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Ceramic-to-ceramic sealing has applications for several technologies that require large and/or complex vacuum-tight ceramic shapes. Information is provided concerning the assembly of complex monolithic ceramic shapes by bonding of subassemblies at temperatures ranging from 450 to 1500°C. Future applications and fabrication techniques for various materials are presented.

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## 1. INTRODUCTION

Large, vacuum-tight ceramic components are needed by the fusion community for a number of applications including Tokamak current breaks, neutral beam injector insulators, superconducting magnet insulation, and several first wall requirements. The entire plasma containment vessels for Reverse Field Pinch Machines are ceramic.

The electrical insulation properties of ceramic materials coupled with high purity, chemical stability, strength, and resistance to heat and radiation damage make them attractive, in fact necessary, for many fusion applications. Most high purity ceramics are commercially available only in relatively small sizes, while very large ceramic shapes are often required for fusion. The use of ceramic shapes having dimensions in the range of one to three meters has been proposed for some applications.

In the first section of this report we described the results of a survey of the major American technical ceramic manufacturers to determine the size limitations for commercially available ceramics. In the second report section methods of joining ceramics components to form large, complex ceramics shapes are reported.

## 2. INDUSTRIAL CAPABILITY FOR LARGE CERAMIC SHAPE FABRICATION

In order to define industrial capabilities for fabrication of large, high purity ceramic products in commercial quantities a survey of the major technical ceramic manufacturers was undertaken. Although there are technologies for fabricating large, high density, high purity parts from several ceramic materials, alumina is the predominant commercial material. Accordingly, the survey was conducted to determine the state of the art for alumina ceramics fabrication.[1]

The five primary concerns for which this survey sought industrial input are presented in Table I.

Table I

Examples of Information Requested

1. Variety of chemistry in commerical bodies including alumina content and major impurities.
2. Maximum sizes of regular and irregular shapes within fabrication capabilities.
3. Types of forming, firing, and finishing facilities.
4. Areas of current technology that show potential for large shapes.
5. Vital factors in future capability development.

This survey also was designed to obtain information about the relationship between raw data points. For example, it is useful to know if fabrication of large plates is limited more by composition than by fabrication or firing system size.

The largest size capability reported for rectangular plates was 560-mm long by 500-mm wide by 40-mm thick. The largest right circular cylinder was 510-mm o.d. by 460-mm long with a 40-mm-thick wall. These sizes are generally independent of composition with the exception of bodies containing more than 99.5% alumina. Limiting sizes were also smaller for slip cast parts than for those made by dry or isostatic pressing. When these sizes were limited by equipment capacity it was a result of a size limitation imposed by the ceramic manufacturer or because of a lack of consumer interest in larger sizes. The fired densities reported for these parts range from 3.40 to 3.94 $Mg/m^3$ (i.e. 90 to 97% theoretical density).

Responses to questions concerning large, complex shape fabrication indicate a general lack of experience in this area. Most frequently these parts are formed by isopressing a billet and machining to the required shape. The current limiting size for finished parts is about 130 by 130 by 130 mm.

It is apparent that the primary factor limiting fabricated part size capability has been the lack of commercial interest in large, high purity parts. The consensus among survey respondents is that dimensions of one-half to one meter would involve very little extension of existing technology, particularly for relatively simple shapes. This opinion presupposes significant interest and financial support for the purchase of larger capacity forming and firing equipment. Significant increases above about a one meter dimension and/or an increase in complexity will require a well-designed development program as well as the procurement of large capacity forming and firing equipment, ample raw material, and sufficient energy supplies.

The commercial alumina compositions of primary interest for use as containment systems contain at least 99.0% alumina. This requirement has been based on the need to minimize materials additions that would reduce the chemical and/or physical stability of the containment system in fusion environments. This requirement has not been corroborated by experimental evidence. The information presented is limited to industrial fabrication of bodies with greater than 95% alumina. It should be noted that significant increases in current part size capabilities could be applied to some of the proposed ceramic requirements if a concession could be made in favor of lower alumina content of the ceramic bodies (e.g. electrical porcelain, etc.).

