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U.S. ITER INDUSTRY COUNCIL STATEMENT ON ITER CONSTRUCTION [*]

The U.S. ITER Industry Council, at its meeting in Washington, D.C., on 7 August, agreed upon a statement concerning the construction phase of ITER. This statement was then presented to the Fusion Energy Sciences Advisory Committee (FESAC) in the course of its discussion of ITER issues. The following are two excerpts from the statement:

"The U.S. ITER Industry Council supports the major goals of ITER and its role in the international fusion program. We believe that the demonstration of sustained production of fusion power, such as ITER promises, is a necessary step if fusion is to become a part of the world's energy supply mix. ITER would also provide necessary integrated tests for fusion energy technology, components, and systems in a real-world, fusion environment.

The U.S. ITER Industry Council believes that construction of ITER is feasible. Furthermore, the amount of design and R&D already completed on ITER exceeds that which typically exists for large projects at the time a decision is made for construction. Pooling of the world's technical resources will provide a broader base of industrial skills and experience than any single nation can provide. There are several examples of multinational industrial efforts which show the effectiveness of this approach. It is appropriate that ITER is done on an international basis. The Council believes participation of U.S. industry in ITER is important for several reasons:

1. *Through participation in ITER, U.S. industry will develop skills and capabilities that will make industry more competitive in the global marketplace;*
2. *The involvement of U.S. industry will provide valuable insights and practical experience, which can lead to lower cost components and improve ITER performance;*
3. *Transfer of technology from ITER will be realized through U.S. industry participation; and*
4. *The project management of ITER will be greatly enhanced by the participation of U.S. industry."*

"The goal should be for the U.S. to be considered an 'equal' participant in the transition and construction phases. Specifically, U.S. industry should be involved in the transition period for the following reasons:

- *ITER designs will be improved via feedback from industry R&D and cost studies;*
- *Manufacturing procedures will be further optimized on high leverage components;*
- *Prototype work started in the EDA will be completed; and*
- *Industrial personnel are best able to help the JCT plan for construction and complete procurement packages.*

In summary, the U.S. ITER Industry Council believes that ITER is ready for the construction phase. Industry participation in the transition phase should be at a sufficient level to improve the manufacturability of the design and prepare for fabrication of long-lead-time components."

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[*] The US ITER Industry Council, currently chaired by Dr. William R. Ellis, Raytheon Engineers & Constructors, Inc., was established by the US Home Team Leader to give him advice from an industry perspective on ITER matters under his purview.

Nb_3Sn CONDUCTOR DEVELOPMENT FOR THE ITER MAGNETS

by Dr. N. Mitchell, ITER Naka Joint Work Site, on behalf of the ITER JCT and Home Teams

ITER Conductor Configuration

The ITER magnet system consists of Toroidal Field (TF) coils, Poloidal Field (PF) coils , the Central Solenoid (CS) and error field correction coils (CC).The conductors for the coils are Nb_3Sn or NbTi cable in conduit type, forced flow cooled with supercritical helium having a maximum operating current in the range 40-60 kA. To qualify the Nb_3Sn conductor, two large model coils (energy up to 640 MJ) are being wound by the Home Teams of the Parties to the ITER EDA Agreement. A total of 24 t of strand has been completed for the CS model coil and 4 t for the TF model coil, and fabricated into 7 km of conductor in unit lengths up to 210 m, by an international collaboration involving 12 companies in Europe, Japan, Russia and the USA.

