Cover Page

Fusion Futures – Direct Industry Stimulus (DIS)

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Purpose of this Report

This report has been produced under the **Fusion Futures Direct Industry Stimulus (DIS)** programme.

This report consolidates over a decade's worth of learning by Tokamak Energy through their research and development alongside working closely with a number of HTS tape suppliers.

DIS projects are targeted, time-limited R&D activities intended to stimulate early industrial capability, generate evidence to inform future fusion delivery and supply-chain decisions, and reduce strategic, technical, and commercial uncertainty in areas critical to UK fusion ambitions.

The outputs are exploratory and developmental in nature. They are intended to inform programme strategy, infrastructure planning, and future investment considerations, and do not constitute detailed design, procurement specifications, or commitments to fund subsequent activity.

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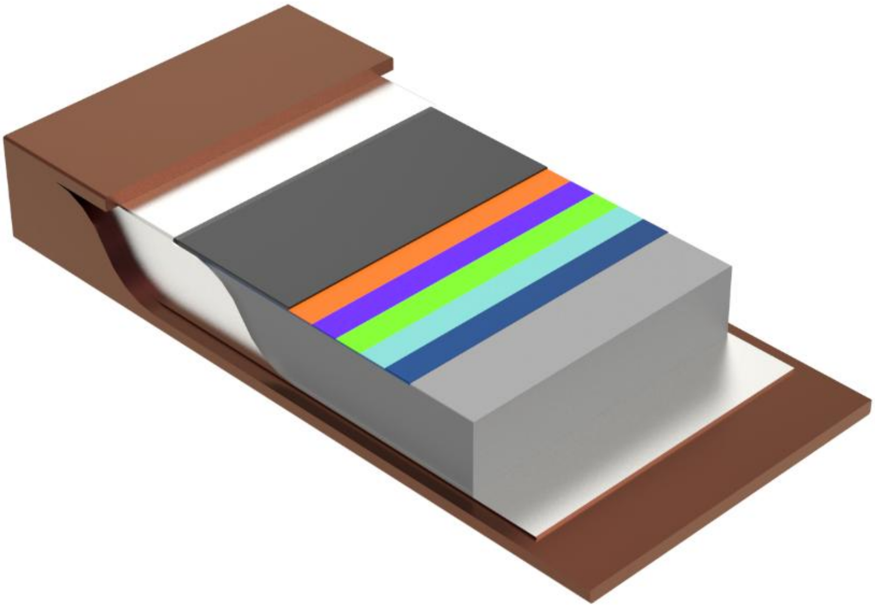
The Quality Control Landscape for HTS Tape: Defining a Strategic Approach for the UK



A Report Commissioned by the UK Atomic Energy Authority

TE Magnetics
A Tokamak Energy solution

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Foreword by Dr Greg Brittles

I have had the privilege of working with High-Temperature Superconducting (HTS) tapes since the early 2010s, initially as a university researcher and subsequently as an engineer and leader. My engagement with the HTS tape supply chain began at Tokamak Energy in 2016, deploying commercially available HTS tapes from all major suppliers in coils and validating their fitness for high field magnets, predominantly fusion magnets. In 2021 I commenced a UKRI Future Leaders Fellowship, a key focus being establishing an industrially scalable quality control framework for HTS tape, identifying this as crucial to enabling rapid deployment of HTS in fusion and other applications. This included building a skilled team to manage HTS tape within the business.

Over this period, we have witnessed a dramatic improvement in HTS tape performance and a significant reduction in cost. While there remains room for manufacturing advancement of HTS tapes, a consensus has formed among HTS tape users that **HTS is ready to meet the demanding technical requirements of major commercial applications**, ranging from fusion and power engineering to transport, science, and medical devices.

Despite this impressive progress, a comprehensive quality control framework around HTS tape has been conspicuously absent, hindering its rapid uptake. Designing with HTS requires a confident understanding of its electrical, physical, mechanical, thermal, and chemical properties. Despite breathtakingly sophisticated manufacturing processes with advanced diagnostics, manufacturers can only partially measure and report the properties of the tape critical to its performance in service. This gap creates a substantial burden on HTS system developers, increasing technical and commercial risk. With numerous large-scale HTS projects such as the UK's Spherical Tokamak for Energy Production (STEP) programme requiring tens of thousands of kilometres of HTS tape, amounting to hundreds of millions of pounds' worth of conductor at today's prices, confidence in tape performance now carries a very high price. **The industry's focus must now shift from raw performance enhancement to quality and cost-focussed maturation.**

This report presents TE Magnetics' perspective on the core quality-control gaps affecting HTS tape, drawing on more than a decade of experience working with HTS technologies—from procuring hundreds of kilometres of tape from all major suppliers to developing uniquely capable HTS technologies and participation in international standards setting through IEC TC90. It summarises the current activities of key stakeholders, including tape manufacturers, universities and research institutes, and end users. It outlines a pragmatic strategy to close existing gaps, strengthen the HTS tape quality-assurance landscape, and build the confidence needed for HTS technology to achieve its full potential across a wide range of applications.

Dr Greg Brittles

Head of Magnets Research and Development.

