Weld Repair of the U.S. Capitol Dome*

A Report to the Office of the Architect of the Capitol, for project 900265K

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This report describes some options for weld repairs to the outer shell of the dome on the U.S. Capitol. During the past 140 years, corrosion products have built up within many of the joints, leading to cracking of some of the iron castings that form the shell. Since the dome is a national landmark, the goal is to restore the structural integrity of the original castings, replacing as few of the components as is absolutely necessary. While mechanical joining of the fractures or filling of the gaps with epoxy are alternative procedures, a fused (leak-tight) and ductile joint is preferred. A major challenge is that the castings were produced with 1850's technology, so the composition is far different from current castings that are designed for weld repair. Therefore, we chose to develop some alternative approaches, designed specifically for the dome castings. Of the various options, oxyacetylene braze welding (a flame repair process where the filler metal melts at a temperature below that of the casting) with low-fuming bronze (about 60Cu-40Zn) worked best. The bronze forms joints that are very similar in strength to the castings. A joining trial in July 2002 demonstrated the utility of this technique in the flat and vertical positions at four corner cracks on the dome. More information on the dome material itself is included in a related report, Metallurgy of the Capitol Dome, NIST Technical Note 1500-11.

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*Tradenames serve only to identify products; neither endorsement nor criticism is intended.

1. Introduction

The activities fit into two separate segments, a short project in 1998, and a follow-on project in 2002. The first project involved a relatively simple screening approach to the problem, and resulted in a recommended procedure. When a joining trial in 1998 showed that this procedure was less than fully successful, the second project was developed. The second project developed two more recommended procedures, and included a field trial on the dome. Since the second project built on what was learned in the first, it seems best to describe them chronologically in the following sections.

2. Development of the First Procedure (1998)

2.1 Background

In June of 1998, a group of researchers from NIST visited with staff from the Office of the Architect of the Capitol to learn whether their skills could help with the planned restoration of the Capitol Dome. Also at the meeting were two outside experts who had been involved with past restoration efforts: Richard Kadlubowski of Hoffmann Architects, the consultant for the rehabilitation of the dome, and A. J. "Bud" Julicher, an independent structural engineer who is familiar with the weld repair that was completed about 1992 on the cast-iron ring at the base of “Freedom”, the statue at the very top of the dome. The restoration efforts have been given a high priority, now that moisture is leaking into some of the interior areas of the building. The goal is to restore the dome to its original condition, with minimal replacement of castings. Therefore, welding is an important option for repair of cracks and corrosion damage to the castings.

We learned that the present dome of the Capitol was designed in the 1850's by Thomas U. Walter and built between 1856 and 1866. It replaced an earlier wooden dome that was no longer in scale with the recent expansions to House and Senate wings (expansions needed to accommodate legislators from the states that had just been added to the Union). A masonry dome was ruled out because the existing Rotunda walls could not support the mass of the larger dome. However, calculations showed that the Rotunda could support a cast-iron dome, which could be cast with cutouts in areas where material was not required. In addition, cast iron was fire resistant, could be formed in complex shapes, and could be erected with pieces of convenient sizes. The designers also recognized that the dome would be subject to movement due to heating and cooling cycles, and the design included features to accommodate this movement. The U.S. Capitol Dome was the second cast-iron dome in the world, and remains the world’s largest iron dome to this day.

Although the majority of the dome, complete with its inner and outer shells and lower skirt, is composed of cast iron, wrought iron was used in a few places. The main framing of the dome consists of 36 arched ribs that bear on 36 paired pillars that, in turn, bear on 36 pairs of cast-iron brackets that are embedded in the masonry walls of the Great Rotunda. The ribs are tied together at multiple levels by bands or hoops, consisting of either cast-iron sections or wrought-iron riveted plates. From the main rib framing, an elaborate arrangement of cast-iron brackets support the outer shell of the dome and give it its distinctive shape. The inner shell is suspended from the main ribs with either wrought-iron hangers or cast-iron brackets. Also suspended from the main ribs near the top of the dome is a shell of cast-iron gratings to which the plaster base of the fresco entitled "The Apotheosis of Washington" is applied. At the top of the dome, the 36 ribs converge into 12 that continue upward to support the Tholos and Lantern Levels, and the statue “Freedom”. These structural parts of the dome were all fabricated in the 1850's and 1860's using the casting technology of the time. More information (including Walter's elevation and cross-section drawings from 1859) is available at the web site of the Architect of the Capitol [1].

In a tour through the dome, we saw that the interior rib structure (the supporting structure) was in good condition, but the outer shell had some cracks and visible corrosion at a number of the joints (where paint did not reach all the surfaces). The current moisture-leakage problems are attributed to gaps caused by expansion and contraction of the exterior shell and failing filler material in the joints between abutting plates. Most of the joints in the exterior skin are lap or butt joints that are difficult to seal. The leakage has led to corrosion at the joints of the outer shell and railings (castings or wrought structural forms about 1 cm thick). The corrosion products accumulate in the joints until they stress the component castings beyond what can be accommodated by the mechanical fasteners, leading to cracking of the shell panels and railing components. This allows the penetration of greater amounts of moisture, which promotes still more corrosion.

We saw a few weld repairs that were thought to have been performed about 40 years ago. Some of these welds had cracks that appeared to originate in the heat-affected zone (HAZ) and then propagated further into the castings, either transverse to the weld or along the HAZ. There was no documentation on the procedures used for these welds, but the shiny surfaces (where the paint had been removed) suggested that they were of one of the nickel-rich compositions (commonly either nearly pure nickel or a 55Ni/45Fe alloy) that are typically used on cast irons, while the bead shape suggested that the welds were applied as a wide-weave bead with a high heat input (leading to a wider and more brittle HAZ).

We learned that the Office of the Architect of the Capitol already has a team with structural analysis and corrosion expertise, and their consultants could oversee most aspects of the repair operation. Therefore, we could best assist by investigating alternative materials and procedures for the weld repairs of the cracked panels of the outer shell. These alternative materials and procedures would be designed especially for the restoration project (optimized for the properties of the castings used in the dome) and be stable over time. In particular, we could look for innovative ways to reduce the tendency for cracking, both during the repair and into the indefinite future. The team that we put together included Tom Siewert (the leader of the welding activities at NIST), Chris McCowan (a metallographer and metallurgist at NIST), and Roger Bushey (the former Chairman of the American Welding Society Subcommittee A5J on electrodes for cast irons, a member of Committee D11 on welding of iron castings, and with research experience at ESAB Welding and Cutting Products). We divided the tasks so that the welds were made and tested for strength in the ESAB Laboratory, then were sent to the NIST laboratory for macrographic and microstructural examination. Both groups were involved with the experimental design.

