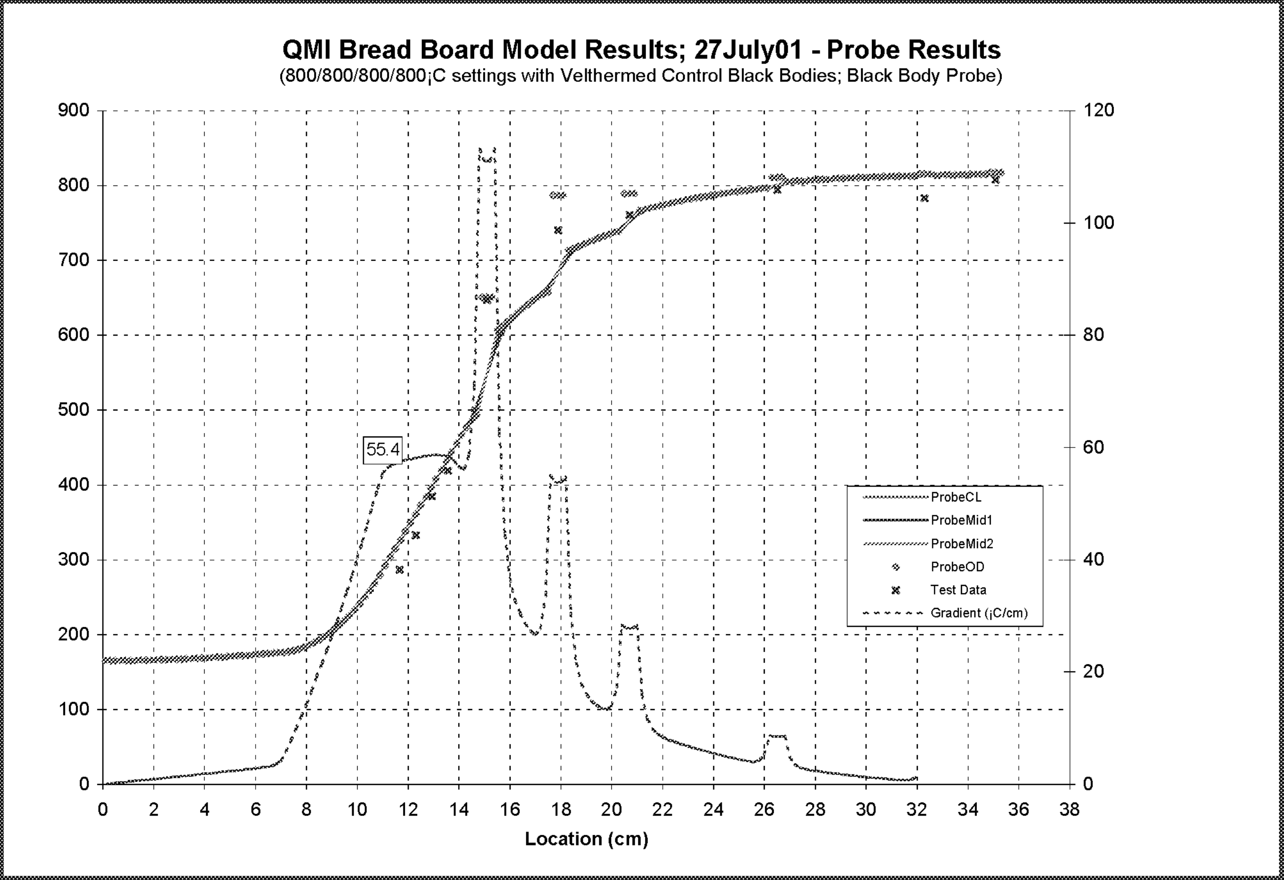

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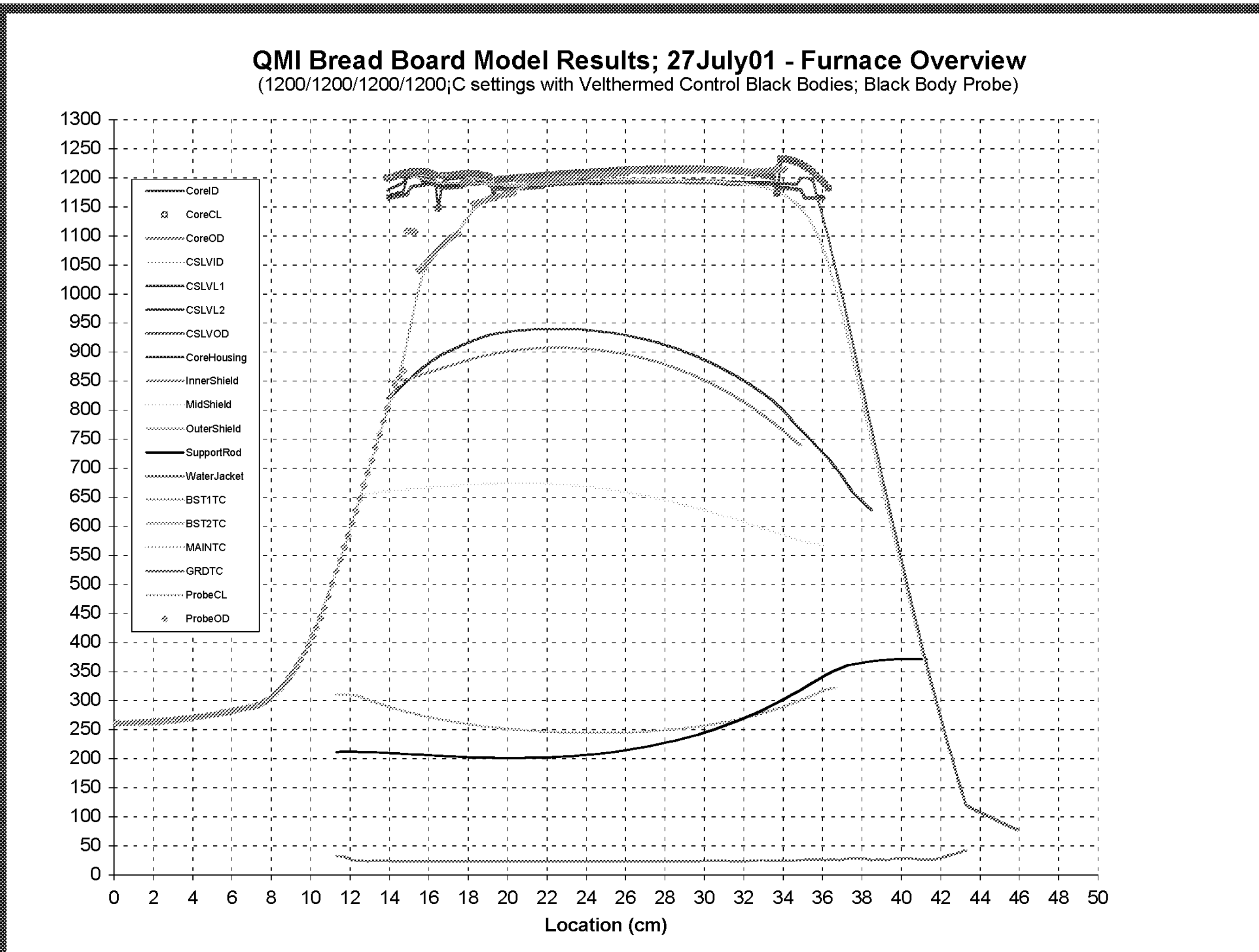

QMI Bread Board Correlation and Performance

Location	ID		05May01 600degC Bbody Cntrl (no chead cooling)	Model Results: bbc00-03l @ 600¡C	Differences	05May01 800degC Bbody Cntrl (no chead cooling)	Model Results: bbc00-03l @ 800¡C	Differences	07May01 1000¡C Bbody Control	Model Results: bbc00-03l @ 1000¡C	Differences	07May01 1200¡C Bbody Control	Model Results: bbc00-03l @ 1200¡C	Differences
CB Outer Sleeve	CB1	degC	26.2	25.8	2%	29.2	28.1	4%	32.47	30.6	6%	35.68	33.2	7%
CB Outer Sleeve	CB2	degC	25.7	25.4	1%	28.5	27.5	4%	31.69	29.7	6%	34.75	32.0	8%
CB Flow	FL1	kg/hr	49.0	50.3	3%	48.8	50.3	3%	49.16	50.3	2%	49.03	50.3	3%
WJ Flow	FL2	kg/hr	38.5	38.3	0%	37.1	38.3	3%	39.00	38.3	2%	38.35	38.3	0%
	FL3	kg/hr	88.8	N/A		86.6	N/A		89.30	N/A		88.54	N/A	
Booster#1 Power	PW1	W	25.3	19.8	22%	50.3	39.7	21%	86.54	67.8	22%	134.03	105.2	21%
Booster#2 Power	PW2	W	11.3	11.7	3%	21.1	21.5	2%	32.11	31.9	0%	42.03	41.9	0%
Main Power	PW3	W	24.2	24.5	1%	35.9	34.1	5%	49.29	43.4	12%	69.55	57.8	17%
Guard Power	PW4	W	16.6	11.8	29%	30.6	22.5	26%	55.94	37.3	33%	90.53	58.2	36%
Total Power	PW	W	77.4	67.8	12%	137.8	117.8	15%	223.87	180.4	19%	336.14	263.0	22%
CB Inlet	RTD1	degC	21.4	21.5	0%	21.4	21.5	1%	21.50	21.5	0%	21.68	21.5	1%
CB Outlet	RTD2	degC	22.0	22.2	1%	22.4	22.5	1%	22.96	22.9	0%	23.60	23.3	1%
