SUPERCONDUCTING MAGNET FABRICATION AND QUALITY CONTROL

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ABSTRACT
A general review of the problems and production risk related to the industrial fabrication of prototypes and/or short series of superconducting magnets is presented. In particular, past and present experience on the manufacture and testing of s.c. devices is described. Cost implications of the design choices and/or requested guaranteed technical specifications are discussed. The types and number of possible factory quality control tests during and after the fabrication are presented.

1. INTRODUCTION
In the last forty years, solid-state quantum mechanical effects have been applied to industrial products. The macroscopic effects of this microscopic phenomena are well known by most people and are part of our everyday life: everybody is familiar with modern electronics! Anyway it seems that Heisenberg’s uncertainty principle affects in some way the production of these industrial components based on the application of quantum mechanics. The probability that a quantistic component fully meets the quality control tests is in general lower than with classical components.

The number of scrapped or declassed pieces in electronics is usually one order of magnitude higher than in mechanics. On the other hand the cost of making electronic components is much lower than for mechanical or electrical ones, and therefore the total production costs of the latter components are more related to the R&D and quality control costs than to the pure manufacturing process.

If the difficulty related to the use of superconductivity is added to that of producing large components, there is a fearful mixing of the most relevant problems present in the electronics industry (e.g. R&D and quality control cost, rejected pieces) and the ones related to the high cost of classically mechanical component production.

2. PRODUCTION RISKS
In the quality control system, a special section is normally devoted to “Special Processes” defined as the manufacturing technique that can be completely verified only by destructive tests: welding is a typical example. Usually, in this case, it is necessary to:

- Qualify the process
- Qualify the operator
- Qualify the non-destructive controls.

The production of a large superconducting device involves several special processes some of which cannot be fully checked before the final test of the complete device. In the following sections I will try to list the main quality control problems related to superconductivity applications and which trouble the life of the designers. These problems have to be added to
the standard ones of insulation, mechanical tolerances, welding, vacuum and cryogenics, etc. that will not be treated here.

2.1 The cable

Before the winding operation and the final test of a s.c. magnet only short sample tests can be made on the cable, and these only from the ends of the produced lengths. This situation is similar to what happens in welding which is sometimes extended, then cut to perform the mechanical test. The results given by this kind of test are significant only if you make the assumption that the production parameters are constant and reproducible in all phases of the production. The more the process is established, the more this method of testing can be safely adopted. Today, the production of s.c. single strands well satisfies these criteria: tests made by cutting long lengths of strand into several pieces then measuring the critical current of each piece never give significant differences. Furthermore, line control using eddy currents tests is normally added to detect local defects.

A different approach has to be taken for the production of cabled conductor and even more so for co-extruded conductor. The cabling in general produces slight degradation of the critical current of the single strand (this has to be added to a change in the transport characteristic due to the self-field effects). This degradation, if present, is often due to microrupture or damage of the internal filament of the strand or to the permanent deformation of the strand during the cabling process. That this degradation is constant along the whole length of a cable (usually some km.) is more questionable.

In the case of aluminium co-extrusion which requires a high temperature we have to add to the possible degradation related to the cabling, the possibility of a temperature degradation: a NbTi wire can withstand a temperature of up to 300°C without changing its critical current characteristic. If this limit is exceeded the degradation is a function of the time of exposure to the high temperature. At 350°C the effect occurs after several minutes, while at 530°C it is reduced to a few seconds.

In general the cabling process is designed to avoid any degradation or to minimise it. Normally the temperature of the environment is kept higher than that of the cable and the maximum temperature that the cable can reach is a function of the external temperature and the cable speed. It is clear that in the case of a stop in the process the cable can reach a temperature well above the designed one. Clearly this event will not affect the results of the short samples taken from the ends of the cable and so the eventual defects will not be detected before the final tests on the magnet. The only possibility to guarantee the results is to constantly monitor and record the process parameters during the fabrication of the cable. The risk increases the higher is the maximum temperature involved in the process: Aluminium co-extruded cable is the more critical but some problems can also occur during the fabrication of tin-soldered or varnish-insulated strand.

Clearly other important controls are more simple to make: for example from the point of view of the quality of the field the dimensions of the cable can be critical; the filament diameter can also have an influence on the persistent-current effect on the field harmonics. Table 1 gives an outline of the Quality Control Plan required to control production of the co-extruded Al cable for the FINUDA detector magnet.