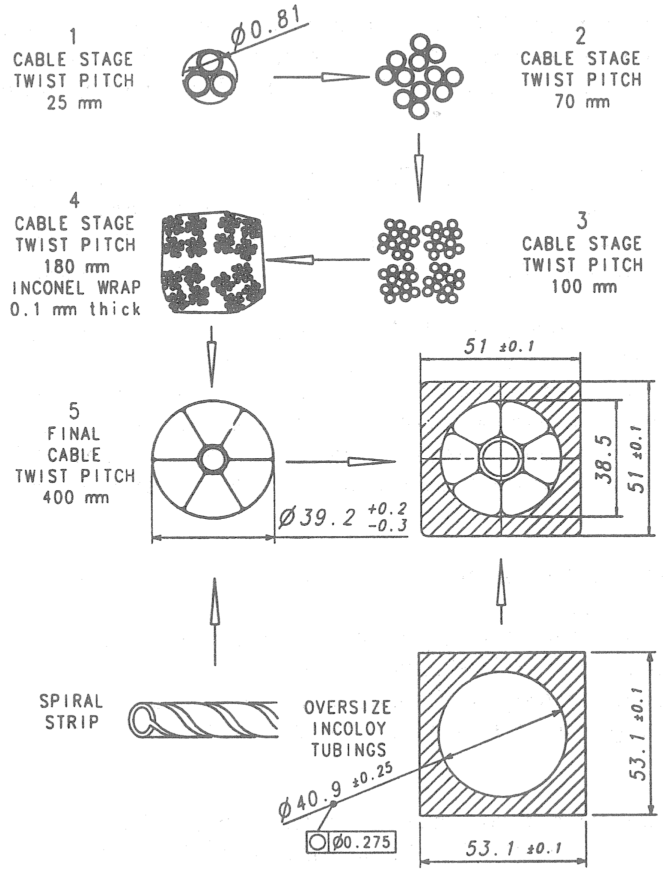

Fig. 1. CS Conductor Components and Assembly

The Nb_3Sn superconducting (s/c) strands are cabled with a multi-stage arrangement around a central cooling tube formed from a spiral as shown in Figures 1 and 2 2. Copper strands are incorporated into the cabling layout for lower field conductors (<11 T).

Inconel-600 strips are used to wrap the last but one stage, and the final cable is wrapped with an overlapped Inconel or stainless steel (SS) strip. The resistive strips around each subcable reduce the coupling currents between the final substages while the outer wrap protects the cable during handling and jacketing and provides dimensional stability during spooling.

The cable is then enclosed in an Incoloy-908 jacket, with a square outer section for the CS coil and a thin circular tube for the TF coils, using a pull-through and compaction process. The conductor unit lengths range from 750 m to 1400 m for the two types of full scale coils.

Incoloy-908 was developed by INCO* and Massachusetts Institute of Technology (MIT) for use in CIC (cable in conduit) conductors, with a thermal contraction coefficient which matches that of Nb_3Sn. There is minimum loss of strand performance due to strain effects in the A15-type superconductor. However, the material is new and has posed several development issues.

Nb_3Sn-type superconductors have to undergo reaction heat treatment (about 650°C for 200 hrs) to form the Nb_3Sn compound. This also hardens the Incoloy 908 to provide good mechanical performance. As Nb_3Sn is brittle, conductor forming operations such as coil winding are completed before heat treatment. Incoloy 908, in common with several iron-nickel superalloys, is sensitive to stress accelerated grain boundary oxidation at temperatures between about 500°C and 750°C. In this range, a combination of oxygen at level above about 1 ppm and tensile stress above about 200 MPa can cause drastic cracking of the material. An extensive programme to avoid stress accelerated grain boundary oxidation (SAGBO) has shown that shot peening of the outer surface to create local compression and careful control of the heat treatment atmosphere to keep

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* *Abbreviations of the companies are defined at the end of the article.*

oxygen levels below 0.1 ppm above 500°C, as well as to avoid organic compounds in the cables, combined with oxygen absorption by the strand chrome coated surface appear to completely prevent SAGBO.

Model Coil Conductor Production

The CS model coil (CSMC) is a layer wound solenoid about 1.6 m high and with a central bore of about 0.8 m (see Newsletter, *Vol. 6, No. 3, March 1997*); the TF model coil (TFMC) is a racetrack shape coil with a central bore of about 1.5 m by 2 m (see Newsletter, *Vol. 6, no. 4, April 1997*). The CSMC will operate under pulse conditions up to 13 T and will form the main testbed for the conductor, TF as well as CS coil. The TFMC operates up to 8.5 T and is mainly intended to demonstrate the more complex winding technique used for the ITER TF coils. Both coils use conductors similar to those proposed for the ITER coils. The CSMC uses two grades of conductor: CS1, which is all s/c strands, and CS2, where one s/c strand in the first triplet is replaced by a Cr coated copper wire. The TFMC uses a cable similar to CS2 but a circular rather than a square outer jacket.

ITER conductor development has focused on the production of conductor for these coils.