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1 Introduction – HTS Tape Quality

We stand at the dawn of the HTS era. Enabled by one of the most significant materials innovations of the last century, REBCO (Rare-Earth Barium Copper Oxide) HTS tape, HTS technologies are now being brought to market, with pioneering companies developing products to solve some of the world's most pressing problems in energy production, transportation, industry and other sectors. These advances are enabled principally by the incredible electrical properties of HTS; the ability to carry thousands of amps of electrical current through a single crystal a few thousandths of a millimetre thick. However, while raw performance drives technology advancement, it is reliability, scalability and cost-effectiveness that will ultimately drive commercial realisation of HTS products.

While HTS tape manufacture is scaling rapidly, with a supply base flourishing predominantly in China and Japan, and growing in the US, the quality control and assurance framework remains fragmented and immature, for several reasons. There is currently little standardisation of testing techniques and protocols, nor certification processes, with most manufacturers having largely self-developed their QC systems. Compounding this, the performance of HTS tape is still evolving, and the parameters that manufacturers focus on to improve performance may not necessarily align with the priorities or critical requirements of all customers. This misalignment creates uncertainty around product suitability for specific applications and underscores the need for a coordinated approach to quality metrics and certification to support scalable deployment.

Some recent industry anecdotes highlight the current immaturity of the HTS tape market and the challenges this creates for customers. In one case, a customer returns a substantial tape batch due to discovering it has unusually poor delamination strength during cable or coil manufacturing. Informal reports of this issue quickly spread to other users, raising concerns that their own stock from the same supplier might be compromised. Many customers lacked the in-house capability to verify this for themselves, and could not draw upon a reported test from the supplier to provide confidence that their batch was unaffected. The supplier's QC framework around this aspect was not well understood by the customer. It is also true to say that no test exists that reliably or accurately measures delamination strength in a manner that can be directly utilised in models by the customer (hence the quantity cannot be meaningfully specified). The critical current testing for Tokamak Energy's Demo4 magnet is another pertinent case. A broad array of tests were conducted comprising: short sample in-field transport current measurements at the Robinson Research Institute; high field magnetometry measurements; and in-house liquid nitrogen Ic measurements on full-width tapes for accurate scaling purposes. These tests represented a significant equipment and personnel cost. This work was critical to the Demo4 project, enabling us to demonstrate the ability to predict the performance of perhaps the most complex HTS coil array ever constructed, over a wide range of temperatures field conditions. Hence there was lasting value generated from this work in the development of analysis processes, software and tools, as well as providing a valuable industry snapshot from significant volumes of tape produced by nearly all major suppliers. It is however true to say that the Ic datasets themselves are now outdated as reflections of the product produced by each supplier, since all of the HTS tape suppliers have since developed new products or adapted their manufacturing techniques. **Suppliers and end-users alike must realise that the price of continuous improvement, is continuous quality assurance.**

Compounding these difficulties, the critical current of HTS tape as a function of field, field angle, and temperature is evolving rapidly. This makes high-specification test results (such as those measurable at a handful of national high field test facilities the world over) expensive and of limited long-term utility, as they often need to be effectively repeated with each large purchase of tape. Together, these episodes

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underscore the need for more predictable and transparent performance metrics, alongside effective and cost-efficient testing methods, to support confident procurement and deployment.

2 Current Status and Issues

2.1 Limitations in Measurable Parameters Across the HTS Supply Chain

A fundamental challenge facing the HTS ecosystem (see Figure 1 overleaf) is that suppliers often cannot measure the quantities that end-users require to qualify materials for advanced applications. Current material specifications are constrained by what suppliers can measure reliably, repeatably and cost effectively including labour. Customer and supplier must then negotiate on what should be specified based on a balance between the demands of the customer's use-case and the equipment available to the supplier. The prototypical example of this is the measurement of critical current – ubiquitously measured by all suppliers in liquid nitrogen (77 K) and zero applied background field, which in many cases does not reflect HTS performance under end-use application (such as 20 K and >10 tesla magnetic fields at varying orientations, for fusion magnets). As a result, users lack the data needed to make robust engineering assessments, and must frequently rely on extrapolation, empirical judgement, expensive auxiliary test programmes and expert staff.

The variability in test methods and measurement capabilities across the supply base further complicates the situation. For instance, reel-to-reel liquid nitrogen (77 K) I_C data produced by the industry-standard TAPESTAR™ or MCORDER^{TM} tools, are valuable primarily as a defect-detection tool rather than a reliable indicator of in-field performance at 20 K. This is with rare exception of a very limited number of suppliers who have invested heavily to prove a fair but robust correlation between 77 K and 20 K in-field Ic, and committed to maintaining this formulation and/or to continually reaffirm that new formulations maintain this correlation. It is valuable to note that quality assurance is now a key source of competitive advantage for suppliers. Manufacturers differ markedly in the test infrastructure available to them: some own 12 T multi field angle systems (such as the SuperCurrent^{TM} system) and characterise every batch; others rely on 7 T magnetic moment measurements; others have limited, intermittent access to low-temperature high-field equipment; and newer entrants may depend entirely on ad-hoc academic collaborations. These disparities produce a fragmented data landscape, making it difficult for customers to benchmark materials, validate performance claims, or compare suppliers on a consistent basis. **This is not a quality framework fit for rapid industrialisation.**

