

Tasks in materials engineering—essence of research and essentiality of application

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Materials engineering, product manufacture and system designing play significant roles in converting basic materials into a performing product. At every stage there is need for research. Many examples of user-driven materials development bear witness to this wherein an application is targeted for a specific set of materials.

I feel greatly honoured to have been asked to deliver the 1991 Professor Brahm Prakash Memorial Lecture. The previous speakers were men of great eminence, several of whom had extremely close association with Professor Brahm Prakash. I cannot lay claim to either of these qualifications. Yet if I accepted the invitation generously extended to me by the Bangalore Chapter of the Indian Institute of Metals, it is essentially to pay my humble homage to the memory of an outstanding leader in the twin fields of materials development and high technology systems integration. The enormous contributions of Professor Brahm Prakash during the formative and the critical phases of the development of our atomic energy and space programmes have been documented following the Hyderabad Seminar organized by Shri C.V. Sundaram in August 1984. Professor Brahm Prakash was a man of sterling personal qualities—and it is always instructive to acquaint oneself with his attributes and these have been superbly expressed in the compilation entitled *Homage to a Doyen—A commemorative Tribute to Professor Brahm Prakash* brought out by Shri R. B. Subramanyam (of Defence Metallurgical Research Laboratory, DMRL). I had the privilege of seeing him at work, as the Chairman of the Mishra Dhatu Nigam Limited. However, I was not intimately associated with him, and my meetings with him were few and far between. Even so, I have learnt a great deal by watching him, hearing about him and also thinking of all that he had done and the way he conducted himself. The lecture that I have composed, I trust, will be seen as not an inadequate product of this learning process.

For many years in my professional career, I was under the impression that research and development in mate-

rials was essentially to study their basic characteristics in terms of the microstructural features, their origin and evolution, and their behaviour especially with respect to mechanical properties. It was only more recently, some time after I joined DMRL in 1982, that I began to appreciate that understanding such characteristics and behaviour is only a small part of materials engineering. What goes with materials development and materials engineering cannot be appreciated unless an *application* is targeted for the material in question. Therefore, in the context of materials engineering, application is the *sine qua non* and often implies going beyond the development of the semi-finished product to designing a component, a cost-effective and energy-efficient manufacturing process to shape the component and seeing it through as part of a system for satisfactory and durable performance (Figure 1). The later stages in this scheme, subse-

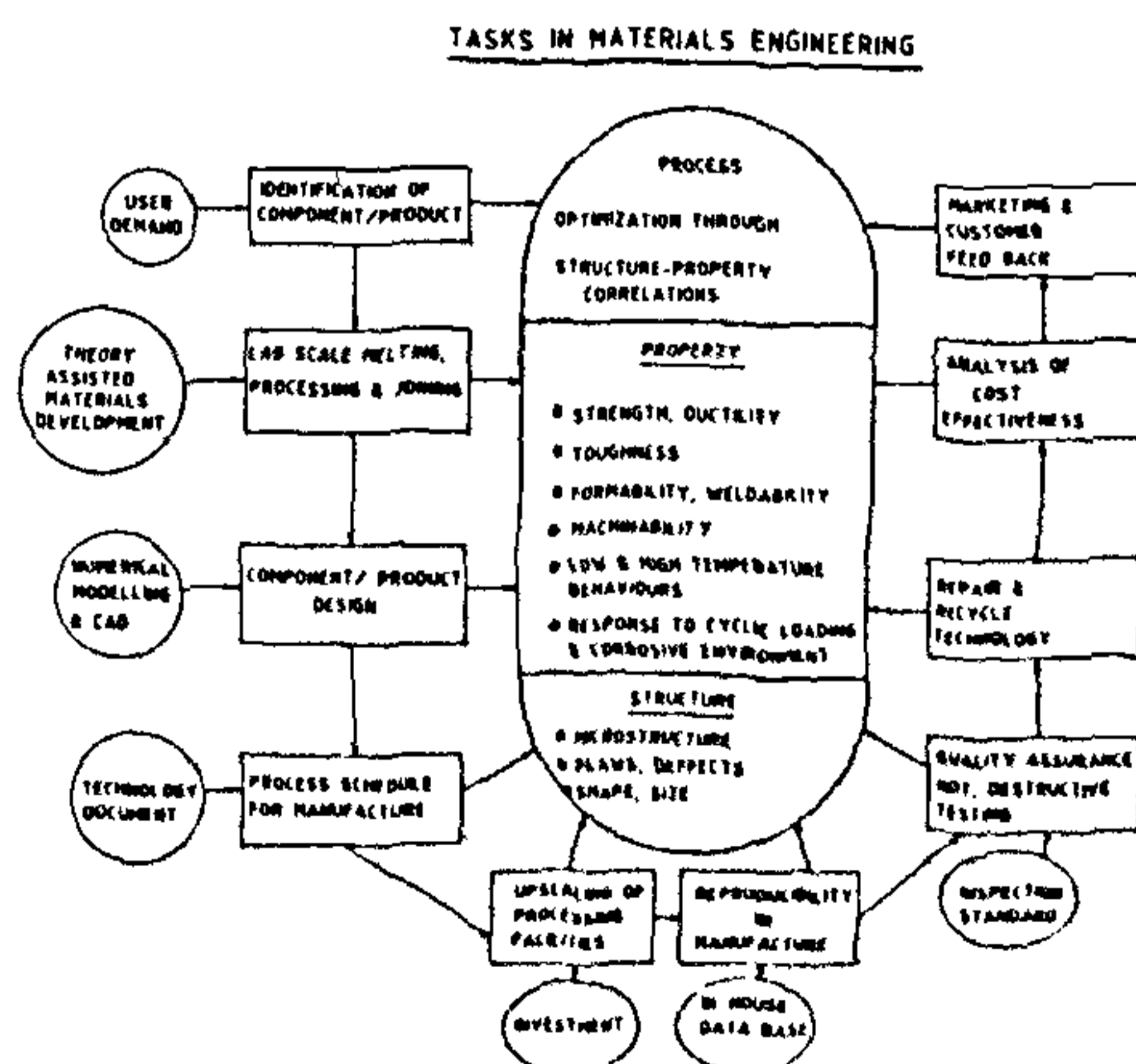


Figure 1. Tasks in materials engineering

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quent to that of a process for the semi-finished product, inevitably necessitate integration of the materials engineer with the product manufacturer and the system designer. It is also clear to me that the *research* aspect is a requirement during all the stages extended right up to engineering service which, when recognized, renders materials engineering at once fascinating and demanding. The story of the discovery of Cottrell creep¹, a new viscous creep phenomenon, at the final stage of actual use of uranium as fuel in the Calder Hall reactor, exemplifies the value of persistent research taken up to the culminating step of putting a new material into engineering service. I shall endeavour to convey to you in this lecture what may be considered as necessary elements in the formidable chain of activities connecting the *basic material* to the *performing product* with the help of appropriate case studies.

W-alloy R&D for a defence application—the case of a strategic need

We shall take up the case of research, development and manufacture of a defence item, namely the fin stabilized armour piercing discarding sabot (FSAPDS) anti-tank kinetic energy ammunition, the projectile of which is a complex tungsten alloy, so chosen because of its high density. The driving force for the development of this product arises from the demand of the user, in this case the Indian Army. The product is one of strategic importance. Consequently the attention and support that it has received in terms of the quality of technical manpower, the financial inputs and the support structure may be said to be of a type that is not *common place*. Nevertheless, a case study of this is relevant as it covers most of the tasks that are involved in seeing a material through to an application.

The chosen tungsten alloy belongs to a complex multicomponent system. Powder metallurgy was the production route. Considerable and prolonged *research* was undertaken to optimize the composition and the process parameters not only at the initial stages and during the laboratory exercise of interim production but also at the plant manufacturing stage. The quality of the metal science input (by S. L. N. Acharyulu and his group) is reflected in the fact that the property levels of the projectile material was raised by a factor of nearly 2 in terms of strength (UTS: 650 to 1200 MPa), ductility (% elongation: 4–5 to 5–8) and impact energy (30–40 to 70–90 J) over the period of the alloy development.

Manufacture of a high-quality product such as this required *inter alia* isostatic powder consolidation and post-sintering thermomechanical treatment. Constant interaction with the ammunition designer (Armament Research and Development Establishment, ARDE) and the ballistic proof at the stage of manufacturing trials

brought out the need for a high level of precision in machining the various components including the tungsten alloy projectile. (See Figure 2 for the way the materials development laboratory, DMRL; the design establishment, ARDE; and the manufacturer, Directorate General of Ordnance Factories, DGOF were intertwined in the organizational scheme.) Rigorous inspection of metallurgical quality was essential as we were concerned with a strategic defence product. This was met not only by a high-precision ultrasonic testing facility for monitoring the defects but also the use of scanning electron microscopy for a check on the internal micro-structure through evaluation of the fracture surfaces.