2.2 The cable joints

Single lengths of s.c. cable must be joined in a way which guarantees very low heat dissipation during operation. Joule effect in the joint has to be limited to some milliWatts and for current in the order of kA demands an electrical resistance of the joint in the order of $10^{-9}$ ohm. For persistent MRI or NMR magnets the specification reaches $10^{-14}$ ohm or better. Clearly it is not possible to verify this value during magnet construction as it is necessary to
have the cable in the s.c. state to be able to measure this level of joint resistance. We have to treat the joint in the same way as the welding of a pressure vessel: we must qualify the process, the operators and the non-destructive controls to be performed. Qualification of the process can be made only by adding to the other possible controls a resistance measurement of samples at the nominal current in the nominal magnetic field. Sometimes a measurement of AC losses is also requested.

Table 1
Example of some of the controls required by the subcontractor for a co-extruded Al cable for detector magnets

<table>
<thead>
<tr>
<th>Examination test</th>
<th>Value</th>
<th>Test specimen or sample</th>
<th>Examination or test frequency</th>
<th>Test method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al chemical analysis</td>
<td>T.B.D.</td>
<td>Billet before extrusion</td>
<td>One sample for each casting</td>
<td>Supplier spec.</td>
</tr>
<tr>
<td>Al RRR</td>
<td>T.B.D.</td>
<td>Billet before extrusion</td>
<td>One sample for each casting</td>
<td>Supplier spec.</td>
</tr>
<tr>
<td>Wire integrity</td>
<td>No more than 5% broken filaments in the final cable</td>
<td>Extracted strand</td>
<td>One sample from each end of each continuous conductor length</td>
<td>Visual and eddy current inspection</td>
</tr>
<tr>
<td>Critical current min. at 1.5 T, 4.4 K (or the equivalent from the extracted strands)</td>
<td>&gt; 8000 A (or the equivalent from the extracted strands)</td>
<td>Cable</td>
<td>One sample for each end of each continuous cable length</td>
<td>ASTM B 714-82</td>
</tr>
<tr>
<td>Transfer resistivity between matrix and Rutherford</td>
<td>@ 1.5 T &lt; 2 x 10⁻¹⁰ •m</td>
<td>Final conductor</td>
<td>One sample from each end of each continuous conductor length</td>
<td>App. 6</td>
</tr>
<tr>
<td>Bond shear test</td>
<td>&gt; 20 MPa</td>
<td>Final conductor</td>
<td>One sample from each end of each continuous conductor length</td>
<td>Supplier spec.</td>
</tr>
<tr>
<td>Surface conditions</td>
<td>No surface defects, burs, sharp edges, slivers, foils, laminations, dirt, inclusions or oxide</td>
<td>Final conductor</td>
<td>100%</td>
<td>Visual</td>
</tr>
<tr>
<td>“n” index at 1.5 T, 4.5 K</td>
<td>&gt; 40</td>
<td>Final conductor</td>
<td>Each end of every continuous length</td>
<td>Amplified voltage signal recording</td>
</tr>
</tbody>
</table>
| Dimensional check | Cable A: (4.13 x 14.40) ± 0.01 mm  
                 | Cable B: (6.03 x 14.40) ± 0.01 mm | Final conductor | Each end of every continuous length | Dimensional |
| Al RRR=R295/R10 Al Cu | > 1100  
                     | > 100 | Final conductor stabiliser and strand | One sample from each end of each continuous conductor length | App. 3 |
| Cu/NbTi ratio     | Cable A: > 1.1:1  
<pre><code>             | Cable B: &gt; 1.1:1 | Extracted strand | One sample from each end of each continuous conductor length | Dimensional |
</code></pre>
<table>
<thead>
<tr>
<th>Edge curvature radius</th>
<th>&gt; 0.5 mm (no sharp edge)</th>
<th>Final conductor</th>
<th>Spot measurement every 1000 m of each continuous conductor length</th>
<th>Dimensional</th>
</tr>
</thead>
</table>

This kind of test is clearly costly, both in money and time, in proportion to the field, the current and the physical dimensions of the sample. Furthermore the joint geometry and technique strictly depend on the type of cable and magnet. In bath-cooled multipole magnets for accelerators, usually Rutherford cable is simply tin soldered and the only problem could be to find the proper flux and brazing material. The Al co-extruded cables for the large detector magnets are TIG welded (with attention to possible temperature degradation) or tin brazed after (or without) copper plating of the aluminium.