2.2 Characterization of the Material

In a separate program, Lucius Pitkin Testing Laboratories had characterized several parts of the dome in 1998 [2]. In their report, they provide some data on the support ribs, the skin, and the tension ring at the base of the dome. They found that the dome ribs were ferritic gray cast iron, the skin was pearlitic gray cast iron, and the tension ring was wrought iron. On one cast-iron rib, they found the composition (in mass %) to be 3.39 C, 1.07 Mn, 0.92 Si, 0.61 P, and 0.10 S. On one piece of wrought iron (boiler plate), they found the composition (in mass %) to be 0.025 C, 0.13 Mn, 0.10 Si, 0.13 P, and 0.01 S. The castings were quite low in strength (with tensile strengths measured between 17.8 and 18.8 ksi). Currently produced gray-iron castings often have strength minima of 210 to 280 MPa (30 or 40 ksi) although there are grades as low as 140 MPa (20 ksi) and as high as 420 MPa (60 ksi) [3]. While gray-iron castings are not expected to have much ductility, a doubling of casting strength through improvements in technology during the last 140 years means that current castings are able to tolerate double the deformation of the castings in the dome simply from the absorption of elastic strain. This means, however, that the traditional casting-repair technology designed for current castings might not be optimal for the historical castings found in the outer skin of the dome. More details are included in the LPTL report [2].

In the NIST laboratory, we examined several sections of the original casting from a railing and confirmed that the microstructure was a pearlitic gray cast iron. We felt that it should be best classified as flake-graphite (type A in ASTM A247) gray cast iron, although the microstructure is quite complicated and there were some regions with graphite rosettes (type B). The microstructure of the iron is mostly pearlitic, but has some ferrite around the graphite flakes and also has a high content of a phosphorus-rich intergranular phase. This intergranular phase is the likely cause of the low effective strength and low ductility of the dome material, compared to most current cast iron. More details on the microstructure of the dome materials (from both the 1998 and 2002 studies) are contained in another report [4].

2.3 Development of a Repair Procedure

The complicated microstructure (together with the low strength and low ductility) of the dome castings reinforced our desire to reevaluate whether the materials and electrodes that are currently recommended and used to repair cast irons were appropriate for use on the unique materials found in the dome. For example, the nickel electrodes designed for joining cast irons (designation ENi-CI-A in AWS Filler Metal Standard A 5.15) are required to meet a specified room-temperature yield strength range of 262 to 414 MPa (38 to 60 ksi) and tensile strength range of 276 to 448 MPa (40 to 65 ksi) [5]. Current technology ENiFe-CI-A (55Ni/45Fe alloy) electrodes have yield strengths between 294 and 434 MPa (43 to 63 ksi) and tensile strengths between 400 and 579 MPa (58 to 84 ksi). These strengths are quite appropriate for gray iron castings, which are manufactured in strength grades ranging up to 400 MPa (60 ksi). For current technology castings, this high-strength filler material keeps the strength of the casting above a specified minimum and reduces the likelihood that a repaired casting will fail in the weld repair through overload. For the castings found in the dome, however, the repair criteria are far different, focusing more on restoring the casting integrity (relatively low loads) and serving as a moisture barrier.

We began by reviewing the various aspects of the previous repair of the outer shell and considered how we might avoid a repeat of the cracking problems noted in the previous repairs. We decided that the fundamental cause of the cracks in those welds was the residual stresses that formed as the weld cooled. These stresses promoted cracking in these low-ductility castings. The careful measurements of ductility in Reference [4] indicate that some specimens from the dome castings fracture before meeting the 0.2 % offset criterion for a valid yield strength. The degradation could occur immediately after welding (as cracks that formed during or shortly after cooling) or after time (such as when seasonal thermal stresses and corrosion damage added to the residual stresses and exceeded the strain tolerance of the castings). Therefore, the optimal filler composition would seem to be one that is near to, or even below, the strength of the castings. A low-strength filler would both induce less stress in the casting (due to the build up of shrinkage stresses during cooling) and be able to selectively accept more of the strains developed during the weld repair and through the future service conditions. In fact, some steel structures have been built with filler materials that have lower strengths than the base plates. This strategy is known as undermatching (of the strength of the base plates) and is applied in situations where more ductility is required. We searched for filler materials and techniques that are not normally used on cast irons, especially those that would produce welds that are lower in strength than the traditional nickel and nickel-iron compositions used on cast irons. This approach of using filler materials of lower strength, but higher ductility, for the dome castings is justified by the fact that the repairs are not in structure-critical regions, but are needed simply to restore the dome's surface integrity.

Another issue that we reviewed is that of preheating, a common recommendation for the welding of cast irons. Preheating slows the cooling rate of the welds and changes the strength and residual stress distribution in a weld, since the cooling rate determines which phases form in the cooling metal and how the stresses build up. Techniques have been developed to calculate a no-crack temperature for castings, a suggested preheat temperature above which the cracking tendency is low. The first step of the procedure is to obtain a carbon equivalent (CE) using an equation such as:

$$CE = C + 0.31\ Si + 0.33\ P + 0.45\ S - 0.28\ Mn, \qquad (1)$$

where these elements are in mass percent [6]. Inserting the composition data (3.39 % C, 2.92 % Si, 0.61 % P, 0.10 % S, and 1.07 % Mn) reported by Lucius Pitkin for one of the dome ribs in this equation gives a CE near 4.24. Next, the CE is matched to a chart that relates the CE to a preheat temperature range [6]. This chart recommends a preheat temperature of 260 to 315 °C (500 to 600 °F). This is quite a bit higher than the preheats used for steel construction and is awkward to maintain for a casting as large as that of the dome's outer shell. Some researchers and welding engineers have found success with the exactly opposite approach for welding cast irons: using a very low or no preheat to reduce the amount of carbon that goes into solution during welding (which is the primary cause of the cracking problem). Our study of preheating was designed to learn what preheat would work best with the alternate weld compositions and on the actual castings of the dome, and whether the benefits of preheating would outweigh the additional complexities of applying it during the repair of the dome.

Another procedural option is to use peening, a mechanical deformation process where the welder strikes the weld repeatedly with a small impact tool or ball-peen hammer just after completing a weld bead. The hot weld is relatively soft, so the blows deform the crystalline structure, which relieves the shrinkage stresses that are forming. The result is a weld with lower residual stresses.

Another procedural option is to use buttering, a technique that can reduce the thermal effects of welding on the casting microstructure and redistribute the residual stresses that form as two castings are joined together. A thin surfacing weld or thermal spray (effectively an overlay) is applied to each surface of the castings at the area of the joint. This thin weld layer cools with very little restraint (so the chance of cracking is minimized) and the low heat input reduces the amount of carbon that can go into solution in the casting. When the two buttered castings are actually joined by producing a weld between the buttered layers, only the outer surfaces of the buttered layers reach the very highest temperatures of welding and experience the highest residual stresses. This allows the welding engineer both to minimize the microstructural changes in the casting and to transfer the residual stresses from the casting to the buttering layers. The material for the buttering layer is selected on the basis of metallurgical stability to the heat of welding and good ductility under the stresses during cooling after welding. Even nickel alloys of the highest strength can serve as a suitable buttering material, since little stress is introduced as thin layers cool without restraint.