The experience of interim production was an essential part of the story and contributed in no small measure to successful technology transfer. If DMRL were not prepared to go beyond the call of their duty as an R&D laboratory to take up interim production, the technology transfer process would have been severely impeded. Figure 3 illustrates how the duration for technology transfer can be significantly reduced when activities at various stages are dovetailed. The practical experience summarized in Figure 3 mirrors the concept by L. L. Hench².

The design of the plant and equipment for eventual manufacture was greatly aided by the experience of interim production. The availability of the ready producer, namely the Ordnance Factory, in this case of a defence item, is to be regarded as a blessing. The project management structure (Figure 4) ensured the involvement of the producer in a powerful position. The Chairman of the Ordnance Factory Board was the Chairman of the Project Steering Committee, which included not

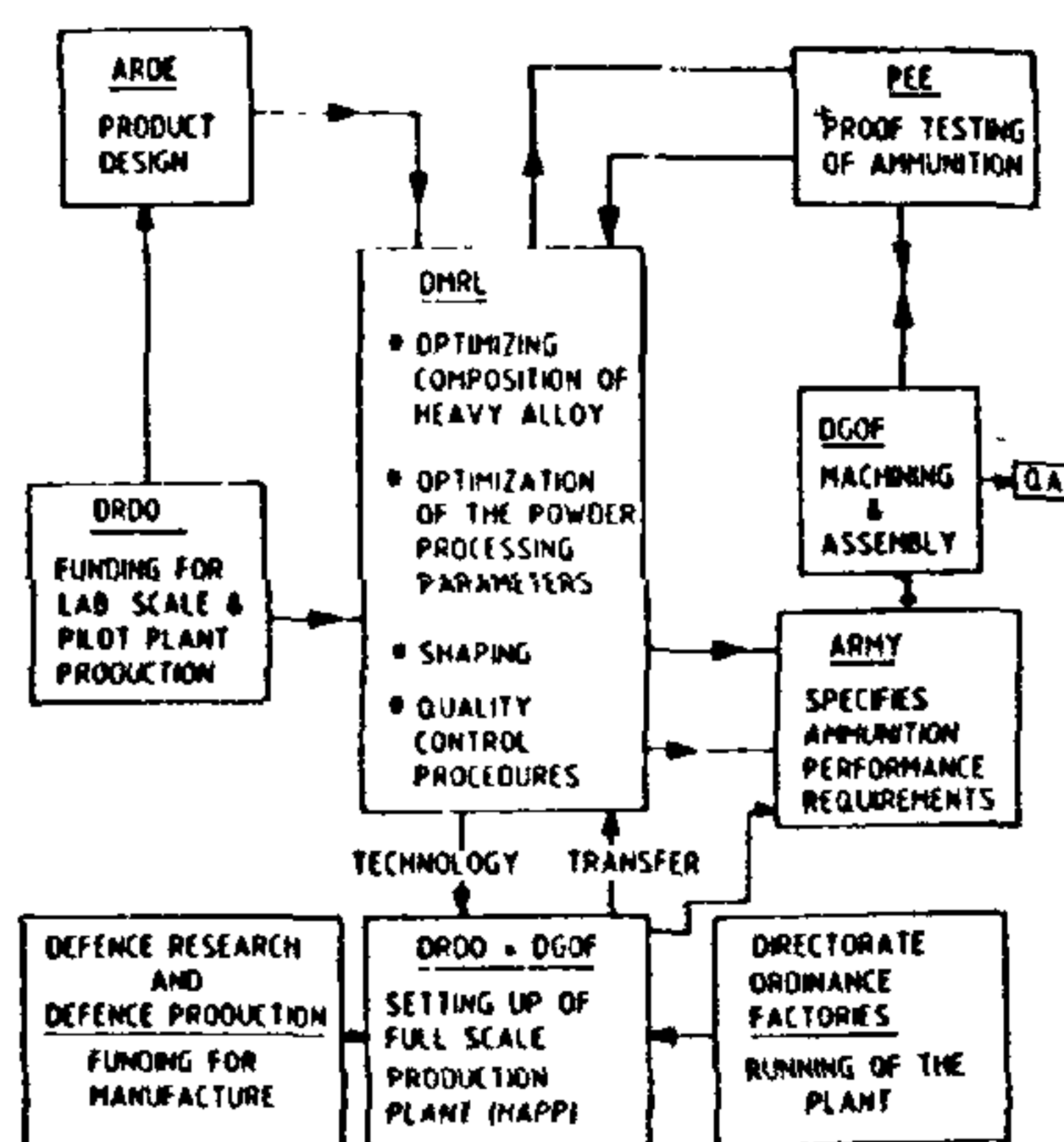


Figure 2. Networking of the various organizations for the purpose of development of the W-alloy based product.

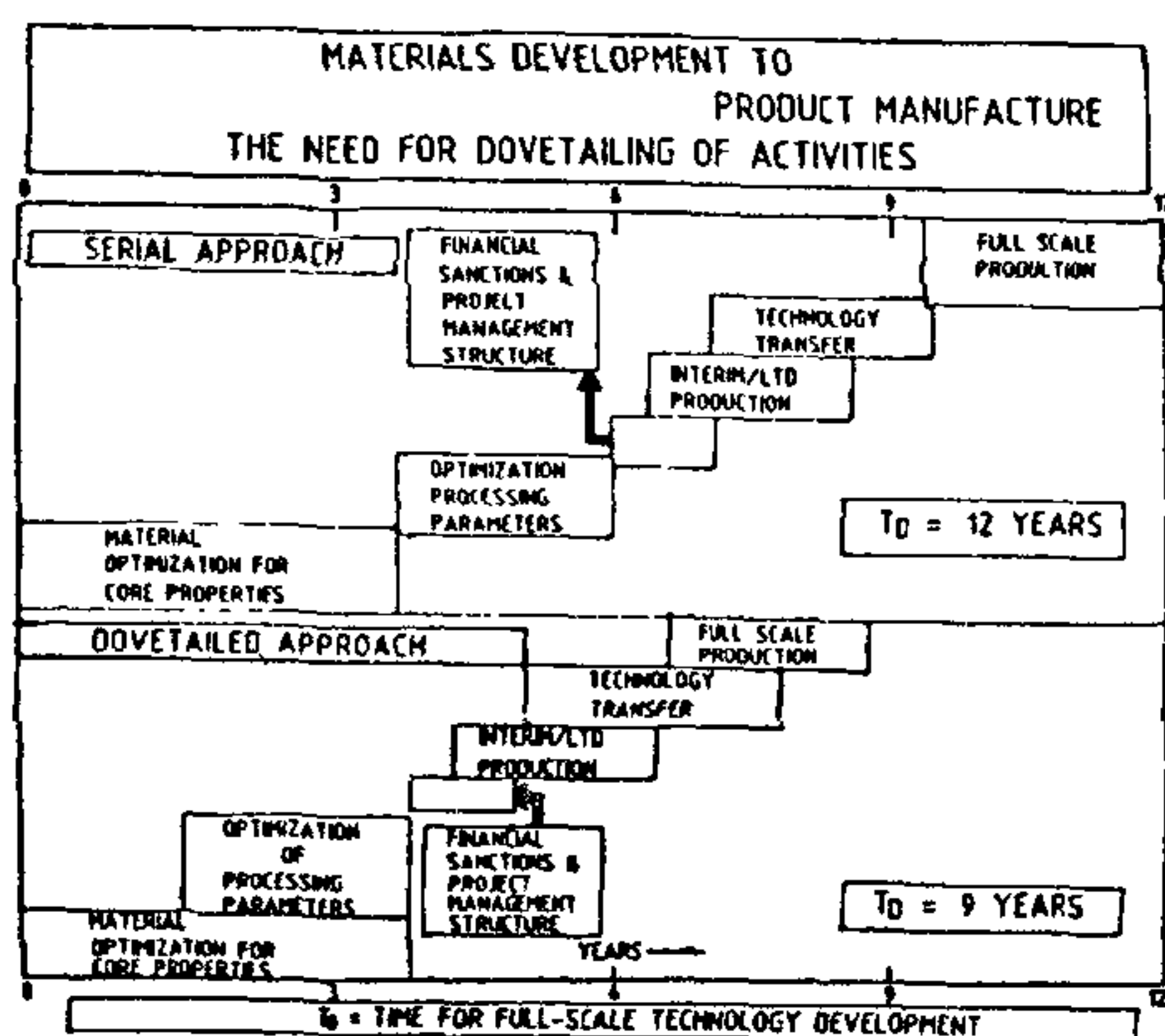


Figure 3. Illustration of how a dovetailed approach at various stages reduces time for technology transfer.