Several materials and fabrication techniques have shown promise for extension of existing technologies to the fabrication of large and/or complex shapes. These promising areas include improvements of forming and firing systems, use of materials with increased reactivity, improving energy efficiency, and the use of component joining techniques.

## 3. FABRICATION OF LARGE SHAPES BY COMPONENT JOINING TECHNIQUES

### 3.1 Bonding with no chemical variation

Several projects requiring fabrication of large, high purity, vacuum-tight ceramic shapes have been pursued successfully at the Los Alamos Scientific Laboratory (LASL) by means of ceramic-to-ceramic sealing of fired and ground subassemblies. Fabrication of large and/or complex, monolithic ceramic shapes in this manner has not been an established commercial capability for high purity ceramic materials.

One approach that has been developed at LASL for ceramic-to-ceramic sealing involves bonding of ceramic components to provide an assembly that is monolithic with regard to both chemistry and refractoriness. This approach consists of sealing two or more ceramic parts using a slip or paste of the same composition as the parts being sealed. An example of a complex, high-purity alumina shape fabricated using this sealing technique is that of a pump-out port (Fig. 1) that was used in a ceramic thermonuclear fusion containment system for the Syllac machine.

Fig. 1. Syllac Pump-Out Port

Because of the complexity of the port, it cannot be fabricated by conventional ceramic forming techniques. The bonds of the port are formed by applying the joining sealant onto the joint area between two unfired preformed shapes. High temperature firing provides a fully sintered port that is monolithic with regard to both strength, chemical composition, and vacuum integrity. This technique also has been applied successfully to other high purity oxide systems including magnesia, zirconia, and thoria. This technology, although developed for relatively small, complex parts, could be extended to larger shapes given adequate capacity forming and firing equipment.

### 3.2 Glass sealant joining

Joining of subassemblies using glass sealants provides a very useful method for fabricating assemblies when chemistry and/or refractoriness are not major considerations.

The basic materials requirements of sealants for large ceramic-to-ceramic seals are: (1) compatible CTE between the components and the sealant; (2) good sealing action when fired at relatively slow heating rates to minimize thermal stresses in the bonded components; and (3) sealants that form a seal and mature chemically at temperatures significantly below the softening or slumping point of the components being sealed. In addition, it is highly desirable to have several sealant materials with maturing conditions covering a wide temperature range.

Seven glass and glass-ceramic materials have been developed or modified at LASL [2] for use in joining of subassemblies. These sealants cover the maturing temperature range from 450° to 1500°C. The general approach used to develop these sealant materials started with a review of materials that form glasses and glazes [3,4], phase equilibria [5] of the systems containing these materials, and estimation of CTE for matured glasses and glazes.[6] Each candidate sealant resulting from the evaluation of these data was tested for its ability to exhibit flow, limited reactivity and compatibility of CTE when matured in contact with high-purity alumina shapes. Sealants that proved successful in these evaluations were then tested for bulk tensile strength using a bonded step joint. All of the sealants described proved to be as strong or stronger than the alumina shapes being bonded in this particular step joint design.

The group of sealants that have been developed have a wide variation in chemistry as a result of the need to maintain a glassy phase with a compatible CTE to alumina while allowing refractoriness over a large temperature range. The materials systems used to develop these sealants include $PbO-B_2O_3-SiO_2$, $BaO-B_2O_3-Al_2O_3$, and $K_2O-Al_2O_3-SiO_2$.

Figures 2 and 3 show assemblies fabricated using the glass sealant approach. Figure 2 shows a 30-cm-diam cylinder of 99.5% alumina which includes seven sapphire windows hermetically sealed in the wall using sealants of six different compositions. Figure 3 shows an assembly of eight 20-cm-diam 96% alumina cylinders that has been sealed using four different sealants. During fabrication of these sealed assemblies, some of the seals were refired several times, in some cases using their original maturing conditions, with no apparent effect on the seal integrity.