Several systemic factors underpin these issues. Firstly, the industry suffers from a shortage of cost-effective, standardised QC equipment suitable for ownership by HTS tape manufacturers. For instance, high field test devices commonly cost well in excess of $1M, presenting a significant capex barrier to suppliers. It is common for suppliers to use bespoke systems developed in-house, resulting in inconsistent capabilities and test conditions across manufacturers, creating a burden of work on supplier and customer alike to form mutually agreeable specifications. Secondly, as HTS materials continue to evolve, their properties vary over time and between batches. Suppliers therefore prioritise exploratory, development-focused measurement campaigns under grants such as the US INFUSE programme, rather than consistent customer-aligned test campaigns. Thirdly, customer requirements themselves are often incomplete or insufficiently defined. Outside of a narrow set of well-understood parameters, end users typically possess only qualitative insights into which properties matter most for their specific applications, making it difficult for suppliers to align their QC regimes with market expectations.

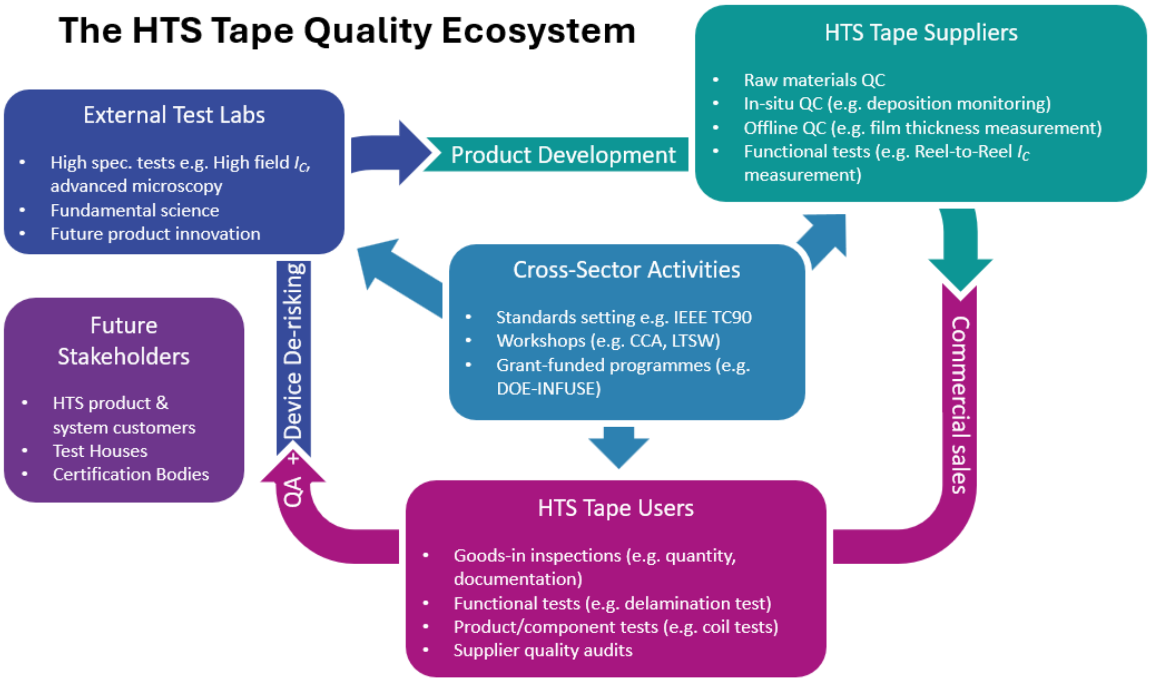

Figure 1: The present day HTS tape quality ‘ecosystem’, intended to show the interconnected web of activity at play between tape suppliers, tape users, external test labs, and future stakeholders not yet in participation.

2.2 The QC Burden on Customers

Specifications require deep specialist knowledge, typically at the level of a PhD in applied superconductivity. Understanding the implications of product quality across all relevant metrics, including those not routinely reported by suppliers, demands expertise that is scarce even within experienced organisations. For instance, it is common for tape performance to vary significantly across the width of a tape, yet it is common for test samples to be made from central regions of the tape, resulting in a systematic bias that must be accounted for in analysis (amongst numerous other such factors). This creates a significant barrier to entry for new industrial adopters, particularly those outside of the fusion and high-energy-physics communities where such expertise is more common. As HTS expands into broader markets such as power engineering, transport, and medical systems, this expert-dependence risks becoming a bottleneck to scaling.

The logistical burden on customers is equally significant. Because supplier data is incomplete, inconsistent, or not application-relevant, customers must undertake their own independent QC testing on delivered spools. This requires access to specialist high-field facilities housing equipment that is costly to access. These are commonly university labs for which access is a considerable constraint and commercial services are not necessarily available. As has already been mentioned, the perpetual need to maintain up-to-date performance data exacerbates this.

A notable and model exception to this landscape is the Robinson HTS Wire Critical Current Database [1], developed by the Robinson Research Institute at Victoria University of Wellington. By providing openly accessible, high-quality critical-current datasets measured across wide ranges of temperature, magnetic field, and field angles, this resource significantly lowers the barrier to entry for new HTS users and enables informed material comparisons without the need for access to specialist equipment. The database does not contain the level of statistical data required to be a comprehensive solution, but it is a shining embryonic example of a part of the solution that will be laid out in Section 3.

