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Design of Experiments Results For the Feedthru Insulator

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Design of Experiments Results for the Feedthru Insulator

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Abstract

A design of experiments (DoE) was performed at Ceramtec to improve the yield of a cermet part known as the feedthru insulator. The factors chosen to be varied in this DoE were syringe orifice size, fill condition, solvent, and surfactant. These factors were chosen because of their anticipated effect on the cermet slurry and its consequences to the feedthru insulator in succeeding fabrication operations. Response variables to the DoE were chosen to be indirect indicators of production yield for the feedthru insulator. The solvent amount used to mix the cermet slurry had the greatest overall effect on the response variables. Based upon this DoE, there is the potential to improve the yield not only for the feedthru insulator but for other cermet parts as well. This report thoroughly documents the DoE and contains additional information regarding the feedthru insulator.

Acknowledgment

The authors thank and acknowledge the important contributions provided by Stephen Crowder, *Statistics & Human Factors dept.*, Sandra Monroe, *Materials Joining dept.*, Scott Holmes, *Design Evaluation & Certification dept.*, John Gieske, *Design Evaluation & Cert. dept.*, and Reggie Wilkerson, *Ceramtec North America*. Stephen Crowder participated in the selection of factors for the design of experiments, reviewed the plan for the design of experiments, and helped analyze the data. Sandra Monroe offered to provide microfocus and ultrasonic testing of the parts to generate additional response variables for the design of experiments. Scott Holmes performed the microfocus tests. John Gieske performed the ultrasonic tests. Reggie Wilkerson made many of the dimensional measurements used in the design of experiments.

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Introduction

A Cermet Process Improvement (CPI) team was formed in November 1998 for the purpose of improving the yield of cermet parts fabricated at Ceramtec North America. The particular part we chose for our study was the feedthru insulator (P/N 443403-02, see Figure 1) also known as the target feedthru. The feedthru insulator is one of nine different ceramic parts used in the MC4277 neutron tube that is assembled into the MC4380 neutron generator. The core members of this team were,

- **Gilbert Benavides**, *Manufacturing Science and Technology*, Sandia National Laboratories
- **Dave Van Ornum**, *Manufacturing Science and Technology*, Sandia National Laboratories
- **Maureen Baca**, *Production Management Center*, Sandia National Laboratories
- **Pat Appel**, *Production Engineering Center*, Sandia National Laboratories
- **John McGinnis**, Ceramtec North America
- **James Tindall**, Ceramtec North America
- **Chuck Stattenfield**, Ceramtec North America

Figure 1. Feedthru Insulator (cross-sectional view of the axisymmetric part)

The CPI team had its first meeting at Ceramtec on December 1, 1998, during which Maureen Baca outlined the nine-step process for problem solving and improvement. The nine-step process outlined below was adopted by the team.

1. **Map the Process and Identify Potential Problems**
2. **Identify Potential Causes**
3. **Identify Potential Root Causes**
4. **Select the Vital 1 or 2 Root Causes**
5. **Identify Potential Solutions**
6. **Evaluate and Select Solution**
7. **Create Action Plan**
8. **Implement Action Plan**
9. **Get Feedback**

Although the CPI team had an interest in improving the yield for all nine cermet parts, the team selected the feedthru insulator as a representative part to demonstrate the benefits of applying process improvement tools. The team also decided to include the effects of the new Sandi94 alumina powder given that the transition from 94ND2 powder to Sandi94 powder was imminent. The process in place at Ceramtec to manufacture feedthru insulators was mapped and is documented in appendix A. After considering the yield loss during the various steps in the manufacturing process, the team decided that a potential problem was the slippage of the part in the collet during the second green machining operation which accounted for a 8% yield loss. The problem was identified by using real data taken from the travelers for five different lots for the feedthru insulator (using 94ND2 powder). This data is summarized in appendix B. The potential cause of the problem was hypothesized to be dimensional inaccuracies such circularity and tapering. The root cause is that the blank is distorted after slurry load and isopress and will not fit properly in collet. The poor fit in the collect can be a result of the OD of the part being either tapered or having poor circularity. We decided to focus our efforts on the cermet slurry formulation and loading operation to search for potential solution opportunities. The cermet slurry material is formulated by mixing together cermet powder, solvent, and surfactant (see Figure 2). The process improvement tool that allowed us to uncover a solution was the Design of Experiments (DoE).

Appendix C contains a memo that details the development of the DoE by the CPI team. The team identified the following five potential factors for the DoE:

1. Quantity of solvent, Diethylene Glycol Monobutyl Ether Acetate (DGMA)
2. Orifice used on the syringe
3. Measured slurry (i.e. fill condition)
4. Surfactant: Nuospense 657 (Modified polyester solution) from Huls America Inc
5. Isopress position

The solvent, DGMA, does not function as a solvent but instead is just a vehicle used in the slurry for transporting the cermet into the alumina blank. The two levels chosen for the solvent quantity were a plus and minus variation about the nominal quantity used. Prior to slurry loading a blank, the slurry is being continuously stirred in a mixer and an alumina blank is prepared by placing a vacuum to the bottom end (see Figure 3). An operator uses a syringe to draw the slurry from the mixer and then uses it to deposit the slurry into the alumina blank. The slurry enters the blank from the top end, flows through a .07 inch diameter via, and settles at the bottom where it is constrained by filter paper. The slurry in the syringe is forced through the needle attached to the syringe. The DoE considered two different needle orifice diameters, small and large. The factor “measured slurry” relates to whether slurry at the top face is about level with the alumina blank or if an excessive amount was deposited to leave a dome of slurry rising above the alumina. The surfactant used in the slurry was also varied to either no surfactant at all or twice the nominal amount. The last factor “Isopress position” refers to the position in the isopress bag (see Figure 4) where position one is at the bottom of the bag and position twenty-five is at the top of the bag. The isopress bag is a product of Autoclave Engineers (P/N P-5019) and is nothing more than a flexible tube having an ID only slightly larger than the OD of the alumina blank. Twenty-five parts are stacked in a single column by placing the bottom end of the part into the bag first. Rubber spacers are placed between parts. The isopress bag prevents the parts from coming into physical contact with the hydraulic fluid in the isopress. Isopress bag position

Figure 2. CND50 Cermet slurry processing (Courtesy of Gary Pressly, dept. 14402)

would be a difficult factor to implement in the DoE because there are twenty-five possible positions unlike the two different levels assigned to the other factors. The baseline experiments were designed to determine if isopress position was worthy of consideration. The baseline experiments indicated that isopress position was an insignificant factor and thus was omitted from the DoE. The baseline experiments are documented in section 1.

The CPI team selected response variables to quantify performance as a function of variations in the combination of factor values. The response variables were selected because they allowed for the measurements to be made at Ceramtec and because they were an indication of a slippage occurring in the collet. We attempted to expand the list of response variables to include measurements performed at Sandia such as ultrasonic and microfocus, however, these variables did not appear to be affected by the factors. These response variables are defined in section 2.

A contract (PO BF-1820) was placed with Ceramtec to perform the baseline experiments, the DoE, dimensional measurements, and X-rays. The analyses for all of these experiments, the ultrasonic tests, and the micro focus X-rays were performed at Sandia. This contract specified that aside from experimental variations all other processes remain the same as for production parts. Many, if not all, of the parts produced through this contract are of WR quality.

Figure 3. Alumina blank

Figure 4. Isopress bag.

Baseline Experiments

Procedure:

The purpose of the baseline experiments was to determine if the position of the feedthru insulator (Figure 1) in the isopress bag (Figure 4) is a factor that should be included in the design of experiments (DoE) described in section 2. One hundred feedthru insulators in four different isopress bags were fabricated up to and including second green machining. The alumina blanks, used to create the final part, were filled with cermet by drawing a vacuum through the bottom end and filling through the top end (see Figure 3). Two isopress bags, at 25 parts per bag, contained parts having the cermet material filled to the level condition. The level condition is defined by the quantity of cermet material that is level (i.e. flush) with the green alumina. Two isopress bags, at 25 parts per bag, contained parts having the cermet material filled to the domed condition. The domed condition is defined to be .5 cc of cermet, which is greater than the volume required to reach the level condition. It was reported that the amount of doming used for this experiment was still less than what has been used in production. The purpose of testing two cermet fill conditions is to determine if isopress position becomes a factor at either fill condition.

The response variables “Alumina diameter”, “Alumina circularity”, and “conical tapering” were measured immediately after isopressing. The response variables “cermet circularity”, “cermet circularity 2”, “cermet concentricity”, and “x-ray voids” were measured after second green machining. Two values of cermet circularity were recorded. “Cermet circularity” is a measure of the circularity of the circular portion of the conical cermet at the top face after the standard second green machining operation. “Cermet circularity2” is a measure of basically the same cermet feature but after an additional .010 inch of material has been removed from the top face. The concern is that the value measured for “cermet circularity” was too prone to nonessential anomalies because of its close proximity to the top surface as isopressed. The final part requires for additional material to be removed from that top face anyway.

Definitions:

- Alumina diameter: The diameter of the OD of the part at the top end after isopressing measured by the RAM optical measuring device which constructs a best fit circle through eight points.
- Alumina circularity: The circularity of the alumina OD measured at the top end using the RAM optical device.
- Conical tapering: The difference between the alumina OD measured at the bottom end and measured at the top end. The OD at the top and bottom are measured at one location each using calipers.
- Cermet circularity: The circularity of the conical cermet measured at the top end using the RAM optical measuring device.
- Cermet circularity2: The circularity of the conical cermet measured at the top end after facing off and additional .010 inch from the top face. Measured by the RAM optical measuring device.
- Cermet concentricity: The concentricity between the cermet diameter at the top face and the alumina diameter.
- X-ray voids: The parts are x-rayed for voids after second green machining.

Experimental notes:

- ◆ Each part was labeled by writing the fill number on the part with a pencil.
- ◆ Position 1 is at the bottom of the isopress bag.
- ◆ Orifice diameter of the syringe used to fill the parts: .054 inch
- ◆ Bag 1 contains parts having fill numbers from 1 through 25.
- ◆ Bag 2 contains parts having fill numbers from 26 through 50.
- ◆ Bag 3 contains parts having fill numbers from 51 through 75.
- ◆ Bag 4 contains parts having fill numbers from 76 through 100.
- ◆ The x-ray used in this experiment is not listed in the process flow found in Appendix A.

Baseline Results:

Table 1 is the data derived from the baseline experiments. Some of the data for the part in bag 4 position 24 is unavailable because the part slipped in the chuck during second green machining. Plots 1 through 6 are plots of the response variables in table 1 versus isopress position. A line derived by linear regression was drawn through the data in plots 1, 3, 4, and 6 to identify trends. Plots 7 through 24 are plots based upon the response variables in table 1 analyzed using Minitab statistical software. For plots 7, 9, 11, 13, 15 and 17, an average of each response variable was calculated as the average of four values (including both level and domed) for each isopress position. For plots 8, 10, 12, 14, 16, and 18, the standard deviation was calculated from these four values for each isopress position. Plots 19 and 20 were attempts to determine if there was any correlation between cermet circularity and alumina circularity or cermet circularity and cermet concentricity. The boxplots in plots 21, 22, 23 and 24 illustrate the distribution of data for the level and domed fill condition regardless of isopress position. The lower whisker indicates the first quartile. The lower portion of the box indicates the second quartile. The upper portion of the box indicates the third quartile. The upper whisker indicates the fourth quartile. The asterisks indicates data considered to be outliers. The horizontal line that separates the lower and upper portion of the box indicates the median.

Baseline Conclusions:

Gilbert Benavides and Steve Crowder analyzed the data derived from the baseline experiments. Based upon this analysis, isopress position does not affect the response variables and isopress position should not be considered a factor for the design of experiments. The recommendation was to proceed with scenario 1 described in appendix C (also referred to as option 1 in P.O. BF-1820).

There are caveats to the above recommendation. The linear regression shown in plot 1 does indicate a trend of smaller alumina diameters with higher isopress position. This trend was discounted because of the small slope of these lines and because of the large scatter in the data. The cermet circularity for bag 4 shown in plot 3 appears to increase with increasing isopress position, however, this trend disappears in plot 4. Plots 15, 16, 17 and 18 indicate that positions 1 and 2 have suspiciously high values. Positions 1 and 2 were monitored in the design of experiments described in section 2 but no suspiciously high values were found.

Plot 5 indicates a positive taper for almost every part, which is not that astonishing given that the cermet has greater shrinkage than the alumina and there is more cermet at the top end. This taper does not appear to be a function of isopress position.

The most interesting result of this baseline experiment is found by examining the x-rays shown in figures 2 and 3. X-ray voids were found in parts having fill numbers 4, 12, 19, 21 and 28 (these parts are shown in bold italics in table 1). All of these parts were domed. Four of the five were in isopress bag number 1; the other part was in isopress bag number 2. Parts 4, 12 and 19 were adjacent to one another having isopress bag positions 15, 16 and 17. At first glance, you might assume that positions in the vicinity of 15, 16 and 17 are more vulnerable to defects, however, part number 21 is at position 3 and part number 28 is at position 20. Also, these vulnerabilities do not appear in bags 2, 3 and 4. This tendency does not appear in the design of experiments describe in section 2.