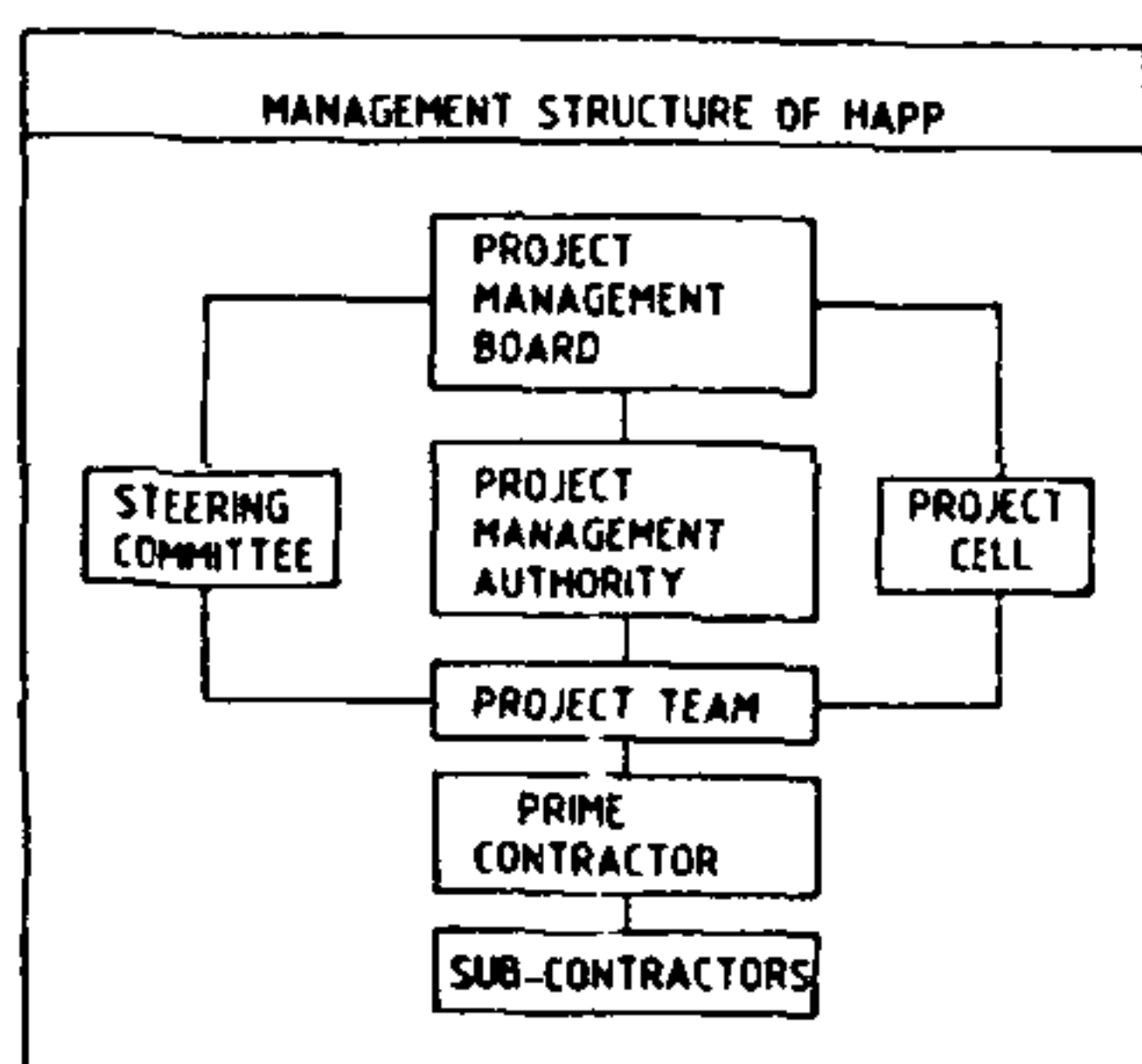


Figure 4. Project management structure for the development of the W-alloy based products.

only the R&D personnel, the system designer and the materials developer but also the Quality Assurance and the User Representatives. DMRL, an R&D Laboratory, was designated as the project implementation authority. The funding was provided jointly by the Department of Defence Research and Development and the Department of Defence Production which symbolized a commitment of the production agency (DGOF) to the project as much as that of the developing agency (Defence Research and Development Organization, DRDO). The project, an example covering a wide range of activities from research to production, is a major milestone in our country's technological development as it has brought into being the first full-fledged Ordnance Factory based on indigenous technology.

There are a number of other instances of successes in the sphere of user-driven advanced materials development in our country. A few of these are given in Table 1 and these pertain to items of strategic nature.

The erstwhile Science Advisory Council to the Prime Minister (1986-90) chaired by Professor C. N. R. Rao recommended³ an integrated approach to Minerals Development (Figure 5).

It may be pointed out that the success of the tungsten alloy ammunition going into manufacture has provided an impetus to achieve backward integration with respect to tungsten resources development, an area that demands attention (Figure 6). A major project for tungsten mineral beneficiation is under way at the National Metallurgical Laboratory, Jamshedpur, and Hindustan Zinc Limited have come forward to take over the Degana Mines in Rajasthan with a view to augment efforts for exploration and mining of ore reserves. DMRL has also completed evaluation of the tungsten binary alloy phase diagrams⁴, an activity of an entirely different nature, and yet stimulated by the laboratory involvement in technology development associated with tungsten alloys.

Table 1. Some examples of user-driven materials development in India

Materials and component development	Developing agency	Production agency	Application	User
Zircaloy tube	BARC	NFC	Nuclear reactors	DAE
Maraging steel rocket motor casing structurals	MIDHANI, VSSC, DMRL	MIDHANI and SAIL	PSLV	ISRO
Aircraft brake pads (Metallo-ceramic friction materials)	DMRL	HAL	Fighter aircraft	Air Force
JACKAL armour	DMRL	SAIL	ICV	Army
Carbon fibre reinforced composites	DRDL	COMPROC, RCI	Missiles	Services

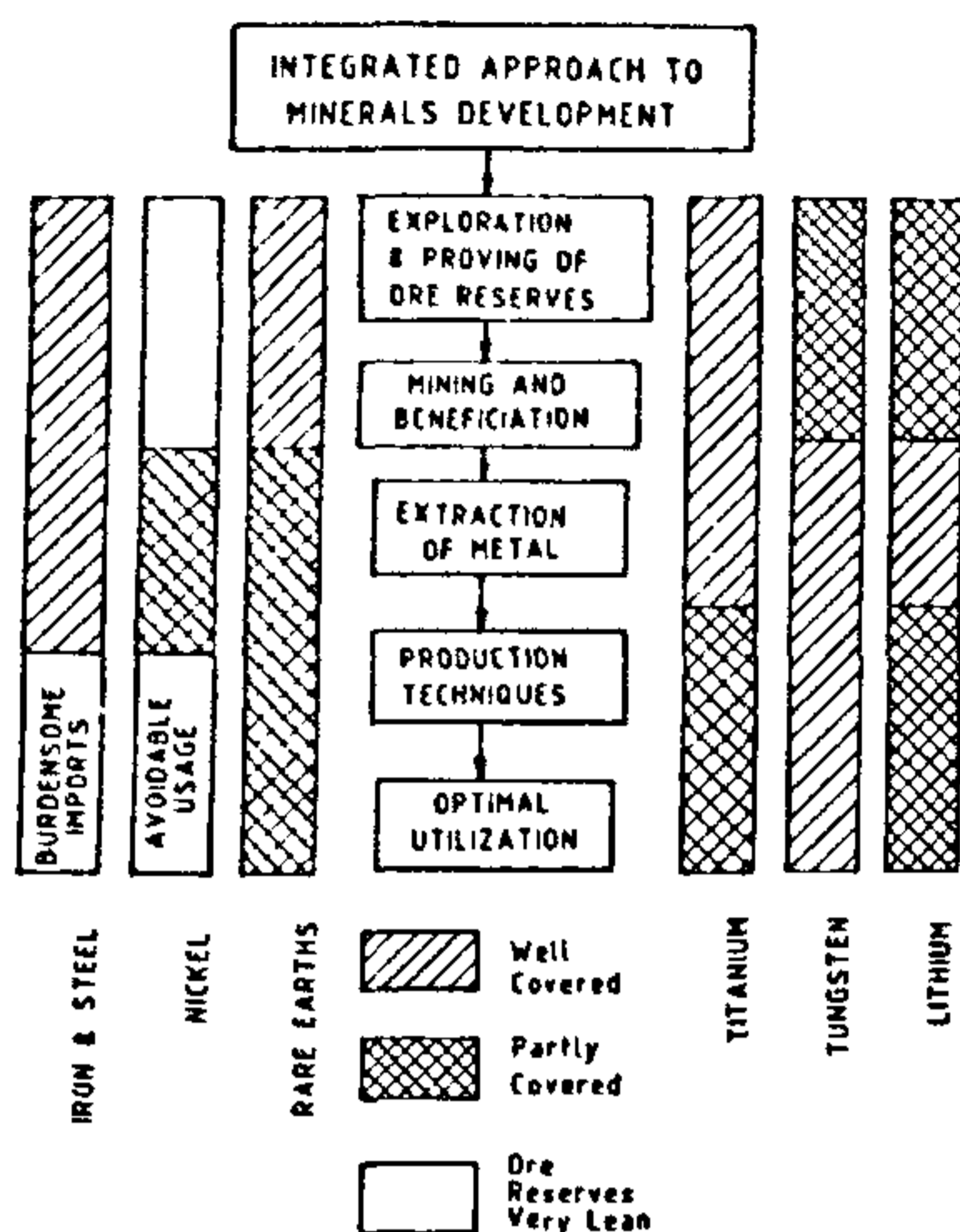


Figure 5. Integrated approach to minerals development.