Strand Manufacturing Process

The metallic precursors of the Nb_3Sn strand are assembled by conventional techniques, according to two methods: "bronze technique" (used by supply companies VAC, Furukawa, Bochvar Institute and Hitachi) and "internal Sn technique" (used by supply companies EM, IGC, TWCA and Mitsubishi). Strands containing 4000-9000 filaments, each of size 2-5 μm are produced by extrusion/drawing. Unit lengths of strand are determined by the precursor size and frequency of breakage, and range from <1 km to >10 km. Materials used for the diffusion barrier are Ta and Nb or a combination of these as a multilayer barrier (with the Nb layer facing the stabilizing copper). A cross- section of an internal tin type strand from Mitsubishi is shown in Fig.2.

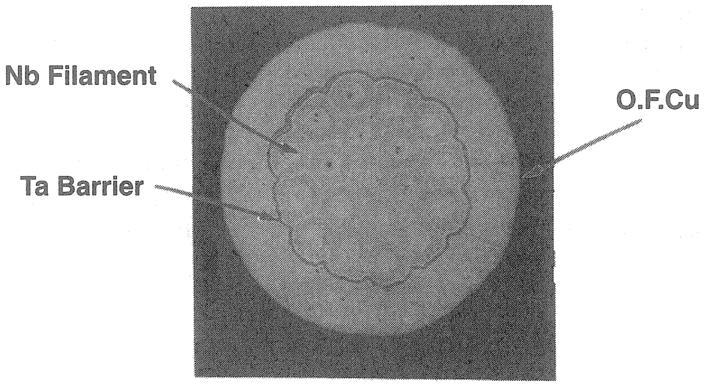

Fig. 2. Cross-Section of Mitsubishi Strand 0.81 mm Diameter

A total of five companies have been qualified by their production for the CSMC and one, EM, by production for the TFMC, as shown in Table I, which shows also the total production from each company. A seventh company, the Bochvar Institute, is engaged in production of strand for an insert coil for the CSMC.

TABLE 1. STRAND PRODUCTION DATA

Company	IGC	Furukawa	VAC	Hitachi	EM	Mitsubishi
Billet Size, kg	20-25	140,225	120	200	20-25	30
Total Production, t	4.24(+0.2 2 TWCA)	7.60	6.60	2.00	3.9	4.0

Cable Manufacturing Process

Each Home Team performed its own cabling. This greatly reduced the international interface problems associated with multiple deliveries of strand and left at a local level the problem of efficiently using the variable strand unit lengths.

All stages were specified to be cabled in the same direction (a right hand twist) as the twist of the superconducting strands. The cabling is performed without lubricants to avoid contaminants. The central tube is formed from a spiral with 20-50% open surface area. The wrapping of the fourth stage (Inconel 600, 0.1 mm thick) is applied in the opposite direction to the cable twist at the point when the stage is still circular and the void fraction slightly larger than the final nominal 36%. The coverage varied from 90% to 60%.

The cables used a range of pitch combinations: having found a stable configuration, each company tended to maintain it. Final stage cabling speeds of about 2 m/min were achieved. The time required for the first triplet dominates the cabling process.

The extent of strand wastage in the cabling process (mostly of strand that could not be used due to the variable unit length) would have amounted to about 10-15% but was often used in the production of extra cable lengths for samples.

Jacket Manufacturing Process

All the square section Incoloy 908 tubes for the CSMC were produced by INCO at their Huntington, West Virginia, plant. The billets were produced by Vacuum Induction Melting (VIM) followed by electroslag remelting. Each billet was preheated to about 1100°C and extruded to a 25% oversize of the final dimensions. The tubes were annealed at 1000°C, followed by a water quench and pickling to remove the oxide coating. After a straightening operation, there was a drawing step, a further annealing/pickling stage and, for the smaller CS2 tubes, another drawing/annealing/pickling step. The tube yield, compared to the original extrusions, was about 50%, with most (40%) being rejected on the final inspection. The average tube length for the CS1 production was 8.69 m and for the CS2, 7.01 m.

The TFMC itself uses round section steel tubes with a 1.6 mm wall thickness. The steel is a modified version of 316LN with extra N and tightly controlled Si and C to avoid embrittlement during the Nb_3Sn heat treatment. A total of 1000 m of the tubes were extruded in unit lengths of about 6-8 m by Cefival. INCO also produced 2500 m of circular Incoloy-908 tubes with a 1 mm wall thickness for the TFMC development work using a tube mill process.

Jacketing Process

The cable and jacket were manufactured separately and then assembled using a pull-through, roll down technique. Three jacketing lines were constructed, one for the CSMC at Ansaldo, Genoa, one for the TFMC at EM, Florence, and one for a demonstration of long length jacketing at VNIIKP, Moscow.

