THE COURSE OF SOLAR ARRAY WELDING TECHNOLOGY DEVELOPMENT*

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SUMMARY

Solar array welding technology is examined from its beginnings in the late 1960's to the present. The U.S. and European efforts are compared, and significant similarities are highlighted. The utilization of welding technology for space use is shown to have been influenced by a number of subtle, secondary factors.

INTRODUCTION

Since the time of the first satellite solar power systems, the preferred method of solar cell interconnect attachment has been solder. Yet for over a decade there has been a continuing if not always steady development of a "better" method. Although a number of satellite solar arrays have been assembled with welding methods by the European industry (ref. 1), welding has not achieved a similar level of application in the U.S. Even though solder has proven suitable for past space efforts, future requirements will most likely exceed its capabilities. For this reason NASA is planning to initiate a U.S. welding program that will provide the knowledge and confidence required to achieve flight ready status. This paper will provide a background to that effort, examining past activities and results in welding for U.S. and European efforts. It will be shown that the two efforts exhibit considerable similarity and that the greatest impediment to weld acceptance has been the lack of suitable in-process NDE (nondestructive evaluation) methods. The following discussion will generally follow a chronological format.

SOLDER

Early studies have shown solder to have a number of critical limitations both at high temperature where creep and even melting can occur, and at low temperatures where fatigue induced failure is of concern (ref. 2). The former limit is readily observable since the melting points of the solders are well documented. The low temperature situation was, and still is, much more difficult to quantify.

Due to thermal expansion mismatches between the cell, solder, and interconnect, various stress distributions will occur depending on temperature limits, bond area, and component thicknesses. Analyses indicated that a small number of very low temperature exposures or a moderate number of less severe low temperature exposures could lead to cracking in the solder (ref. s 2 & 3). Since the acceptance of a solder bond has been tied to the appearance of the solder fillet, changes in ap-

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pearance which were observed during thermal cycling were occasions for concern. It was felt that these changes ultimately lead to bond failure including possible silicon divoting. The correlation between solder cracking and observable surface appearance changes and actual bond or silicon failure was not however, clearly demonstrated. At the same time since actual stresses within the bond were influenced by the materials used, stress reduction could be achieved by means of changes in materials or thickness (ref. 4). As a result, the present day solder system is considerably improved over that used in the late 1960's. Solder pressing and preforms have reduced the solder thickness in the bond, and interconnectors with coefficients of expansion close to silicon's, such as molybdenum, both create a more favorable situation than the earlier systems. As a result, it is now possible to withstand over 1000 cycles typical of GEO (equivalent to over 10 years orbit), something that might not have been expected from early analyses (ref. 5). By comparison early tests of soldered interconnects with less optimum configurations typically suffered modest to severe damage under similar thermal cycle conditions (ref. 2).

The case for long term LEO use of solder has not been as optimistic. Even though temperature extremes are less pronounced, the need to demonstrate survival capability for tens of thousands of cycles means that the costs and time required to adequately test the LEO simulations is considerable and as a result a greater reliance must be placed on theoretical analyses for guidance. These analyses indicate that the solder system should be replaced with a welded (brazed) one. As time has shown, this has not been a trivial task. Solder's easy repairability, relative insensitivity to process parameters, suitability to visual inspection, and large bond area with resultant high bond strength, have proved a challenging combination to overcome.

WELDING TECHNOLOGY DEVELOPMENT
(EXPLORING ALTERNATIVES 1965-1970)

The beginning of serious solar cell weld development can be traced to the development of the palladuim passivated cell contact. This meant that humidity resistance could be achieved without the use of solder (ref. 6), allowing non-solder interconnection methods to be freely pursued. During this early phase, European and U.S. organization pursued a great number of interconnecting schemes such as ultrasonic, thermal diffusion, thermocompression, parallel gap resistance welding (R.W.) and even laser welding (ref. 7). These were examined for use with a wide variety of interconnetor materials including silver, aluminum, gold, silver plated copper, molybdenum, and Kovar. Various degrees of success were obtained in these exploratory efforts resulting in a narrowing of options by 1970. The European choice was primarily R.W. in conjunction with silver plated molybdenum tabs, although pulse welding has continued to receive significant although limited development (ref. 8). Pulse welding is actually a version of the more familiar R.W. technique where the heat for the bond fusion is formed in one of the two weld electrodes rather than in the cell/interconnector contact region.