WJ Inlet	RTD3	degC	21.5	21.6	1%	21.5	21.6	0%	21.68	21.6	0%	21.90	21.6	1%
WJ Outlet	RTD4	degC	22.0	22.2	1%	22.7	22.8	1%	23.77	23.7	0%	25.52	24.9	2%
	RTD5	degC	26.2	N/A		26.5	N/A		27.00	N/A		27.73	N/A	
B1 Bbody	ST01	degC	423.2	425.5	1%	647.2	650.2	0%	872.80	881.2	1%	1107.35	1106.6	0%
B2 Bbody	ST02	degC	524.7	585.4	12%	740.4	786.8	6%	959.56	989.7	3%	1181.19	1193.0	1%
Main/B2 Bbody	ST03	degC	548.8	590.5	8%	760.4	789.2	4%	972.97	992.2	2%	1190.56	1196.7	1%
Main/Mid Bbody	ST04	degC	579.6	609.5	5%	794.3	810.9	2%	1001.06	1012.3	1%	1210.59	1212.7	0%
Main/Guard Bbody	ST05	degC	580.8	616.1	6%	783.2	815.7	4%	980.67	1013.0	3%	1178.00	1209.1	3%
Guard Bbody	ST06	degC	598.0	618.7	3%	808.0	817.3	1%	1017.54	1014.5	0%	1231.64	1212.1	2%
GZ TCs - CB	ST07	degC	183.4	226.1	23%	286.4	338.0	18%	419.41	459.7	10%	566.51	584.9	3%
GZ TCs	ST08	degC	212.5	240.9	13%	332.6	361.2	9%	477.22	492.1	3%	634.50	627.3	1%
GZ TCs	ST09	degC	245.2	255.9	4%	384.5	384.5	0%	550.55	524.9	5%	727.79	670.2	8%
GZ TCs - BST	ST10	degC	269.2	270.9	1%	418.6	407.9	3%	595.47	557.8	6%	786.42	713.6	9%
SACA Mtg. Plate	ST11	degC	34.2	20.0		42.1	20.0		51.91	20.0		65.05	20.0	
B1 Control	TC01	degC	595.9	599.5	1%	794.6	800.3	1%	993.45	1000.4	1%	1200.04	1200.3	0%
B1 Redunt.	TC02	degC	600.0	599.5	0%	800.0	800.3	0%	999.99	1000.4	0%	1204.94	1200.3	0%
B2 Control	TC03	degC	600.0	600.2	0%	800.0	800.2	0%	1000.00	1000.0	0%	1200.00	1199.9	0%