The lines all operate on the same principle, but the welding procedure for the thick CS type square jacket is the most difficult. The jacket was assembled by butt welding short (about 5-8 m) sections of extruded seamless sections using orbital welding. Weld chamfers are machined at the ends of each section length to allow for the inward shrinkage produced by the welding. The sections were aligned using the chamfers on the central hole so that tolerance effects appeared on the outside and an inner step due to the position accuracy of the hole was avoided. Both manual and semi-automatic processes were used, with, in each case, final filling of the square corners being done manually. Welding times of about 2 h/weld were achieved in the final production, with Quality Control requiring a further 60 min.

As the conduit was assembled, it extended along a 320 m roller line at Ansaldo or EM (1 km at VNIIKP, Podolsk). The insertion of the cable inside the jacket was performed by pulling the cable through the conduit. A nominal insertion gap (total) of 1.7 mm was sufficient (i.e. the jacket hole diameter is 1.7 mm oversize on the cable diameter). Tolerances on the cable and jacket sections gave a range of 1.2 to 2.2 mm on this gap. Pull-through speeds were about 2 m/min. A diagram of the Ansaldo line is shown in Figure 3.

The square jacket was compacted onto the cable in a single step by two sets of four rollers, the first (driven) compacting and the second (free) straightening. The compaction was sufficient to ensure that the maximum value of the clearance gap was closed and there was therefore the possibility of some additional compaction of the cable. The conductor dimension change is shown in Figure 1. A view of a short piece of the final CSMC conductor is shown in Figure 4.

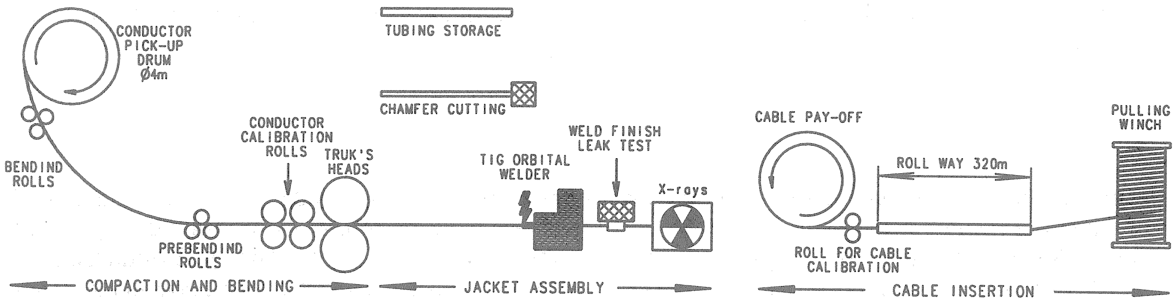

Fig. 3. Diagram of Ansaldo Jacketing Line

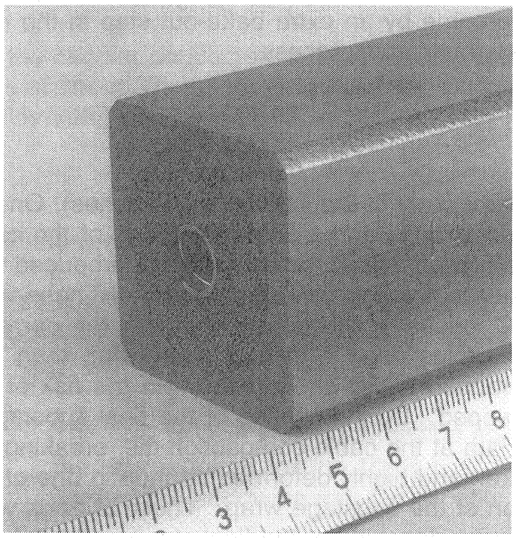

Fig. 4. Section of the Final CSMC Conductor

At Ansaldo, overall jacketing rates reached about 600 m of conductor each month, with the operation of two orbital welding stations, one assembling two jacket sections together off-line and the other assembling the double lengths into the final conductor. A total of 5.6 km of conductor was produced.

All CSMC conductor pull-throughs were performed with a braking load of about 2.5 kN applied to the cable drum. The pull-through load usually increased approximately linearly with the conductor length and was within the range of 15-20 N/m. There were two exceptions where the value increased rapidly towards the end of the insertion and reached 30-35 N/m (where the clearance gap was at the lower end of the range) and two cases where the force was only 10 N/m. Unit lengths from 80 to 200 m have been produced, in a total of 36 pull-through operations.