Plot 21 indicates a remarkable difference in cermet circularity between level and domed. The boxplot for the domed fill condition shows improved circularity as compared to the level fill condition. As shown in plot 22, this improvement all but vanishes when an additional .010" of material is removed from the top surface.

Plot 23 illustrates a noticeable difference in the spread (distribution) of the alumina diameter data between the level and domed fill conditions. The ideal alumina diameter in the range shown is not nearly as an important consideration as lessening the spread. A more consistent diameter is desirable for more consistent chucking in a collet during second green machining. Concluding that doming produces a more consistent alumina diameter is incorrect as can be shown by the evidence in plot 24.

Plot 24 indicates that the dome fill condition produces more taper in the part than the level fill condition. Taper is calculated by subtracting the top diameter from the bottom diameter. Plot 23 and plot 24 appear to be in disagreement given that plot 23 is a plot of the top diameter. The spread in the data for the level condition is not reflected in plot 24. The reason for the discrepancy is that the spread in the alumina diameter was built into the part prior to slurry filling. The same spread exists for the alumina diameter at the bottom of the part. The baseline experiments was not properly controlled to average the effects of first green machining between the level and domed conditions. The filling operation was not performed over a random order of parts that had been "first green machined". The experiments performed for the actual design of experiments (see section 2) were performed much more carefully.

Iso bag	Iso Pos	Fill Cond	Fill #	AI dia	AI circularity	Cermet circularity	Cermet circularity2	Cermet concentricity	Centr-Top	Bot-Centr	Bot-Top
1	1	Dome	10	0.7491	0.0010	0.0003	0.0004	0.0016	0.0010	0.0005	0.0015
1	2	Dome	23	0.7487	0.0005	0.0012	0.0008	0.0068	0.0020	0.0005	0.0025
1	3	Dome	21	0.7497	0.0008	0.0013	0.0005	0.0009	0.0015	0.0015	0.0030
1	4	Dome	1	0.7495	0.0012	0.0005	0.0007	0.0022	-0.0005	0.0020	0.0015
1	5	Dome	17	0.7480	0.0012	0.0013	0.0006	0.0028	-0.0015	0.0015	0.0000
1	6	Dome	8	0.7480	0.0011	0.0011	0.0008	0.0019	0.0010	0.0010	0.0020
1	7	Dome	15	0.7471	0.0001	0.0008	0.0007	0.0007	0.0025	0.0000	0.0025
1	8	Dome	2	0.7490	0.0015	0.0014	0.0011	0.0033	0.0000	0.0015	0.0015
1	9	Dome	24	0.7482	0.0007	0.0009	0.0006	0.0023	-0.0005	0.0005	0.0000
1	10	Dome	14	0.7488	0.0006	0.0004	0.0006	0.0015	0.0035	-0.0010	0.0025
1	11	Dome	3	0.7488	0.0006	0.0007	0.0005	0.0046	-0.0005	0.0020	0.0015
1	12	Dome	22	0.7491	0.0007	0.0009	0.0006	0.0041	0.0000	0.0015	0.0015
1	13	Dome	5	0.7494	0.0005	0.0012	0.0008	0.0030	0.0010	0.0005	0.0015
1	14	Dome	25	0.7470	0.0003	0.0010	0.0006	0.0027	0.0005	0.0005	0.0010
1	15	Dome	4	0.7488	0.0008	0.0010	0.0006	0.0014	0.0010	0.0005	0.0015
1	16	Dome	12	0.7487	0.0009	0.0003	0.0005	0.0013	0.0010	0.0005	0.0015
1	17	Dome	19	0.7472	0.0006	0.0013	0.0012	0.0038	0.0010	0.0010	0.0020
1	18	Dome	13	0.7490	0.0004	0.0006	0.0006	0.0008	0.0005	0.0010	0.0015
1	19	Dome	9	0.7481	0.0006	0.0013	0.0005	0.0015	0.0000	0.0025	0.0025
1	20	Dome	7	0.7466	0.0008	0.0012	0.0005	0.0027	0.0010	0.0020	0.0030
1	21	Dome	6	0.7479	0.0005	0.0007	0.0009	0.0046	0.0010	0.0010	0.0020
1	22	Dome	11	0.7484	0.0003	0.0007	0.0006	0.0019	0.0000	0.0025	0.0025
1	23	Dome	16	0.7474	0.0007	0.0007	0.0009	0.0009	0.0010	0.0010	0.0020
1	24	Dome	18	0.7474	0.0010	0.0033	0.0011	0.0022	0.0005	0.0005	0.0010
1	25	Dome	20	0.7478	0.0004	0.0015	0.0007	0.0011	0.0000	0.0005	0.0005
2	1	Dome	41	0.7479	0.0007	0.0008	0.0009	0.0056	0.0030	0.0020	0.0050
2	2	Dome	29	0.7474	0.0011	0.0009	0.0010	0.0011	0.0005	0.0015	0.0020
2	3	Dome	34	0.7482	0.0004	0.0006	0.0003	0.0016	0.0020	0.0030	0.0050
2	4	Dome	36	0.7488	0.0013	0.0005	0.0006	0.0028	0.0020	0.0000	0.0020
2	5	Dome	46	0.7481	0.0009	0.0024	0.0007	0.0016	0.0015	0.0005	0.0020
2	6	Dome	30	0.7481	0.0005	0.0006	0.0009	0.0023	0.0000	0.0020	0.0020
2	7	Dome	45	0.7480	0.0003	0.0007	0.0006	0.0032	-0.0005	0.0010	0.0005
2	8	Dome	50	0.7481	0.0004	0.0011	0.0009	0.0015	0.0005	0.0000	0.0005
2	9	Dome	47	0.7476	0.0006	0.0008	0.0008	0.0029	0.0015	0.0010	0.0025
2	10	Dome	43	0.7443	0.0102	0.0009	0.0009	0.0009	0.0010	0.0000	0.0010
2	11	Dome	26	0.7480	0.0006	0.0013	0.0005	0.0046	0.0015	0.0010	0.0025
2	12	Dome	42	0.7475	0.0006	0.0009	0.0004	0.0022	-0.0020	0.0025	0.0005
2	13	Dome	33	0.7477	0.0007	0.0006	0.0004	0.0009	0.0020	0.0005	0.0025
2	14	Dome	37	0.7481	0.0005	0.0015	0.0003	0.0046	0.0010	0.0005	0.0015
2	15	Dome	31	0.7488	0.0030	0.0004	0.0004	0.0013	0.0020	0.0005	0.0025
2	16	Dome	32	0.7476	0.0007	0.0008	0.0003	0.0036	0.0015	-0.0005	0.0010
2	17	Dome	49	0.7440	0.0004	0.0004	0.0006	0.0016	0.0030	0.0025	0.0055
2	18	Dome	35	0.7475	0.0003	0.0007	0.0003	0.0009	-0.0005	0.0025	0.0020
2	19	Dome	44	0.7473	0.0013	0.0007	0.0004	0.0025	0.0020	0.0005	0.0025
2	20	Dome	28	0.7483	0.0011	0.0006	0.0004	0.0030	0.0000	0.0015	0.0015
2	21	Dome	27	0.7469	0.0006	0.0005	0.0005	0.0012	0.0005	0.0015	0.0020
2	22	Dome	38	0.7484	0.0021	0.0003	0.0005	0.0022	0.0000	0.0030	0.0030
2	23	Dome	48	0.7483	0.0004	0.0006	0.0008	0.0031	0.0015	0.0005	0.0020
2	24	Dome	40	0.7475	0.0007	0.0012	0.0006	0.0006	0.0020	0.0000	0.0020
2	25	Dome	39	0.7480	0.0005	0.0005	0.0005	0.0009	0.0020	0.0005	0.0025

Iso bag	Iso Pos	Fill Cond	Fill #	Al dia	Al circularity	Cermet circularity	Cermet circularity2	Cermet concentricity	Centr-Top	Bot-Centr	Bot-Top
3	1	Level	66	0.7469	0.0006	0.0016	0.0008	0.0084	0.0025	0.0040	0.0065
3	2	Level	54	0.7502	0.0010	0.0010	0.0005	0.0045	0.0000	0.0010	0.0010
3	3	Level	59	0.7480	0.0005	0.0009	0.0005	0.0008	0.0010	0.0005	0.0015
3	4	Level	61	0.7453	0.0004	0.0005	0.0004	0.0018	0.0010	0.0000	0.0010
3	5	Level	71	0.7480	0.0012	0.0006	0.0006	0.0026	0.0005	0.0015	0.0020
3	6	Level	55	0.7484	0.0002	0.0019	0.0004	0.0022	0.0010	0.0000	0.0010
3	7	Level	70	0.7495	0.0005	0.0009	0.0005	0.0026	-0.0005	0.0010	0.0005
3	8	Level	75	0.7486	0.0005	0.0007	0.0005	0.0030	0.0000	0.0010	0.0010
3	9	Level	72	0.7475	0.0004	0.0007	0.0011	0.0035	0.0010	0.0000	0.0010
3	10	Level	68	0.7481	0.0006	0.0012	0.0005	0.0018	0.0025	0.0000	0.0025
3	11	Level	51	0.7481	0.0009	0.0005	0.0006	0.0024	-0.0005	0.0015	0.0010
3	12	Level	67	0.7479	0.0006	0.0044	0.0005	0.0008	0.0005	0.0010	0.0015
3	13	Level	58	0.7480	0.0015	0.0038	0.0007	0.0026	0.0005	0.0010	0.0015
3	14	Level	62	0.7501	0.0101	0.0016	0.0004	0.0011	0.0010	0.0005	0.0015
3	15	Level	56	0.7482	0.0009	0.0003	0.0007	0.0004	0.0015	0.0005	0.0020
3	16	Level	57	0.7478	0.0007	0.0041	0.0004	0.0047	0.0015	-0.0005	0.0010
3	17	Level	74	0.7465	0.0014	0.0010	0.0004	0.0011	0.0010	0.0005	0.0015
3	18	Level	60	0.7487	0.0003	0.0005	0.0005	0.0022	0.0020	-0.0005	0.0015
3	19	Level	69	0.7453	0.0006	0.0009	0.0004	0.0048	0.0020	0.0000	0.0020
3	20	Level	53	0.7460	0.0004	0.0014	0.0007	0.0029	0.0035	0.0020	0.0055
3	21	Level	52	0.7484	0.0008	0.0014	0.0013	0.0013	-0.0015	0.0020	0.0005
3	22	Level	63	0.7474	0.0006	0.0009	0.0006	0.0030	0.0015	0.0000	0.0015
3	23	Level	73	0.7483	0.0009	0.0004	0.0007	0.0014	0.0005	0.0015	0.0020
3	24	Level	65	0.7445	0.0002	0.0006	0.0009	0.0035	0.0005	0.0010	0.0015
3	25	Level	64	0.7488	0.0008	0.0006	0.0004	0.0017	0.0020	-0.0005	0.0015
4	1	Level	85	0.7489	0.0011	0.0014	0.0010	0.0007	-0.0015	-0.0010	-0.0025
4	2	Level	98	0.7494	0.0013	0.0010	0.0008	0.0045	-0.0010	0.0010	0.0000
4	3	Level	96	0.7460	0.0006	0.0012	0.0006	0.0023	0.0010	0.0025	0.0035
4	4	Level	76	0.7497	0.0005	0.0006	0.0009	0.0016	0.0010	0.0000	0.0010
4	5	Level	92	0.7450	0.0011	0.0065	0.0020	0.0016	0.0005	0.0020	0.0025
4	6	Level	83	0.7500	0.0006	0.0038	0.0007	0.0027	0.0000	0.0030	0.0030
4	7	Level	90	0.7487	0.0007	0.0013	0.0008	0.0027	0.0000	0.0000	0.0000
4	8	Level	77	0.7469	0.0008	0.0011	0.0008	0.0026	-0.0005	0.0015	0.0010
4	9	Level	99	0.7482	0.0008	0.0016	0.0010	0.0045	0.0010	0.0030	0.0040
4	10	Level	89	0.7489	0.0004	0.0058	0.0005	0.0016	0.0000	0.0015	0.0015
4	11	Level	78	0.7492	0.0006	0.0006	0.0003	0.0029	0.0010	0.0005	0.0015
4	12	Level	97	0.7449	0.0021	0.0034	0.0003	0.0036	0.0020	0.0015	0.0035
4	13	Level	80	0.7463	0.0008	0.0011	0.0005	0.0029	0.0005	-0.0005	0.0000
4	14	Level	100	0.7481	0.0005	0.0052	0.0006	0.0013	-0.0010	0.0025	0.0015
4	15	Level	79	0.7440	0.0007	0.0049	0.0006	0.0017	0.0020	0.0005	0.0025
4	16	Level	87	0.7464	0.0011	0.0013	0.0006	0.0041	0.0000	0.0020	0.0020
4	17	Level	94	0.7476	0.0006	0.0007	0.0008	0.0035	0.0005	0.0015	0.0020
4	18	Level	88	0.7490	0.0004	0.0010	0.0005	0.0033	-0.0010	0.0010	0.0000
4	19	Level	84	0.7448	0.0007	0.0070	0.0005	0.0022	0.0020	0.0030	0.0050
4	20	Level	82	0.7493	0.0005	0.0077	0.0008	0.0009	0.0000	0.0010	0.0010
4	21	Level	81	0.7480	0.0003	0.0106	0.0008	0.0037	0.0005	0.0015	0.0020
4	22	Level	86	0.7494	0.0004	0.0007	0.0005	0.0010	0.0010	0.0000	0.0010
4	23	Level	91	0.7489	0.0005	0.0020	0.0005	0.0012	0.0005	0.0005	0.0010
4	24	Level	93	0.7453	0.0013	0.0006	Slipped		0.0000	0.0005	0.0005
4	25	Level	95	0.7475	0.0004	0.0007	0.0007	0.0035	0.0015	0.0005	0.0020

Table 1: Data derived from the baseline experiments.