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2.3 Lack of Standardisation Across the Industry

Overlaying these challenges is an absence of standardisation in QC methods, application-specific performance parameters, and the prioritisation of those parameters in manufacturing. The most consequential gap is not merely that properties are measured differently; it is that performance under application-relevant operating conditions is rarely measured directly with sufficient statistical confidence. For many end-uses, key parameters include in-field critical current at 20 K across defined field strengths and angles, mechanical robustness under numerous realistic strains, internal resistances that determine dissipation in joints, many more. Most suppliers have evaluated many of these aspects of their tape's performance at some point during their development process (perhaps under a university PhD project), and continue to monitor many others on a regular basis. Yet routine supplier QC seldom captures these in-situ conditions at the batch level with defined sampling plans, confidence intervals, or control. Consequently, even when indicative data exist, they often lack the repeatability, traceability, and statistical power necessary for risk-based engineering decisions and formal qualification. Customers can compare materials across suppliers, but such comparisons come with a substantial margin of error. Variations in test rigs, and limited batch-to-batch sampling introduce uncertainty that is difficult to quantify precisely. In practice, users include a safety margin when designing based on these limited data, because under-sampling can overlook performance issues. This tightens the effective performance window and slows adoption, even where headline figures appear strong. A convincing example of this scenario is the tolerance of HTS tapes to transverse compressive stress (i.e. compression of the tape in its thickness direction). This is strongly dependent on copper thickness and its profile across the width of the tape. It has been studied in a handful of academic projects (with strongly variable results between suppliers), and the test protocol proven to achieve reliable results is not standardised, but has been honed by at least one supplier. This parameter is critical to the design of spherical tokamak toroidal field magnets, and as such is an aspect of functional testing under by Tokamak Energy as an end-user.

Closing this gap requires standardised, application-condition test protocols coupled with statistically robust QC practices: clear definitions of the operating envelope to be measured, minimum sampling frequencies based on evidenced control, calibration and uncertainty budgets for critical instruments, and shared data formats that report distributions rather than single-point values. Until these elements see broad uptake, material comparisons will remain possible but imprecise, and specifications will continue to rely on conservative margins that elevate system-level cost and complexity.

There has been a substantial degree of organic standardisation of the form factor and structure of HTS tapes, and in many aspects of the HTS tape manufacturing process itself. Almost all manufacturers have converged upon a 12 mm tape width; use ion beam assisted deposition of buffer layers; use silver as an encapsulant and surround the tape in copper. This has proceeded largely as standardisation by natural selection, with the winning approaches gathering traction. However, with such considerable scope for continual improvement, an ever present need for suppliers to compete with one another on performance, and new applications arising that change the paradigm on requirements, the incentive to keep innovating is strong. As an industry we must find ways to enable standardisation where it is effective and appropriate, while enabling innovation in ways that allow suppliers to gain competitive advantage. Our recommendation on this is laid out in Section 3.

2.3.1 Differences of Opinion

A commonly cited pathway to reducing cost per unit electrical performance, expressed most commonly as dollars per kiloamp-metre ($/kAm), is the continued increase of critical current in HTS conductors. By achieving higher I_C, a given electromagnetic design can reach its required amp-turns with fewer tapes, directly lowering material costs and simplifying assembly. This approach can also mitigate performance

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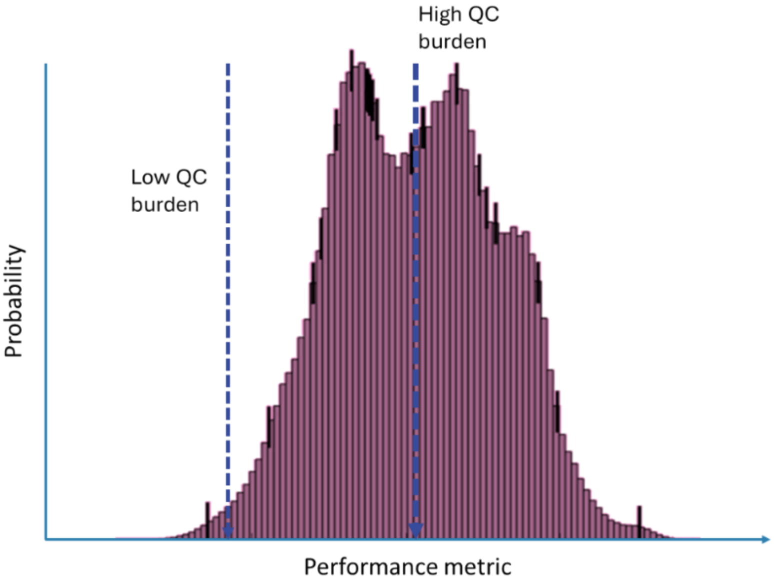

Figure 2: Probability distribution of an arbitrary tape's performance along its length or between batches, against an arbitrary performance metric. The specific dataset shown here is the 77 K critical current of tape from a single supplier for the Demo4 coil programme. This illustrates the simple point that if one selects a minimum performance requirement (dotted vertical lines) within the supplier's output distribution, the QC burden is high as there is a significant chance a given piece of tape will underperform. Conservative design reduces the probability of underperformance and hence reduces the QC burden.

