A unique approach to an urban magnetic levitation vehicle (Refs. 1–3) was developed by a multiorganizational team led by General Atomics. Powerful NdFeB magnets arranged in a “Halbach” array were coupled with more than 700 ft of Litz wire ladder track to produce levitation and control. The conceptual vehicle, demonstration vehicle, and details of track and magnet relationship are shown in Fig. 1. The Federal Transit Administration sponsored the Urban Maglev program and the Litz ladder track was fabricated for General Atomics, San Diego, Calif.

The vehicle is propelled by a fixed linear synchronous motor reacting with permanent propulsion magnets attached to the vehicle — Fig. 1. Two other sets of NdFeB magnets with poles aligned in a specific pattern provide levitation. As these magnets pass over the fixed Litz ladder track, opposing magnetic field loops are generated. This sequential interaction or repulsion is responsible for levitation and path control. Successful operation of the vehicle depends on copper wires inside the Litz ladder bars being metallurgically bonded to the copper extrusions shown in Fig. 1.

The track also has a structural function. As seen in Fig. 1, the Litz track is cantilevered off a fixed guideway foundation weldment. This means the track must be able to support the weight of the vehicle through magnetic force levitation reaction.

Although this vehicle has a maximum speed of about 100 mph and normal operational speed of about 35 mph, magnetic levitation vehicles in operation today have attained speeds in excess of 300 mph. Advantages of these vehicles include pollution-free operation, adaptability to existing roadways, no vehicle/track friction, and good acceleration and ride characteristics.

Tract Construction Details

A finished Litz bar track is shown in Fig. 2. The individual Litz track bars consisted of ~144 insulated oxygen-free high-conductivity (OFHC) copper wires encased in 1-in.-square Type 304/304L tubes. The wires are originally installed in oversized round tubes and then both are extruded to the square shape. The wires have a spiral contour within the tubing that is important for proper magnetic performance. It was also important to maintain the integrity of insulation on each Litz wire due to the skin effect present at the high operational frequencies. Shorting from wire to wire had to be avoided. Details of the Litz bar construction are seen in Fig. 3.

The OFHC copper extrusions had to be designed and purchased. This was a critical part of the project since the ends of the Litz bars had to closely nest in the extrusions so that the ends of the wires could be soldered. Since 201 bars had to be soldered into both extrusions, some tolerance for out of straightness and twist had to be considered. At the same time, clearance of the stainless steel tube with the extrusion “trough” could not be excessive or joint strength would suffer. One important extrusion detail was to provide undercuts in the interior corners so interference with the stainless steel bars was avoided. An extrusion and joint cross section are shown in Fig. 4.

KENNETH H. HOLKO, P.E., (kholko1@san.rr.com) is with Holko Consulting, San Diego, Calif.

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A cross section through the Litz wires and bars is shown in Fig. 5 to illustrate the tight spacing and insulation coating. It was essential for the ends of each wire to be soldered to the copper extrusions, so the magnetic loops necessary for levitation could be developed. The low and repeatable interface resistance was necessary for adequate lifting force to be generated and to provide a smooth ride.

**Track Requirements**

Track requirements were stringent in that 17-ft track sections were required to be flat within 0.08 in. and within drawing contour to 0.04 in. About half of the 42 sections fabricated had unique, nonlinear designs. These various track curvatures were necessary so the final test track could include a 165-ft radius turn. Total test track length was about 360 ft. Also, bar-to-bar spacing had to be held to 0.04 in. to ensure optimum vehicle performance.

Each joint in each track was tested by applying high amperage and measuring resistance. Each joint was required to have less than $40 \mu \Omega$ electrical resistance.

Since measurement for contour and resistance was done at the customer’s facility, each completed track section had to be shipped on a custom strongback to avoid damage. Since each track section weighed in excess of 1500 lb, this also enabled safe handling.

**Development**

After the copper extrusions were received they were solvent cleaned and lightly etched to remove surface oxide. The Litz bars were also solvent cleaned. One-ft-long qualification samples were soldered and provided to the customer for electrical testing. Initial samples did not pass the resistance test. It was learned that a pretinning step the customer suggested for the bar ends and the method of solder application were critical to successful soldering. This was learned through metalurgical sectioning and examination. The problem was largely related to removal of the electrical insulation around each Litz.
wire at the solder joint.