Also, we reviewed the criteria for selection of the welding processes. The leading candidate welding processes seemed to be shielded metal arc welding (SMAW) and oxyacetylene (gas) welding (OAW) variants such as flame spraying and braze welding. These processes have the widest selection of compositions, can be used in all orientations, and are efficient for the short repair welds that would be needed. Additional advantages of flame spraying and braze welding include:

- Because they are performed at lower temperatures, less carbon enters the welds, and the heating is more gradual so thermal shock and distortion are reduced;
- Because the weld deposits are relatively soft and ductile, residual stresses are very low;
- The equipment is very simple and easy to use; and
- The flame heating during welding reduces the need for additional preheat.

The potential disadvantages of flame spraying and braze welding include: low joint strength, service temperatures of 260 °C or less, and poor color match, none of which is a problem for this particular application.

Other welding processes (gas metal arc, flux cored arc, etc.) were not included in this study because of factors such as their higher penetration into the base-metal castings, limits to the orientations that can be welded, and fewer options on compositions. Gas tungsten arc welding (GTAW) has been used very effectively for autogenous welds when the heat input is kept low, but was not included in this study of alternative procedures and compositions.

2.4 Evaluation of Alternate Welding Consumables and Procedures (at ESAB)

The test matrix included more than just the composition of the filler material. We also investigated the effects of preheat temperature, peening, and buttering.

The evaluations of alternate filler materials and the test procedure variables proceeded in several steps. We began with very general weldability evaluations of a wide range of candidate materials, and then conducted more detailed evaluations of the one that performed the best. These evaluations are summarized in the following paragraphs by test series.

We wanted to save the limited supply of the dome material for some final compatibility testing, and so for our preliminary screening tests, we obtained a cast iron of current manufacture that was as similar as possible to the dome iron. Microstructural examination revealed that the current technology cast-iron base material was predominantly a type A gray iron (uniform graphite flakes with random orientations) in a matrix of pearlite and some ferrite. Some areas had a small amount of type B (rosette grouping of flakes) structure. The composition was 3.56 % C, 0.55 % Mn, 2.41 % Si, 0.11 % P, and 0.14 % S. This composition has a similar preheat recommendation, but differs from the composition reported by Lucius Pitkin by having a lower manganese content and a substantially lower phosphorus content. During the mechanical tests, we found that this cast iron has a tensile strength near 175 MPa (25 ksi). In general, this current technology cast iron was considered to be suitable for early screening of filler materials. However, a final check of compatibility with the actual dome material was included as the last step in our study.

2.4.1 Screening Test 1 (Five candidate alloys and/or procedures on current cast iron)

This first test was designed to screen the suitability of the following five shielded metal arc electrode compositions on the current technology cast iron;

- Electrode A: a copper-tin alloy, identified as A/S 24 AC,
- Electrode B: a typical ENi-CI-A composition, identified as Ni99,
- Electrode C: a typical ENiFe-CI-A composition, identified as Ni550,
- Electrode D: an aluminum-bronze alloy, identified as Al Bronze A2, and
- Electrode E: a composition of nearly pure copper, identified as A/S 26.

The electrodes were used to make transverse tensile test specimens that had cast iron at each end and a transverse weld in the middle. Each electrode was welded in four conditions;

- 1: No preheat, interpass temperature of 167 to 204 °C (350 to 400 °F),
- 2: No preheat but with peening, interpass temperature of 167 to 204 °C (350 to 400 °F),
- 3: 93 to 149 °C (200 to 300 °F) preheat, interpass temperature of 121 °C (250 °F), and
- 4: 260 to 315 °C (500 to 600 °F) preheat, interpass temperature of 121 °C (250 °F).

After welding the specimens were inspected visually for cracks, then pulled to failure in tension.

The results are as follows:

Electrode A. No obvious cracks during visual inspection, but welds with conditions 1 and 2 were so brittle that they broke prior to tensile testing. Welds with conditions 3 and 4 produced transverse tensile strengths between 84 and 112 MPa (12 and 16 ksi). When preheat was used, the performance was fairly good, and this composition advanced to the next level of screening tests.

Electrode B. Conditions 2, 3, and 4 showed slight cracking along the sides of the welds during visual inspection. Condition 1 produced a strength near only 70 MPa (10 ksi), condition 2 broke prior to testing, condition 3 produced a strength near 45 MPa (6 ksi), and condition 4 produced a strength near 175 MPa (25 ksi). The tendency toward cracking was considered undesirable, although the data for condition 4 were promising. A compositional variant (electrode F in the next screening test) could overcome the cracking, and so was included in screening test 2.

Electrode C. All welds showed at least slight cracking during visual inspection, but the condition 4 weld produced a strength of 175 MPa (25 ksi). The tendency toward cracking was undesirable, and with no ideas for modification, this composition was excluded from further testing.

Electrode D. Conditions 1, 3, and 4 showed slight cracking along the sides of the welds during visual inspection. Condition 2 produced a strength near 70 MPa (10 ksi). The tendency toward cracking was considered undesirable, and this composition was excluded from further testing.

Electrode E. The electrode showed poor weldability, and so was eliminated from further evaluation.

Summary of Screening Test 1. We were looking for a combination of weld composition and procedure that produced good ductility in the weld and no cracks. What we found was that only condition 3 was considered suitable for further evaluation. These conditions were 93 to 149 °C (200 to 300 °F) preheat, interpass temperature of 121 °C (250 °F). All the welds without preheat had poor performance, and the very high preheat (as suggested by the predictive diagrams) was considered impractical for the dome shell. Of the various compositions, only the copper-tin and nearly pure nickel compositions were recommended for further evaluation.

2.4.2 Screening Test 2 (Three candidate alloys/procedures on current cast iron)

This second test was designed to screen the suitability of the following three revised shielded metal arc electrode compositions and procedures on the current technology cast iron:

- Electrode F: a special ENi-CI-A compositional variation of electrode B, identified as NC. This variant had a coating without the carbon that is traditionally added to ENi-CI-A electrodes, and so had a lower strength (a better match to the dome castings) and less tendency toward arcing to the joint sidewalls, but at the cost of poorer weldability.
- Electrode G: a copper-nickel composition, identified as CuNi, and
- Electrode H: a copper-tin alloy, identified as A/S 24 AC. This is the same as electrode A, but was given a new letter to distinguish the revised welding procedure.

The electrodes were again used to make transverse tensile test specimens, which had cast iron at each end and a transverse weld in the middle. Each of these electrodes was welded in two conditions:

- 1: 93 to 149 °C (200 to 300 °F) preheat, interpass temperature of 93 to 149 °C (200 to 300 °F), and
- 2: 93 to 149 °C (200 to 300 °F) preheat, interpass temperature of 93 to 149 °C (200 to 300 °F), followed by peening.

After welding the specimens were inspected visually for cracks, then pulled to failure in tension.