Fig. 2. Multiple Window Seal Segment

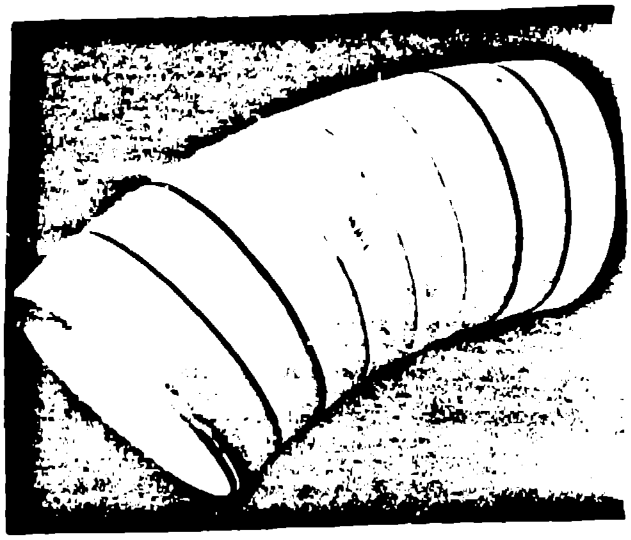

Fig. 3. Multiple Segment Seals

Each of the sealants described above has been used to repair unsatisfactory seals formed by other glass sealants with equal or higher maturing temperature. This capability enhances the versatility of this group of sealants. For example, given the requirement for fabrication of a complex alumina assembly, seals and/or coatings may be applied to the developing assembly in at least six different stages. Each stage, evolving at a lower maturing temperature, would provide the capability to repair any defective seals appearing during prior processing.

## 4. SUMMARY

Industrial sizes of high purity ceramic parts are currently limited to relatively simple shapes with maximum dimensions in the range of one-half meter. The availability in sealing systems, such as those described, greatly expands current commercial fabrication capabilities for large and/or complex alumina shapes. The capability has been demonstrated to form multiple, vacuum-tight seals up to 5.0-m long between alumina and/or sapphire parts during one or more firing operations using the compositions described. These sealants also were used to repair and/or modify previously formed seals. It is felt that there is a potential for application of these technologies to other ceramic systems.

## REFERENCES

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3. H. Rawson, Inorganic Glass Forming Systems (Academic Press, New York, 1967).
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PRESCHEDULED AUTOSTART program which zeros the common area status words and CONNECTs the RMI interrupts. If errors are detected during this initialization the operator is notified that all or part of the communication system is not operational.

## Common Block Structure

Each of the four common areas is structured as in the following diagram:

| word | |
|---|---|
| 0 | Status Word (RRXSTA)<br>(1 word) |
| 1 | Register Area (RRXREG)<br>(15 words) |
| 16 | UFT Area (RRXUFT)<br>(8 words) |
| 26 | I/O Buffer (RRXBUF)<br>(128 words) |
| 154 | File Pos. Index (RRXDPI)<br>(2 words) |
| 156 | Remote Device Name (RRXDEV)<br>(1 word) |
| 157 | Remote Device Class (RRXDCL)<br>(1 word) |
| 158 | Spares<br>(34 words) |

## Status Word (RRXSTA)

The common status word has the following bit definitions:

| EQU | Bit | Meaning |
|---|---|---|
| RRXBSY | 0 | Set if the common area is busy. |
| RRXONL | 1 | On-line test bit. The requesting computer can set this |

bit and interrupt the other computer to see if the other computer is on-line. The other computer should reset this bit to indicate that it is on-line. At the present time the on-line test bit is not used. If an attempt is made to request a service from an off-line computer the symbiont will relinquish forever while waiting for the "operation completed" bit to be set.

| | | |
|---|---|---|
| RRXASS | 2 | Set if the requested file is not assigned in the task of the remote computer. |
| RRXHOL | 3 | I/O hold condition. Set if the remote device is not ready and action by the operator is required. This indicates that the symbiont is in a "stall" condition. |
| | 4 | Spare |
| | 5 | Spare |
| 6,7,8,9 | | Bits 6,7,8,9 are reserved for future services other than REX I/O requests. For example, other types of REX services or simple core-to-core data transfers. |
| RRXREQ | 10 | Set if a REX I/O request is the service requested. |
| RRXCOM | 11 | Operation complete. Set if the remote operation has been completed. |
| CC | | Bits 12,13,14,15 are used to transmit back to the requesting cpu the condition codes as returned by the remote REX I/O service. At the present time the symbiont does not use this information. |