• BACKWARD INTEGRATION (TUNGSTEN "ORE-TO PRODUCT" CHAIN)

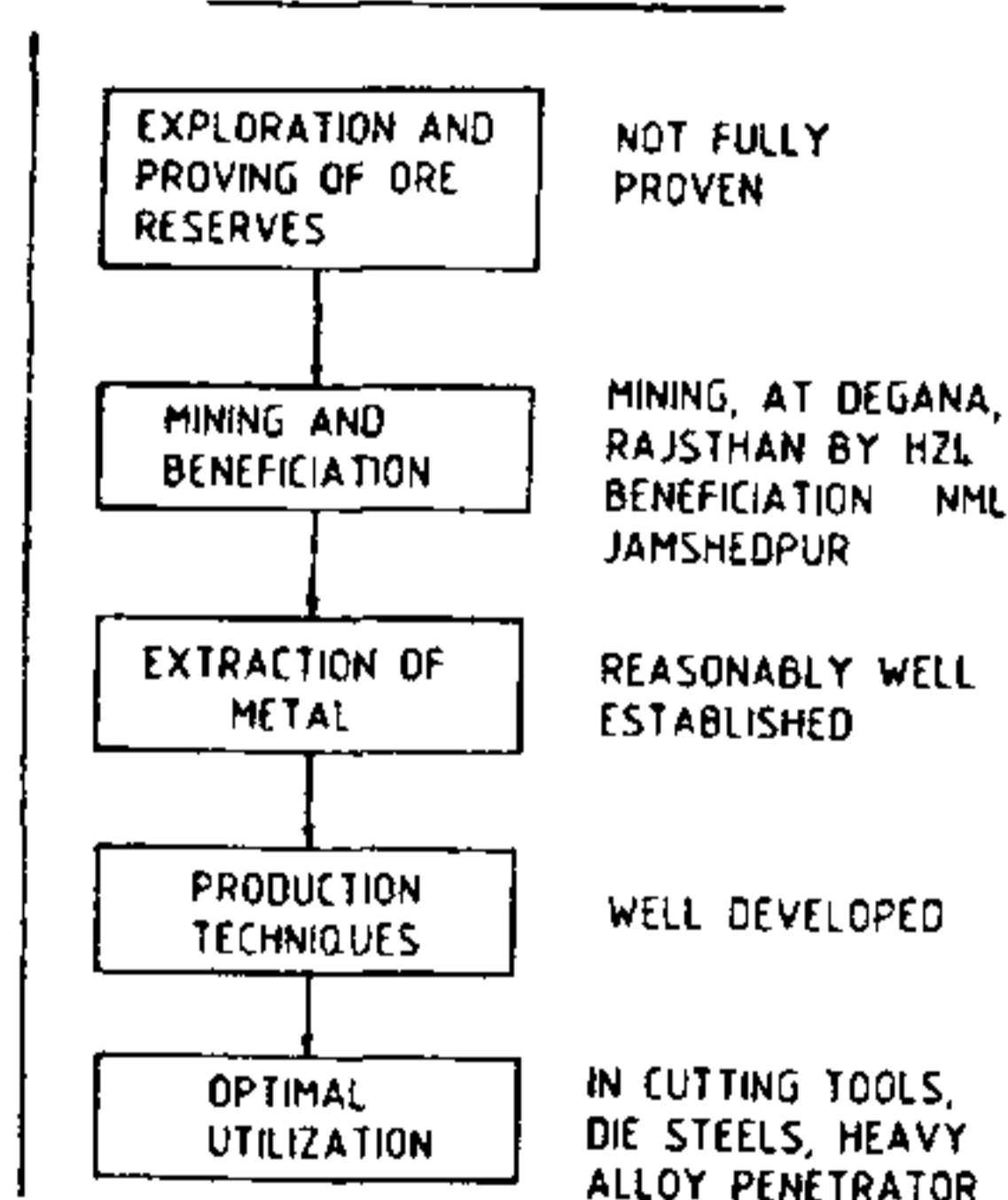


Figure 6. Backward integration in the case of tungsten.

OFE Cu development—the case of a market need

More than a decade ago, DMRL worked on vacuum melting/refining technology for the production of Oxygen Free (OF) copper when the laboratory was called upon to meet the requirement of a material called 'ball coppers' for use in guns and mortars as pressure gauges. Although the technology was proven, there was no large-scale production of OF copper until Hindustan Copper Limited (HCL) came along to work jointly

with DMRL. DMRL, endowed with limited laboratory-scale equipment, increased the quantum of production to four tonnes per annum which opened up a new era of consortium approach to facilitate scale-up and commercialization of technology developed by the laboratory.

The consortium that is now functioning at DMRL with the unstinted support of the Department of Mines, Government of India, is called the Nonferrous Materials Technology Development Centre (NFTDC). The nodal Government Laboratory for this consortium is DMRL. The participating industrial units (Public Sector Undertakings) are the four primary nonferrous metal producers, namely the Hindustan Copper Limited (HCL), the Hindustan Zinc Limited (HZL), the National Aluminium Company (NALCO) and the Bharat Aluminium Company (BALCO). The objectives of the Centre are:

- (i) technology development for selected nonferrous materials,
- (ii) sensitization of the market,
- (iii) pilot production, and
- (iv) technology transfer for large-scale production.

NFTDC has had the influence of broadening the DMRL mission to cater for market requirements in selected high-quality materials and may prove to be a needed model in the present context of scarce hard currency. The organizational structure (Figure 7) in this case of a non-strategic material development and production may be compared with the one (Figure 2) described in the last section where a strategic defence item was dealt with.

The way the existence of NFTDC stimulated growth in the quantum of OF copper production and investment is depicted in Figure 8. Further, the manner in which OF electronic grade copper technology aspects were researched and improved upon, clearly because of its being an NFTDC programme, is briefly described below.

For critical electronics applications involving high-vacuum levels such as electron devices, anodes and