The results are as follows:

Electrode F: The weld prepared by condition 2 was so brittle that the specimen broke prior to tensile testing. The weld prepared by condition 1 produced a strength near 120 MPa (17 ksi).

Electrode G: The welds prepared by both conditions broke prior to the tensile test, and so this electrode was eliminated from further consideration.

Electrode H: The weld produced by condition 1 broke prior to testing and condition 2 produced a strength near only 21 MPa (3 ksi).

Summary of Screening Test 2: Again, we were looking for a combination of a weld and a procedure with no cracks and good ductility in the weld. What we found was that only condition 1 was considered suitable for further evaluation. This was 93 to 149 C (200 to 300 F) preheat, and an interpass temperature of 93 to 149 C (200 to 300 F). Peening was not found to be beneficial. Of the various compositions, only the composition of nearly pure nickel (with the special coating without carbon) was recommended for further evaluation.

2.4.3 Screening Test 3 (Two candidate alloys/procedures on dome cast iron)

At this point, we used what we had learned in the first two screening tests to search for an alternate material or technique that could be compared to the best candidate from Screening Test 2, when welded on pieces of casting from the dome. In particular, we searched for another low-strength material that could meet our goals of good ductility and crack resistance. We selected a nickel composition (called PA-7) that could be applied as a flame-spray powder. This composition has the advantage of low strength and low melting point (below that of the cast iron) and so was added to this screening to see whether it could offer advantages over welding. In addition, the spray coating was used to butter the casting surface before welding, to spread the stresses, and to minimize cracking at the heat affected zone in the casting. Therefore, this third test was designed to screen the suitability of the best electrode composition and procedure against a spray technique, as follows:

- Electrode J: the same ENi-CI-A composition variation that was identified as electrode F in screening test 2, and
- Spray powder K: high-nickel content powder (with some Si, Cr, and B), identified as PA-7.

Both, the electrode and spray powder were used to make two transverse tensile test specimens, which had cast iron from the dome at each end and a transverse weld in the middle. Electrode J was welded with the preheat and interpass temperatures identified in screening test 2: (93 to 149 °C (200 to 300 °F) preheat, and interpass temperature of 93 to 149 °C (200 to 300 °F); the powder spray weld K was made by bringing the joint up to temperature (red heat) with the torch and then adding the powder to the flame.

The results are as follows:

Electrode J: Under tensile testing, both welds fractured in the base material, well away from the weld (like that for weld K, as shown in Figure 1) indicating that the weld was stronger than the casting, but that the HAZ was not the critical fracture location. In other words, the HAZ was free from crack starters and unacceptably high residual stresses. The tensile strengths of the two welds were 56 and 63 MPa (8 and 9 ksi), substantially lower than the values reported by Lucius Pitkin. Since both fractures were away from the welds and HAZ, these strengths suggest that at least some parts of the Dome shell might be best characterized as a Grade 10 casting. These data support the case for treating the casting in a very gentle manner, and that this repair procedure is appropriate.

Spray powder K: Under tensile testing, both welds fractured in the base material, well away from the weld (as shown in Figure 1) indicating that the weld was stronger than the casting and the HAZ was not the critical fracture location. Once again, the HAZ was free from crack starters and unacceptably high residual stresses. The tensile strengths of the two welds were 49 and 91 MPa (7 and 13 ksi). Again, these strengths suggest that the dome might be best characterized as a Grade 10 casting. The regions in the casting adjacent to welds J and K have a HAZ that is about 2 mm thick. The first 0.5 mm nearest the fusion boundary has a high fraction of martensite, a brittle phase formed in iron castings from the heat of the welding process. This phase should be controlled by minimizing the time and temperature of the welding process. As shown in Figure 2, the graphite flakes exhibit a combination of type A and type B morphology right up to the fusion line where the filler metal begins. The exception was in the root of the weld, where there was less of the type A structure and more of a brittle martensite phase in the HAZ of the weld. The weld has numerous pores, which tend to be arranged in linear or planar configurations (Figure 1) and are an artifact of the powder-spray technique. The level of porosity appears to be within an acceptable (and expected) range.

The fusion zones at the interface are very similar for both welds J and K, as expected, since PA-7 was used at the interface of both welds. The interface is very nearly a straight line, the same boundary that was produced during the joint beveling operation just prior to welding. This means that the PA-7 never reached a temperature at which it melted the cast iron at the surface; however, the fusion bond is very good. The quality of this bond is substantiated by the fact that most of the transverse tensile tests failed far away from the weld or HAZ, and by the fact that we found that the PA-7 penetrated into cracks on the beveled surface. This penetration into the cast iron produced mechanical, as well as metallurgical bonding across the interface. In one case, J1, the failure traveled through a portion of the HAZ, but seemed to have originated at an imperfection on the surface, not as a result of this microstructure.

We measured a hardness profile across the HAZ in weld K. Figure 3 shows the results of this hardness survey, with negative position numbers indicating measurements in the casting and positive numbers indicating measurements in the weld (PA-7). The far left exhibits data outside the HAZ, and shows a range of hardness between about 150 and 300 Vickers (HV). The Vickers indenter is a microindentor, and so measures local regions much smaller than those detected by the 10 mm ball used by Lucius Pitkin for their Brinell hardness tests, yet the scale is quite similar. Therefore these data values are close to the 142 and 171 BHN values reported by Lucius Pitkin. The reason the Vickers data show more variation is that the small indentor is able to distinguish individual phase regions in the castings (some only a few micrometers across), rather than providing an average number. The finer resolution of the Vickers indentor is also able to distinguish the effects in the HAZ of the weld thermal cycle. The region between 1 and 2 mm into the casting was where the heat from the application of the PA-7 caused hardening of the microstructure, with several values above 400 HV. These hard regions indicate an area that is more sensitive to cracking, and so supports the need for a repair procedure that minimizes strain in this area. Between the fusion line and 1 mm into the casting, the hardness was lower, perhaps due to a slightly slower cooling rate. Finally, the hardness profile shows a hardness in the weld repair near 260 HV. This hardness is a reasonably good match to the hardness of the casting.

2.5 Conclusions and Recommendations on 1998 project

A. Two products were found to produce the best performance with the cast iron in the shell of the Capitol dome.

   The top performance came from a nickel-base spray powder identified as PA-7. This product showed the lowest tendency for cracking in the castings, and all joints exhibited good strengths (under tensile testing, broke in the casting away from the weld and heat-affected zone). In addition, microstructural evaluations showed excellent wetting to the cast iron surfaces at each side and the least degradation of the heat-affected zone of the casting. Because this product is not traditionally used with present-day cast irons (which are higher in strength and higher in ductility than those found in the dome), its suitability should be confirmed as a part of development of the repair procedures.