Plot 1: Alumina outside diameter measured at the top end vs. isopress position

Plot 2: Circularity of the Alumina outside diameter after isopressing vs. isopress position measured with the RAM optical system.

Plot 3: Cermet circularity of the top end of the cermet cone after second green machining vs. isopress bag position. Measured with the RAM optical system.

Plot 4: Cermet circularity after removing an additional .010 inch of material from the top face vs. isopress bag position. Measured with the RAM optical system.

Plot 5: Difference in bottom and top diameters as measured by the calipers.

Plot 6: Cermet concentricity with Alumina OD after removing an additional .010 inch of material from top face. Measured with the RAM optical system.

Plot 7: Average alumina OD

Plot 8: Standard deviation of alumina OD

Plot 9: Average alumina circularity.

Plot 10: Standard deviation of alumina circularity.

Plot 11: Average cermet circularity.

Plot 12: Standard deviation of cermet circularity.

Plot 13: Average Cermet circularity after removing additional .010" of material.

Plot 14: Standard deviation of cermet circularity after removing additional .010" of material.

Plot 15: Average cermet concentricity

Plot 16: Standard deviation of cermet concentricity.

Plot 17: Average conical tapering of alumina.

Plot 18: Standard deviation of conical tapering of alumina.

Plot 19: Cermet circularity (after removing additional .010" of material) vs. alumina circularity for baseline parts.

Plot 20: Cermet circularity (after removing additional .010" of material) vs. cermet concentricity for baseline parts.

Plot 21: Boxplot of cermet circularity vs. fill condition for baseline parts.

Plot 22: Boxplot of cermet circularity (after removing additional .010" of material) vs. fill condition for baseline parts.

Plot 23: Boxplot of alumina diameter vs. fill condition for baseline parts.

Plot 24: Boxplot of alumina taper (i.e. bottom – top) vs. fill condition for baseline parts.

Figure 5. Baseline parts X-rayed after second green machining. Parts having fill numbers 1 through 50.

Figure 6. Baseline parts X-rayed after second green machining. Parts having fill numbers 51 through 100.

Design of Experiments

The actual design of experiments (DoE) for the feedthru insulator as outlined in Table 2 was performed at Ceramtec on April 19, 1999. One hundred parts were used in this DoE. Given the sixteen different runs in Table 2, twelve runs were repeated six times and four runs were repeated seven times. Although there are some minor differences, Table 2 is essentially the same as scenario 1 in appendix C. The order looks different but given that this experiment is a full factorial, all possible combinations exist in both tables. The table in appendix C was designed for a recipe of one slurry batch, however, when we performed the experiments at Ceramtec we decided to mix enough for two batches at once which explains the doubling of the factor levels for the solvent and the surfactant in Table 2. Also, while at Ceramtec, we decided to tweak the planned low and high solvent levels. A slurry mix having 16 grams of solvent seemed too thick (the mixing balls were stuck in the slurry) and a slurry mix having 24 grams of solvent seemed too runny. The preparation of the slurry used for WR parts is defined by Work Instruction number WI-704191-040 Issue B, however, for this experiment we used Sandi94 powder instead of 94ND2 powder. For reference purposes, a nominal two batch slurry mixture would contain 40 grams of CND50 powder, 20 grams of solvent (DGMA), and 6 drops of surfactant. An explanation of the factor levels shown in Table 2 is given below.

Orifice: This factor refers to the inside diameter of the needle used on the syringe that dispensed the slurry. The small orifice was .033 inches in diameter and made of metal. The large orifice was .060 inches in diameter and made of plastic.

Fill: This factor refers to the fill condition of the slurry when placed into the alumina blank. The level condition is reached when the slurry is level (or flush) with the top surface of the alumina. Part number 53 in Figure 7 was filled with a large orifice to the level condition and part number 69 in Figure 8 was filled with a small orifice to the level condition. The domed condition occurs when additional slurry is deposited beyond the level condition. Doming was defined by filling the syringe to a preset amount. Through experimentation doming for the small orifice was defined by filling the syringe to the .4 cc mark, but, for the large orifice, doming was defined by filling the syringe to the .6 cc mark. The reason for the difference is unclear because the desired effect was to deposit the same amount whether the small or large orifice was used. The larger dead volume in the large orifice may be responsible for requiring more slurry in the syringe to obtain the same desired effect. In spite of our objective to have consistent doming, the doming was not that consistent as the filling progressed from slurry mix to slurry mix. This difference is evident in Figure 7 and Figure 8. Part numbers 52 and 55 in Figure 7 were filled with a small orifice to the domed condition while part numbers 16 and 54 in Figure 8 were filled with a large orifice to the domed condition. The average dome height for the small orifice appears to have been less than the average dome height for the large orifice. Dave Van Ornum who did the slurry filling for the baseline experiments said that doming was even less prominent in the baseline experiments. According to Dave Van Ornum and the operator at Ceramtec, some doming is preformed on all WR parts.

Solvent: This factor refers to the amount of DGMA used in the slurry mixture. The lower level was 18 grams and the upper level was 22 grams. Calling the DGMA a solvent is really a misnomer for this application, rather, the DGMA acts as a vehicle to transport the cermet.

Surfactant: This factor refers to the amount of surfactant (Nuospense 657) used in the slurry mixture. The lower level was 0 drops and the upper level was 12 drops.

Run	Orifice	Fill	Solvent (grams)	Surfactant (drops)
1	small	level	18	0
2	large	level	18	0
3	small	dome	18	0
4	large	dome	18	0
5	small	level	22	0
6	large	level	22	0
7	small	dome	22	0
8	large	dome	22	0
9	small	level	18	12
10	large	level	18	12
11	small	dome	18	12
12	large	dome	18	12
13	small	level	22	12
14	large	level	22	12
15	small	dome	22	12
16	large	dome	22	12

Table 2: The design of experiments. A full factorial of four factors.

1.0	<u>Slurry mix #1</u>	Solvent: 18 grams	Surfactant: 0 drops
1.1	Small orifice, domed condition		
1.2	Small orifice, level condition		
1.3	Large orifice, level condition		
1.4	Large orifice, domed condition		
2.0	<u>Slurry mix #2</u>	Solvent: 18 grams	Surfactant: 12 drops
2.1	Large orifice, domed condition		
2.2	Large orifice, level condition		
2.3	Small orifice, domed condition		
2.4	Small orifice, level condition		
3.0	<u>Slurry mix #3</u>	Solvent: 22 grams	Surfactant: 0 drops
3.1	Large orifice, domed condition		
3.2	Large orifice, level condition		
3.3	Small orifice, domed condition		
3.4	Small orifice, level condition		
4.0	<u>Slurry mix #4</u>	Solvent: 22 grams	Surfactant: 12 drops
4.1	Large orifice, domed condition		
4.2	Large orifice, level condition		
4.3	Small orifice, domed condition		
4.4	Small orifice, level condition		

Table 3: Slurry fill sequence.

Figure 7. Picture of slurry filled parts after the drying operation but before isopressing. Note the part numbers written on the part.

Figure 8. Picture of slurry filled parts after the drying operation but before isopressing. Note the part numbers written on the part.

Figure 9. Picture of slurry filled parts after isopressing. Note the part numbers written on the part.

Figure 10. Picture of slurry filled parts after isopressing. Note the part numbers written on the part.

Given the two levels for each factor, namely solvent and surfactant, there are four different slurry mixtures used in this DoE. We mixed and used each mixture one at a time before proceeding to the next mixture in order to avoid the risk of a drying out the mixture. Even though the mixture is covered when not in use the mixture can still dry out if not readily consumed. The slurry filling operation of the DoE took an entire day to complete. The slurry filling sequence is outlined in Table 3. The filling sequence constraint prevented us from having a truly random filling sequence.

Experimental Notes:

- Prior to filling a part (any part) the syringe was rinsed in Butoxyethoxy ethyl acetate.
- There was a concern that the level fill condition caused the slurry to pull away from the alumina along the top edge of the cone. The operator swirled the syringe in circles while filling to combat this potential problem.
- The operator commented that air pockets seem to be noticeable with slurry mix #1.
- The parts were placed in four different isopress bags. Each bag held 25 parts.
- The oven was given two hours to warm up to 248 deg F. The parts were placed in the oven during this warm up period. The oven was then held to this temperature for 16 hours.
- The machining sequence was randomized among the part numbers.
- The optical measurement sequence was randomized among the part numbers.
- Surface cracks were prominent with slurry mix #3 upon drying in ambient conditions.
- We observed that the parts that had 22 grams of solvent tended to have more surface cracks after drying in the oven than those parts that had only 18 grams of solvent. Cracking was not a response variable in the DoE and hence was not included in the formal analysis. Parts in Figure 7 and Figure 8 show evidence of this observation. The surface cracks seen in many of the parts appear to be superficial and are not good predictors of yield in the downstream processes. These surface cracks appear to heal after isopressing as can be seen in Figure 9 and Figure 10. In particular, parts 55 and 56 in Figure 7 and part 54 in Figure 8 are shown to have surface cracks, however, these same parts appear healed in Figure 10. The parts shown in the first two rows in Figure 8 do not have surface cracks and had just the 18 grams of solvent.

The data was collected at Ceramtec but the analysis was performed at Sandia. Minitab Release 12.1 software was the tool used to for the Design of Experiments (DoE) analysis and statistical analysis. The response variables for the DoE analysis shown in Table 5 and Table 6 are defined below. Due to character limitation in Minitab, alternate names for some of the response variables were used and are shown in italics. The terminology face or face-off is used to denote that the measurement was made directly after second green machining as listed in appendix A.

- ♦ Taper: The difference between the alumina OD measured at the bottom end and measured at the top end. The OD at the top and bottom are measured at one location each using calipers. The measurements are made directly after isopressing.
- ♦ Al dia optical (*Al dia*): The outside diameter of the part at the top end after isopressing measured by the RAM optical measuring device which constructs a best fit circle through eight points.
- ♦ Al circ optical (*Al circ*): The circularity (roundness) of “Al dia optical” measured by the RAM optical device.
- ♦ Al dia face-off: The outside diameter of the part at the top end after second green machining measured by the RAM optical device which constructs a best fit circle through eight points.

- ◆ Al circ face-off: The circularity (roundness) of the “Al dia face-off” measured by the RAM optical device.
- ◆ Cermet dia (*Cer dia face*): The diameter of the circular face of the conical cermet after second green machining measured at the top end using the RAM optical measuring device. The intersection of the cone and the top face defines a circle.
- ◆ Cermet circ (*Cer circ face*): The circularity of the “Cermet dia” measured by the RAM optical device. This measurement occurs after second green machining.
- ◆ Conc (*Cer conc*): The concentricity between the “Al dia face-off” and the “Cermet dia” measured by the RAM optical measuring device.
- ◆ X-ray voids: A score from 0 to 5 was assigned to each part based upon the size of the void found in the x-rays shown in **Figure 11**. All of the voids occurred in the columnar portion of the cermet (not the conical portion). If no void was found, the score of zero was assigned. Part number 41 was not assigned a score because the conical section of the cermet fell out upon inserting the part into the isopress bag.