variability and reduce the QC burden, as demonstrated in Figure 2: by shifting the statistical distribution of tape performance to higher I_C while holding design operating current constant, the risk of underperformance is reduced. In many applications this logic holds—for example, a power cable designed around 100 tapes in parallel could be built with 50 tapes if I_C were doubled. Stress limitations are often cited as a counterargument, but in most systems mechanical stresses scale primarily with total amp-turns and magnetic field rather than with I_C per tape. As such, stress constraints limit the pursuit of ever-higher magnetic fields from higher I_C tapes, rather than the use of higher- I_C conductors at fixed system performance. A notable exception is small magnets wound from a low number of tapes in parallel, for which tape numbers cannot so trivially be reduced.

However, this strategy presents an inherent trade-off in manufacturing mindset. Continuous R&D aimed at I_C improvements can divert focus from stabilising manufacturing processes and simply replicating machines, with implications for yield, consistency, and long-term supply reliability; challenges that suppliers have demonstrably faced. At the same time, major customers, including the high-energy physics community, continue to specify improved conductor performance, reinforcing this cycle with a considerable incentive to suppliers. Some might think this a madness of crowds, others might think this the natural state of a free market that needn't be interfered with by standardisation committees. Complicating this discussion is the lack of a single, universal definition of "higher I_C." Depending on the application, relevant metrics may include peak I_C at parallel field, angular tolerance of the I_C peak, or minimum I_C under perpendicular field. Different magnet geometries and operating regimes place emphasis on different aspects of conductor performance, underscoring the need for clearer alignment between system requirements and conductor development goals. There is room to challenge this dynamic on several fronts. Most magnet and cable designs can be successfully realised using today's commercially available conductors, provided designs are adapted accordingly and with knowledge gleaned by first movers. For instance, both Tokamak Energy and Commonwealth Fusion Systems have both openly disclosed the adoption of "dropout tolerant" HTS tape specifications, permitting

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acceptance of tape formerly discarded as defective. Tokamak Energy has publicly disclosed test results demonstrating that reliable magnets can be built from tapes with intermittent dropouts, providing they are appropriately designed. Tokamak Energy evidence this by drilling holes through a coil and demonstrating it to function stably, with negligible performance degradation. Strategic sharing of select technical results such as these can help to create a common voice of customer that will drive a harmonisation of the ask to suppliers, with no loss of free market forces. There are many ways that industrial communities can work together to drive standardisation on technical aspects agreed to be of mutual benefit and negligible competitive advantage (spool design being one such logical proposition).

2.4 Implications for Industry Growth

Collectively, these issues represent a major structural barrier to the widespread adoption of HTS technologies. Without harmonised test methods, accessible QC equipment, and clearly defined customer requirements, the industry cannot reliably qualify materials, control quality, or scale manufacturing output with confidence. As HTS transitions from a research-driven field into a commercially emerging sector, addressing these measurement and standardisation gaps will be critical. Establishing common QC frameworks, improving reliability of material performance, and lowering the technical and logistical burden placed on end-users are essential steps for developing a predictable, interoperable supply chain that will stimulate growth.

2.5 Anticipated Trajectory of an Emerging & Maturing HTS Industry

As the HTS industry matures, the roles and contributions of manufacturers, universities, and users will evolve in predictable and mutually reinforcing ways. Manufacturers will shift toward increasingly standardised production routes, tighter process control, and more stable product formulations. Over time, it is anticipated that primary conductor “recipes” will become firmly established, variability will shrink, and production capability will rise—mirroring the historical trajectory of other advanced materials industries as they transition from artisanal processes to repeatable, industrialised manufacturing. In parallel, the role of universities will naturally diminish from intensive early-stage collaboration—providing high-spec characterisation, microscopy, models, and empirical scaling relations—to more targeted, long-horizon research. Their initial heavy involvement reflects the scientific complexity and uncertainty of a nascent field; as materials stabilise and processes converge, industry-grade QC and professional test houses will likely take over much of this work.

For users, the long-term outlook is one of increasing simplicity. As HTS products converge toward commodity-like behaviour—with well-understood performance envelopes, consistent inter-supplier comparability, and predictable reliability—the risk associated with adoption falls dramatically. Knowledge barriers shrink; bespoke expertise becomes less essential; and qualification becomes faster, cheaper, more routine, and even less essential due to mounting data. What today demands “more brains than hands” will progressively invert as HTS moves toward becoming a standard engineering material rather than a specialised and research-driven technology. Consistent products, shared standards, and widely accessible data will combine to create a healthier, more navigable marketplace—one where design decisions are guided by engineering rules rather than fundamental calculation, and where large-scale deployment becomes both practical and economically attractive. **We can shorten this journey by learning from prior experience.**

A valuable historical example comes from the large-scale Nb-Ti procurement for the Tevatron accelerator, which at the time represented more than half of global Nb-Ti demand [2]. Prior to this, billets were typically produced in either 45 wt.% or 48 wt.% Ti, with many proprietary wire variants clustered around that range, each giving different suppliers their own performance characteristics. To