## Other EQU Locations

| | | |
|---|---|---|
| RRXLNT | 192 | Length of an individual common area. |
| MYCPU | #BF | Actual memory location of the cpu number (0,1,2). This location is actually reserved by the system for the 63rd party line interrupt vector. |

## Some Comments on the Tasks
## Which Respond to the RMI Interrupts
## RHR,RVR,RTR

These tasks are actually two source codes because the DMP's of the satellite computers cannot access the common memory which resides in the host. That is, RVR and RTR are identical and RHR must transfer the I/O buffer from its private memory to the common area for a write operation using the DMP and from common to private with a read operation using the DMP.

The tasks are designed to be general programs which can perform remote functions other than REX I/O services.

## Resources of the Tasks

Fig. 5 and Fig 6 are sample listings of the resources of the tasks as they might be cataloged.

Notice also that practically all of the disc files on the Host are accessible by the satellites, but only two files (BSL and the random access file RAD) on the satellites are accessible by the Host. Like the magnetic tapes and the card reader these disc files also have logical file names which are the same as the device names. The exceptions to this are those disc files and devices which exist on all machines.

Fig. 6 is a list of the resources of the symbionts RT, RH AND RV. The source codes and resources for these symbionts are identical.

## Error Conditions

Various error conditions can arise during operation of the symbiont. These are outlined below:

| Error | Action |
|---|---|
| File not assigned at the remote cpu | The symbiont types "FILE xx NOT ASSIGNED AT REMOTE CPU" and aborts the calling program. Here xx is the name of the file after all file-to-file assignments have been resolved.<br>Note that files may be "protected" by not |

```
SOURCE OF RESOURCES FOR  RTR


DEFAULT
FILE  SM
TASK  RTR     #C8 #C8
STACKS #0064 #000C
IOPERATIONS   #02
PAGESHARING   #01
SYSPAGES #02
DEALLOCATE  ALL
BIAS #0000
OPTION  NO6
OPTION    6
LOGFILE MC  SSL,SSL,
LOGFILE MT1 MT1,MT1,
LOGFILE MT2 MT2,MT2,
LOGFILE CR    CR, CR,
LOGFILE PSL PSL,PSL,
LOGFILE FSL FSL,FSL,
LOGFILE SSL SSL,SSL,
LOGFILE AS7 AS7,AS7,
LOGFILE DNO DNO,DNO,
LOGFILE DNA DNA,DNA,
LOGFILE DNB DNB,DNB,
LOGFILE DNC DNC,DNC,
LOGFILE DND DND,DND,
LOGFILE AS1 AS1,AS1,
LOGFILE AS2 AS2,AS2,
LOGFILE AS3 AS3,AS3,
LOGFILE AS4 AS4,AS4,
LOGFILE AS5 AS5,AS5,
LOGFILE AS6 AS6,AS6,
LOGFILES #04
LOGFILE QPM QPM,QPM,
LOGFILE LP  LP2,LP2,
LOGFILE ULH BSL,BSL,
LOGFILE TYH  TY, TY,
LOGFILE RAH RAD,RAD,
LOGFILE MAF MAF,MAF,
ID  3 5 76
PECULIAR PRIVLEGED
SPACE  #0000 #0000
```

```
SOURCE OF RESOURCES FOR  RVR


DEFAULT
FILE  SM
TASK  RVR     #C8 #C8
STACKS #0064 #000C
IOPERATIONS   #02
PAGESHARING   #01
SYSPAGES #02
DEALLOCATE  ALL
BIAS #0000
OPTION  NO6
OPTION    6
LOGFILE MC  SSL,SSL,
LOGFILE MT1 MT1,MT1,
LOGFILE MT2 MT2,MT2,
LOGFILE CR    CR, CR,
LOGFILE PSL PSL,PSL,
LOGFILE FSL FSL,FSL,
LOGFILE SSL SSL,SSL,
LOGFILE AS7 AS7,AS7,
LOGFILE DNO DNO,DNO,
LOGFILES #04
LOGFILE DNA DNA,DNA,
LOGFILE DNB DNB,DNB,
LOGFILE DNC DNC,DNC,
LOGFILE DND DND,DND,
LOGFILE AS1 AS1,AS1,
LOGFILE AS2 AS2,AS2,
LOGFILE AS3 AS3,AS3,
LOGFILE AS4 AS4,AS4,
LOGFILE AS5 AS5,AS5,
LOGFILE AS6 AS6,AS6,
LOGFILE QPM QPM,QPM,
LOGFILE LP  LP1,LP1,
LOGFILE MAF MAF,MAF,
LOGFILE ULH BSL,BSL,
LOGFILE TYH  TY, TY,
LOGFILE RAH RAD,RAD,
ID  3 5 76
PECULIAR PRIVLEGED
SPACE  #0000 #0000
```