Table 6 is a compilation of the collected data necessary to perform the design of experiments analysis sorted by factor levels. The table in appendix D contains the same information found in Table 6 plus some additional information. Also, the table in appendix D is sorted by part number not factor levels. The additional information found in appendix D is *Run #*, *ISO bag #*, and *Bag pos*. *Run #* refers to the run number found in Table 2 that identifies the factor levels but does not represent the order of the experimental tests. *ISO bag #*, refers to one of four isopress bags used for the isopressing operation. All the parts with the same *ISO bag #* were placed in the same isopress bag. *Bag pos.*, refers to the position that part occupied while in the isopress bag (see Figure 4); position 1 is at the bottom of the bag and position 25 is at the top of the bag. Table 4 is a summary of the disposition of the parts used in the design of experiments process that were scrapped. The information regarding the disposition of parts is reiterated in Table 6 and in appendix D by using color-coding defined at the bottom of each table. The blue color indicates measured values that appeared suspiciously high compared to similar measurements made in other parts. The DoE analysis was done with and without these suspiciously high values to judge their impact. The analysis without the high values was not much different than the analysis with the high values; therefore the analysis included in this report is only the analysis including these high values. The orange color indicates that the part did not survive the entire fabrication process as outlined in appendix A and were therefore scrapped. Part #41 lost the conical section of the cermet slurry while being placed into the isopress bag. Part #82 was discharged from the chuck during the final green machining operation, however, all the data shown in Table 6 was collected prior to it being scrapped. As required in the normal fabrication process, three parts are D-tested per lot prior to the final inspect operation. During the final inspect operation, three parts were rejected because of chips in the cermet located along the circumference of the bottom via. Table 4 lists the part numbers of the parts that dropped out of the process, the D-tested parts, and the rejected parts.

	Part numbers
Dropped out of process	41, 82
D-test at Ceramtec	7, 21, 77
Rejected by Ceramtec	32, 37, 60

Table 4: Disposition of parts that did not result in a deliverable part (i.e., scrapped parts).

Plot 25 through Plot 47 illustrate the analysis derived from the Minitab software. Four different plots are used, pareto charts, main effects plot, Interaction plots and boxplots. The pareto charts are used to gage the relative significance of factors that affect the response variables. This chart allows us to concentrate our effort on the significant few factor rather than the less significant many. A single letter to the left of a bar on the pareto chart denotes a main effect; multiple letters denote interactions. The pareto chart includes a red vertical dashed line which is (with the exception of Plot 38) located at the 90% confidence level. Setting Alpha equal to .10 in Minitab causes Minitab to construct a line at the 90% confidence level. Thus bars that extend to the right of the vertical dashed line are considered statistically significant. Plot 38 is the exception; it has alpha set equal to .20, which corresponds to a confidence level of 80%. Not only should consideration be given to the statistical significance of the plots but also to the significance of the effect. The change in the response variable could be so miniscule that it is not worth investigating. The main effects plot gives an indication of variations in the response variable as a function of changing one factor level at a time. The interaction plot indicates the variation in the response variable due to interactions between two factors. The effects of three way and four way interactions are generally less significant to the analysis and are therefore not included in this report. The complete effect on the response variable should be calculated by superimposing the main effect onto the interaction effect. Before interpreting either the main effects or the interaction effects, it is advisable to check the pareto chart to determine whether or not the factor or factors are considered statistically significant. The boxplots illustrate the spread (distribution) in the data. The lower whisker and any outliers below the lower whisker represent the first quartile. The bottom portion of the box represents the second quartile. The upper portion of the box represents the third quartile. The upper whisker and any outliers above the upper whisker represent the fourth quartile. The horizontal line separating the lower and upper portions of the box represents the median. The asterisks represent the outliers that are defined by a formula in Minitab. Minitab plots for the response variables *Al circ face* and *Al dia face* are absent from this report because those response variables were not significantly affected by the factors. The interpretations of Plot 25 through Plot 47 are provided below. The Cermet Process Improvement (CPI) team examined these plots and decided upon factor level recommendations. The preliminary recommendations based upon these interpretations are summarized in Table 5.

Plot 25 indicates that the interaction between the factors orifice and fill affect the response variable alumina circularity. Alumina circularity is also affected by the single factor surfactant, but to a lower confidence level (i.e. >80%). Plot 26 indicates that lowering the surfactant from 12 drops to 0 drops only reduces the alumina circularity by .0001 inch. Plot 27 indicates that the interaction between the factors orifice and fill affect the circularity by .0002 inch. The undesirable combination would be a large orifice and a dome condition. Obviously, a smaller value for alumina circularity is desirable. Therefore the recommendation would be to use a small orifice and fill to a level condition. The total effect of the level condition is computed by summing its main effect (Plot 26) with its interaction effect. Plot 28 indicates that the level fill condition results in less spread in the data which reinforces the level fill condition recommendation. Plot 29 indicates that 0 drops of surfactant result in less spread in the data, which reinforces the main effects recommendation of 0 drops. The summation of effects due to implementing the recommended factor levels as compared to a poor combination of levels can make a difference as much as .0005 inch.

Plot 30 indicates that all of the main effects and many of the interactions are statistically significant for the response variable, alumina diameter. The fill condition has the greatest main effect (see Plot 31) making a difference in .0025 inches on alumina diameter. Contrary to one's

intuition, the dome fill condition results in a smaller alumina diameter. In fact, part 41 which had no cermet material in its conical section prior to isopressing, has the largest alumina diameter. Plot 32 indicates significant interaction between orifice and fill. By superimposing the main effects and the interaction effects, a total difference in diameter of about .004 inch could be implemented by just changing the factor levels. Even though the effects are significant, the CPI team could not make recommendations based upon these effects because the CPI team could not decide what a desirable alumina diameter should be. We considered the possibility that the success of the healing phenomenon is a function of factor levels. That is the ability of the cermet, during isopressing, to close voids and seal cracks depends upon the factor levels. A smaller alumina diameter may be an indication that healing process was more complete. It is interesting to note that a small orifice results in a larger diameter. A smaller orifice requires greater pressure inside the syringe to extract the cermet slurry. It is possible that the greater pressure is pre-compressing the cermet prior to filling. It is desirable, however, to have a consistent diameter to minimize the number of collets needed for the second green machining operation. Therefore the recommendation to use 22 grams of solvent is made based upon the boxplot (see Plot 33) indicating a narrower spread in the data for the greater solvent condition.

Plot 34 indicates that the factor solvent has a significant main effect on the response variable Cermet circularity face. This response variable is a measure of the circularity of the cermet diameter. There are also two significant interactions to consider, one is between the factors fill and solvent and the other is between the factors solvent and surfactant. The main effects plot, Plot 35, indicates that 22 grams of solvent results in less circularity than 18 grams of solvent. The interaction plot, Plot 36, also indicates that 22 grams of solvent is better than 18 grams. The effect on circularity seems to be minimal, however, the sum of all the effects (i.e. main plus interactions) was judged significant enough to warrant a preliminary recommendation in Table 5. Plot 37 is a boxplot that reinforces the recommendation of 22 grams of solvent because at that solvent level there is less spread in the data.

Plot 38 indicates that there are two different interactions that affect cermet concentricity beyond the 80% confidence level. The confidence level was lowered from 90% to 80% on this plot because the change in the cermet concentricity was significant. None of the main effects (see Plot 39) are deemed significant. Plot 40 illustrates that dome condition with zero surfactant minimizes concentricity.

The cermet diameter (*Cer dia face*) was not significantly affected by main effects or interaction effects so those plots were omitted from this report. The only plot worth considering is Plot 41, which illustrates the spread in the data as a function of surfactant level. The preliminary recommendation based upon Plot 41 is for twelve drops of surfactant because that condition results in less spread in the data.

Plot 42 indicates that the response variable taper is very sensitive to factor levels. Since taper is a function of the alumina diameter we would expect Plot 42 to be consistent with Plot 30 and it is. All of the main effects and many of the interactions are statistically significant. Even though the effects are significant, the CPI team could not make recommendations based upon the main effects shown in Plot 43 because the CPI team could not decide what a desirable taper should be. On one hand, zero taper is desirable for proper fit into a collet. On the other hand, perhaps tapering is an indication of the cermet healing itself and therefore should be encouraged. The CPI team recommended 22 grams of solvent based upon the spread in data shown in Plot 44 because it is desirable to have a consistent taper.

The x-ray voids response variable is probably the most insightful and should be given the greatest weight when deciding upon the various factor levels. A void in the cermet is an indication that the cermet slurry is having difficulty flowing to its destination. Even though the voids, that were found, occurred in locations that were eventually machined away, the CPI team felt that the slurry filling process would be much more robust without the voids. This situation may be extremely important for other cermet piece parts that have more intricate passages. Plot 45 indicates that the factor solvent has a significant (greater than 90% confidence) main effect on the response variable x-ray voids. The factor surfactant also has a main effect but only to a confidence level of about 80%. Plot 46 illustrates the main effect due to solvent level is much greater than the main effect due to surfactant. Plot 47 illustrates the interaction effects, which are not as significant as the main effects. In order to minimize the score given to the response variable, x-ray voids, the preliminary recommendation is made to increase the solvent level to 22 grams and to reduce the surfactant level to zero drops.

The CPI team attempted to include ultrasonic tests and microfocus x-ray as response variables, but no distinguishing features from part to part could be found to enable a DoE analysis. Neither ultrasonic tests nor microfocus x-rays could find flaws within the cermet. Plot 48 is derived from a ultrasonic test and is typical of all the DoE parts. **Figure 12** is a microfocus image of part # 52 and is typical of all DoE parts.

Some thought was given to considering the scrapped parts shown in Table 4 as a response variable in the DoE analysis. Ceramtec stated that the D-tested units were marginal in regards to product acceptance. Unfortunately the sample size is too small and no patterns could be detected.

The final recommendations based upon the DoE analysis is given in the next section.

	Orifice		Fill		Solvent		Surfactant	
Response	DoE	St dev	DoE	St dev	DoE	St dev	DoE	St dev
Al circ	small		level					0
Al circ face								
Al dia	?		?		?	22	?	
Al dia face								
Cer circ face					22	22		
Cer conc			dome				0	
Cer dia face								12
Taper	?		?		?	22	?	
X-ray voids					22		0	

Table 5: Preliminary recommendations for factor levels to improve the response variable based upon the results of the design of experiments and from analyzing the standard deviation of the response data. The “?” denotes that the factor has a significant effect on the response variable, however, a desirable value for the response variable could not be determined.