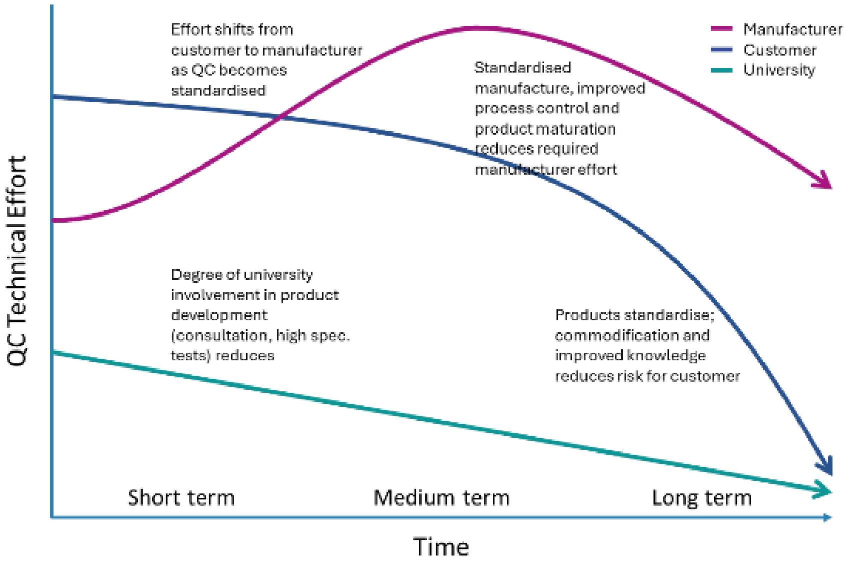

Figure 3: Relative technical effort required by manufactures, customers and universities in the quality control of HTS tape as the market matures.

avoid favouring any single manufacturer, the Tevatron team mandated a common alloy composition of Nb-46.5 wt.% Ti, ensuring no supplier had a built-in process advantage. The scale of the order was so significant that this composition rapidly became the cross-sector, de facto industry standard. *To informally quote the recently departed Bruce Strauss, "We banged their heads together and told them to stop messing with the formula".* Yet even with alloy chemistry fixed, substantial variation in wire performance persisted. Through sustained collaboration between industry and academia—most notably via an annual workshop led by David Larbalestier—the root cause was ultimately identified as microstructural variation and inhomogeneity arising from inconsistent heat-treatment process control. This insight drove improvements in manufacturing practices and paved the way for Nb-Ti to evolve into a reliably produced, commoditised superconducting material.

HTS may not follow this path. REBCO is a significantly more complex material, manufactured by a significantly more complex process, and with a significantly higher cost curve to descend than Nb-Ti alloy. It's performance drivers and control of key manufacturing process parameters are undeniably an order of magnitude more challenging. Furthermore, the demand side is not driven by a single public customer as it was for the Nb-Ti-based Tevatron accelerator. The voice of the customer is a mixed one consisting of both private and publicly funded entities, each differing in technical risk appetites, and present different financial risk to suppliers. They represent an expansive variety of applications with differing requirements, and almost all present "lumpy" demand signals based on large device demonstrations (such as fusion pilot plants) rather than the sought-after repeat product demand. **HTS tape manufacturers cannot be regarded as foolish for hedging their bets and continuing to innovate. They should however be cognisant of the risk of failure to develop a reliable product in the process.**

We don't believe that HTS suppliers will be incentivised to work to a single formula as was done for Nb-Ti- there are simply too many counter-drivers to this. We can however take positive collective action on several fronts to accelerate the adoption of HTS together.

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3 The Solution

3.1 For Industry: Targeted Standardisation

The first and most important step is to establish clear, explicit standardisation across the HTS quality management ecosystem and to anchor that framework in application driven specifications. We must remedy today's fragmented landscape in which suppliers utilise uncertified test equipment, measurement techniques and interpretations. HTS users from various key application areas (e.g. fusion, HEP, power transmission), critically including those placing the largest orders, should each agree on minimum performance metrics and acceptance criteria that define "fitness for purpose" for each use case. A fusion grade tape standard, for example, could introduce tiered classes based on a common "menu" of parameters: for instance the allowable length between dropouts, with a common dropout specification, or the minimum I_C at select operating conditions. These metrics would be paired with standardised measurement systems, test techniques, reporting formats, and QC processes, all tied to well defined operational envelopes (field, temperature etc.). Harmonisation at this level ensures every supplier measures the same parameters in the same way (or by suitably certified equivalents), enabling meaningful comparison, reducing ambiguity, and providing users with data that directly map to real world magnet requirements wherever physically possible. The drive for providing quality assurance to customers will also drive targeted improvements in identified issues in their product performance that will materially improve consistency and yield. Pioneering steps in this regard have been made by the IEEE CSC Standards Committee and the IEC Technical Committee 90 [3] .