The second-best performance was exhibited by electrode J. This is a nickel-based composition, ENi-CI-A, that has been modified by eliminating carbon from the coating. The result is an electrode with lower strength (for lower residual stresses in the cast iron) but at the cost of poorer weldability. We suggest that this is a good trade-off because of the desire to eliminate the tendency toward cracking found in previous repairs to the dome. In addition, we found that it was best to butter the faces of the castings with the PA-7 powder before welding, to further reduce the weld-solidification stresses on the castings.

B. The traditional electrodes used to repair cast irons, ENi-CI-A and ENiFe-CI-A, were found to produce some cracks in the heat-affected zones of evaluation welds, but could serve as backup electrodes if some problem were discovered with the electrodes described in recommendation 1. If this option is selected, the use of a buttering layer with PA-7 should be investigated as a way to reduce the solidification and shrinkage stresses that promote cracking.

C. A wide variety of other processes and electrodes were evaluated as a part of this study, but all showed some disadvantages, either cracking or poor weldability, that eliminated them from further consideration. In all cases that were tried, weld peening was found to degrade the weld quality. A moderate preheat, 93 to 149 °C (200 to 300 °F), was found to produce less cracking than did no preheat. This is within a feasible preheat range for use on the dome.

2.6 Field Trial on the First Project (November 1999)

Screening Test 3 was made under conditions that were thought to simulate the expected repair conditions as closely as possible, including the use of small pieces of castings that had been removed from the dome. However, the joint was produced by a highly skilled welder in a laboratory environment. Therefore, a further field trial was recommended on a larger, and more complex shape of dome casting.

In November 1999, Robinson Iron performed such a repair trial by attempting to reattach an access window to its original location, above rib 23 on the Tholos level. After preheating both sides of the joint, short welds (tack welds) were placed along the joint. By the time the sixth weld was made, the first four tacks had cracked (through the center of the welds). The welder then went back and rewelded the tacks, making them thicker (the full 8 mm thickness) and longer (about 25 mm). New cracks appeared in these new welds and cracks also began to appear in the corners of the castings. The ESAB advisors suggested that the welding might be at too high a temperature, leading to excessive expansion strains.

After lunch, the welder tried heating the casting to only a dull-red glow instead of an orange glow. He made a 50 mm weld near the bottom of the panel, skipped 100 mm, then make two more 50 mm welds. By now, the first weld had detached from the casting, and could be peeled away with a knife. A final weld was made along a vertical joint where the first layer was applied at an orange heat, and the following layers with a red heat. This weld held nicely, but the horizontal weld cracked. Also, a crack extended across the weld into the casting. The welder stopped the repair with one-third of the joint completed, because it appeared that the repair process was damaging the castings.

Analysis of the repair trial indicated two reasons for the problems. First, the heat of welding led to expansion strains, which were a major source of shear and tensile loads on the welds. Second, the cold and brisk winds on that November day led to rapid cooling of the casting and welds. Thus, the welds cooled before strains could be released.

The welder suggested that future trials include: placing bolts through the gap in the weld (to maintain the spacing and alignment of the joint until much of the weld was in place) and reducing in the cooling rate (through insulating blankets, or just welding in warmer weather).

Although welding in summer might allow the process to succeed, this procedure seemed to lack the robustness desired for general use on the dome, especially considering the wide variety of orientations and access problems. Therefore, we designed a second project to address these issues.

3. Development of the second procedure (2002)

3.1 Plan

Another opportunity to develop a repair procedure occurred in spring 2002, in conjunction with a cleaning and lead-paint abatement program in the dome. In February, we were offered access to the dome that summer (July), and so developed a fast-track plan to lead up to an in-place trial on several cracks.
Knowing the shortcoming of the previous project, we assembled a team with broader expertise in welding consumables and weld repair of castings. We reaffirmed our goal of developing procedures that can be used to repair the existing cracks (without removing any panels) and reattaching fractured pieces in the outer cast-iron shell of the Capitol dome. The major challenges remained the same: (1) the cast iron has very poor tensile properties (due to its age and composition) and (2) the dome skin has a complex geometry that requires an all-position and robust repair procedure. We decided to compare and evaluate various possible procedures that met the criteria for the onsite repair, then demonstrate the optimal procedure on material from the dome.

Team:

The core of our team was selected from members of AWS Committee D11 on Welding of Iron Castings, and from major manufacturers that produce welding consumables or repair cast irons. The core of our team included:

- Roger Bushey, ESAB Corp., with experience in electrode formulation, previous work on the dome (in the 1998 project), and the past chairman of the AWS Committee D11 on Welding Iron Castings,
- Sam Kiser, a Welding Engineer at Special Metals, with experience in repair of cast irons and current chair of AWS Committee D11,
- Damian Kotecki, Technical Director for Stainless and High-Alloy Product Development at Lincoln Electric, with experience in electrode formulation and repair procedures,
- Bill Myers, recently retired from Dresser Rand Co. (a high-volume user of castings), with experience in casting repair and a long-time member of AWS Committee D11,
- David Olson, a Professor at the Colorado School of Mines, with many years of experience in welding of cast iron and in the development of electrodes, and
- Tom Siewert, Leader of the Structural Materials Group at NIST, with industrial experience in electrode formulation and procedure development.

As additional needs arose, we added a few more members. These included:

- Jerry Doherty, an Applications Engineer at ESAB, recommended by Roger Bushey,
- Chris McCowan, a Metallurgist at NIST, with expertise in sectioning and imaging of microstructure,
- Evan Hinshaw, a Welding Engineer at Special Metals, recommended by Sam Kiser, and
- Tom Christ, an Applications Engineer recently retired from ESAB and with experience from the 1998 project.

Tasks:

1. Review the wide range of repair alloy compositions that have been developed over the years. Especially search for compositions that might tolerate higher levels of phosphorus, typical of castings produced over 100 years ago.
2. Review the procedures that have been developed for hard-to-weld castings.
3. Begin laboratory trials (on common cast irons) to determine which repair alloys and procedures are best matched to the needs of the cast iron present in the dome.
4. Select the best three or four alloys for detailed evaluations.
5. Select the best two alloys and procedures for trials in Washington, D.C., under the supervision of the Office of the Architect of the Capitol (by July 2002).
6. Final report to the Office of the Architect of the Capitol (this report).

3.2 Identification and Development of Alternative Procedures (2002)

The team from ESAB was familiar with the situation and began to work on the task immediately. The very first subtask was a literature search for new developments and for ideas that might have been missed in the 1998 project. In particular, we were looking for alternate solutions to the deficiencies that were found during that field trial. Several papers provided useful information that was used in the selection of the materials and the process details.

We also decided to design and start some experiments immediately, to be sure of having several options ready for the July field trial. Jerry Doherty and Roger Bushey suggested that we evaluate GTA (or TIG) brazing. This involves replacing the oxyacetylene flame heat source with an arc from a tungsten electrode. One of the main advantages using this process is that the parent material is not melted and therefore the weld metal is not contaminated with the high levels of residual elements (especially phosphorus) that might be present in the parent metal. This process has been used successfully in the repair of iron castings and is a reasonable alternative for this project.