So, the first challenge was to develop a repeatable tinning technique for both ends of the 8400 Litz bars that needed to be soldered. The solder material the customer selected was 95 wt-% Sn–5 wt-% Ag. This alloy was used for tinning and fabrication.

A necessary step was to preheat the bars in an air furnace before fluxing and tinning in a solder pot. The preheat and solder pot temperatures were critical. (See the boxed item to review the actual parameters and procedures for soldering the track.) The function of these steps was to burn off the insulation, but only from the ends of the wires, and simultaneously wet the copper wires and stainless steel tubing.

Time in the solder pot was also critical as too much or too little solder could be drawn up between the wire ends. Figure 6 shows the preheat, flux, solder pot immersion steps, and final appearance after wiping off excess solder.

Harris Stay Clean liquid flux (Fed. Spec. OF506, Type 1, Form B) was used to facilitate wetting. The small holes near the ends of the Litz tubes are vent tubes to allow insulation vapor to escape. Reliable wetting could not be achieved without these vents. It was also critical to remove excess solder from the tube ends while the solder was still molten. A combination of snapping each tube and wiping with a wet rag was used. Both tube ends had to be kept above the solder liquidus for this to work. Excess solder on even one tube end would prevent proper fit, later, in the copper extrusion.

Another challenge remained in Litz bar preparation for fitting later in the extrusions. About half the bars contained an unacceptable amount of twist and/or bend. Therefore, each bar had to be untwisted or straightened in a hydraulic press. Care had to be taken not to overtwist or overstraighten the bars. This operation was done both before and during fitting into the extrusions. The untwisting operation is shown in Fig. 7.

After the bars were prepared they were set up on an aluminum fixture with proper spacing controlled by stainless steel shims. As seen in Fig. 8, the aluminum fixture was built in two halves to clamp and hold the Litz bars.

After light clamping to hold position, the copper extrusions were sequentially drawn into tight contact with bar ends through the use of clamps as shown in Fig. 8.

During assembly and before soldering could begin, the position of each tube and extrusion location and profile had to be checked against each unique drawing. Since a coordinate measuring machine was not available, a number of full-size vellums were created from the CAD files for the track segments. By laying the vellums on the assembled tubes and extrusions, position could be corrected and fit into tolerance. Figure 9 shows the use of vellum.

Fig. 9 — Vellum used to fit tubes and extrusions.

Fig. 10 — Moving assembly into position for induction soldering.

Fig. 11 — Induction soldering equipment.

Fig. 12 — Coil providing heat for soldering.

Fig. 13 — Dam used to control solder flow.
Induction Soldering Procedure

The final procedure developed and used on most of the maglev tracts was as follows.

1. Check Litz bars for straightness and twist. Straighten bars as necessary.
2. Degrease Litz bars and copper extrusions with acetone. Lightly etch copper extrusions in Citirinox at RT. Rinse in DI water and dry.
3. Preheat Litz bars in air at 275°–300°F metal temperature for 30 min minimum.
4. Fill solder pot with 95 wt-% Sn–5 wt-% Ag solder and heat to 650°–700°F.
5. Remove bars from preheat furnace and briefly immerse ends in Harris Stay-Clean liquid flux.
6. Immediately tin ends of Litz bars by immersing in solder pot to a depth of 1 in. for a minimum time of 3 min and a maximum time of 5 min.
7. Remove from pot and use a combination of snapping bar and wiping with a wet rag to remove excess solder.
8. Inspect Litz wire ends for untinned areas and re-tin if necessary.
9. Install bars in extrusions, apply fixtures and clamps. Located bars per applicable customer drawing using tape, precision scale, and vellum. Install solder dams at both ends of extrusion.
10. Rotate track into position for soldering.
11. Setup traveling Tocco 25-kW induction unit, custom two-turn saddle coil, and track. Check coil spacing (~1⁄4 in.) and travel along extrusion bar. Set travel speed for 3 in./min.
12. Starting with coil stationary and centered about 3 in. from one end, squirt Harris Stay-Clean liquid flux into joint, and begin heating at ~50% power setting.
13. When melting temperature is reached, begin pushing the ¼-in.-diameter 95 wt-% Sn–5 wt-% Ag solder rod into joint. Note: Best results were achieved with an operator on both sides of the track.
14. When molten solder reaches dam, start coil travel away from dam while continuing to feed solder into joint.
15. Maintain ~¼-in. coil to extrusion gap, feed solder rod, add flux as necessary for good wetting, and adjust power for control of melting and solidification in front and behind coil position. A uniform solder fillet should form behind the coil position as the solder solidifies.
16. Turn off induction power and stop travel ~3 in. from end of extrusion. Continue to add flux and feed solder until joint is filled and solidified.
17. Inspect entire length of extrusion, both sides, for joint fill and uniform fillet formation. Go back and repair questionable locations while track is still in fixture.
18. Rotate track and solder other side in same manner.
19. After both sides are finished and inspected, remove track. Check with appropriate vellum and correct/resolve any discrepancies with customer representative.
20. Use solvent to remove excess flux. Use sanding discs with fine grit to touch up areas with excess solder.
21. Strap to strongback and prepare shipping documents.