Within this framework, QC becomes both more efficient and more informative. With a common framework for compliance in respect of quality management, suppliers remain able to compete on product performance and to innovate. Suppliers would apply recognised measurement techniques to the agreed parameter set, but the frequency and degree of testing would be tailored to their demonstrated manufacturing capability. If a manufacturer can robustly demonstrate that a given property exhibits low inter- and intra-batch variability, then that parameter need not be measured at high frequency to meet the standard; the customer gets simple performance certification, while the supplier sees reduced QC cost through evidenced control. Conversely, properties for which the manufacturer cannot yet demonstrate tight statistical control would necessarily be sampled more frequently until such capability is established. On the user side, design practices can exploit these standards: engineers can dramatically reduce QC burden by simply designing to the "standard", safe in the knowledge that a certified product has been robustly proven to meet it (referring back to the principle in Figure 1). QC becomes problematic mainly when designs aim to extract performance higher up the distribution where variability inevitably causes occasional shortfalls. By designing with appropriate margin to the agreed specification tiers, users simplify qualification and long-term operation and can plan around predictable performance. Of course, HTS users remain able to compete on product performance by pushing designs beyond the standard and "up the distribution", with associated increased technical risk and QC burden. Finally, open access to high quality performance data—ideally a comprehensive database spanning all key metrics and tiers—would accelerate adoption, learning curves for new entrants, and support robust engineering decisions. Such an activity would only be undertaken naturally by the HTS supply-side, or a government body such as the UK for whom building an HTS industry is the target. The HTS user side may be incentivised to contribute financially to such a scheme on a subscription basis if they see reduced QC cost and burden overall and are willing to forego the competitive advantage of internalised QC.

Taken together, application aligned standards, capability driven QC, robust design margins, and open data provide a clear pathway to a more predictable, scalable, and user friendly HTS supply chain—directly addressing the structural issues limiting adoption today and laying the groundwork for HTS to

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mature into a stable, globally deployable industrial platform. While there are numerous challenges and compromises that must be overcome to see widespread adoption, as well as a significant administrative overhead to bear in implementation of such standards, there is a credible path forward.

Establish application-driven HTS standards: Convene application communities (e.g. fusion, HEP, power transmission) to define minimum, *fit-for-purpose* performance metrics and acceptance criteria for HTS conductors.

Define tiered, application-specific tape classes: Introduce standards such as a "fusion-grade" tape with multiple tiers, based on a common menu of parameters (e.g. allowable dropout length, I_C vs field angle at agreed temperatures).

Standardise measurement and QC methodologies: Agree on standardised measurement systems, test techniques, reporting formats, and QC processes tied to well-defined operational envelopes (field, temperature, strain), ensuring all suppliers measure the same parameters in the same way.

Enable meaningful comparison and reduce ambiguity: Use harmonised standards to allow direct comparison between suppliers and provide users with data that maps clearly onto real-world magnet and system requirements.

Adopt capability-driven QC regimes: Tailor the frequency and depth of QC measurements to each supplier's demonstrated statistical process capability, rather than applying uniform testing requirements across all parameters. Incentivise statistical proof of process control.

Reduce user QC burden through standard setting: Use agreed specification tiers and appropriate performance margin to simplify qualification, procurement, and long-term operation. Users can choose to design to standards (minimum performance criteria) and forego QC and extensive specification setting activities.

Create open, shared performance data resources: Develop a comprehensive, open-access database covering key HTS performance metrics and specification tiers to support new entrants, accelerate learning, and improve engineering confidence.

These measures will enable a predictable and scalable HTS supply chain: Combine application-aligned standards, capability-driven QC, robust design margins, and open data to address structural barriers to adoption and support HTS maturation into a stable, globally deployable industrial platform.

3.2 For Public Bodies: Establish a UK National HTS Tape Characterisation Facility

A national capability for end-use HTS qualification should begin with the establishment of a dedicated facility equipped with a comprehensive suite of purpose-built HTS test systems. Such a centre would provide full-envelope characterisation of conductor performance including electrical, mechanical, thermal and other properties at conditions relevant to the most demanding applications (such as fusion reactors). Crucially, the facility would operate at a level of technical capability that neither most suppliers nor individual users can economically justify on their own, ensuring that all parties in the supply chain have access to independent, high-fidelity testing aligned to real operational environments.

To be effective, this capability must function as a commercial, industry-facing test house, not primarily an academic research laboratory. Operating outside the university environment avoids competition for equipment time with scientific experiments, prevents delays associated with academic administrative

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processes, and establishes a professional service culture built around industrial turnaround times and reliability. With careful strategizing in consideration of geographical location and talent pipelines, a prosperous symbiotic relationship could be formed that enhances both the commercial delivery and the academic field. While not an academic centre, it should maintain strong collaborative links with leading research institutions, or one particular institute with strong relevant capability, to ensure that the latest scientific understanding of HTS behaviour, measurement techniques, and emerging standards is continuously transferred into practice and fed back to the supply chain. By explicitly aligning with application-driven HTS standards (using agreed measurement systems, techniques, reporting formats, and operational envelopes) the facility would provide suppliers and users with a trusted, standardised "clean bill of health" for conductor performance. With academically-linked research alongside it, deeper insights on routes for material improvement can lift the entire field.