Joining high-current CIC (cable in conduit) is more difficult because the problem of helium circulation and tightness is added to the electrical low resistance. A further problem occurs with Nb3Sn cable that has to be treated at 650°C after winding. In this case, due to the fragility of the reacted cable, the junction has to be made in different steps: position and press after winding, close and tin solder (if necessary) after the heat treatment but before vacuum impregnation.

In Figs. 1 and 2 are shown two examples of samples made for joint qualification for fusion magnets. Both use Nb3Sn CIC cable: some (circular shape) were tested up to 8 T with a 10 kA current (2 nOhm) [2], the other (straight) was tested to 40 kA in a 12 T field (0.2 nOhm) [3].

![Fig. 1 NET 40 kA short sample cable joints](image1.png)  ![Fig. 2 12 T CIC cable joint sample](image2.png)

### 2.3 The training or degradation of magnets

Briefly, these effects are due to a mechanical movement of the coil (or in the coil) which releases energy and locally heats the superconductor which then quenches to the normal state. We speak of training if this event produces a crack in the resin insulation or a permanent deformation. In this case each subsequent time that his value of stress (or, if you like, this value of current and field) is exceeded there is no further energy release and the magnet can be so trained to reach the nominal working condition. But if this release of energy is elastic a quench will happen every time at the same value of stress, so this level of field never can be overcome and the degraded magnet will never reach its nominal condition.

We can act on two parameters to avoid this effect: increase the cable stability or decrease the possible energy realise.

#### 2.3.1 Stability
Cable stability is a well-defined parameter: it is well known how to calculate and how to measure it. Different effects (flux jump, self field, dynamic, cryogenic stability) are used to define the wire or cable stability.

One way to increase the stability is by increasing the minimum propagating energy (MPE) (the energy release that the cable can withstand before starting quench propagation). This is related to the margin between the working temperature and the quench propagation temperature of the cable in the operating condition as well as the thermal capacity of the cable. The quench propagation temperature is related to the current sharing temperature (when the current starts to pass in the matrix because the superconductor is saturated) and to the electrical resistance of the matrix (that determines the joule dissipation). So, to increase the MPE, it is possible to use better s.c. material, more s.c., or more or better matrix material.

In general increasing the stability implies decreasing the overall current density with a consequent increase in the dimensions of a magnet and its cost, and a decrease in its general performance. If the overall current density is fixed the only degree of freedom is the choice of the s.c. and matrix materials and the ratio between them. Optimising this choice is one of the more delicate stages in the design of a s.c. magnet.

It is also possible to use the large heat capacity of helium to increase the stability of the cable. This was achieved in the past by allowing the coolant to wet the bare conductor. The technique is still used today in dipoles where the cable is wrapped with Kapton and in CIC magnets [3]. Unfortunately the “void fraction” used for the helium decreases the overall current density. Ratios between conductor and void area are usually in the range of 1:1 to 1:30.

2.3.2 Mechanical energy release

This problem is more difficult to treat as it is related not only to the design but to the whole fabrication process. From this point of view, we can, in practice, consider the total winding as a Special Process.

There are two possibilities to decrease the energy release:

– Avoid or reduce the coil (or turns) movement
– Let the coil (or turns) move freely with little or no energy release peak.

These two philosophies are quite different and it is dangerous to mix them in the same design.

In a s.c. magnet, the forces act mainly on the cable (while in the conventional magnet they mainly act on the iron): for this reason it is not possible to avoid stress and strain on the superconductor. To allow the turns to move freely is usually impossible since the forces acting on the different layers are different, so producing relative movement and friction between the layers.

It is sometimes possible to allow the whole winding to move freely if it is able to self sustain the electromagnetic force: this can happen in solenoids but not in other magnets which will always need an external mechanical structure to withstand the forces.