• A SUITABLE ORGANIZATIONAL STRUCTURE TO COORDINATE THE WORK IS THE FIRST REQUIREMENT

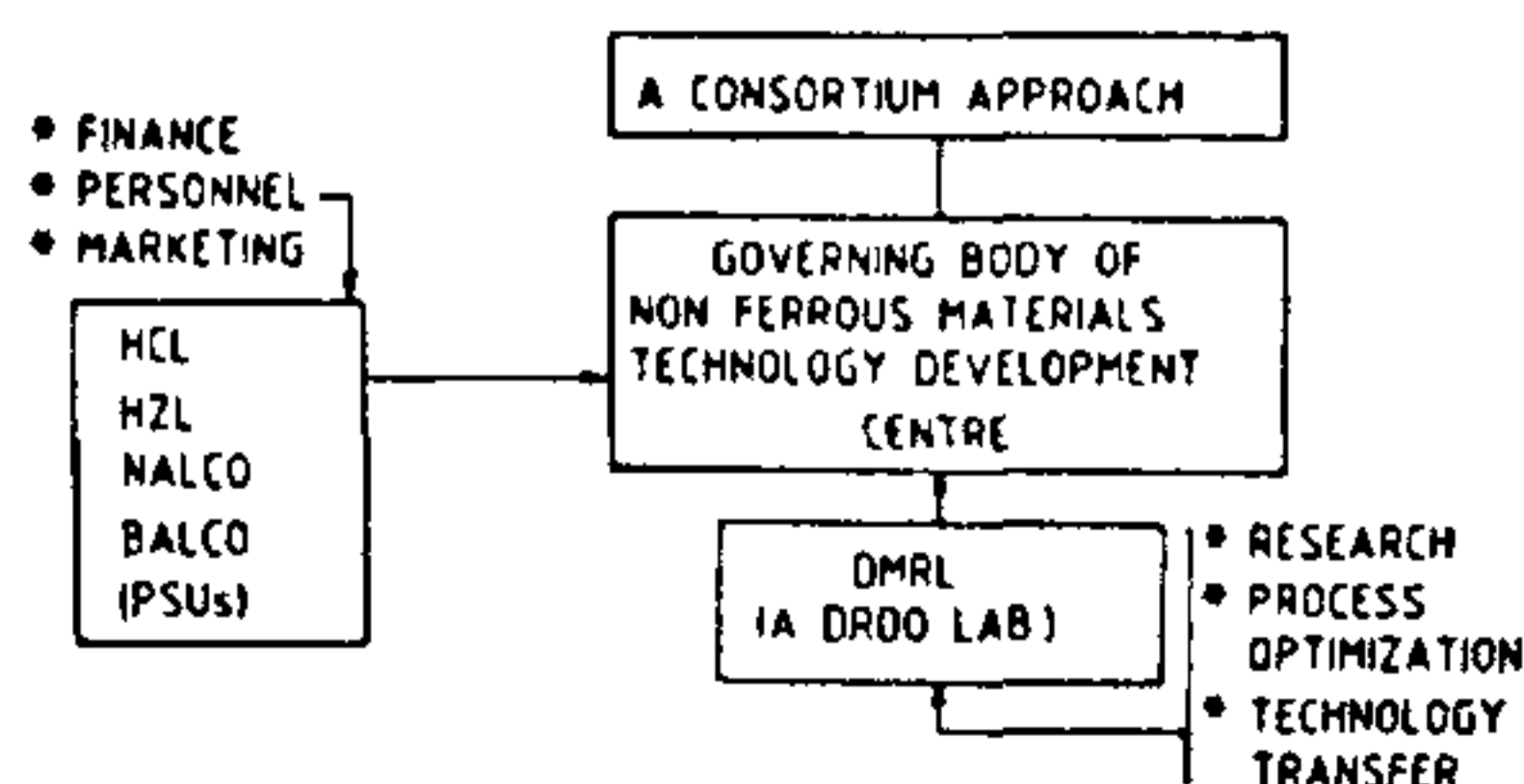


Figure 7. NFTDC set-up.

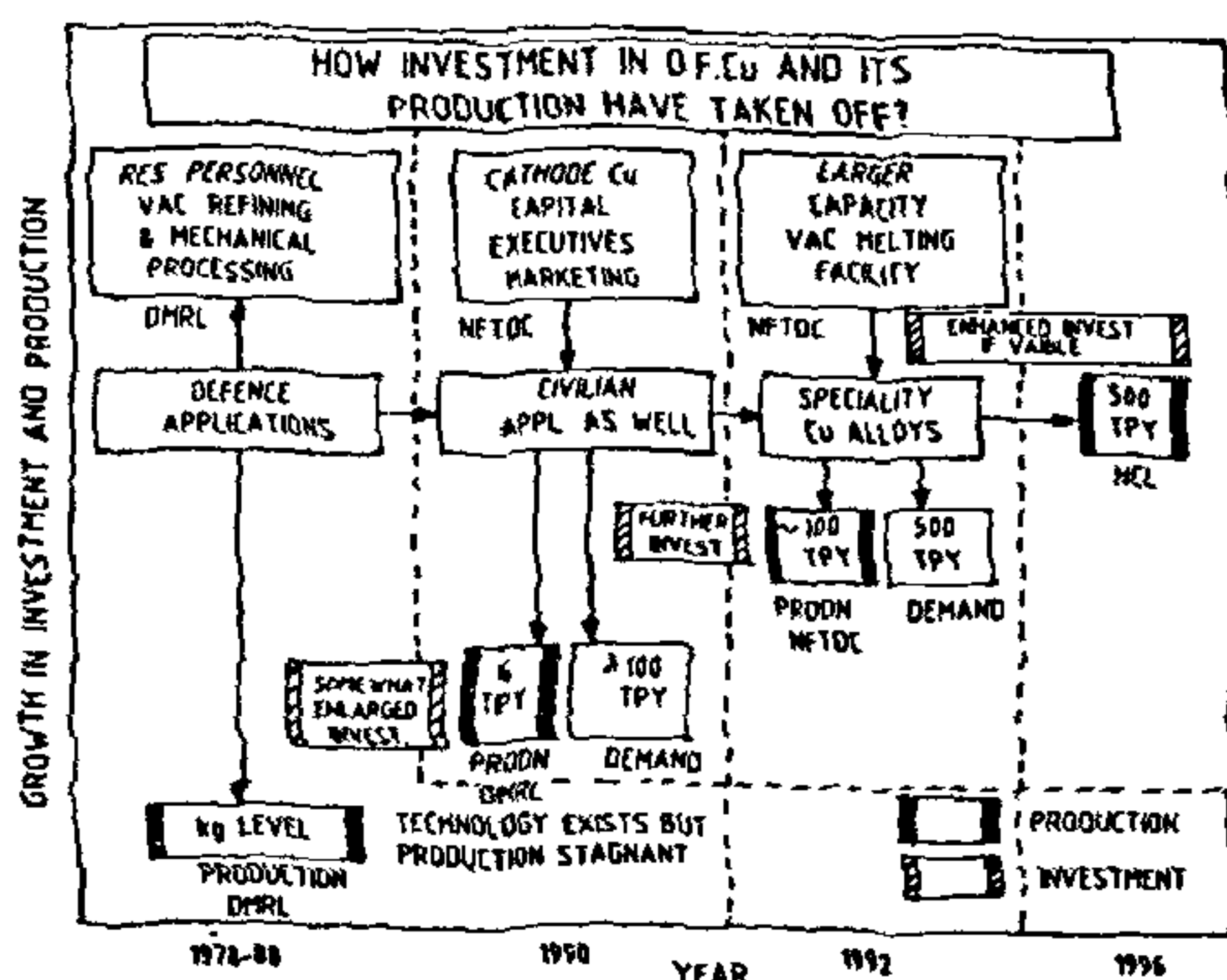


Figure 8. Growth in investment and production in the case of OF copper.

commutators, copper with very high purity is required. Besides oxygen levels to be maintained at ~ 5 ppm, it is necessary that volatile impurities such as Zn, Cd, Hg, Fe, Ni, As, Sb, Bi, Te and Se are kept at very low levels. This called for stringent specification (see Table 2 and specification ASTM B-170-89a) with respect to each of these elements (total 17) and copper then is termed Oxygen Free Electronic (OFE) copper. It is this premium-grade copper that is currently being imported to the tune of nearly 500 tpy. Demand for this grade from the electronic industries like Bharat Electronics necessitated the upgradation of DMRL technology.

In order to develop a high purity material the fundamental principles of refining have to be understood. Development of suitable processes for refining, casting

and deformation forms the core of the technology. Fabrication and modifications to the equipment to engineer the technology forms the next logical step. An economically viable technology has to consume the least amount of energy and time while providing consistently high quality and yield. Thus, the process parameters have to be optimized to meet these requirements. Incorporation of flexible manufacturing features (in terms of production of various shapes and sizes) into the engineering aspects of the technology is also required.

While the emphasis in the production of Oxygen Free (OF) copper for 'ball copper' was on the removal of oxygen via carbon-oxygen reaction and the application as pressure gauges depended essentially on low strength and uniform deformation of the copper spheres, the production of Oxygen Free Electronic Copper (OFE) requires the understanding of the thermokinetics of removal of nearly 16 elements. While application of vacuum does remove the volatile elements, proper optimization of the time-temperature schedule is required to bring down the level of impurities within the specification limits. The thermodynamics of dissolution and removal (evaporation) of the impurities has to be studied to understand the feasibility of refining in vacuum. In order to improve kinetics as well as to remove elements otherwise not removed (e.g. Fe, Ni), the introduction of gas purging (equivalent to creating a vacuum level of 10^{-12} atm) was considered. Casting of such a purity material requires controlled conditions and special handling procedures. The cast ingots have to be processed to quality semifinished products (rods, wires, strips, sheets and slabs) which calls for the understanding of the hot and cold deformation principles and processes. (We shall refer to recent hotworking research at the end of this section.)

Scale-up to much higher levels (e.g. 1000 tpy of OFE copper) would require (i) making the process continuous, (ii) automation of material handling and material flow, and (iii) automatic control of the process. If we attain these, the technology can be termed fully mature.