Part #	Orifice	Fill	Solv.	Surf.	AI dia top	AI dia bottom	Taper	AI dia optical	AI circ optical	AI dia face off	AI circ face off	Cermet dia	Cermet circ	Conc.	X-ray voids
10	small	dome	18	0	0.745	0.746	0.001	0.7432	0.0004	0.6257	0.0005	0.2957	0.0003	0.0001	0
25	large	dome	18	0	0.742	0.748	0.006	0.7396	0.0005	0.6260	0.0004	0.2990	0.0007	0.0029	0
35	large	dome	18	0	0.742	0.748	0.006	0.7402	0.0006	0.6259	0.0007	0.2940	0.0007	0.0007	0
40	large	dome	18	0	0.742	0.749	0.007	0.7399	0.0005	0.6260	0.0006	0.2913	0.0006	0.0005	0
44	small	dome	18	0	0.743	0.749	0.006	0.7406	0.0005	0.6257	0.0007	0.2940	0.0007	0.0020	0
49	small	dome	18	0	0.744	0.748	0.004	0.7423	0.0002	0.6260	0.0005	0.2931	0.0002	0.0021	4
68	small	dome	18	0	0.744	0.747	0.003	0.7441	0.0005	0.6262	0.0005	0.2933	0.0005	0.0005	0
72	large	dome	18	0	0.742	0.747	0.005	0.7404	0.0012	0.6259	0.0005	0.2946	0.0003	0.0011	0
73	large	dome	18	0	0.742	0.747	0.005	0.7412	0.0003	0.626	0.0005	0.2956	0.0008	0.0013	0
80	small	dome	18	0	0.743	0.746	0.003	0.7409	0.0006	0.6259	0.0005	0.2953	0.0007	0.0042	1
84	large	dome	18	0	0.743	0.747	0.004	0.7409	0.0004	0.6255	0.0007	0.2933	0.0009	0.0007	0
91	small	dome	18	0	0.744	0.748	0.004	0.7419	0.0011	0.6259	0.0005	0.2943	0.0018	0.0021	0
4	large	level	18	0	0.744	0.748	0.004	0.743	0.0008	0.6261	0.0006	0.2928	0.0015	0.0013	0
8	small	level	18	0	0.743	0.748	0.005	0.7428	0.0009	0.6261	0.0008	0.2939	0.0003	0.0015	0
12	large	level	18	0	0.746	0.748	0.002	0.7442	0.0004	0.6261	0.0005	0.2910	0.0010	0.0014	0
15	small	level	18	0	0.744	0.748	0.004	0.7426	0.0005	0.6256	0.0004	0.2920	0.0006	0.0004	1
19	large	level	18	0	0.744	0.747	0.003	0.7433	0.0005	0.6257	0.0007	0.2936	0.0013	0.0006	0
21	large	level	18	0	0.746	0.747	0.001	0.745	0.0005	0.6260	0.0004	0.2971	0.0011	0.0031	0
22	small	level	18	0	0.744	0.747	0.003	0.7427	0.0004	0.6260	0.0007	0.2929	0.0008	0.0008	1
34	large	level	18	0	0.743	0.746	0.003	0.7425	0.0006	0.6258	0.0006	0.2944	0.0007	0.0022	0
38	large	level	18	0	0.745	0.748	0.003	0.7447	0.0004	0.6260	0.0008	0.2934	0.0010	0.0018	0
41	large	level	18	0	0.748	0.748	0	0.7472	0.0005	0.6259	0.0008				
70	small	level	18	0	0.745	0.748	0.003	0.7433	0.0007	0.6256	0.0008	0.2957	0.0016	0.0045	0
83	small	level	18	0	0.746	0.748	0.002	0.7448	0.0004	0.626	0.0003	0.2936	0.0009	0.0021	0
87	small	level	18	0	0.744	0.747	0.003	0.7437	0.0006	0.6262	0.0006	0.2952	0.0005	0.0047	0
97	small	level	18	0	0.745	0.745	0	0.7425	0.0006	0.6257	0.0005	0.2933	0.0008	0.0009	2
2	large	dome	22	0	0.742	0.749	0.007	0.7405	0.0007	0.6259	0.0004	0.2928	0.0006	0.0024	0
3	large	dome	22	0	0.742	0.748	0.006	0.7396	0.0007	0.6262	0.0009	0.2927	0.0005	0.001	0
16	large	dome	22	0	0.742	0.748	0.006	0.7422	0.0004	0.6259	0.0008	0.2933	0.0006	0.0018	0
23	small	dome	22	0	0.743	0.748	0.005	0.7432	0.0003	0.6259	0.0004	0.2921	0.0009	0.0018	0
45	small	dome	22	0	0.744	0.748	0.004	0.7426	0.0003	0.6259	0.0006	0.2957	0.0006	0.0015	0
50	large	dome	22	0	0.741	0.747	0.006	0.7401	0.0004	0.6258	0.0004	0.2945	0.0006	0.0018	0
54	large	dome	22	0	0.744	0.748	0.004	0.7421	0.0005	0.6260	0.0007	0.2966	0.0008	0.0014	0
58	small	dome	22	0	0.743	0.748	0.005	0.7416	0.0006	0.6258	0.0006	0.2914	0.0007	0.0013	0
75	small	dome	22	0	0.743	0.747	0.004	0.7424	0.0004	0.6265	0.0006	0.2938	0.0006	0.0004	0
81	large	dome	22	0	0.741	0.747	0.006	0.7383	0.0007	0.6260	0.0003	0.2914	0.0003	0.0016	0
89	small	dome	22	0	0.743	0.747	0.004	0.7406	0.0004	0.6257	0.0005	0.3006	0.0005	0.0023	0
98	small	dome	22	0	0.743	0.748	0.005	0.7407	0.0004	0.6258	0.0004	0.2934	0.0004	0.0023	1
1	small	level	22	0	0.745	0.749	0.004	0.7426	0.0004	0.6258	0.0002	0.2941	0.0007	0.0025	0
13	large	level	22	0	0.744	0.748	0.004	0.7441	0.0003	0.6257	0.0003	0.2937	0.0003	0.0008	0
17	small	level	22	0	0.744	0.748	0.004	0.7427	0.0003	0.6259	0.0005	0.2919	0.0005	0.0012	0
29	small	level	22	0	0.745	0.749	0.004	0.7433	0.0006	0.6256	0.0005	0.2912	0.0007	0.0031	0
30	small	level	22	0	0.744	0.747	0.003	0.7431	0.0008	0.6261	0.0005	0.2915	0.0005	0.0030	0
31	large	level	22	0	0.743	0.747	0.004	0.7417	0.0004	0.6258	0.0004	0.2937	0.0004	0.0025	1
43	large	level	22	0	0.744	0.748	0.004	0.7427	0.0006	0.6257	0.0006	0.2931	0.0007	0.0025	0
46	small	level	22	0	0.744	0.749	0.005	0.7423	0.0006	0.6256	0.0003	0.2931	0.0006	0.0006	0
60	large	level	22	0	0.744	0.748	0.004	0.7415	0.0006	0.6261	0.0005	0.2920	0.0006	0.0038	1
61	large	level	22	0	0.744	0.746	0.002	0.7413	0.0008	0.6263	0.0005	0.2975	0.0007	0.0047	0
71	large	level	22	0	0.744	0.747	0.003	0.7423	0.0002	0.6260	0.0005	0.2923	0.0003	0.0013	0
79	large	level	22	0	0.743	0.746	0.003	0.7412	0.0006	0.6257	0.0005	0.2962	0.0006	0.0014	0
86	small	level	22	0	0.744	0.748	0.004	0.7421	0.0006	0.6259	0.0018	0.2908	0.0007	0.0011	0
88	small	level	22	0	0.743	0.748	0.005	0.7411	0.0005	0.6259	0.0008	0.2992	0.0003	0.0023	1
6	large	dome	18	12	0.743	0.747	0.004	0.7401	0.0003	0.6260	0.0005	0.2941	0.0005	0.0023	2
18	small	dome	18	12	0.743	0.748	0.005	0.7408	0.0004	0.6257	0.0006	0.2924	0.0004	0.0011	0
28	large	dome	18	12	0.742	0.748	0.006	0.7394	0.001	0.6259	0.0004	0.2918	0.0006	0.0034	5
32	small	dome	18	12	0.743	0.748	0.005	0.7414	0.0007	0.6261	0.0012	0.2955	0.0004	0.0023	0
33	small	dome	18	12	0.742	0.748	0.006	0.7399	0.0003	0.6258	0.0004	0.2951	0.0008	0.0005	1

Part #	Orifice	Fill	Solv.	Surf.	AI dia top	AI dia bottom	Taper	AI dia optical	AI circ optical	AI dia face off	AI circ face off	Cernet dia	Cernet circ	Conc.	X-ray voids
36	large	dome	18	12	0.742	0.748	0.006	0.7395	0.0006	0.6257	0.0006	0.2929	0.0004	0.0029	1
47	small	dome	18	12	0.742	0.749	0.007	0.7396	0.0007	0.6258	0.0004	0.293	0.0003	0.003	1
48	large	dome	18	12	0.742	0.749	0.007	0.7407	0.0007	0.6258	0.0003	0.2929	0.0006	0.0020	0
51	small	dome	18	12	0.742	0.748	0.006	0.7393	0.0006	0.6258	0.0008	0.2939	0.0003	0.0012	3
63	small	dome	18	12	0.74	0.748	0.008	0.7395	0.0003	0.626	0.0006	0.295	0.0003	0.0034	0
64	large	dome	18	12	0.742	0.747	0.005	0.7389	0.0005	0.6260	0.0008	0.2967	0.0005	0.0025	0
76	large	dome	18	12	0.741	0.748	0.007	0.7397	0.0013	0.6259	0.0004	0.2945	0.0008	0.0017	0
24	small	level	18	12	0.745	0.748	0.003	0.7431	0.0003	0.6255	0.0006	0.2933	0.0009	0.0026	1
37	small	level	18	12	0.744	0.747	0.003	0.7429	0.0006	0.6259	0.0008	0.2932	0.0004	0.0004	0
57	small	level	18	12	0.745	0.748	0.003	0.7432	0.0003	0.6258	0.0005	0.2921	0.0008	0.0008	1
59	large	level	18	12	0.745	0.747	0.002	0.7434	0.001	0.626	0.0004	0.2949	0.0007	0.0023	0
62	large	level	18	12	0.744	0.747	0.003	0.7431	0.0005	0.6261	0.0006	0.2926	0.0003	0.0028	0
66	small	level	18	12	0.745	0.747	0.002	0.7424	0.0009	0.6259	0.0003	0.2945	0.0006	0.0028	0
67	small	level	18	12	0.744	0.744	0	0.7438	0.0004	0.6261	0.0005	0.2929	0.0007	0.0031	3
69	small	level	18	12	0.744	0.747	0.003	0.744	0.0005	0.626	0.0007	0.2939	0.0003	0.0008	0
74	large	level	18	12	0.743	0.746	0.003	0.7439	0.0003	0.6259	0.0004	0.294	0.0006	0.0018	0
85	large	level	18	12	0.743	0.748	0.005	0.7429	0.0004	0.6259	0.0003	0.2956	0.0014	0.0013	0
92	large	level	18	12	0.744	0.748	0.004	0.7431	0.0006	0.6259	0.0009	0.2927	0.0006	0.0025	0
94	large	level	18	12	0.745	0.748	0.003	0.7454	0.0006	0.6259	0.0008	0.2933	0.0011	0.0017	1
9	large	dome	22	12	0.744	0.748	0.004	0.7406	0.0005	0.6258	0.0006	0.2945	0.0005	0.0033	0
27	small	dome	22	12	0.744	0.749	0.005	0.7425	0.0006	0.6261	0.0008	0.2932	0.0009	0.0016	0
39	large	dome	22	12	0.742	0.748	0.006	0.7405	0.0024	0.6259	0.0007	0.2934	0.0008	0.0019	1
42	large	dome	22	12	0.742	0.748	0.006	0.7387	0.0012	0.6257	0.0003	0.2909	0.0009	0.0022	0
52	small	dome	22	12	0.743	0.748	0.005	0.7409	0.0007	0.6259	0.0005	0.2923	0.0012	0.0004	0
55	small	dome	22	12	0.742	0.749	0.007	0.7411	0.0004	0.6259	0.0004	0.2935	0.0004	0.0020	0
65	large	dome	22	12	0.741	0.748	0.007	0.7397	0.0003	0.6260	0.0008	0.2919	0.0005	0.0008	0
77	small	dome	22	12	0.743	0.748	0.005	0.7406	0.0009	0.6260	0.0005	0.2947	0.0006	0.0020	0
93	large	dome	22	12	0.741	0.749	0.008	0.7383	0.0012	0.6260	0.0009	0.2959	0.0009	0.0055	0
95	large	dome	22	12	0.742	0.748	0.006	0.7395	0.0004	0.6261	0.0007	0.2945	0.0005	0.0015	0
99	small	dome	22	12	0.743	0.747	0.004	0.7406	0.0007	0.6262	0.0007	0.2948	0.0008	0.0004	0
100	small	dome	22	12	0.744	0.749	0.005	0.7425	0.0003	0.6258	0.0008	0.2929	0.0007	0.0008	1
5	small	level	22	12	0.745	0.748	0.003	0.7437	0.0009	0.6258	0.0006	0.2944	0.0005	0.0022	0
7	small	level	22	12	0.744	0.749	0.005	0.741	0.0003	0.6257	0.0005	0.2945	0.0005	0.0006	0
11	large	level	22	12	0.745	0.748	0.003	0.7456	0.0004	0.6259	0.0002	0.2941	0.0006	0.001	0
14	large	level	22	12	0.745	0.749	0.004	0.7436	0.0003	0.6258	0.0002	0.2908	0.0004	0.0038	1
20	small	level	22	12	0.744	0.748	0.004	0.7416	0.0002	0.626	0.0004	0.2928	0.0002	0.0013	1
26	large	level	22	12	0.744	0.748	0.004	0.742	0.0002	0.6259	0.0005	0.2923	0.0006	0.0025	0
53	large	level	22	12	0.744	0.749	0.005	0.7429	0.001	0.6261	0.0008	0.2915	0.0005	0.0005	0
56	large	level	22	12	0.744	0.748	0.004	0.7427	0.0004	0.6258	0.0004	0.2927	0.0004	0.001	0
78	small	level	22	12	0.744	0.748	0.004	0.7411	0.0003	0.6258	0.0003	0.2938	0.0004	0.0042	0
82	large	level	22	12	0.744	0.748	0.004	0.7434	0.0006	0.6258	0.0004	0.2917	0.0011	0.0012	0
90	small	level	22	12	0.744	0.748	0.004	0.7421	0.0006	0.6263	0.0005	0.2965	0.0004	0.0015	0
96	small	level	22	12	0.743	0.747	0.004	0.7419	0.0015	0.6261	0.0005	0.2936	0.0005	0.0003	0

	Suspiciously high values
	Parts were scrapped while in process
	Parts were destructively tested
	Parts were rejected at the end of the process

All dimensions are in inches

Table 6: Design of experiments data. Arranged by factor levels.

Figure 11. Design of experiments parts X-rayed after second green machining.

Figure 12. Microfocus x-ray of part # 52.

Figure 13. Optical micrograph photo of D-tested part #7. Part #7 was previously cross-sectioned at Ceramtec.

Plot 25: Pareto chart of the standardized effects for the response variable, Alumina circularity. Alpha=.10.

Plot 26: Main effects plot for the response variable, Alumina circularity.

Plot 27: Interaction plot for the response variable, Alumina circularity.

Plot 28: Boxplot of Alumina circularity by fill condition.