To avoid the relative movements, one can use:

• Bonding
• Pre stress

Both are normally used for fixing the turns between themselves: winding is carried out under tension, turns are compressed one against the others and finally bonded using pre-preg, wet-winding or vacuum-impregnation techniques. Usually local resin cracks can occur during first powering of the magnet but most magnets are stable enough to withstand them. Bonding the coils against the mechanical structure could be dangerous due to their different thermal and mechanical behaviour which could induce a large shear stress on the bonding itself. When a
magnet is designed to avoid relative movements between the coils and structure, the latter must be fixed extremely well: if the bonding or the pre-stress is not enough to withstand the shear, the resulting peak release of energy will usually be enough to induce a magnet quench and training or degradation will occur.

Now the problem is:
How can we forecast the value of the energy release peak for glass-epoxy cracks or friction movements?
How can we be sure about the bonding and pre-stress in the magnet?
The number of reports on mechanical energy release in magnets is perhaps two orders of magnitude less than the number of papers about the stability of s.c. cables, whereas equal knowledge of both phenomena is necessary in designing a magnet!
The value normally used for resin-crack energy-density release at liquid helium temperature is about \(10^5\) J/m\(^3\) (100 mJ/mm\(^3\)). As simple calculation on the work per volume unit involved in the movement of a wire in an external magnetic field gives: \(E/V = B \cdot J \cdot s\);
For \(B = 5\) T and \(J = 10^4\) A/mm\(^2\), a movement of 1 micron give an energy of \(5 \times 10^3\) J/mm\(^3\), fifty times that of the resin crack.

The choice of the stability margin to be used against possible energy release is still a matter of discussion by the designers of new magnets and **is also related to the confidence they have on the capacity of the workshop** to build the device in the proper way.

### 2.4 Heat treatment of the winding

Some coils have to be heat treated after being wound. This treatment is usually for the winding and reaction technique used for Nb,Sn magnets but sometimes for other reasons such as the ageing of the aluminium in co-extruded cable. During this process the temperature has to be controlled for homogeneity and for a given time. To cure large A15 superconductor magnets such as the ITER model coil (4 x 3 m) a large oven with controlled temperature and atmosphere is required. Temperature homogeneity of ± 3°C is necessary at 650°C for 220 hours. This implies a guaranteed power supply able to maintain this temperature in the case of an energy supply fault.

### 2.5 Winding of reacted Nb3Sn cable

Since some tape insulation is not able to withstand the high temperature necessary for curing of A15 superconductors, it may be necessary to apply it after reacting the cable. However, reacted wire is able to withstand a strain of only 0.2% without degradation of the critical current. This makes the winding or transfer operation incredibly critical because there is no way to control the cable condition after the winding but before the final test of the magnet.

### 3. PROTOTYPES

It is particularly difficult to make decisions on the prototypes to be manufactured before starting the real production (to make them or not, how many, full scale or reduced in dimension, ...). The reasons for this are related to the high costs for prototype construction as well as to a relatively high risk of failure. On the other hand, due to the complexity of the production process it is difficult to be sure about it without having first fully tested it. Interactions between different parts of the magnet may not have been considered during the design and become evident only after testing the complete full-scale component. Anyway, for the production of large amounts of similar magnets everybody agrees on the necessity to make some prototypes before starting series production (see Fig. 3).
Unfortunately people do not always look on prototype construction with the same point of view: some think that it is useful for testing the reliability of the design and the production method, others think that it is an occasion to improve the product performance or to reduce production costs. These two approaches are in conflict since in the first case you need to make several prototypes all the same as the production magnets, in the second one often changes the design in order to optimise it.

In any case changing the design of superconductor magnets is never trivial: sometimes it is even dangerous after having made several prototypes to change during the production a minor item that was considered insignificant but turns out not to be.

The full-scale LHC prototypes made so far and tested at CERN used basically the same design but some technical details were different and gave different ways to reach the same goals. Nevertheless their tests gave different results.

It is important that a company large enough to construct a series of production magnets be asked to participate in the R&D programme and in any prototype construction right from the beginning in order to decrease the risk, cost and time for the final work [4].

4. QUALITY CONTROL DURING THE PRODUCTION

The quality system has normally to control: material, process and performance of the product.

Control of material usually starts at the subcontractor’s factory to monitor their production process and continues during magnet production by recording the components used for each magnet. This was done for the more critical materials where it was requested not only to control if the parameters were within the specified values but also to measure the actual value of that parameter (the s.c. cable is the clearest example where it is necessary to record which particular length was used for the winding of each particular magnet).