In the example we have considered, the production of oxygen free copper for ball copper applications started on a few kilogram laboratory scale with the emphasis on low oxygen content for the necessary mechanical properties. The upgradation of the technology resulted in a few tonnes per annum production meeting the demand for high-conductivity applications. Further upgradation and refinement (largely due to research and development by K. Balasubramanian) has resulted in the production of premium-grade electronic copper and the stage is set at NFTDC for the production of this grade to the extent of over 100 tonnes per annum. All through this development, the quality and yields have improved and energy consumption and production time have decreased significantly (Table 3). The future lies in the scaling up to nearly 1000 to 2000 tpy which

Table 2. Specified and obtained levels of impurities in OFE copper

Chemicals (ppm levels)	ASTM B-170-89a (specified)	Process improvements (obtained)	
		Before	After
Oxygen	5	7-10	3-5
As	5	8-11	<1
Sb	4	1-5	<1
Bi	1	0.2	<1
Cd	1	1	<1
Fe	10	10-60	5
Mn	0.5	2-3	<1
Hg	1	1	<1
Ni	10	2-8	5
Pb	5	1-8	<2
P	3	1	<1
S	15	8-17	10
Se	3	1-5	<1
Ag	25	1-17	<1
Te	2	1-2	<1
Zn	1	6-10	<2
Sn	2	1-6	<1

Table 3. Results of process improvements in the melting and casting of OI E copper at DMRL

Feature	Prior to process improvement	After process improvements via a research effort
Charge capacity, kg	80	100-105
Refining time, min	120	30
Charge-to-charge time, hr	11-12	7
Energy consumption per kg melted, kWh	10	3-3.5
Ingot weight before machining, kg	75	90-95
Ingot weight after machining, kg	35-40	65-70
Percentage ingot yield	45-55	75-80
Production of ingots, tpy	4-8	20-25
Net yield (products), tons	2-4	12-15
Quality of ingot	Large-scale rejection due to carbon entrapment	Carbon entrapment eliminated

would place us on the export map—a success story of alleviation of import burden with the potential of finally resulting in export.

It is heartening to refer here to the recent research carried out by Prasad⁶ and his group on the influence of oxygen on dynamic recrystallization during hotworking of polycrystalline copper. This research effort bears upon the downstream processing of copper products. The work shows that, in copper, which is a low stacking fault energy metal, dynamic recrystallization is controlled by the rate of interface formation which is slower than the rate of interface migration. Oxygen in an interstitial form pins the dislocations effectively and increases the rate of interface formation. At higher oxygen concentration, copper oxide particles act as strong barriers to dislocation motion and enhance the rate of interface formation more significantly. Both these effects result in lowering the strain rate for dynamic recrystallization (Figure 9). Also the large back stress caused by the presence of oxide particles is responsible for increase in the dynamic recrystallization temperature at

higher oxygen content (Figure 9). This work⁶ suggests that lower oxygen considerably enhances formability of copper and that at oxygen contents about 10 ppm or lower, one can resort to high-speed hotworking technologies (e.g. hammer) and make good products (microstructurewise). If oxygen were to be present as particles in large volume fractions, appropriate hot deformation rates would be far lower, forging technology would then have to be based on the slower hydraulic presses (Figure 9).

JACKAL Armour steel—multiple applications

It is worthwhile to point out that a given material can have more than one application and, therefore, is likely to have a multiplier effect, once capacity is established for its synthesis and processing. JACKAL steel developed by DMRL is an example.

JACKAL, a rolled armour steel found to be ballistically good in small thicknesses up to about 20 mm, was initially developed as a shield for the Indian field gun. There followed a major application for use of the steel to build the infantry combat vehicles. Presently, the demand for this steel has increased severalfold as it has been found to be a good choice for building vehicles used by the National Security Guard and the Border Security Force.

Prior to commercial exploitation of JACKAL steel, two major issues, namely (i) optimization of heat treatment schedule and (ii) establishment of welding technology, had to be resolved. Transmission electron microscopy and SEM fractography observations were related to fracture toughness (K_{IC}) measurements to delineate safe tempering temperature regimes avoiding tempered martensite embrittlement (TME) that can occur as a result of decomposition of interlath retained austenite into carbides (Figure 10a). TME also causes a trough in the work hardening exponent n (Figure 10b), a parameter that has a bearing on the ballistic performance. There was no way for this development to see

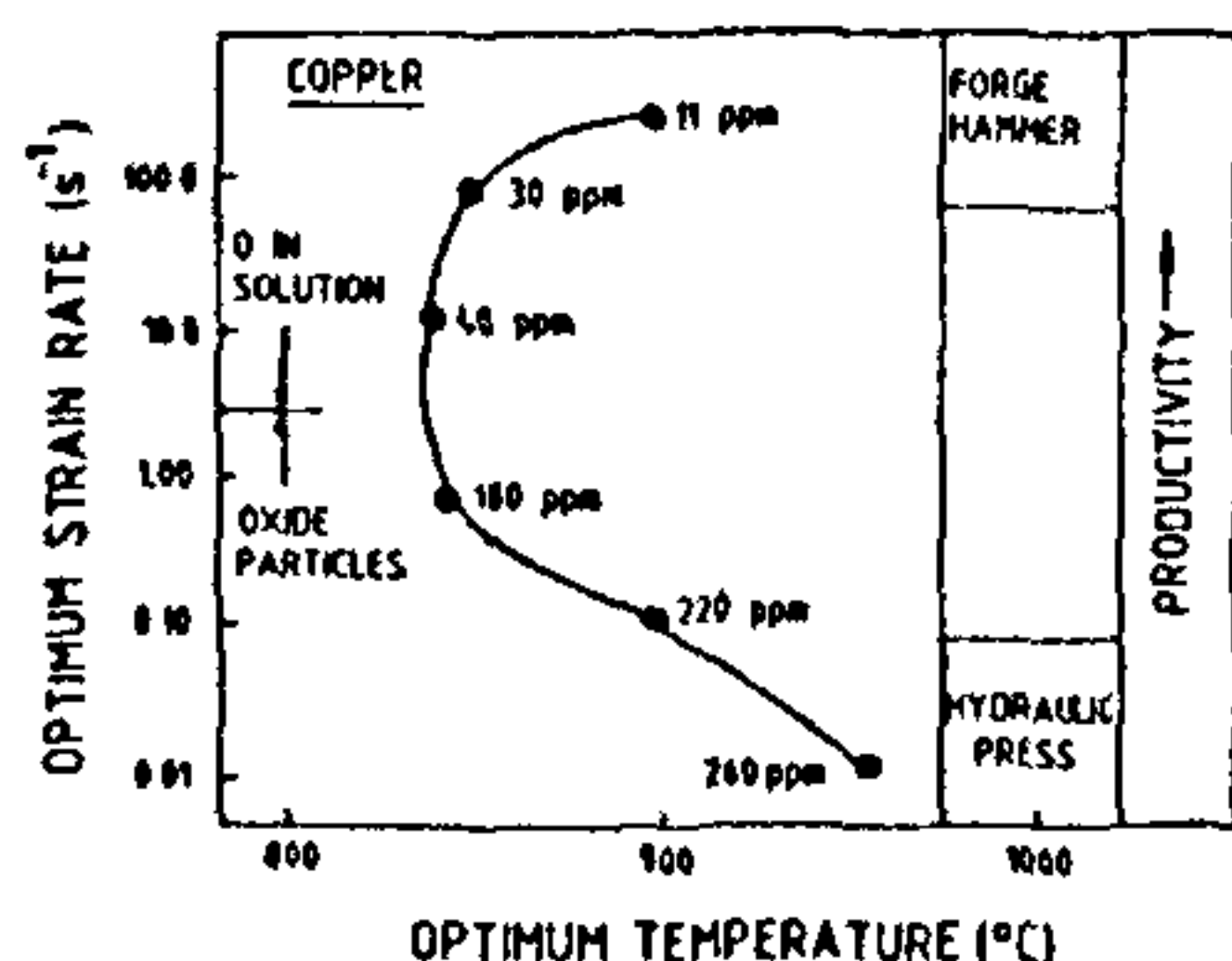


Figure 9. Effect of oxygen on the process parameters for dynamic recrystallization in copper (from the work of Prasad *et al.*).