The TIG brazing evaluation included making a butt joint followed by a grinding or machining process to end up with a transverse tensile specimen. The test design also included finding the lowest possible interpass and preheat temperatures. The first series of tests used contemporary cast iron for the screening test. The consumables selected for the evaluation included:

- Silicon bronze rods,
- Phosphorus bronze C rods,
- Aluminum bronze rods, and
- Nickel-based rods.

Several joints with the oxyacetylene process and a low fuming bronze (60Cu-40Zn) filler material were also produced for comparison.

The pros and cons of the TIG brazing process include:

Pros:

- The parent material is not melted and therefore the high phosphorus level in the casting will not affect the properties of the weld deposit like they would in an arc process. This advantage applies also to powder spray and brazing techniques.
- The heating by the TIG torch can be easily be controlled by the operator.
- The bronze fillers have a lower strength than conventional cast iron fillers (mostly nickel alloys) and therefore would have greater ductility than that of the parent cast iron, for a lower cracking potential.
- The amount of preheat should be no different from that used for more conventional welding processes.

Cons:

- The technique will produce localized heating that will require some control of the preheat and interpass temperature during the welding process. The extent of this preheat will have to be determined through experimentation.
- The accessibility of the heat source (getting the electrode near the groove) may be a problem, depending on the location of the discontinuity or crack to be fixed.

Special Metals also agreed to start on some evaluations. They selected the SMAW process, since it is widely used (so most welders would be familiar with it) and it produces a low heat input. They evaluated three electrodes: ENi-CI (a nearly-pure nickel alloy), ECuNi (copper-nickel alloy), ENiCu-7 (another copper-nickel alloy), and ENiFe-CI (a nearly 50-50 mix of nickel and iron). They found that ENiFe-CI produced the lowest heat-input settings (60 A, 18 to 20 V) when using stringer beads to butter the surface of a piece of a commercial gray cast iron (with no post- or preheat). They found it difficult to maintain an arc with the other consumables (at the very low heat inputs) and the other consumables produced a very rough weld bead. Therefore the ENiFe-CI will produce welds (for a buttering layer) that are higher in strength than those of the other consumables, but this should not be an issue if the brazing compound to be used will have a yield strength lower than that of the cast iron of the dome.

Meanwhile, the new members of the team wanted to evaluate the situation firsthand, so we scheduled a meeting at the dome. This meeting, held in May 2002, consisted of an overview of the dome restoration plan (by the Office of the Architect of the Capitol), and progress reports on the metallurgy of the dome (by NIST), a progress report on the new weld evaluations (by ESAB), and a tour of the dome. Also, we requested and received a section of a casting that had been removed from the dome during replacement of a badly damaged railing.

Immediately after the progress meeting and tour, we held a brainstorming session. We reviewed the progress that we had made over the past few months, and developed a list of ideas that would result in optimal repairs to the dome skin. The list had two parts: things that might realistically be accomplished in two months (and so be ready to evaluate during the weld trial in July 2002), and a longer-term list of things that might result in even better joints (but could not be ready by July 2002). (The good ideas that could not be evaluated in time for the July 2002 trial are summarized in Appendix A of this report.)

We concluded that the 1998 trial with the PA-7 filler was not made under optimum conditions, and it might have been successful had we maintained better control over the temperature and step pattern. Nevertheless, we agreed to develop a procedure that would overcome the shortcomings found with PA-7, and that would use the PA-7 as a baseline against which our improvements might be compared.
Some of our ideas were based on traditional processes and materials. Nearly pure Ni (Ni 61, with 3.5 Ti) has been used for buttering in previous work, and might serve as an interface that would reduce the strain on the cast iron during the closure weld. Also, Ni 200 (a nickel of higher purity) is a good candidate. Then, we could finish the joint with copper- or silver-based filler. One option was 70-30 Cu-Ni. Another option was to try low-fuming bronze or silicon bronze using short-circuiting-transfer GMAW. The tin may contaminate the tungsten used in GTAW, but maybe a plasma melting technique could be substituted. Roger Bushey and Jerry Doherty offered to try several combinations of buttering with short-arc using pure nickel (on a spool) and cut lengths of Ni-3.5 Ti for GTA, then finishing the weld with bronze or a silver-based alloy. We agreed to check the melting-point ranges in the annex to AWS Standard A5.8 to make recommendations on silver alloys. Ceramic backing materials can be used to avoid fusion to the underlying support structure.

In addition to fairly conventional compositions for joining cast iron, we considered some very innovative ideas (realizing that some new concepts might offer higher payoffs, even though they take longer to develop). These more innovative ideas will be developed as time permits, without delaying our progress toward the July trials. For example, cobalt might be a good base for a repair alloy, because mixing with appropriate amounts of iron or nickel would form an invar-like alloy with a low coefficient of expansion (and so reducing cooling stresses on the cast iron). Also, cobalt can tolerate dilution by carbon from the cast iron. We might also consider a cobalt-copper alloy. A nearly pure Co (or Co-5Fe) will produce excellent ductility, and we could contact Stoody or Thermadyne-Deloro in St. Louis for more advice. Dave Olson would be willing to advise on experiments with the Co-based alloys.

Other items that came from the brainstorming were:

- We decided to put a braze weld along an edge of the long test piece (a railing section from the dome) to see whether we get cracking from a buttering overlay alone.
- We may need to restrict heat input during joint preparation (grinding or milling) to minimize damage to the cast iron, especially for large or complex cracks. Too much heat from grinding might initiate crack growth. This can be determined only during field trials.
- We decided to contact Sandia about a new cold-welding technique, and furnish some material if they are willing to try a weld. Damian Kotecki reported that Mark Smith of Sandia National Laboratory has been giving talks on "Cold Gas Dynamic Spray." This presentation indicated a very high bond strength in cold deposition of soft metal spray powders. He has sprayed copper, iron and nickel, but not onto cast iron. The trick is to get enough kinetic energy into the particles that their momentum produces enough surface deformation and a cleansing jet of expelled surface oxides so that a cold weld results — a true metallurgical bond, unlike the mechanical bond one gets with thermal spray. Heavy buildup is possible. It's a newly developed process looking for a good application. This might be just the thing for the dome repair — no fusion zone and no HAZ. (The following week we contacted them and learned that a portable machine, such as what would be needed for the dome, was still in development. More information would be available after September 2002, the date of an ASM International Conference on this technique.)
- The section of gutter from the dome will go to ESAB for sectioning and use in the final laboratory trials leading up to the field trial. Tabs on the edges of the piece of the gutter will be sent to NIST (for microstructure and composition).

3.3 Evaluation of Alternate Welding Consumables and Procedures (2002)

In the time between the brainstorming session and the field trial, we decided to concentrate on confirming the utility of several procedures:

- Use the TIG process to apply a nickel-based buttering layer to the casting, then follow this with TIG brazing using low-fuming bronze;

- Use oxyacetylene welding to close the cracks with low-fuming bronze; and
- Use the TIG process to join the cast iron with a nickel-based composition (base-line test).