By contrast, a consensus was not as rapidly attained in the U.S. This can be traced primarily to the emphasis on development of Al contacted cells for satisfying military requirements. As a result the U.S. effort was initially biased towards ultrasonic welding of aluminum interconnectors to cells with aluminum (Al) contacts. The Al-Al system did not prove highly successful, so it wasn't until after 1970 that the U.S. effort focussed on the R.W. method. Similar to the Europeans, a single significant alternative method has survived this initial exploratory period. In this case, it is ultrasonic welding, now used with Ag interconnects and conventional silver contacted cells (ref. 3).

It is interesting at this point to compare the European and U.S. efforts resulting from the exploratory period. Both ultimately emphasized the R.W. method, based on use of the Hughes MCW 550 power supply. The interconnectors of primary choice were usually silver plated rigid materials with thermal expansion coefficients somewhat matched to silicon's. Yet both efforts also resulted in a single significant alternate method, pulse welding in Europe and ultrasonic in the U.S., that were tied to the use of a relatively flexible interconnect material, silver. In fact both these alternates have received continuous although limited support through the present. They share another similarity--rather than rely on spot bonds such as occur with R.W., they use tooling that provides a linear bond.

A EUROPEAN COMMMITMENT, 1970-1974

By 1972 the European effort achieved a milestone with the commitment of R.W. to the Helios solar probe (ref. 9). Due to the high temperature environment that the probe would observe, it was obvious that solder would not be suitable and welding was necessary. However, excluding the high temperature exposure (175°C) the mission thermal cycling environment was not particularly severe. At the same time, a number of developments served to reduce the concern over individual weld bond integrity such as the cell interconnector-cover (CIC) "sandwich" assembly, and increased interconnect redundancy (ref. s 9 & 10).

Studies of bond joints had indicated that solder bonds are subject to high stress not only due to the thermal coefficient mismatch, but also because of the large bond area. Advantages for welded systems then, would be to reduce the thermal coefficient mismatch and also to provide a smaller bond area. Both would serve to minimize stresses. However, the smaller bond area translates to reduced bond strengths, particularly under torsional loading of rigid interconnectors, such as were in use (ref. 7).

The use of the CIC not only provided protection to the cell's complete top surface, but it also mechanicaly constrained the tab at the weld joint, providing protection against torsional loading. It is even possible that under a debond situation the mechanical coupling provided by the CIC assembly might allow full electrical contact, simulating a sliding contact.

The cell design used with the CIC assembly allows the use of 3 bond joints per side of the cell. This redundancy reduces the need for 100% bond integrity since only one joint per side would be needed for useful cell output. Since it was not possible to verify the quality of each individual bond this approach provided a practical method for using an "imperfect" weld process. As a further attempt at maximizing the bond integrity, automated indexing and welding of the CIC assemblies was introduced so as to minimize operator dependence. The combination of weld, CIC, and redundancy, thus allowed an unproven technology to provide a confident interconnect method. This was all applied to an almost perfect first mission need for a weld interconnect system.

During this period although evaluation of weld schedules and the influence of component variations continued, the emphasis of U.S. and European welding was placed on developing methods for ensuring individual bond quality since the basic weld optimizations had been performed. The primary problem was that, unlike solder, the bond was not visible for inspection, particularly for rigid interconnect systems. Some correlation between the bond characteristics and deformations in the welded interconnect was possible with the silver system (ref. s 4 & 7), but in general visual inspection was not felt to be sufficiently reliable. Since the R.W. method relies on current flow in the bonding components to generate sufficient but not excessive heat (which could degrade the cell junction), initial efforts were based on pre-weld measurements of resistances between the electrodes, interconnector, and cell in order to establish go/no-go conditions of resistance that would impact the weld process. The heat generated in the weld bond was then related to characteristics of the weld pulse such as current and energy flow so that conditions of over (excess melting) and under (insufficient heat) welding could be estimated for each individual weld (ref. s 11, 12, 13 & 14).

These of course are secondary approaches to accounting for actual heat flow at the bond surface, but have proven to be reasonably reliable. For example, in one study, the application of these methods was evaluated against weld pull strengths and it was determined that for a moderately large sample size, it was possible to identify nearly 92.5% of the bad welds (over or under welds) (ref. 11). During this period AEG Telefunken reported that they had accumulated experience with over one hundred thousand weld processes, a significant quantity.

In the U.S. encouraging thermal cycle results were reported using ultrasonic welding and silver interconnects. After 700 cycles of a simulated GEO environment no electrical degradation was observed for sample test modules. However, it was noted that soldered samples performed as well (ref. 15).