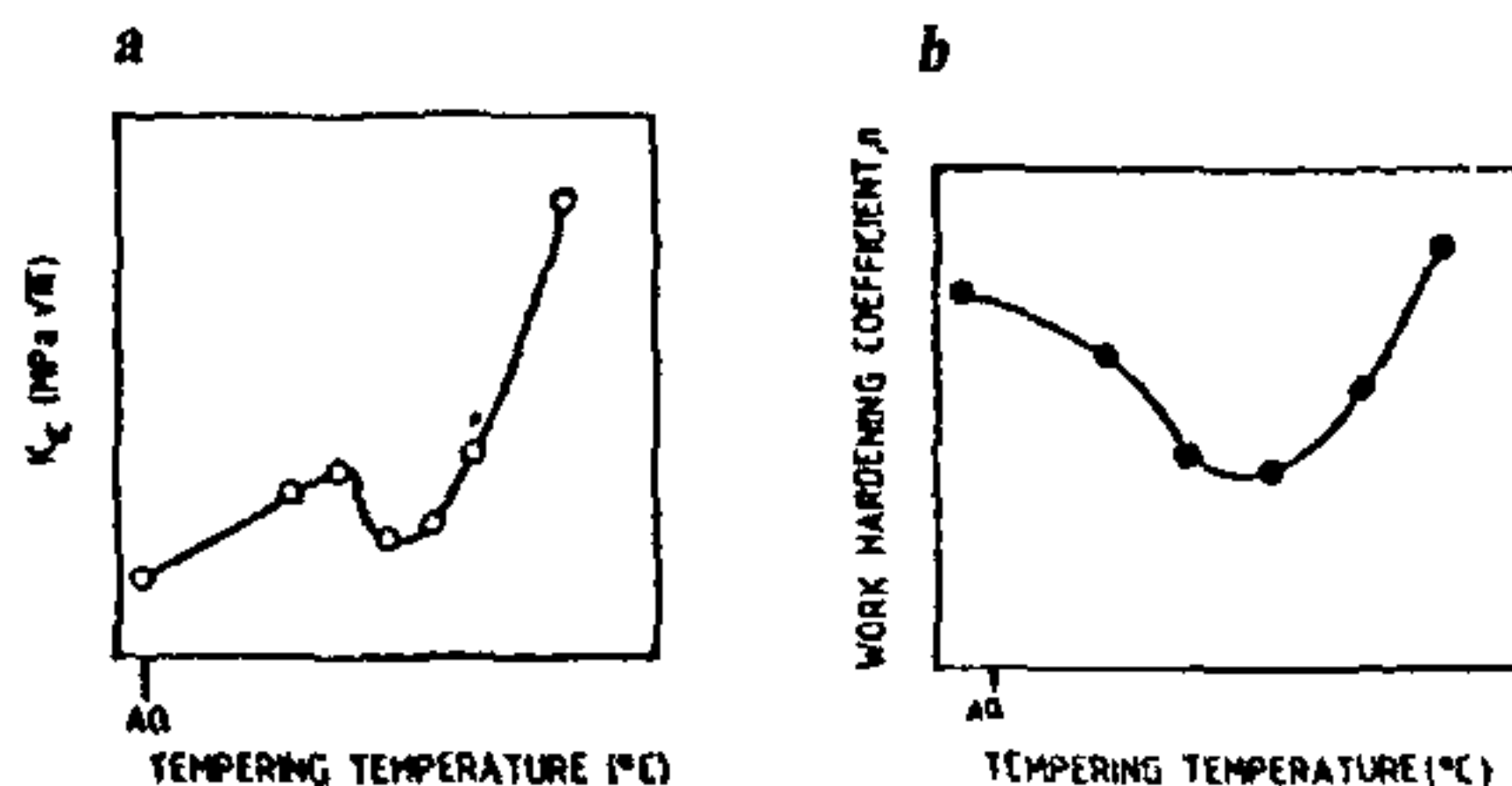


Figure 10. a, K_{IC} versus tempering temperature for JACKAL steel. b, Workhardening exponent versus tempering temperature for JACKAL steel.

practical applications unless weldability was declared as satisfactory and an appropriate filler material was determined. The weldability studies were carried out by DMRL in collaboration with Bharat Heavy Plates and Vessels (BHPV), Visakhapatnam, and Welding Research Institute (WRI), Trichy. (See Figure 11 for the network of activities and organizations in the development of JACKAL steel.) These studies showed that JACKAL was a weldable material and suggested an austenitic steel as a preferred filler material.

While welding with austenitic consumables, it is desirable to have around 5–10% ferrite in the austenitic matrix of weld metal to avoid solidification cracking. With the help of the Schaeffler diagram a suitable austenitic steel was chosen and welding procedures were established to join the steel in different thicknesses and heat-treated conditions.

JACKAL steel has now gone into multifarious uses. These include body armour, vehicles for National Security guard (NSG), Border Security Force (BSF) and Defence Research and Development Laboratory (DRDL).

There is a growing demand for body armour from the paramilitary forces in the country, namely BSF, NSG, Central Reserve Police Force (CRPF) and State Police. For the next two years, the demand of body armour that DMRL has agreed to meet is valued at several crores of rupees. As the imported product for the same purpose is much more expensive, the indigenous development of this special steel has contributed to a substantial saving in foreign exchange. The experience has another important pointer. Wherever infrastructure exists for large-scale manufacture, subsequent fabrication and finishing operations, even small improvements in the properties of known materials through indigenous research, can give rise to major benefits in the development, use and commercialization of products.

Composite product development—civilianizing defence products

JACKAL steel described above demonstrates also that materials and products developed exclusively for a defence hardware can find application in the civilian sector. We need to exploit this potential more widely not only in the area of materials with which we are concerned here but also in other fields. Composite materials, polymer matrix composites (PMC) and the carbon-carbon (C-C), developed by DRDL, Hyderabad, provide another example which we shall discuss briefly. While PMC has been developed for missile structural applications, the C-C composite was specifically developed for the missile nose cone. The nose tip experiences temperatures in excess of 3000°C during the missile reentry into the earth's atmosphere and C-C is a material that can contend with such a high-temperature situation. To extend this development experience for products of interest to the civilian sector, two noteworthy steps have been taken. First, a joint-sector production unit between DRDO and a private firm is envisaged to manage the Composite Production Centre (COMPROC), which has been set up by DRDO at RCI (Research Centre Imarat), Hyderabad. Second, Technology Information, Forecasting and Assessment Council (TIFAC), whose executive functions are carried out through the Department of Science and Technology (DST), and RCI (DRDO) have jointly launched a 'National Programme for Composite Product Technology' with a view to promote and intensify the deployment of composite products in the civilian sector. The immediate objectives of this tie-up are as follows: (1) conduct market research to establish current and future demand for composite products; (2) lend research and design support to industries for application of composite products, and (3) compilation of a composite product design manual.

Carbon-carbon (C-C) composites have found application as brake pad materials for both military and civilian aircraft. The high specific heat, low thermal expansion, low density, retention of strength even at high temperatures and the high 'melting point' of C-C composites make them an attractive material for brake pads.

To explore the use of C-C composites as brake pad materials, a joint programme among ADA (Aeronautical Development Agency), DRDL and DMRL is under way. While ADA represents the user and DRDL the producer of C-C composites, DMRL was involved in the tribological characterization of C-C composites. For this purpose, a sophisticated friction dynamometer (FD) built⁷ at DMRL was utilized⁸. This dynamometer has the capability to measure and monitor the coefficient of friction, the wear rate and the interface temperature continuously and *in situ* during the wear test. An

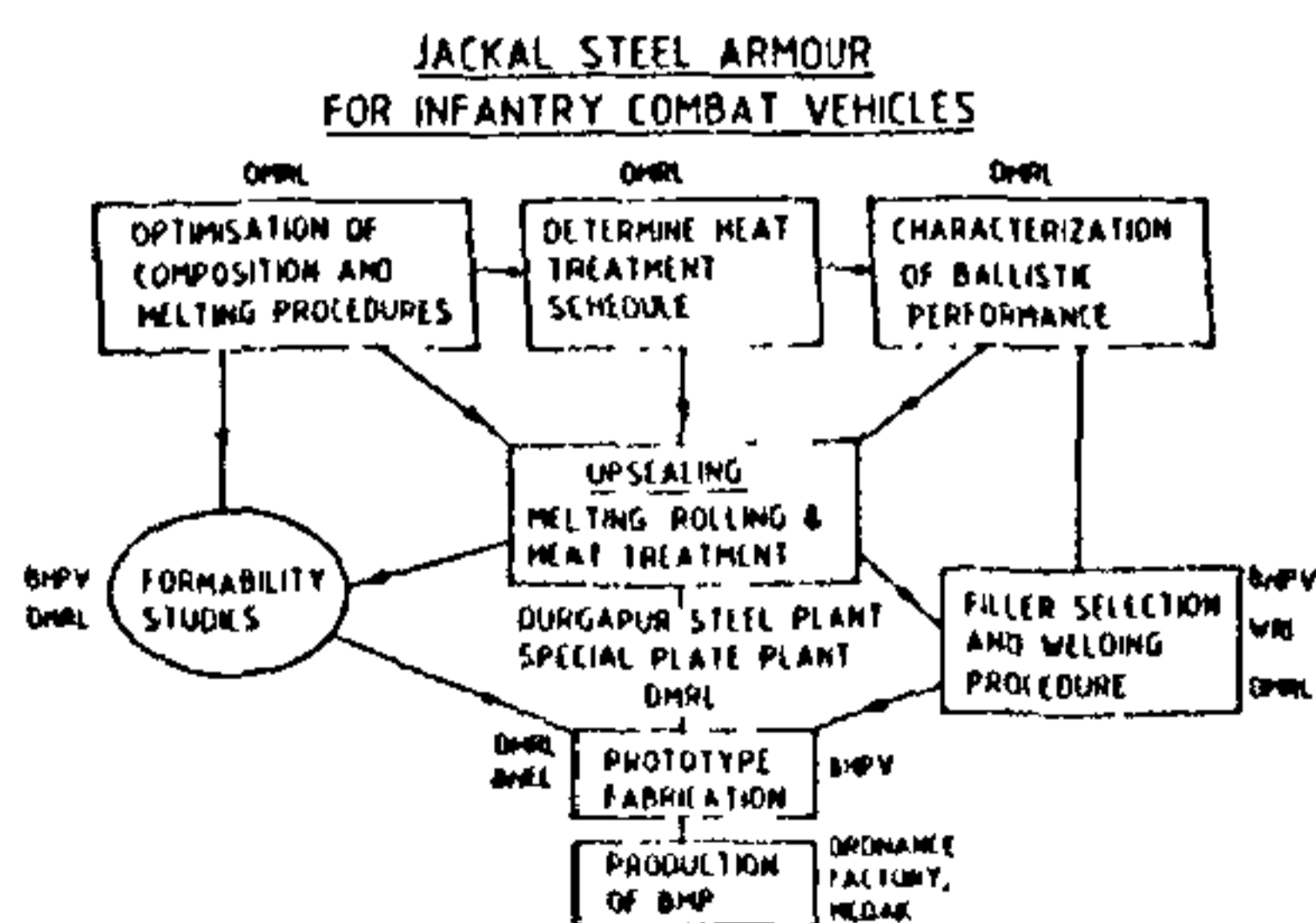


Figure 11. Network of activities and organizations for the development of JACKAL steel