B2 Redunt	TC04	degC	598.5	600.2	0%	798.5	800.2	0%	997.84	1000.0	0%	1199.32	1199.9	0%
Main Control	TC05	degC	596.1	601.6	1%	796.1	799.2	0%	996.18	999.9	0%	1199.53	1201.0	0%
Main Redunt.	TC06	degC	600.0	601.6	0%	800.0	799.2	0%	999.99	999.9	0%	1200.01	1201.0	0%
Guard Control	TC07	degC	600.0	599.7	0%	800.0	800.5	0%	1000.00	1000.3	0%	1200.00	1199.6	0%
Guard Redunt.	TC08	degC	595.1	599.7	1%	793.6	800.5	1%	990.93	1000.3	1%	1194.10	1199.6	0%
WJ Upper	TC11	degC	29.6	25.3	15%	36.1	28.2	22%	45.45	32.1	29%	58.35	37.2	36%
WJ Mid	TC12	degC	22.5	22.2	1%	23.3	22.8	2%	24.86	23.7	5%	27.30	25.1	8%
WJ Lower	TC13	degC	28.4	30.6	8%	32.3	35.2	9%	37.23	40.8	10%	43.72	47.4	8%
Guard Plate	TC14	degC	32.0	31.5	2%	37.8	36.5	3%	44.88	42.6	5%	53.94	49.7	8%
Adj. Screw	TC15	degC	267.1	249.0	7%	347.7	341.4	2%	429.03	422.2	2%	498.48	494.7	1%
Support Rod	TC16	degC	234.9	305.7	30%	297.1	457.7	54%	352.98	603.4	71%	409.88	739.3	80%
CB Plate 1	TC17	degC	34.7	34.8	0%	44.7	46.2	3%	58.49	62.6	7%	76.83	85.8	12%
CB Plate 2	TC18	degC	48.5	63.8	31%	67.9	100.6	48%	92.09	146.8	59%	117.97	201.2	71%
CB Plate 3	TC19	degC	32.1	25.6	20%	40.3	28.8	29%	51.83	33.0	36%	67.64	38.5	43%
Power Trans.	TC20	degC	38.4	30.8	20%	45.5	35.5	22%	53.54	41.2	23%	63.30	47.9	24%
TIC	TC22	degC	27.8	28.6	3%	31.7	32.4	2%	36.12	36.6	1%	40.19	40.8	1%
Devo/BST	TC23	degC	300.4			462.6			640.10			808.41		
Devo/CB	TC24	degC	226.3			348.5			482.30			609.71		
Furnace Flange	TC25	degC	26.0			28.2			30.51			35.05		