TECHNOLOGY EVOLUTION-QUALITY ASSURANCE CONCERNS (1975-1982)

By 1975 the European program was moving rapidly with a variety of new welded solar arrays being assembled for missions. In fact 5 space projects were well underway, and the number of weld joints that had been made was estimated to be well over a million (ref. 13). However, this was not to imply that the R.W. method was completely reduced to practice since work on weld parameter optimization and on inprocess controls continued to be published. For example, work continued on determination of an optimum range for the parallel gap weld pulse duration. This was of interest since a number of studies had shown that good welds (based on pull strengths and cell electrical effects) could be achieved for a wide range of pulse durations as long as the pulse voltage was simultaneously adjusted (ref. s 4 & 13). Along with earlier results (ref. s 7 & 14), the new work indicated an optimum duration of approximately 100 msec (ref. 13). Also this time, AEG Telefunken proposed that the weld pulse shape be changed from the "standard" rectangular wave to a trapezoidal shape (ref. 13).

In the U.S., similar activities were conducted although again without any significant flight program application. The use of a combination of preweld, in weld, and post weld tests was examined and found to be a reasonable predictor of weld strength. In fact, one study showed a 93% correlation could be made with acceptable bond quality (ref. 17), a value surprisingly similar to European results published somewhat earlier.

The similarity of the U.S. and European efforts and results to this point can be dramatically shown by examining the data presented for independent weld optimizations done on similar interconnect systems.

In 1970 AEG Telefunken reported that Ag (5 μM) plated molybdenum (30 μM) could be best welded with the following conditions (ref. 7):

pressure = .75 → 2.5 kg
duration = 100 msec
voltage = .65V front, .70V rear

In 1974 Lockheed reported that optimum conditions for a similar interconnect system were (ref. 14):

pressure = .68 kg
duration = 100 msec
voltage = .64V front, .72V rear

The results are very similar. In view of the many possible subtle differences in cells and interconnectors such as contact thicknesses, surface smoothness, and plating methods, these results indicate a strong consistency in the R.W. weld process.

After 1976, less welding work was being reported, but the concern for NDE methods was still evident. Clearly the problem of individual weld integrity has not been solved. Both U.S. and European efforts report encouraging results in using Infrared (IR) monitoring to detect the temperature of the weld. Although detection of heat from portions of the interconnector and weld electrodes can interfere with actual temperature measurement at the bond line (ref. 18), the method is felt to be sufficiently useful that it has been incorporated into one manufacturer's weld process. In practice the detected thermal signal is used to terminate the weld pulse when a preset IR sensor output value is measured, compensating for variations in the cells and interconnectors (ref. 19).

Competitive alternates continued to show progress on both continents. The MBB pulse weld method is combined with Ag mesh to provide CIC assemblies for Intelsat V (ref. 20). Hughes Aircraft determined that the small bonds obtained with ultrasonic spot welding methods were unacceptable and developed a rotary ultrasonic seam welder that when used with Ag mesh can provide a strong and highly redundant interconnect system (ref. 3). Advanced methods such as laser welding continue to receive support (ref.'s 21 & 22).

CONCLUSION

A review of weld technology developments shows many similarities between the U.S. and European efforts. The major difference has been one of flight hardware experience. At the same time, with the exception of the high temperature Helios mission, the environmental requirements of those welded arrays flown could have been met by use of solder, somewhat mitigating these as full endorsements of weld capabilities. In fact, it is the influence of a number of secondary factors, shown in Table 1, rather than basic differences in welding capabilities that have determined the use of welding for space applications.

Extensive work on weld optimization, when combined with pre-weld and in-weld monitoring, has lead to a fairly reliable technique on both continents. Ultimately a temperature detection system might prove more valuable than the weld pulse monitoring methods commonly used since it should avoid uncertainities involved in the indirect measurement of the bond temperature.

The single most significant impediment to weld technology acceptance is the lack of a non destructive inspection technique to evaluate an individual bond. Recent work on viewing of the internal weld structure, using IR and ultrasonic techniques (ref. s 19 & 23) may provide a solution to this limitation and lead to full confidence in the welding process.

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Table 1

Factors Influencing Weld Development

- Passivated Cell Contact
- Aluminum Cell Contact
- Cell-Interconnector-Cover Assembly
- Redundant Interconnections
- Helios Near-Sun Probe
- Pre-Weld, In-Weld Monitoring
- NDE Techniques for Bond Evaluation