The TFMC jacketing at EM produced very similar data for pull-through loads. 500 m of dummy conductor and 880 m of the final superconductor has been produced on this line, with unit lengths of about 90-180 m. The production capacity of this line could reach 1600 m/month with a single welding station, as the welding procedure for the TF jacket is much faster.

A line for TF type conductors with a thin circular Incoloy-908 jacket has been assembled by VNIIKP, at Podolsk, with the same process. A successful trial with a dummy copper conductor has demonstrated the insertion of 860 m of cable with a pull-through force of about 30 N/m, No braking force was applied and the cable-jacket clearance in this case ranged from 1.2 to 2.0 mm.

Quality Assurance Issues

Quality assurance (QA) procedures have been implemented for the model coils that will also be relevant for the full size coils. Careful quality control is also essential in a production process that involves international collaboration, to ensure that each partner receives a component of defined quality as a starting point for their work.

The QA procedures adopted for the conductor were broadly defined in advance by the JCT and then expanded by the individual companies in the development stage of the work (during production of dummy conductors) into a set of procedure definitions. An essential set of QA documents from each component (strand, cable, jacket) was identified and was supplied along with delivery of the components. On assembly of the final conductor at Ansaldo, a conductor QA book was produced for each unit length, defining the most important conductor data and QA documentation. This QA book will be supplemented during the winding process and for the final coil will allow full identification of the components and manufacturing history of every conductor unit length.

Strand QA

After the initial development stage of the work, the original performance specification was adjusted to suit individual suppliers. Monitoring of the strand production relied almost completely on testing of the head and tail of each billet for critical current, hysteresis and Residual Resistivity Ratio (RRR). Standardized testing procedures had to be established . The most significant problem outside the performance issues (and their verification by testing) was the omission of a proper inspection of the strand for organic surface contamination after Cr coating by some suppliers. In some plating processes it appears that continuous recycling of the washing water can lead to a build-up of oleic amide compounds which can be deposited on the strand, to the extent of up to several hundred mg/km. The difficulty was overcome by an extra bake-out step in the heat treatment process, but this is an undesirable extension to the coil fabrication process.

Cable QA

The cable QA consists mainly of process setting verification (particularly of the various twist pitches). On-line inspection consists of visual monitoring of the stages for broken strands and a final monitoring of the cable diameter. Three significant problems occurred during the cable production. Three cables were produced with all components (except the strand) having a left hand twist instead of a right hand as specified. These were accepted as no correction is possible. The impact on the AC losses at the connection with the correctly twisted cable is not quantifiable but may be significant. Two cables used a thinner outer wrap than that specified (0.025mm instead of 0.1mm), which could not be wrapped tightly enough to avoid the risk of the wrap bunching during jacketing. These two cables were rewrapped. During cabling of the final substages, overtensioning of the substage wrap caused it to break and to jam at the cable compaction die, breaking the cable. During final stage cabling of one cable, a series of broken and highly deformed strands in one of the substages were discovered, apparently due to the cutting action of the substage wrap. These strands were fortunately at one end of the final cable. The whole unit length was decabled at the final stage and the faulty subcable was scrapped.

Jacket QA

The jacket QA procedures for the square jacket sections concentrated on an eddy current survey of the inner surface and dye penetrant inspection of the outer, a hydrostatic pressure test and a final geometric survey.

Initial problems were found with poor tube washing after pickling which gave a loose black oxide deposit on the inner bar surface. The specifications on geometric tolerance in Figure 1 were originally intended to produce an acceptable cable clearance (and hence acceptable pull through force) and minimum loss of wall thickness at the butt joint, as well as, after compaction, a limited (34%-36%) void fraction range in the cable and the absence of a gap between cable and jacket. Initial production experience showed that these requirements could not be met and the values had to be relaxed, to +0.375-0.25 mm on the hole and ±0.375 mm on the outer dimensions. This allows a gap between cable and jacket of up to 0.4 mm (with the potential for cable movement in operation) and the void fraction ranges from 32% to 36%.