Transl. Bkt.	TC26	degC	29.0			33.0			37.80			44.60		
Total Cooling	Qt	W	55.7	65.8	18%	107.6	112.7	5%	178.27	174.1	2%	270.69	253.7	6%
Chill Block Cooling	Qcb	W	31.5	38.4	22%	57.9	59.5	3%	83.75	82.1	2%	109.48	105.3	4%
Water Jacket Cooling	Qwj	W	24.2	27.4	13%	49.7	53.2	7%	94.52	92.0	3%	161.21	148.4	8%

Summary and Conclusions

- Current Bread Board testing indicates that the QMI thermal design models and methods are very accurate
  - Probe gradient zone temperature results have been used to judge initial furnace positioning measurement and have aided in trouble-shooting 5-8mm offsets of the furnace/probe positioning
  - Thermal probe black body zone readings have been used to troubleshoot the temperature control system. Control thermocouple attachment methods have been evaluated based upon the black body temperature readings obtained in the main/guard zones
  - One simplified SACA prototype run has shown the ability to produce greater than 90°C/cm thermal gradients in an 11.7mm diameter pure aluminum sample at a 900°C sample processing temperature
- Results obtained and design lessons learned from the bread board testing are being "flowed up" to the flight design. The QMI bread board is providing invaluable information on the capabilities and evaluation of the flight design.
- Currently retrofitting the control instrumentation for the hot zones
- Additional testing is soon to begin and will include quench testing