Induction Soldering the Tracks

Once the bars and extrusions were set and clamped into correct position, the same setup fixtures were used to hold and manipulate the tracks during induction soldering. Rotating the fixtured assembly into position for soldering is shown in Fig. 10.

Induction soldering was performed with a 25-kW Tocco variable-frequency induction unit, remote station, and custom water-cooled coil as seen in Fig. 11.

As seen in Fig. 11, the power supply, remote station, and coil were mounted on an adjustable stand and track so the coil could travel under the extrusion/Litz bars to provide heating. The coil in position during soldering is shown in Fig. 12.

Solder was manually introduced to the joint from ¼-in. straight lengths. The joint was fed simultaneously from both sides. Liquid flux was also added to the joint during soldering to aid wetting. Shims were left in place (top of Fig. 12) during soldering to hold the required bar-to-bar gap.

Controlling the soldering operation was a careful balance between coil design, power input to the joint, localization of heating, and travel speed. If heating was too spread out over the extrusion, solder would run away from the joint and fill and solidification control would be lost. This was particularly a problem at the beginning and end of each track where physical “dams” had to be used as seen in Fig. 13.

Several coil designs were tried and used for production. Best results were obtained with the two-turn “saddle” coil design shown in Fig. 11. To obtain a tight coil geometry for heat concentration and provide for water cooling, ¼-in.-square OFHC copper tubing with a round hole was used. The coil was made from cut and mitered segments silver brazed together to avoid bend problems. Insulation tape was used to minimize coil shorting to the extrusions.

When proper balance was achieved, induction soldering could be done at 3 in./min without overdriving the coil or power supply. The induction soldering operation went smoothly after the lessons described here were learned. Occasional low fill areas or small fillets could be repaired by reheating with the induction coil and adding more solder. Cleanup of excess solder, as seen in Fig. 13, was eventu-
ally minimized and good cosmetic appearance was achieved as seen in Fig. 2. No rejects for high resistance were reported for the 42 segments fabricated.

Metallography was used to determine interior quality by sectioning small samples during the program. Examples of sections through the Litz bar to copper extrusion joints are shown in Figs. 14 and 15. Good fill, fillet, and joint formation were observed. Occasional oxide-type inclusions can be seen that are probably a result of residual wire insulation. However, overall quality is good.

The vellum approach previously described was used for final inspection as seen in Fig. 16. On rare occasions, the track was reinstalled in the fixture, re-heated, and a dimension restored, such as bar-to-bar spacing.

Track flatness was checked on the assembly table shown in Figs. 8 and 10, which had been ground flat prior to the beginning of this program. Conventional height and feeler gauges were used.

Preparation for shipment is shown in Fig. 17.

**Conclusions**

This was a very successful program and fabrication experience as proven by the tracks meeting all design and operational requirements. The track was installed in 2004 and is still being operated today. In fact, new interest in this system has developed for moving cargo containers at port locations as seen in Fig. 18.

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**References**