Fig. 5

```
SOURCE OF RESOURCES FOR  RHR


DEFAULT
FILE  SM
TASK  RHR    #FF #FF
STACKS #0064 #000C
IOPERATIONS  #02
PAGESHARING  #01
SYSPAGES #02
DEALLOCATE  ALL
BIAS #0000
LOGFILES #04
LOGFILE ULV BSL,BSL,
LOGFILE ULT BSL,BSL,
LOGFILE TYV  TY, TY,
LOGFILE TYT  TY, TY,
LOGFILE RAV RAD,RAD,
LOGFILE RAT RAD,RAD,
ID  3 5 76
PECULIAR PRIVLEGED
SPACE  #0000 #0000
```

```
SOURCE OF RESOURCES FOR  RH


DEFAULT
FILE  SM
TASK  RH     #FF #06
STACKS #0064 #0008
IOPERATIONS  #00
PAGESHARING  #01
SYSPAGES #02
DEALLOCATE  ALL
BIAS #0000
ID  3 5 76
PECULIAR PRIVLEGED
PECULIAR SYMBIONT
SPACE  #0000 #0000
```

Fig. 6

| | |
|---|---|
| | assigning them in the task of the target cpu or by not placing them in the SYSGEN of the sending cpu. |
| Remote device is off line | Types "REMOTE DEVICE xx IS OFFLINE" and sets the symbiont device off-line. Here xx is the actual device name. |
| Remote card reader/punch, paper tape reader/punch or printer is not ready | The symbiont types "!xx ? (bell)" and goes into a "stall" condition until the operator either fixes the device or aborts the calling program. When the remote device is made ready the I/O will resume. |
| The program aborts during a remote I/O operation and leaves the "common busy" bit set. | At the moment the common status word must be zeroed using the operator command "//MAC " -- modify actual memory. A better way might be to put this into an operator command (OC) to initialize the communications symbiont and common areas. In the six months we have been using the system, however, this error has yet to occur. |

## SYSGEN Statements

The following SYSGEN statements were added to the Host SYSGEN source:

```
MYCPU   BORG           #BF,2                     HOST IS CPU 2
        GLOBAL         GXFER,3,,,252,XCPU        COMMON FOR COMMUNICATIONS
        SYMCONTROLLER RV                         SYMBIONT FOP VERTICAL
        SYMCONTROLLER RT                         SYMBIONT FOR TANDEM
        DEVICE         ULV,RV,200,1,,,0,0,0,0,0,0,0  USER LIB ON VERTICAL
        DEVICE         ULH,RH,200,1,,,0,0,0,0,0,0,0  USER LIB ON TANDEM
        DEVICE         RAV,RV,200,1,,,0,0,0,0,0,0,0  RAND. ACCESS VERTICAL
        DEVICE         RAT,RV,200,1,,,0,0,0,0,0,0,0  RAND. ACCESS TANDEM
        DEVICE         TYV,RV,80                    TYPEWRITER ON VERTICAL
        DEVICE         TYT,RT,80                    TYPEWRITER ON TANDEM
        PRESCHEDULE RV,,SM                       SYMBIONT TO VERTICAL
        PRESCHEDULE RT,,SM                       SYMBIONT TO TANDEM
        PRESCHEDULE RVR,.SM                      RESPOND TO VERTICAL
        PRESCHEDULE RTR,,SM                      RESPOND TO TANDEM
```