Plot 29: Boxplot of Alumina circularity by surfactant levels.

Plot 30: Pareto chart of the standardized effects for the response variable, Alumina diameter. Alpha = .10.

Plot 31: Main effects plot for the response variable, Alumina diameter.

Plot 32: Interaction plot for response variable, Alumina diameter.

Plot 33: Boxplot of Alumina diameter by solvent levels.

Plot 34: Pareto chart of the standardized effects for the response variable, Cermet circularity face. Alpha = .10.

Plot 35: Main effects plot for the response variable, Cermet circularity face.

Plot 36: Interaction plot for the response variable, Cermet circularity face.

Plot 37: Boxplot of cermet circularity after face-off, by solvent level.

Plot 38: Pareto chart of standardized effects for the response variable, Cermet concentricity. Alpha = .20.

Plot 39: Main effects plot for the response variable, Cermet concentricity.

Plot 40: Interaction plot for the response variable, Cermet concentricity.

Plot 41: Boxplot of the Cermet diameter after face-off by surfactant levels.

Plot 42: Pareto chart of the standardized effects for the response variable, Taper. Alpha = .10

Plot 43: Main effects plot for the response variable, Taper.

Plot 44: Boxplot of Taper by solvent level.

Plot 45: Pareto chart of the standardized effect for the response variable, X-ray voids.

Plot 46: Main effects plot for response variable, X-ray voids.

Plot 47: Interaction plot for the response variable, X-ray voids.

Plot 48: Typical ultrasonic plot of the DoE parts.

Factor level recommendations

Table 5 is a summary of the analysis described in this report, and it consistently recommends that more solvent (22 grams) will improve the performance of the corresponding response variables. More solvent means a more robust process that is less sensitive to uncontrollable variables (e.g. operator fatigue). Although more solvent appears to be a clear winner, the recommendation here is to proceed with caution prior to changing the production process. More experimental data needs to be collected to verify that more solvent will result in higher yield. The response variables chosen in this Design of Experiments (DoE) are considered indirect indicators of yield. A smaller orifice on the syringe may be better than a larger orifice, however, the evidence is not as convincing as the solvent data. No recommendation is given for fill condition or surfactant amount because the data are contradictory. It is interesting to note that adding surfactant may not have any benefit and perhaps could be eliminated from the process. Again, further experimentation would need to confirm this preliminary recommendation prior to making a formal recommendation to remove surfactant from the process. These recommendations could be significantly affected if a decision could be made regarding a desirable alumina diameter or a desirable taper.

Concluding remarks

The fabrication process for the feedthru insulator in place at Ceramtec prior to the DoE resulted in a 73% yield (815 good parts out of 1118 parts started) according to the travelers in appendix B. The 73% yield was calculated counting the D-tested parts as good parts. The yield for this DoE was 92% even if we assume that the D-tested parts would have been scrapped (see Table 4). Somehow the fabrication process used for the DoE was not reflective of the lower yield process that is currently in place at Ceramtec. Perhaps the DoE process took more time and allowed for more attention to detail. Perhaps the switch from 94ND2 powder to Sandi94 powder improved the yield. It would be interesting to conduct a test at Ceramtec, without the aid of Sandia, having Ceramtec build feedthru insulators using the recommended factor levels.

The feedthru insulator (alias target feedthru) is not as challenging as the source feedthru. The lower yield of the source feedthru provides a greater opportunity for improvement. The cermet passages in the source feedthru are smaller and more restrictive to slurry flow. The source feedthru could very well benefit from a similar DoE.

If a DoE is performed on a cermet part again, the factors and the factor levels should be reconsidered. Points to consider: Did the CPI team select the most relevant factors? Were the factor levels extreme enough to make a measurable difference? Other factors worth considering are: drying time, machining feed rates, and grinding wheel grit size. An important response variable missing from our analysis was yield. Yield was not a response variable in our DoE because the factors and the factor levels chosen did not significantly affect yield.

There have been questions regarding differences in the isopressing of parts at Ceramtec compared to Sandia. This report contains measurements such as circularity and concentricity that should be compared to similar measurements made at Sandia.

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Appendix A

Process flow for Feedthru Insulator

11/16/98

**Process flow for Feedthru Insulator
P/N 443403-02**

Process	Subprocess	Traveler seq. #
Press Blank	Get Sandi94 powder	10
	Put in die	
	Press the blank	
	Green bulk density check	
First Green Machine	Machine OD & ID	50
(creates green machine blank)	Machine length and counterbore	
	Section a part for verification (scrap)	
Mix slurry	Weigh CND50 powder	
	Weigh DGMA	
	Pour into mixer	
	Mix for a minimum of 30 minutes	
Load slurry into blank	Fill syringe with slurry	70
	Slurry load part with vacuum & filter paper	
Dry slurry loaded blank	Place entire lot on a tray	
	Place tray in oven	
	Set temperature control to 120 deg C	
	Set timer for 16 hour soak at 120 deg C	
	Remove and cool for 2 hrs	
Isopress slurry loaded blank	Insert 20 to 25 parts w/spacers in rubber bag	
	Cap/plug bag	
	Load bag into isopress	
	Press parts at 30kpsi for 10 minutes (autocycle)	
	Remove bag from press	
	Rinse and dry rubber bag	
	Remove cap/plug	
	Carefully remove blanks & spacers	
	Place parts in cardboard box	
Second green machine	Remove excess slurry from bottom	91
	Load part in chuck (top)	
	Machine top and OD	
	Load part in chuck (bottom)	
	Face the bottom	
	Load in cardboard box	
	Send to gage lab	
Gage lab	Measure by video/optical method	
	Parts are grouped by OD to the nearest .001 inch	
	Calculate stock to be removed	
	Put in cardboard box	
	Send to green machining	
1st operation, final green machine	Set machine up to chucked blank	100
	Machine face, OD & drill hole on top	
	Section a part for dimensional verification (scrap)	
2nd operation, final green machine	Set machine up to chucked blank	110

	Face thickness on back side	
	Remove & put in cardboard box	
3rd operation, final green machine	Chuck part on camera mill	
	Drill bottom hole	
	Remove & put in cardboard box	
	Send box to kiln	
Firing	Load parts on moly plates (75 to 100 parts)	150
	Put 3 density standard on firing plate	
	Stack plates on pusher block	
	Push into kiln (33 hours to push through)	
	Fire @1620 deg C in cracked ammonia on 45 minute push	
	Remove parts from kiln	
	Check density standard	
	Put in cardboard box	
	Send to x-ray	
X-ray parts	Place 100 to 150 parts on tray	170
	Place tray in faxitron x-ray	
	Develop film	
	Check for defects	
	Scrap defects	
	Place defect free parts in cardboard box	
Grinding (Blanchard)	Load parts bottom up on waxed plate (100 parts)	
	Put plate on hot plate until wax melts	
	Put plate on cold plate until wax hardens	
	Carry to Blanchard grinder	
	Remove .005" to .010"	
	Put back on hot plate (de-wax parts)	
	Load parts top up on waxed plate (100 parts)	
	Put plate on hot plate until wax melts	
	Put plate on cold plate until wax hardens	
	Carry to Blanchard grinder	
	Remove .005" to .010"	
	Put back on hot plate (de-wax parts)	
	Put in cardboard box	
Centerless grinding, OD	Load up to 5 parts in guide	
	Grind OD	
	Load in cardboard box	
	Send to gage lab	
Gage lab	Measure by video/optical method	
	Parts are grouped to the nearest .001 inch	
Grinding (Blanchard)	Load parts on vacuum chuck	
	Grind top cermet to 0.195 based on groupings from gage lab .	
	Turn over, use vacuum, & grind bottom to final dimension	
Studer CNC grinder	Load 1 part into chuck (CNC setup)	
	Grind post on bottom	
	CNC setup for top	

	Rough grind conical section on top	
	Put in cardboard box	
Universal Grinder	Set up grinder and chuck part	
	Finish grind top angle	
	Operator scopes overlap/pull back	
	If greater than .003" then scrap	
OD Chamfers	Set up and chuck part	
	Chamfer OD	
	Unload, flip, and rechuck	
	Chamfer other side	
	Unload and put in cardboard box	
ID Chamfers	Chuck part	
	Manually chamfer	
	Operator visually scopes	
	Flip and rechuck	
	Manually chamfer the other side	
	Operator visually scopes	
	Put in cardboard box	
Cleaning	Load up to 90 in "ice" trays	
	Place in ultrasonic cleaner with soapy deionized water	
	Turn on ultrasonic cleaner	
	Put tray in cleaner for 30 minutes	
	Remove tray while leaving ultrasonic cleaner on	
	Rinse parts with deionized water	
	Rinse with acetone	
	Air dry	
	Put in cardboard box and send to QC	
	3 parts are D tested	
Final Inspect	Inspect every part	

Appendix B

Summary of travelers for the Feedthru Insulator

		Work Order														
Seq.	Operation	7-54			7-51			7-53			7-52			5-1		
		In	Out	%	In	Out	%	In	Out	%	In	Out	%	In	Out	%
10	Pressing	200	0	0%	200	0		250	0		268	0		200	0	
50	1st Op GM	185	15	8%	195	5		250	0		267	1		200	0	
55	2nd GM	185	0	0%	195	0		250	0		267	0		199	1	
70	Slurry Load	185	0	0%	195	0		249	1		267	0		199	0	
91	Face 1st Op	170	15	9%				214	35		261	6		191	8	
92	Face 2nd Op	168	2	1%	137	48		214	0		256	5		184	7	
100	1st Op Finish	158	10	6%				214	0		255	1		177	7	
110	2nd Op Finish	158	0	0%	137	0		214	0		250	5		171	6	
120	Drill Hole	155	3	2%	136	1		200	14		247	3		164	7	
	GM Subtotal		45	23%		54	27%		50	20%		21	8%		36	18%
150	Fire	144	11		136	0		199	0		247	0		164	0	
170	X-Ray	144	0		136	0		199	0		244	3		164	0	
190	Grind Top	144	0		136	0		199	0		244	0		164	0	
200	Grind Bottom	144	0		136	0		199	0		244	0		164	0	
210	Grind OD	144	0		136	0		199	0		243	1		164	0	
260	Ruff Grind Top	144	0		136	0		195	4		242	1		164	0	
270	= Overall Length	144	0		136	0		195	0		242	0		164	0	
280	Finish Grind Top	144	0		136	0		195	0		242	0		164	0	
290	Final Thickness	144	0		136	0		195	0		242	0		164	0	
300	Hole Depth Ck.	144	0		131	5		195	0		242	0		163	1	
310	Ruffgrind OD Step	144	0		131	0		195	0		238	4		163	0	
320	Finish Step	141	3		131	0		194	1		238	0		163	0	
330	Ruff Grind Angle	141	0		131	0		185	9		236	2		163	0	
340	Finish Angle	141	0		123	8		169	16		235	1		157	6	
350	OD Chamfers	141	0		122	1		169	0		231	4		157	0	
360	ID Chamfers	141	0		121	1		169	0		231	0		157	0	
	Hd Mach Total		14	10%		15	11%		30	15%		16	6%		7	4%
	Overall Subtotal		59	30%		69	35%		80	32%		37	14%		43	22%
380																
390	Clean/Inspect															
	*D-Test (NoCount)	141	0		116	5		167	2		224	7		156	1	
			3			3			3			3			3	
	Clean/QC Total		0	0%		5	4%		2	1%		7	3%		1	1%
	Overall Subtotal		59	30%		74	37%		82	33%		44	16%		44	22%

Appendix C
Design of Experiments for the Feedthru Insulator
(SNL dwg # 443403)

Sandia National Laboratories

Operated for the U.S. Department of Energy by
Sandia Corporation
Albuquerque, New Mexico 87185-0958

date: January 15, 1999

to: Distribution

from: Gilbert Benavides, dept. 1484, MS-0958

subject: Design of Experiments for the Feedthru Insulator (SNL dwg # 443403)

At the Cermet Process Improvement Team (CPIT) meeting held on 12/16/98 we discussed the Design of Experiments (DoE) to be performed at Ceramtec for the purpose of improving the yield of the feedthru insulator. The five controlled factors that were deemed important and selected by the team are,

Controlled factors:

1. Solvent quantity (DGMA)
2. Orifice size (syringe orifice)
3. Measured slurry (to be deposited into alumina blank)
4. Surfactant (added to slurry)
5. Isopress position (position of part in isopress bag)

The CPIT selected four response variables that will allow us to quantify the performance of each experimental run. These response variables are,

Response variables:

1. Alumina roundness
2. Cermet cone roundness (the roundness of the base of the cermet cone at the top face)
3. Tapering (The degree of tapering along the alumina that fits into the chuck)
4. X-ray defects (The number/size of defects found by X-raying the isopressed part)

Each experimental run would include all the process steps up to and including isopressing for the measurement of alumina roundness and tapering. Second green machining would be performed prior to measuring cermet cone roundness and x-ray defects.