The eddy current inspection on the inside (maximum allowable crack < 10% of the wall thickness, plane area <5 mm^2) led initially to the rejection of about 40% of the tubes (improving to < 20% at the end), but was still found to be unsatisfactory, with cracks being found coincidentally in the neighbourhood of a butt weld that exceeded this specification. This particular fault was traced to inadequate bar cropping after inspection, but the eddy current procedure was also found to be insensitive to cracks aligned along the tube axis. In the CSMC, the fatigue conditions are less severe than in the full size coils and the presence of undetected cracks up to 20% of the wall thickness is not serious, although not acceptable for the full size coils.

Jacketing QA

The jacketing QA processes concentrated on the butt welding and consisted of leak checks, X ray and dye penetrant inspections.

For the CS conductor, leaks were never found after the first welding pass. The X-ray inspection led to the rejection of about 30 welds (out of a total of 776) in the conductor production. The frequency was higher at the start of the work, sometimes reaching 20% in a length, and became near zero at the end.

The CS butt welding was the most difficult item in the jacketing process, and the pull through and roll down stages gave no QA problems at all. Some 65% of the welds required surface defects to be removed (and occasionally filled) after compaction and/or spooling. After investigation (and the identification of some procedural errors in the weld pass procedure), the occurrence of surface cracks in the welds during conductor spooling (up to 2-3 mm in length and 1 mm in depth) was determined to be a materials problem due to precipitation at the weld grain boundaries of niobium compounds. Again, this does not pose a problem for the CSMC but is not acceptable for the full size coils.

For the circular conductor, the QA processes were similar but the allowable defects were smaller. Rejection rates of about 3% are achieved in the production in EM on the steel tubes and slightly less at VNIIKP on the Incoloy-908.

Conclusions

Some 5.5 km of Nb_3Sn 40-50 kA conductor for the CSMC and 900 m of 50-60 kA for the TFMC has been successfully produced and delivered to the companies winding the coil. 75% of this CSMC conductor has now been wound and heat treated. The following implications can be drawn for the full size coil production:

i) The total Nb_3Sn strand production reached the equivalent of about 40t/year. This is about one fifth of the rate required for the ITER coils . ITER production needs to be associated with almost all the companies worldwide that are capable of Nb_3Sn strand production.

ii) Cabling losses were substantial (>10%) due to the variable unit length. This problem would be worse with the long lengths required for ITER, if the delivery length distribution stays the same (> 20%). Research on the impact of a limited number of strand joins within a cable could give valuable gains.

iii) The Incoloy tube QA procedures would need to be improved in a future production. The impact of possible production process errors has not been examined for impact on the tube mechanical performance in the coil. Better inspection techniques are needed that can detect longitudinal as well as transverse defects. Ultrasonics are being examined. The final allowable level for tube defects is likely to be less than the present threshold.

iv) Further Incoloy-908 butt weld development is needed to solve the cracking during bending. Recent results with a different (low Nb) weld filler wire suggest a cure for this.

v) A slightly larger insertion gap and some improvement in the jacket ID tolerances would reduce the potential for a gap around the cable in the final conductor.

vi) The jacketing technique can be applied to conductors with unit lengths in excess of 1 km without exceeding a 30 kN force on the cable. A minimum clearance gap of 1.5 mm should be maintained for the cable insertion.

The conductor was manufactured with a high degree of international collaboration between the partners of the ITER project. Interface issues, intercontinental transportation to tight schedules and customs clearance problems have all been successfully resolved. Many quality assurance issues have been successfully overcome during the production, and the experience gained gives confidence that the much larger production required for ITER (some 230 km) can be carried out successfully and to the required level of reliability, within an international framework needed to satisfy the production capacity requirement.

ACKNOWLEDGMENTS

We would like to acknowledge the efforts of our colleagues in the following companies in performing the work and maintaining a collaborative spirit while successfully resolving the many technical problems we have encountered:

> Vacuumschmelze GmbH (VAC), Europa Metalli Spa (EM), Ansaldo Energia Spa (Ansaldo), Intermagnetics General Corp (IGC), Teledyne Wah Chang (TWCA), Bochvar Institute (Bochvar), BIW Cable Systems Inc (BIW), VNIIKP Joint Stock Co (VNIIKP), INCO International Alloys Inc (INCO), Cefival, Hitachi Cable Ltd (Hitachi), Mitsubishi Electric Co Ltd (Mitsubishi), Showa Electric Wire and Cable Co Ltd (Showa), Furukawa Electric Co Ltd (Furukawa).

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