During fabrication it is important to control all the parameters related to the special processes: in particular, the cable tension, cleanness integrity and compression of insulation, vacuum level during impregnation, cable temperature during the joint welding and so on.
Dimensional control is also very important as it is related to the coil pre-stress and to the final field quality. The mechanical tolerances requested are usually very tight and sometimes not even possible to reach in a single step construction. In this case it is necessary to use the technique of “measure and correct” or “measure and pair”. The winding of the Tore Supra magnet where the tolerance of 0.3 mm for the 2.75 m external diameter of the winding was achieved only by a constant feedback between the cable tension and the actual winding diameter. The HERA dipole coils were measured and then paired to decrease the relative difference.

These examples give an impression of the impact on the production cost of the quality control work. Sometimes the designers start to think about the problems related to production quality control only after the design and final drawings are completely finished. A typical example is the multipole magnet collars and yoke laminations where all dimensions, with very small tolerances, were given with respect to the centre of the beam that is outside the piece itself. This kind of drawing makes it more difficult to control the dimensions.

Electrical testing during fabrication is usually restricted to an insulation check of turns-to-turns and turns-to-ground. The number and types of these tests should be decided by the constructor who has to guarantee the final result. However, the client sometimes asks for electrical tests that could be dangerous for the coil if they are made before the coil is completed.
The final test of a s.c. device can be made only at low temperature (until room temperature s.c. materials are available that is). This implies costly tooling and manpower to cool down and maintain cold the component during testing. For this reason and also because not every factory had its own refrigeration plant only the room temperature tests (insulation, vacuum, low current field quality) were made in the factory while the final tests were made at the client’s premises. Today the tendency is to always ask for delivery of a fully tested magnet, an example being the FINUDA magnet which was tested with its iron yoke (250 tons), including complete field mapping, in the Ansaldo test room (see Fig. 4). Other examples of factory testing are illustrated in Figs. 5 and 6.

Fig. 4 CERN field mapping device in the FINUDA magnet under test at ANSALDO [5]

Fig. 5 AGOR cyclotron under test at

Fig. 6 ZEUS compensator [6] under factory
5. ANALYSIS OF REAL SERIES PRODUCTION

Unfortunately the series production of s.c. magnets or other devices is relatively rare, so that a statistical analysis is related only to a few examples. In the following some of the results related to production at ANSALDO are analysed.

5.1 HERA dipoles

Ansaldo produced 232 s.c. dipoles for the DESY accelerator in the years 1984–1988. Final discussions about the guaranteed performance of these dipoles was made with DESY only after completion and testing of the first ten prototypes. Since, however, the results were excellent, ANSALDO decided to accept to fully guarantee the requested values for field intensity and quality.

Tables 2–4 and Fig. 7 summarise the results [7] on the warm field quality measurements made in the factory before putting the coils into their iron yokes since the DESY specification obviously includes the variation induced by the iron. If a magnet was out of tolerance, the collars were removed and the shims changed in order to reach the right value. Among the 29 dipoles out of tolerance at the first attempt 27 had problems with A2 component, 1 with A2 and A4, 1 with B3.

Table 2
Attempts to reach the right harmonic content

<table>
<thead>
<tr>
<th>Harmonic content in tolerance</th>
<th>No. of dipoles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st attempt</td>
<td>201 (87.4%)</td>
</tr>
<tr>
<td>2nd attempt</td>
<td>23 (10%)</td>
</tr>
<tr>
<td>3rd attempt</td>
<td>4 (1.7%)</td>
</tr>
<tr>
<td>4th attempt</td>
<td>1 (0.4%)</td>
</tr>
<tr>
<td>5th attempt</td>
<td>_ 1 (0.4%)</td>
</tr>
<tr>
<td></td>
<td>230</td>
</tr>
</tbody>
</table>

Table 3
Harmonic components of collared coils (over 230 dipoles)