There was a lot of discussion regarding the factor "Isopress position" as to the degree of its importance and also the number of levels necessary to capture the effects of this factor. The position of the part in the tube defines what stuff is adjacent to the part. Obviously the parts at either end of the tube will have different neighbors than a part in the middle. The isopressing performed at Ceramtec is different than isopressing at Sandia because of differences in the bag and the use of spacers. Ceramtec uses a reusable, stiff rubber tube as a bag whereas Sandia uses disposable medical tubing that is thin and

flexible (Penrose 12" drain, 1" ID). Ceramtec stacks 25 feedthru insulators with rubber spacers in-between whereas Sandia does not stack the parts and leaves plenty of space from one part to the next by sectioning off the tubing with hair pins. Results from a previous study indicate that there was not a significant difference in the two methodologies (based on dimensional measurements). What was ultimately decided in a follow up meeting on 1/5/98 among Steve Crowder, Dave Van Ornum and Gilbert Benavides, was to perform two baseline experiments of the Ceramtec isopressing process that would allow us to properly consider the effects of isopress position. These baseline experiments would then drive us to one of the three controlled factors DoE outlined below.

Baseline experiments:

One baseline experiment would set all the factors to their nominal values and have cermet mounded above the top face at a set measured cermet volume. The other baseline experiment would also set all the factors to their nominal value, however, the cermet material would be flush (level) with the alumina. Since all the parts will be numbered and their relative location recorded, differences due to the placement in the isopress bag can be quantified by measurement of the response variables.

Other factors that will not be included in the controlled factors DoE but will be either monitored, held constant, or ignored are listed below.

Monitored factors:

Dome peak position
Precise position (not just a zone position) in isopress bag
Time of day while filling (includes order of fill)
Order of fill for nominal runs

Hold constant factors:

Moly %
Drying temperature
Drying time
Prewetting (none)
Isopress pressure (30,000 psi)
Vacuum pressure
Operator (same operator)

Ignored factors:

Particle size of alumina
Particle size of moly
Location of drawing slurry from cup
Operator fatigue (perhaps related to time of day while filling)
Syringe angle
Syringe position

The CPIT selected levels for the controlled factors. These levels are listed below.

Levels:

Solvent quantity: 8 grams, 12 grams
Orifice size: small, large (actual size to be determined by Ceramtec)

Measured slurry: level, domed (by dispensing a known TBD quantity)

Surfactant: 0 drops, 6 drops

Isopress position: either 2 levels or 3 levels.

(The number of levels and the level values are to be determined from the baseline experiment).

Three different DoE scenarios are outlined below. One of these scenarios will be chosen depending upon the outcome of the baseline experiments.

Scenario 1:

The first DoE would be chosen if the baseline experiments indicate that part location in the isopress bag is not important. This scenario has four factors and does not include isopress position as a factor. Each run would be repeated four times for a total of 64 experiments. Given 25 parts per isopress bag, this DoE would require three bags. Although scenario 1 appears to be the simplest DoE, it has as many experimental runs as scenario 2 which has five factors. If we assume that interactions among factors will be limited to two factors at a time, then the greater resolution of scenario 1 is of no value. What this means is that we could, at no additional cost, add another factor to scenario 1.

Scenario 2:

The second DoE would be chosen if the baseline experiments indicate that there are only two different isopress positions that need to be considered. This scenario has five factors and isopress position is one of those factors. As a placeholder, these position levels are listed as “end” and “middle”, however, any other two position levels can be substituted, for example, “upper end” and “lower end”. Each run would be repeated four times for a total of 64 experiments. Given 25 parts per isopress bag, this DoE could require as few as three bags if the isopress position levels can be generalized into two zones that are somewhat equivalent in size. *(for example, a “middle zone” comprising the middle thirteen locations in the isopress bag and an “end zone” comprising six locations at the upper end and six locations at the lower end of the isopress bag)* At the other extreme, if one of the significant position levels is the bottom location in the bag and the other position level is comprised of the remaining 24 locations in the bag, then we would require as many as 32 isopress bags (800 parts)! This figure is calculated by multiplying four repetitions times eight experimental runs having the isopress position level at the very bottom location.

Scenario 3:

The third DoE would be chosen if the baseline experiments indicate that there are three different isopress positions that need to be considered. This scenario, like scenario 2, has five factors, however the isopress position factor has three levels which result in the 48 unique runs for the full factorial. As a placeholder, these position levels are listed as 1, 2, and 3. Unlike scenarios 1 and 2, two repetitions for each run is recommended resulting in a total of 96 experiments. Given 25 parts per isopress bag, this DoE could require as few as four bags if the three isopress position levels can be generalized into three zones that are somewhat equivalent in size. *(for example, an “upper end zone” comprising the upper eight locations in the isopress bag, a “middle zone” comprising the middle nine locations in the isopress bag, and a “lower end zone” comprising the lower eight location in the isopress bag)* At the other extreme, if any one of those three position levels is defined by a location that contains only one part, then we would require 32 isopress bags (800 parts)! This figure is calculated by multiplying two repetitions times 16 experimental runs having the isopress position level at one unique position in the isopress bag.

Controlled factors Design of Experiments:**Scenario 1: 4 factors, full factorial 4 repetitions per run**

StdOrder	Solvent quantity	Orifice size	Measured slurry	Surfactant	Alumina roundness	Cermet cone roundness	Tapering	X-ray defects
1	8 grams	small	level	0				
2	12 grams	small	level	0				
3	8 grams	large	level	0				
4	12 grams	large	level	0				
5	8 grams	small	domed	0				
6	12 grams	small	domed	0				
7	8 grams	large	domed	0				
8	12 grams	large	domed	0				
9	8 grams	small	level	6				
10	12 grams	small	level	6				
11	8 grams	large	level	6				
12	12 grams	large	level	6				
13	8 grams	small	domed	6				
14	12 grams	small	domed	6				
15	8 grams	large	domed	6				
16	12 grams	large	domed	6				

Scenario 2: 5 factors, 1/2 factorial, 4 repetitions per run

StdOrder	Solvent quantity	Orifice size	Measured slurry	Surfactant	Isopress position	Alumina roundness	Cermet cone roundness	Tapering	X-ray defects
1	8 grams	small	level	0	end				
2	12 grams	small	level	0	middle				
3	8 grams	large	level	0	middle				
4	12 grams	large	level	0	end				
5	8 grams	small	domed	0	middle				
6	12 grams	small	domed	0	end				
7	8 grams	large	domed	0	end				
8	12 grams	large	domed	0	middle				
9	8 grams	small	level	6	middle				
10	12 grams	small	level	6	end				
11	8 grams	large	level	6	end				
12	12 grams	large	level	6	middle				
13	8 grams	small	domed	6	end				
14	12 grams	small	domed	6	middle				
15	8 grams	large	domed	6	middle				
16	12 grams	large	domed	6	end				

Scenario 3: 5 factors, full factorial, 4 factors at 2 levels, 1 factor at 3 levels, 2 repetitions per run

StdOrder	Solvent quantity	Orifice size	Measured slurry	Surfactant	Isopress position	Alumina roundness	Cermet cone roundness	Tapering	X-ray defects
1	8	small	level	0	1				
2	8	small	level	0	2				
3	8	small	level	0	3				
4	8	small	level	6	1				
5	8	small	level	6	2				
6	8	small	level	6	3				
7	8	small	domed	0	1				
8	8	small	domed	0	2				
9	8	small	domed	0	3				
10	8	small	domed	6	1				
11	8	small	domed	6	2				
12	8	small	domed	6	3				
13	8	large	level	0	1				
14	8	large	level	0	2				
15	8	large	level	0	3				
16	8	large	level	6	1				
17	8	large	level	6	2				
18	8	large	level	6	3				
19	8	large	domed	0	1				
20	8	large	domed	0	2				
21	8	large	domed	0	3				
22	8	large	domed	6	1				
23	8	large	domed	6	2				
24	8	large	domed	6	3				
25	12	small	level	0	1				
26	12	small	level	0	2				
27	12	small	level	0	3				
28	12	small	level	6	1				
29	12	small	level	6	2				
30	12	small	level	6	3				
31	12	small	domed	0	1				
32	12	small	domed	0	2				
33	12	small	domed	0	3				
34	12	small	domed	6	1				
35	12	small	domed	6	2				
36	12	small	domed	6	3				
37	12	large	level	0	1				
38	12	large	level	0	2				
39	12	large	level	0	3				
40	12	large	level	6	1				
41	12	large	level	6	2				
42	12	large	level	6	3				
43	12	large	domed	0	1				
44	12	large	domed	0	2				
45	12	large	domed	0	3				
46	12	large	domed	6	1				
47	12	large	domed	6	2				
48	12	large	domed	6	3				

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Intentionally Left Blank

Appendix D
Additional design of experiments data

Part #	Run #	Orifice	Fill	Solv.	Surf.	ISO Bag #	Bag Pos.	AI dia top	AI dia bottom	Taper	AI dia optical	AI circ optical	AI dia face off	AI circ face off	Cermet dia	Cermet circ	Conc.	X-ray voids
1	2	small	level	22	0	2	1	0.745	0.749	0.004	0.7426	0.0004	0.6258	0.0002	0.2941	0.0007	0.0025	0
2	8	large	dome	22	0	3	1	0.742	0.749	0.007	0.7405	0.0007	0.6259	0.0004	0.2928	0.0006	0.0024	0
3	8	large	dome	22	0	4	1	0.742	0.748	0.006	0.7396	0.0007	0.6262	0.0009	0.2927	0.0005	0.001	0
4	3	large	level	18	0	4	2	0.744	0.748	0.004	0.743	0.0008	0.6261	0.0006	0.2928	0.0015	0.0013	0
5	10	small	level	22	12	1	1	0.745	0.748	0.003	0.7437	0.0009	0.6258	0.0006	0.2944	0.0005	0.0022	0
6	15	large	dome	18	12	1	2	0.743	0.747	0.004	0.7401	0.0003	0.6260	0.0005	0.2941	0.0005	0.0023	2
7	10	small	level	22	12	2	2	0.744	0.749	0.005	0.741	0.0003	0.6257	0.0005	0.2945	0.0005	0.0006	0
8	1	small	level	18	0	3	2	0.743	0.748	0.005	0.7428	0.0009	0.6261	0.0008	0.2939	0.0003	0.0015	0
9	16	large	dome	22	12	2	3	0.744	0.748	0.004	0.7406	0.0005	0.6258	0.0006	0.2945	0.0005	0.0033	0
10	5	small	dome	18	0	1	3	0.745	0.746	0.001	0.7432	0.0004	0.6257	0.0005	0.2957	0.0003	0.0001	0
11	12	large	level	22	12	4	3	0.745	0.748	0.003	0.7456	0.0004	0.6259	0.0002	0.2941	0.0006	0.001	0
12	3	large	level	18	0	1	4	0.746	0.748	0.002	0.7442	0.0004	0.6261	0.0005	0.2910	0.0010	0.0014	0
13	4	large	level	22	0	3	3	0.744	0.748	0.004	0.7441	0.0003	0.6257	0.0003	0.2937	0.0003	0.0008	0
14	12	large	level	22	12	2	4	0.745	0.749	0.004	0.7436	0.0003	0.6258	0.0002	0.2908	0.0004	0.0038	1
15	1	small	level	18	0	4	4	0.744	0.748	0.004	0.7426	0.0005	0.6256	0.0004	0.2920	0.0006	0.0004	1
16	8	large	dome	22	0	1	5	0.742	0.748	0.006	0.7422	0.0004	0.6259	0.0008	0.2933	0.0006	0.0018	0
17	2	small	level	22	0	4	5	0.744	0.748	0.004	0.7427	0.0003	0.6259	0.0005	0.2919	0.0005	0.0012	0
18	13	small	dome	18	12	2	5	0.743	0.748	0.005	0.7408	0.0004	0.6257	0.0006	0.2924	0.0004	0.0011	0
19	3	large	level	18	0	1	6	0.744	0.747	0.003	0.7433	0.0005	0.6257	0.0007	0.2936	0.0013	0.0006	0
20	10	small	level	22	12	4	6	0.744	0.748	0.004	0.7416	0.0002	0.626	0.0004	0.2928	0.0002	0.0013	1
21	3	large	level	18	0	3	4	0.746	0.747	0.001	0.745	0.0005	0.6260	0.0004	0.2971	0.0011	0.0031	0
22	1	small	level	18	0	1	7	0.744	0.747	0.003	0.7427	0.0004	0.6260	0.0007	0.2929	0.0008	0.0008	1
23	6	small	dome	22	0	3	5	0.743	0.748	0.005	0.7432	0.0003	0.6259	0.0004	0.2921	0.0009	0.0018	0
24	9	small	level	18	12	1	8	0.745	0.748	0.003	0.7431	0.0003	0.6255	0.0006	0.2933	0.0009	0.0026	1
25	7	large	dome	18	0	1	9	0.742	0.748	0.006	0.7396	0.0005	0.6260	0.0004	0.2990	0.0007	0.0029	0
26	12	large	level	22	12	4	7	0.744	0.748	0.004	0.742	0.0002	0.6259	0.0005	0.2923	0.0006	0.0025	0
27	14	small	dome	22	12	4	8	0.744	0.749	0.005	0.7425	0.0006	0.6261	0.0008	0.2932	0.0009	0.0016	0
28	15	large	dome	18	12	2	6	0.742	0.748	0.006	0.7394	0.001	0.6259	0.0004	0.2918	0.0006	0.0034	5
29	2	small	level	22	0	2	7	0.745	0.749	0.004	0.7433	0.0006	0.6256	0.0005	0.2912	0.0007	0.0031	0
30	2	small	level	22	0	4	9	0.744	0.747	0.003	0.7431	0.0008	0.6261	0.0005	0.2915	0.0005	0.0030	0
31	4	large	level	22	0	1	10	0.743	0.747	0.004	0.7417	0.0004	0.6258	0.0004	0.2937	0.0004	0.0025	1
32	13	small	dome	18	12	3	6	0.743	0.748	0.005	0.7414	0.0007	0.6261	0.0012	0.2955	0.0004	0.0023	0
33	13	small	dome	18	12	4	10	0.742	0.748	0.006	0.7399	0.0003	0.6258	0.0004	0.2951	0.0008	0.0005	1
34	3	large	level	18	0	4	11	0.743	0.746	0.003	0.7425	0.0006	0.6258	0.0006	0.2944	0.0007	0.0022	0
35	7	large	dome	18	0	3	7	0.742	0.748	0.006	0.7402	0.0006	0.6259	0.0007	0.2940	0.0007	0.0007	0
36	15	large	dome	18	12	4	12	0.742	0.748	0.006	0.7395	0.0006	0.6257	0.0006	0.2929	0.0004	0.0029	1
37	9	small	level	18	12	3	8	0.744	0.747	0.003	0.7429	0.0006	0.6259	0.0008	0.2932	0.0004	0.0004	0
38	3	large	level	18	0	3	9	0.745	0.748	0.003	0.7447	0.0004	0.6260	0.0008	0.2934	0.0010	0.0018	0
39	16	large	dome	22	12	4	13	0.742	0.748	0.006	0.7405	0.0024	0.6259	0.0007	0.2934	0.0008	0.0019	1
40	7	large	dome	18	0	2	8	0.742	0.749	0.007	0.7399	0.0005	0.6260	0.0006	0.2913	0.0006	0.0005	0