Special Metals' work on very-low-current welding with a nickel-based composition could also be used to produce a buttering layer on the cast iron.

Using the material from the dome, ESAB welded and braze welded a number of joints and provided sections for testing at NIST. The most promising was the oxyacetylene braze weld with low-fuming bronze, followed by the TIG weld with a nickel-based composition. Standard reduced-section specimens were machined from these joints, and are shown in Figures 4 and 5. Both types of specimens had wide ends (for gripping in the tensile machine) and a thin center section (with the joint near the middle). Some specimens were instrumented with strain gages so we could develop very accurate data on the modulus and stress-strain behavior. No specimens were produced with TIG braze welding in time for tensile testing, although it was ready for the field trial.

The side view of a nickel specimen in Figure 4 shows a bend caused by solidification shrinkage during the later passes of the welding process. The side view of a low-fuming bronze specimen in Figure 5 shows that it remained very straight, the preferred shape.

The specimens were tested in tension following the procedures in ASTM Standard E8 "Standard Test Methods for Tension Testing of Metallic Materials" [7]. The tensile test fixture, with a specimen in place, is shown in Figure 6.

The nickel-based specimens (with the bend) broke in the casting's heat-affected zone as the grips were tightened, so no strength data were developed on these. Obviously, a joint this brittle is not a good candidate for repairs to the dome, so we excluded this technique from further consideration. This does not exclude the use of nickel as a buttering layer, but we do need to use a very soft filler that can absorb some bending or expansion-induced strains.
Two low-fuming bronze specimens, WM-1 and WM-2, were tested successfully. The fractures are shown in Figures 7 and 8. We collected data on ultimate strength and elongation as listed in Table 1.

Table 1. Strength and elongation data.

Specimen	Ultimate strength		Elongation (total strain to failure)
	MPa	ksi	%
WM-1	150	21.8	0.22
WM-2	156	22.6	-

Both tensile specimens broke in the HAZ, indicating that both the base metal and the welds were stronger than the HAZ. We obtained accurate strain data only for specimen WM-1, where we collected data from stain gages on both the base material and on the bronze filler. No yield strength is listed because the specimen did not attain a plastic elongation of 0.2 %, which is the usual definition of yield. The use of strain gages rather than a clip gage allowed us to distinguish the plastic strain after failure in both the base metal and bronze. We measured a plastic strain of 0.05 % in the cast iron and 0.14 % in the bronze, indicating that both materials do exhibit a small amount of plastic deformation before fracture. The higher strain in the bronze confirmed that a softer filler shields the sensitive casting from some strain damage. Although we did not obtain strain data for specimen WM-2, a very similar strength and load-versus-time curve appearance would suggest a similar plastic strain.

After the tensile tests, specimen WM-2 was examined with optical and scanning electron microscopes, and the hardness was measured across the filler-base metal interface. The most important observation was the lack of any martensite, the brittle phase found in the HAZ of the 1998 trial with filler PA-7, and which caused the high hardness noted in the HAZ of Figure 3. We attribute the lack of martensite to the braze welding technique (with applied flux) being applied at a temperature lower than that used for PA-7. This very desirable result further supports the choice of braze welding with low-fuming bronze for the repairs to the dome.

Figure 9 shows the cross section through the low-fuming bronze joint at a magnification of about 10 X. The bronze shows good fusion to the cast iron and no porosity is visible at this magnification. Figure 10 shows the cast iron-bronze interface at higher magnification (about 100 X). This image, taken before etching the surface, clearly reveals the carbon flakes in the cast iron (on the left), and a few pores in the bronze, especially along the interface. Since no fracture or cracks occurred at the pores, they have no effect on the integrity of the joint. The interface between the cast iron and bronze is straight (confirming the expected low solubility of the cast iron in the bronze), yet with good wetting (confirming the ability of the bronze to bond to the cast-iron surface).
Figure 11 shows the typical structure inside the HAZ of the cast iron at a still higher magnification (about 1000 X). The large dark lines are the graphite flakes, the white area with the sharp boundaries is iron phosphide eutectic, the gray areas are non-metallic inclusions, the white areas with the softer boundaries are ferrite, and the brown areas are pearlite. The pearlite is slight more spheroidal than that found further from the fusion line, indicating that the braze-welding operation brought it to a fairly high temperature. There is no evidence of martensite in the HAZ of the WM-2, indicating that this braze weld did not reach as high a temperature as that in the PA-7 repair performed in 1998. In comparison, figure 12 shows the structure in the HAZ of an earlier trial of the braze weld procedures on the dome cast iron. This trial was made on the edge of the casting that we received at the May 2002 meeting, and was used as a quick evaluation of whether the low-fuming bronze would wet the cast iron, but on the edge where there is much less thermal mass than on a butt weld. Here, the sharp, black needle shapes are martensite, formed when carbon dissolved (while at the braze-welding temperature), then precipitated (on cooling) as martensite. The martensite is undesirable, as it makes the cast iron

even more sensitive to cracking. The message is that the braze-weld procedure must be controlled to keep the maximum temperature low (as in Figure 11), to minimize the formation of martensite in the casting's HAZ.

Figure 13 is a microhardness traverse taken across the braze weld in specimen WM-2. Notice the similar hardnesses in the weld and HAZ, as compared to that of the hard HAZ shown in Figure 3. This is further support for the absence of martensite in the final test made with the bronze.

Meanwhile, in preparation for the field trial, we collected the equipment that we would need. The maintenance staff for the Capitol agreed to furnish acetylene and oxygen bottles and hoses and the Lincoln Electric District Office in Washington, D. C. offered to loan us one of their commercial TIG power supplies. However, we decided that the 300 kg mass of this 300 A unit would make movement to the repair site very difficult. In effect, we would not be able to roll it along the catwalks or up the steps between the various parts of the roof, and so would need to place it by crane. Also, its significant power requirements (104 A at 208 V) would require special wiring. Diesel- or gas-driven power sources would eliminate the electrical power requirements, but would be even heavier and add the flammability hazards of fuel. Instead, ESAB furnished one of their portable TIG units, which we could carry to the roof. Although this unit provided only 200 A, Jerry Doherty determined that it would be sufficient for the trial. In addition to being light in weight, its input power requirement was much lower (30 A at 208 V), so we could connect to a more common outlet. (The choice between a heavy-weight 100 % duty-cycle power source and a light-weight portable power source will need to be made again by the contractor during the actual repair contract.) ESAB agreed to collect and bring the other equipment (bronze and nickel filler materials, oxyacetylene torch, grinder, etc.) to the field trial.

4.4 Field Trial on the Second Project

On July 18th, Jerry Doherty, Roger Bushey, Tom Christ, and Tom Siewert went to the Capitol to test several repair procedures. Also in attendance were Kevin Hildebrand, and about 10 others associated with the Architect's Office or Capitol staff (most from the maintenance staff, but also an official photographer and videographer).