The satellite computers have the same SYSGEN sources except for the cpu numbers -- the Vertical cpu is cpu 0 and the Tandem is cpu 1:

```
MYCPU   BORG         #BF,0                    0 FOR VERT., 1 FOR TANDEM
        GLOBAL       GXFER,3,,,764,XCPU       COMMON FOR COMMUNICATIONS
        SYMCONTROLLER RH                      SYMBIONT FOR HOST
        DEVICE       TYH,RH,80                   TYPEWRITER ON HOST
        DEVICE       CR,RH,80                    CARD READER ON HOST
        DEVICE       LP,RH,134                   LINE PRINTER ON HOST
        DEVICE       MT1,RH,256               MAG TAPE 1 ON HOST
        DEVICE       MT2,RH,256               MAG TAPE 2 ON HOST
        DEVICE       AS1,RH,256,1,,,0,0,0,0,0,0,0   FHD PARTITION
          .
        All partitions on the host's fixed head disc
          .
        DEVICE       AS7,RH,256,1,,,0,0,0,0,0,0,0   FHD PARTITION
        DEVICE       DNA,RH,200,1,,,0,0,0,0,0,0,0   M1 MHD PARTITION
          .
        All partitions on the host's moving head disc (M1)
          .
        DEVICE       PSL,RH,200,1,,,0,0,0,0,0,0,0   M1 MHD PARTITION
        DEVICE       RAH,RH,200,1,,,0,0,0,0,0,0,0   RAND. ACCESS
        DEVICE       ULH,RH,200,1,,,0,0,0,0,0,0,0   HOST BSL
        PRESCHEDULE RH,,SM                    SYMBIONT TO HOST
        PRESCHEDULE RHR,,SM                   RESPOND TO HOST
```

The BORG macro is a MODCOMP SYSGEN macro which "back-origins" to the address given as the first argument and puts in the value of the second argument. The 7 extra words at the end of the DEVICE statements allow the MAX IV system to put in the information about these "disc files" without destroying the next DEVICE statement. That is, the seven extra words make the code generated by the DEVICE statements the same length as the code generated by the DISCDEVICE statements.

## Program Sizes

The sizes of the programs are as follows, omitting the 768 words of GLOBAL COMMON:

RT,RV,RH (the symbionts) ......................#414 ($1044_{10}$)
RVR,RTR (respond to interrupt) ................#5C ($92_{10}$)
RHR (respond to interrupt) ....................#100 ($256_{10}$)
Cold Start Initialization .....................#85 ($235_{10}$)

## Limitations

The symbiont system of communication does not, at the present time, support system I/O which uses the DMP chaining. This would include such operations as loading a program (quick load module) from a remote disc. We have also found that using the "LIST" command in the Task/Overlay Cataloger (TOC) when the disc partition is remote is also not possible. It is possible, however, to GET, PUT, SAVE and RESTORE remotely using TOC. Basically the system described here is designed to allow the use of remote peripherals.

## Speed

The speed of the system is slower than a comparable I/O operation locally because of the additional overhead of a second call to BIOS in the remote computer and the time required for the taskmaster to schedule the tasks which are connected to the RMI interrupts. However, This time is usually small compared to disc arm motiom. In fact, we routinely use a scratch partition of the M1 disc of the host to compress satellite disc files because the lack of arm contention makes the operation proceed almost twice as fast than if the same local disc is used.

As an example of the difference in speed, the following test was made:

A FORTRAN program on disc M1 of the host was compiled by a satellite computer and the output was sent back to the host for printing. The binary output was placed on the satellite's local disc. The same operation was done on the host with M0 being used for the binary output. In both cases the line printer spooling was done to the host's fixed head disc. This way the disc arm contention should be about the same.

Using the satellite the time required was one minute and fifty-two seconds and, using the host, with all local devices, the time required was one minute and forty-eight seconds -- a difference of four seconds or less than 4%.