<table>
<thead>
<tr>
<th>Harmonic component</th>
<th>DESY request</th>
<th>Measured values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nominal value</td>
<td>Mean value</td>
</tr>
<tr>
<td>A2 (quadrupole)</td>
<td>0 ± 4</td>
<td>0.47</td>
</tr>
<tr>
<td>A3</td>
<td>0 ± 3</td>
<td>-0.49</td>
</tr>
<tr>
<td>A4</td>
<td>0 ± 6</td>
<td>-0.07</td>
</tr>
<tr>
<td>A5</td>
<td>0 ± 2</td>
<td>-0.08</td>
</tr>
<tr>
<td>A6</td>
<td>0 ± 2</td>
<td>-0.05</td>
</tr>
<tr>
<td>A7</td>
<td>0 ± 2</td>
<td>-0.06</td>
</tr>
<tr>
<td>B2</td>
<td>0 ± 4</td>
<td>0.13</td>
</tr>
<tr>
<td>B3 (sextupole)</td>
<td>-14.3 ± 10</td>
<td>-15.4</td>
</tr>
<tr>
<td>B4</td>
<td>0 ± 3</td>
<td>-0.06</td>
</tr>
<tr>
<td>B5</td>
<td>1.3 ± 4</td>
<td>1.98</td>
</tr>
<tr>
<td>B6</td>
<td>0 ± 2</td>
<td>-0.12</td>
</tr>
</tbody>
</table>
It has to be pointed out that some of the problems encountered were related to the measurement device itself. After several months the friction in the supports of the centring system degraded and falsely indicated a component in the harmonics which we then corrected by shimming the coils!

**Table 4**

Main harmonic component mean values (and their standard deviations) measured in different positions along the beam axes

<table>
<thead>
<tr>
<th>Position</th>
<th>A2</th>
<th>A4</th>
<th>B3</th>
<th>B5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (electrical exit end)</td>
<td>-0.05 ± 2.6</td>
<td>0.1 ± 1.3</td>
<td>-13.6 ± 3</td>
<td>0.7 ± 1</td>
</tr>
<tr>
<td>2</td>
<td>0.25 ± 2.4</td>
<td>-0.15 ± 1.3</td>
<td>-15.0 ± 3.2</td>
<td>3.0 ± 1.1</td>
</tr>
<tr>
<td>3</td>
<td>0.75 ± 2.3</td>
<td>-0.22 ± 1.3</td>
<td>-15.4 ± 3.0</td>
<td>3.0 ± 1.0</td>
</tr>
<tr>
<td>4 (opposite end)</td>
<td>1.0 ± 3.1</td>
<td>0.54 ± 1.3</td>
<td>-17.4 ± 3.1</td>
<td>1.0 ± 1.2</td>
</tr>
</tbody>
</table>

![Fig. 7 Distribution of some harmonic components over the whole production of HERA dipoles](image-url)
Fortunately we had an old magnet with which to repeat the test and so found the mistake. From this experience it is clear how important it is to have not only the measurement device but also the possibility to periodically re-calibrate it.
Another analysis was made of the field intensity. The data are related to the 29 collared coils tested in our factory (Fig. 8) over the whole production run of 232 magnets [8]. As the test involved magnets made with different cable characteristics but little difference in the helium temperature, the quench data were given for the temperature margin of the quench defined as the difference between the helium bath temperature and the critical temperature of that coil at the quench field and current calculated from the short-sample measurement of the cable. As stated before, this difference is related to the mechanical disturbance and energy release that induces a transition before the short-sample critical current is reached.

Taking into account that we used a numerically controlled winding machine to ensure the most reproducible winding process, that the curing and collaring process were constantly monitored and that the 27 magnets tested were exactly similar in design and used the same tooling, it is surprising how variable were the results: only five of them reached the guaranteed current without training, another seven only after five or six attempts, the remainder falling somewhere between these extremes.

Fig. 8 Collared HERA coil during insertion in the vertical cryostat for quench testing at ANSALDO
6. CONCLUSION

As stated in the introduction, the production cost of superconducting devices (also for series production) is due not only to the material and manpower for simply manufacturing them but is strongly related to the quality control cost and the percentage of scrapped pieces. This highlights the importance of having the possibility to use skilled personnel and to produce prototypes to test the processes. It is important to optimise the cost from the point of view of reliability of the process more than, for example, by simply decreasing the material cost.

If a firm is asked for a fixed price offer with two possible options where in the second option the cost of material is lower but the process is a little less reliable, the firm has to forecast the price increase for quality control work and the possible number of rejected pieces. This is normally one of the more difficult items to be decided and, due to prudence, is usually overestimated. Since the cost of rejected pieces includes not only the lost material but also the cost of wasted work, the total price for the second option may well be higher than for the first one.

REFERENCES