Perhaps half of the day was taken up in getting the equipment in place, replacing a bottle of oxygen, and discussing the repair details. The rest of the time was used to repair four cracked corners on the dome skin. We had planned, in the time that was available, to evaluate both oxyacetylene braze welding with low-fuming bronze and GTA buttering with nickel, however, we ran into a problem with the GTA technique when gases started to bubble from the pool. We think this may have been due to contamination (this area had been repaired before), and so just switched to low-fuming bronze for the last two repairs. It is unlikely that the SMAW buttering process would have worked any better on the contamination, but there was not enough time to evaluate this.

We repaired a total of four cracks, in two locations. Location 1 was at a corner (just about 0.5 m above the roof of the main part of the Capitol) where two castings met, as shown in Figure 9. These two castings were complex in shape, as they made the transition from the vertical wall to a horizontal shelf. The actual cracks were on the horizontal shelf between about 8 and 14 cm from the corner of the casting, one crack on each casting. One crack passed through a bolt hole (used to fasten the corner), and proceeded at about a 45 ° angle from one edge to the other, a distance of about 8 cm. The other crack propagated above the bolt, also at about a 45 ° angle and over a distance of about 12 cm. After disassembly, the smaller cracked corner was found to be less than half its original thickness, and the group decided that we could replace it with another dome piece (from a gutter) left from the procedure development. A piece was ground to size and used in the repair. The bevel was slightly too large on one side, and the bronze was used to build the casting back to its original shape. Therefore, the repair process might be applied to various types of corrosion damage as well.

Location 2 was on the wall (about 2 m above the roof of the main part of the Capitol) where two castings met, as shown in Figure 10. These two castings were almost perfectly flat. The actual cracks were about 15 to 20 cm in from the abutting corners of the two castings, one crack on each casting. Each crack passed through a bolt hole (used to fasten the corner), and proceeded at about a 45 ° angle from one edge to the other, a distance of about 15 to 20 cm. During final grinding, we found a small crack (about 6 cm long) propagating at right angles to the repair. We think that this was a preexisting crack that had been hidden by the paint until the grinding operation. This crack was prepared by light grinding and was also filled with bronze. This other crack was at a right angle to the main crack, and proceeded down at a 45 ° angle into the plate.

The low-fuming bronze technique worked equally well in both the horizontal and vertical orientations. The oxyacetylene process requires a modest preheat of the casting around the repair, and the temperature during brazing never exceeds a red heat, certainly less than the temperature reached during welding. Figure 11 was taken during the repair and illustrates the process of heating and adding the bronze filler. The general repair procedure is listed in the conclusions.

One repair ended with a bend in the joint, where the far corner of the casting was about 1 cm out from flush. The braze weld was reheated and the corner was gently hammered back to where it should be. Such an adjustment would never have been possible with a high-strength filler.

Each repair was completed in less than an hour, and might proceed faster once the grinding and fixturing procedures are optimized. The final braze welds, after grinding, are shown in Figures 12 and 13. The grinding operation was purely for aesthetic reasons; it smoothed the surface and removed any excess buildup.

Jerry did a great job of demonstrating the optimum technique to the maintenance staff of the

Capitol while making the demonstration repairs. The final inspection showed that the repairs were sound, and a check several weeks later did not reveal any delayed cracking. We recommend that these repairs be inspected every six months or so. Absence of any delayed cracking will strengthen our theory that the cracks in the 1960-era welds were due to excessive strength of the nickel-based weld metal.

In all, we proved that we can repair corner cracks, but may need to go back again some time to demonstrate repairs on the more complex geometries.

We were prepared to use backing strips to support the filler material in wide grooves and to prevent the repair from fastening the skin to the supporting ribs and brackets, but these were not needed for the joints that we repaired. In one type of backing strip, small ceramic tiles were attached to the center of a fairly wide adhesive strip, allowing the backing material to be centered on the back side of the joint and to adhere to curved surfaces within the dome. After braze welding, the adhesive was removed so the inside surface of the joint was exposed for cleaning and painting. The ceramic supports the molten pool until it cools and helps to produce a smooth, rounded profile on the back. Over the internal structural elements (e.g., adjacent flanges or ribs) to which the braze weld should not bond, a thin strip of nickel (perhaps a millimeter or less) can be placed at the bottom of the joint before repair. Proper selection of the thickness of the nickel strips will give a heat sink that will prevent penetration.

4.5 Repair Procedure Used in Field Trial

Joint preparation: To get good fusion, the joint was opened up to give access to the bottom of the joint and to allow room to manipulate the puddle. The joints were ground to give a 2 mm (about 3/32 in) root opening (minimum), and the sides were beveled to produce a 70 ° (minimum) included angle.

The filler material was flux-coated low fuming bronze (60Cu-40Zn) meeting the requirements of American Welding Society (AWS) Standard A5.8, class RBCuZn-C. It is nominally 60 % Cu and 40 % Zn, but also contains about 1 % Sn, 1 % Fe, and smaller amounts of some trace elements. The diameters used for this repair work were 2.4 and 3.2 mm (3/32 and 1/8 in).

The flux coating on the bronze was supplemented with a powdered flux, meeting AWS A5.31 Class FB3-F. This red-brick colored flux improved the wetting of the low-fuming bronze filler rod to the cast iron. Also, the melting point of this flux served to indicate that the joint was hot enough to accept filler material and fuse properly.

Before braze welding, the cast iron was preheated by continually moving the torch over the cast iron (never keeping it in any place long enough to overheat the casting). The preheat temperatures were approximately 260 to 315 °C (500 to 600 °F) in an area 10 to 13 cm (4 to 5 in) adjacent to the joint to be brazed. The actual temperature used for the braze welding is near 982 °C (1800 °F). A neutral flame was used throughout the repair operation.

Approximately four to five passes were used to fill the joints in the cast iron (nominal thickness of 8 mm). After completion, the joints were ground to match the height of the cast iron.

4.6 Conclusions and Recommendations on 2002 Project

- Oxyacetylene braze welding with low-fuming bronze (60Cu-40Zn) produced four fully acceptable repairs in the simple corner-crack geometries tested during the field trial. Mechanical testing and microstructural evaluation of the procedure on cast iron from the dome also confirmed the suitability of the procedure. Therefore, this seems to be a very realistic option for many of the cracks in the dome. Additional tests on more complex geometries and conditions will help to define the acceptable range of this repair technique. Also, the integrity of these four repairs should be monitored occasionally.
- The repair procedure is listed in section 4a.
- Those who made the braze welds at the field trial might be used to train those who will perform the actual repairs, or at least give an overview on the details.

4.7 Plans

Some of the team members volunteered to work on their own after the completion of the 2002 repair trial. In particular, they wish to investigate some promising ideas that just could not be evaluated and completed within the tight schedule of the July 2002 trial. These ideas are described in more detail in Appendix A. Those who will participate in these future efforts will report their findings back to the Office of the Architect of the Capitol.

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