Part #	Run #	Orifice	Fill	Solv.	Surf.	ISO Bag #	Bag Pos.	Al dia top	Al dia bottom	Taper	Al dia optical	Al circ optical	Al dia face off	Al circ face off	Cermet dia	Cermet circ	Conc.	X-ray voids
41	3	large	level	18	0	2	9	0.748	0.748	0	0.7472	0.0005	0.6259	0.0008				
42	16	large	dome	22	12	4	14	0.742	0.748	0.006	0.7387	0.0012	0.6257	0.0003	0.2909	0.0009	0.0022	0
43	4	large	level	22	0	2	10	0.744	0.748	0.004	0.7427	0.0006	0.6257	0.0006	0.2931	0.0007	0.0025	0
44	5	small	dome	18	0	2	11	0.743	0.749	0.006	0.7406	0.0005	0.6257	0.0007	0.2940	0.0007	0.0020	0
45	6	small	dome	22	0	2	12	0.744	0.748	0.004	0.7426	0.0003	0.6259	0.0006	0.2957	0.0006	0.0015	0
46	2	small	level	22	0	1	11	0.744	0.749	0.005	0.7423	0.0006	0.6256	0.0003	0.2931	0.0006	0.0006	0
47	13	small	dome	18	12	4	15	0.742	0.749	0.007	0.7396	0.0007	0.6258	0.0004	0.293	0.0003	0.003	1
48	15	large	dome	18	12	2	13	0.742	0.749	0.007	0.7407	0.0007	0.6258	0.0003	0.2929	0.0006	0.0020	0
49	5	small	dome	18	0	3	10	0.744	0.748	0.004	0.7423	0.0002	0.6260	0.0005	0.2931	0.0002	0.0021	4
50	8	large	dome	22	0	3	11	0.741	0.747	0.006	0.7401	0.0004	0.6258	0.0004	0.2945	0.0006	0.0018	0
51	13	small	dome	18	12	2	14	0.742	0.748	0.006	0.7393	0.0006	0.6258	0.0008	0.2939	0.0003	0.0012	3
52	14	small	dome	22	12	4	16	0.743	0.748	0.005	0.7409	0.0007	0.6259	0.0005	0.2923	0.0012	0.0004	0
53	12	large	level	22	12	3	12	0.744	0.749	0.005	0.7429	0.001	0.6261	0.0008	0.2915	0.0005	0.0005	0
54	8	large	dome	22	0	2	15	0.744	0.748	0.004	0.7421	0.0005	0.6260	0.0007	0.2966	0.0008	0.0014	0
55	14	small	dome	22	12	2	16	0.742	0.749	0.007	0.7411	0.0004	0.6259	0.0004	0.2935	0.0004	0.0020	0
56	12	large	level	22	12	2	17	0.744	0.748	0.004	0.7427	0.0004	0.6258	0.0004	0.2927	0.0004	0.001	0
57	9	small	level	18	12	2	18	0.745	0.748	0.003	0.7432	0.0003	0.6258	0.0005	0.2921	0.0008	0.0008	1
58	6	small	dome	22	0	1	12	0.743	0.748	0.005	0.7416	0.0006	0.6258	0.0006	0.2914	0.0007	0.0013	0
59	11	large	level	18	12	3	13	0.745	0.747	0.002	0.7434	0.001	0.626	0.0004	0.2949	0.0007	0.0023	0
60	4	large	level	22	0	4	17	0.744	0.748	0.004	0.7415	0.0006	0.6261	0.0005	0.2920	0.0006	0.0038	1
61	4	large	level	22	0	4	18	0.744	0.746	0.002	0.7413	0.0008	0.6263	0.0005	0.2975	0.0007	0.0047	0
62	11	large	level	18	12	3	14	0.744	0.747	0.003	0.7431	0.0005	0.6261	0.0006	0.2926	0.0003	0.0028	0
63	13	small	dome	18	12	1	13	0.74	0.748	0.008	0.7395	0.0003	0.626	0.0006	0.295	0.0003	0.0034	0
64	15	large	dome	18	12	4	19	0.742	0.747	0.005	0.7389	0.0005	0.6260	0.0008	0.2967	0.0005	0.0025	0
65	16	large	dome	22	12	3	15	0.741	0.748	0.007	0.7397	0.0003	0.6260	0.0008	0.2919	0.0005	0.0008	0
66	9	small	level	18	12	3	16	0.745	0.747	0.002	0.7424	0.0009	0.6259	0.0003	0.2945	0.0006	0.0028	0
67	9	small	level	18	12	1	14	0.744	0.744	0	0.7438	0.0004	0.6261	0.0005	0.2929	0.0007	0.0031	3
68	5	small	dome	18	0	4	20	0.744	0.747	0.003	0.7441	0.0005	0.6262	0.0005	0.2933	0.0005	0.0005	0
69	9	small	level	18	12	4	21	0.744	0.747	0.003	0.744	0.0005	0.626	0.0007	0.2939	0.0003	0.0008	0
70	1	small	level	18	0	1	15	0.745	0.748	0.003	0.7433	0.0007	0.6256	0.0008	0.2957	0.0016	0.0045	0
71	4	large	level	22	0	3	17	0.744	0.747	0.003	0.7423	0.0002	0.6260	0.0005	0.2923	0.0003	0.0013	0
72	7	large	dome	18	0	3	18	0.742	0.747	0.005	0.7404	0.0012	0.6259	0.0005	0.2946	0.0003	0.0011	0
73	7	large	dome	18	0	4	22	0.742	0.747	0.005	0.7412	0.0003	0.626	0.0005	0.2956	0.0008	0.0013	0
74	11	large	level	18	12	4	23	0.743	0.746	0.003	0.7439	0.0003	0.6259	0.0004	0.294	0.0006	0.0018	0
75	6	small	dome	22	0	4	24	0.743	0.747	0.004	0.7424	0.0004	0.6265	0.0006	0.2938	0.0006	0.0004	0
76	15	large	dome	18	12	3	19	0.741	0.748	0.007	0.7397	0.0013	0.6259	0.0004	0.2945	0.0008	0.0017	0
77	14	small	dome	22	12	3	20	0.743	0.748	0.005	0.7406	0.0009	0.6260	0.0005	0.2947	0.0006	0.0020	0
78	10	small	level	22	12	2	19	0.744	0.748	0.004	0.7411	0.0003	0.6258	0.0003	0.2938	0.0004	0.0042	0
79	4	large	level	22	0	1	16	0.743	0.746	0.003	0.7412	0.0006	0.6257	0.0005	0.2962	0.0006	0.0014	0
80	5	small	dome	18	0	1	17	0.743	0.746	0.003	0.7409	0.0006	0.6259	0.0005	0.2953	0.0007	0.0042	1

Part #	Run #	Orifice	Fill	Solv.	Surf.	ISO Bag #	Bag Pos.	AI dia top	AI dia bottom	Taper	AI dia optical	AI circ optical	AI dia face off	AI circ face off	Cermet dia	Cermet circ	Conc.	X-ray voids
81	8	large	dome	22	0	1	18	0.741	0.747	0.006	0.7383	0.0007	0.6260	0.0003	0.2914	0.0003	0.0016	0
82	12	large	level	22	12	1	19	0.744	0.748	0.004	0.7434	0.0006	0.6258	0.0004	0.2917	0.0011	0.0012	0
83	1	small	level	18	0	2	20	0.746	0.748	0.002	0.7448	0.0004	0.626	0.0003	0.2936	0.0009	0.0021	0
84	7	large	dome	18	0	1	20	0.743	0.747	0.004	0.7409	0.0004	0.6255	0.0007	0.2933	0.0009	0.0007	0
85	11	large	level	18	12	1	21	0.743	0.748	0.005	0.7429	0.0004	0.6259	0.0003	0.2956	0.0014	0.0013	0
86	2	small	level	22	0	1	22	0.744	0.748	0.004	0.7421	0.0006	0.6259	0.0018	0.2908	0.0007	0.0011	0
87	1	small	level	18	0	4	25	0.744	0.747	0.003	0.7437	0.0006	0.6262	0.0006	0.2952	0.0005	0.0047	0
88	2	small	level	22	0	3	21	0.743	0.748	0.005	0.7411	0.0005	0.6259	0.0008	0.2992	0.0003	0.0023	1
89	6	small	dome	22	0	1	23	0.743	0.747	0.004	0.7406	0.0004	0.6257	0.0005	0.3006	0.0005	0.0023	0
90	10	small	level	22	12	3	22	0.744	0.748	0.004	0.7421	0.0006	0.6263	0.0005	0.2965	0.0004	0.0015	0
91	5	small	dome	18	0	3	23	0.744	0.748	0.004	0.7419	0.0011	0.6259	0.0005	0.2943	0.0018	0.0021	0
92	11	large	level	18	12	2	21	0.744	0.748	0.004	0.7431	0.0006	0.6259	0.0009	0.2927	0.0006	0.0025	0
93	16	large	dome	22	12	2	22	0.741	0.749	0.008	0.7383	0.0012	0.6260	0.0009	0.2959	0.0009	0.0055	0
94	11	large	level	18	12	2	23	0.745	0.748	0.003	0.7454	0.0006	0.6259	0.0008	0.2933	0.0011	0.0017	1
95	16	large	dome	22	12	1	24	0.742	0.748	0.006	0.7395	0.0004	0.6261	0.0007	0.2945	0.0005	0.0015	0
96	10	small	level	22	12	3	24	0.743	0.747	0.004	0.7419	0.0015	0.6261	0.0005	0.2936	0.0005	0.0003	0
97	1	small	level	18	0	2	24	0.745	0.745	0	0.7425	0.0006	0.6257	0.0005	0.2933	0.0008	0.0009	2
98	6	small	dome	22	0	3	25	0.743	0.748	0.005	0.7407	0.0004	0.6258	0.0004	0.2934	0.0004	0.0023	1
99	14	small	dome	22	12	1	25	0.743	0.747	0.004	0.7406	0.0007	0.6262	0.0007	0.2948	0.0008	0.0004	0
100	14	small	dome	22	12	2	25	0.744	0.749	0.005	0.7425	0.0003	0.6258	0.0008	0.2929	0.0007	0.0008	1

	Suspiciously high values
	Parts were scrapped while in process
	Parts were destructively tested
	Parts were rejected at the end of the process

All dimensions are in inches

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