In parallel, the facility must support rapid industrial feedback loops by delivering test results on timescales compatible with supplier process optimisation and user design cycles. Its role is not to replace in-house QC (which must remain with manufacturers for batch-to-batch control and pass/fail tests) but to provide deeper, independent validation and advanced characterisation when required. Investment in HTS-specific, purpose-designed rigs ensures that testing is both relevant and reliable, avoiding the pitfalls of repurposed cryogenic or materials equipment not optimised for REBCO coated conductors (such as those employing liquid helium). Finally, the centre must be governed with strict independence, confidentiality protections, and transparent data-ownership rules to build trust across competing suppliers and diverse end-users. As the HTS quality landscape matures and manufacturing processes stabilise, the need for such advanced qualification will naturally decline; the centre should therefore plan for a long-term evolution, for example, pivoting from conductor qualification towards HTS component and subsystem certification as the industry progresses. This will require planning for space to expand.

Provide national capability for end-use HTS qualification: Establish a facility equipped with a comprehensive suite of HTS-specific test rigs capable of fully qualifying conductor performance for demanding applications (e.g. fusion reactors), at a level beyond what most suppliers or users can economically provide individually.

Operate as a commercial, industry-facing service: Structure the centre as a professional test house serving the HTS supply chain, rather than as an academic research facility. This avoids competition for equipment time with scientific studies and eliminates the overheads and delays associated with university-based operation. The centre should have close relationships with leading institutions to ensure necessary knowledge transfer, staff pipelines, and linked academic research.

Enable standardised and trusted testing: Align the facility with emerging application-driven HTS standards, using agreed measurement techniques, reporting formats, and operational envelopes. This would allow suppliers and users to obtain a recognised "clean bill of health" for conductor performance, supporting procurement, qualification, and risk reduction.

Support rapid industrial feedback loops: Deliver test results on timescales compatible with industrial decision-making and process optimisation. The facility should explicitly complement, not replace, in-house supplier QC by providing independent validation and deeper characterisation rather than batch-to-batch control, which must be in-house to provide immediate feedback.

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Deploy HTS-specific, purpose-designed equipment: Invest in test systems designed explicitly for HTS conductors (electrical, mechanical, thermal, and environmental), rather than generic materials or cryogenic equipment adapted for HTS use, ensuring relevance and reliability of results.

Ensure independence, confidentiality, and trust: Implement strong governance, information barriers, and data-ownership rules to protect commercially sensitive information and maintain confidence among both suppliers and end users.

Legacy planning: As the HTS quality landscape matures, the need for advanced QC will decline and the centre's value will reduce. Prepare a legacy plan such as pivot to HTS component certification.

3.3 For Public Bodies: Fund cost-effective, low-temperature, in-field QC device R&D

A critical gap in today's HTS quality control landscape is the lack of routine access to high field tape measurement equipment at the supplier level. This gap is especially problematic for the largest and most technically demanding customer base (fusion) where conductor performance must be validated under high magnetic fields, variable field angles, and cryogenic temperatures far below 20 - 40 K. Without affordable, high field test capability integrated directly into manufacturing environments, suppliers cannot perform the in-house QC that is essential for rapid process control, reliable batch to batch characterisation, and early detection of performance drift. The result is a structural bottleneck in the supply chain: users need application relevant data, but suppliers lack the tools to generate it at industrial cadence.

To break this blockade, there is a clear case for supporting the design and deployment of compact, HTS specific high field test devices that can be operated directly by manufacturers. These units should be engineered to meet a firm cost target below USD 1 million, ensuring they are accessible not only to major producers but also to smaller or emerging suppliers. By focusing on measurement conditions aligned to real applications rather than defaulting to legacy 77 K self-field measurements, such tools would enable suppliers to generate large, statistically and operationally meaningful datasets as part of routine QC. Given the wide intrinsic spread in HTS tape performance (often tens of percent), measurement speed should take precedence over high precision: the value lies not in resolving single digit error bars, but in gathering enough data to understand distributions, variability, and process stability.

For maximum impact, these tools must be purpose designed for HTS and built around standardised fixtures, protocols, and reporting formats to ensure direct comparability across the supply base. Their role should be framed clearly as complementary to national HTS test facilities, not as replacements. While compact factory floor devices enable rapid, routine QC and process tuning, national centres provide broader, multi condition qualification and independent verification for high consequence applications. Together, these capabilities form a coherent ecosystem: fast, statistically rich supplier side QC feeding into trusted, standardised, application condition certification, ultimately strengthening confidence across the entire HTS value chain.

Fund affordable, supplier-side high-field test devices: Support the design and deployment of compact HTS-specific test devices that enable routine in-field tape characterisation directly at tape manufacturers.

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Set a sub-USD 1 million cost target: Cap unit cost well below $1 million USD to ensure accessibility for smaller and emerging suppliers and to reduce barriers to market entry.

Enable end-use-relevant measurements: Prioritise tools that measure performance under magnetic field, angle, and temperature conditions relevant to applications, rather than defaulting to 77 K I_C due to legacy tool availability.

Increase data volume and statistical confidence: Allow suppliers to generate large, statistically meaningful datasets as part of routine manufacturing, strengthening qualification and customer confidence. Speed of measurement should take precedence over accuracy and precision (to more than a few %) given the high spread in tape performance (commonly tens of percent).

Ensure HTS-specific design and standardised outputs: Use purpose-designed HTS test equipment and protocols and use a consistent reporting format to ensure simple comparability across suppliers.

Position as complementary to national facilities: Define these devices as front-line manufacturing tools that complement, rather than replace, a national HTS characterisation facility equipped for comprehensive, multi-physics qualification.

4 References

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