interesting outcome of the experiments done at DMRL is the observation of critical interface (between C-C discs sliding against each other) temperature. This temperature (T_c) represents a critical interface temperature which separates a 'moderate friction-low wear rate' regime ($T < T_c$) from a 'high friction-high wear rate' regime ($T > T_c$) (Figure 12). Thus, the brake should be so designed that the interface temperature does not exceed T_c . The interface temperature in turn is determined by the interface stress, the sliding speed and the time of continuous contact (i.e. each braking cycle). In an application, these parameters should be so optimized that the interface temperature does not exceed the critical interface temperature.

In conclusion, the following may be stated. Investments in terms of a range of resources made in Defence R&D are of a superior quality and quantity as the applications are of a strategic nature and the performance requirements are stringent. The realization of the full potential of the products that so result, when channelled for civilian and other non-defence uses, is likely to be rewarding and fulfils the great need of the day, namely deriving financial returns on the investments made. There is a research element that underlies diversification of applications which must be attended to.

Development of a low-alloy ultra-high-strength high-toughness steel—from basic research to a useful product

For improved performance of a component or a structure, while ensuring integrity, the material should possess a combination of high strength and high toughness. Maraging steel⁹ has an attractive combination of these properties. Professor Brahm Prakash was responsible for the crucial decision to use maraging steel for making the booster rocket structural parts of the Polar Satellite Launch Vehicle (PSLV). He has thus provided a fillip to the indigenous development of this important product. It is so gratifying to note that maraging steel is now being produced at MIDHANI on a commercial scale. To meet the specified property

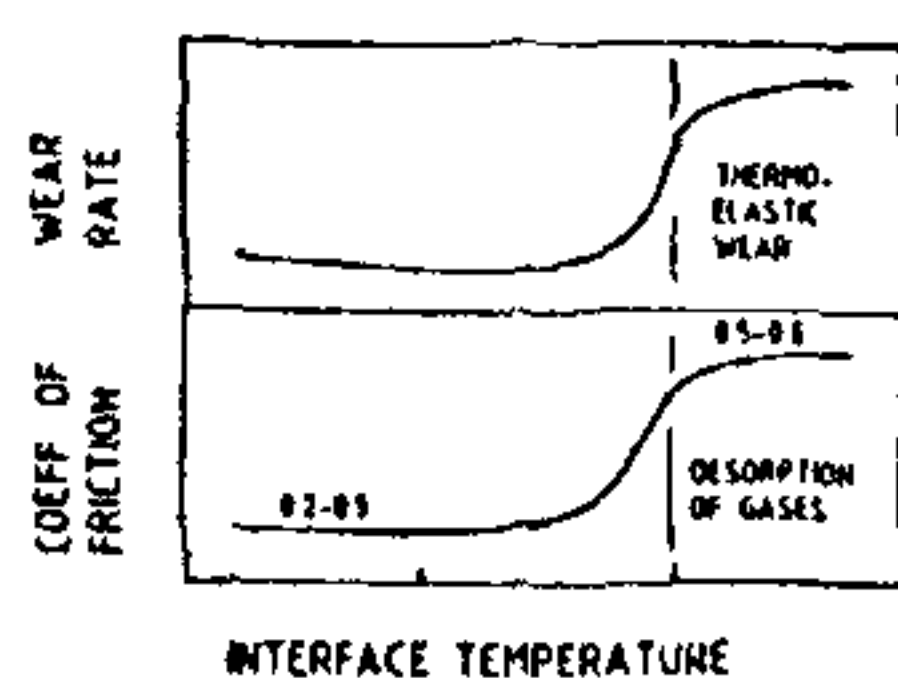


Figure 12. Measurement of wear rates, coefficient of friction as a function of interface temperature for C-C brake pad material

requirements in the weldments, especially in terms of fracture toughness, it was necessary to choose a filler material with higher fracture toughness than that of the base material at matching strength levels. VSSC, MIDHANI and DMRL made a choice in favour of a higher cobalt containing steel (to put it in somewhat simplistic terms and highlight the cobalt aspect), which is also now made routinely at MIDHANI. Broadly speaking, an increase in the cobalt content of the filler material from 8 to 12 wt%, with minor changes in the concentration of molybdenum and titanium, was seen to result in an increase in fracture toughness of the weldment from 74 MPa√m to 85 MPa√m at matching strength levels. This experience, and the fact that cobalt has substantial solid solubility in iron, prompted us to look at the effect of various solute elements on the fracture toughness of Armco iron and simple Fe-C alloys. Fracture toughness measurements¹⁰ on iron-based solid solutions, employing the J-integral method, have revealed that among the four solutes considered, namely nickel, molybdenum, cobalt and silicon, cobalt significantly improves¹¹ the fracture toughness of the base metal iron (Figure 13). Secondary ion mass spectroscopy (SIMS) has provided experimental evidence, for the first time, in support of the suggestion¹² that removal of carbon from the grain interior to the grain boundary occurs (Figure 14) in cobalt containing iron solid solution alloys. The effect of this is to ductilize ferrite grains and enhance grain boundary cohesion. We attribute to this effect the experimentally observed improved fracture toughness of Fe-Co solid solution alloys (Figure 13). Hall-Petch analysis, which was resorted to for separating out the solute effects in the grain interior (by measuring σ_0) and on the grain boundary resistance (by measuring K_p) substantiated the SIMS observations. Cobalt addition was seen¹⁰ to lower σ_0 and increase K_p , in support of the concept of carbon segregation to the grain boundary.

The beneficial effect of cobalt with regard to J_{IC} of Armco iron was found to be more pronounced in the presence of carbon (Table 4). With 5% cobalt addition the J_{IC} of Fe-0.2C alloy was enhanced by nearly 80% while maintaining the same strength level. On the other hand, nickel, generally considered to be a

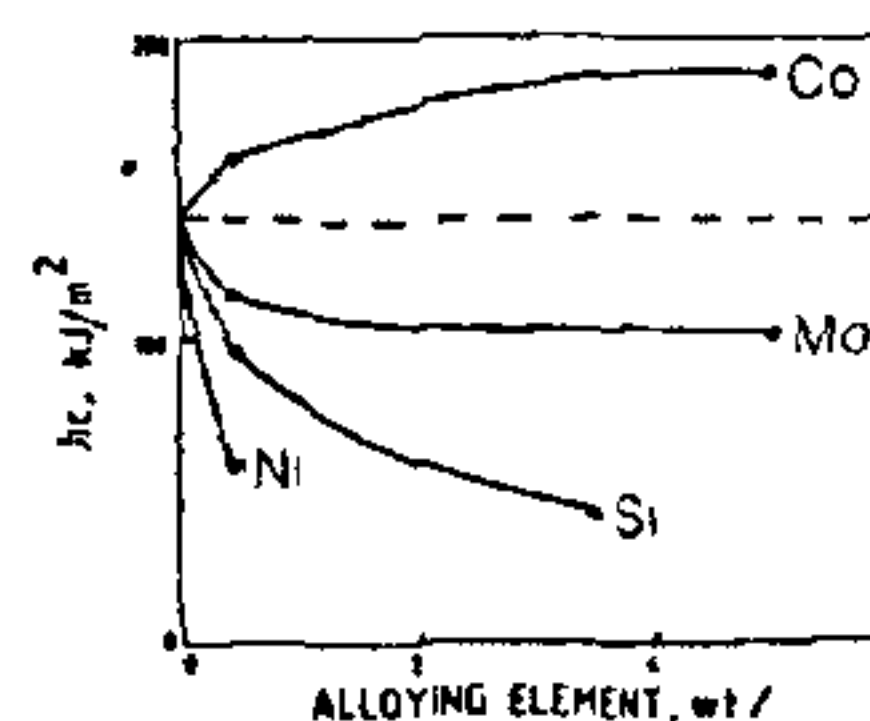


Figure 13. Effect of solute additions on the fracture toughness of Armco iron

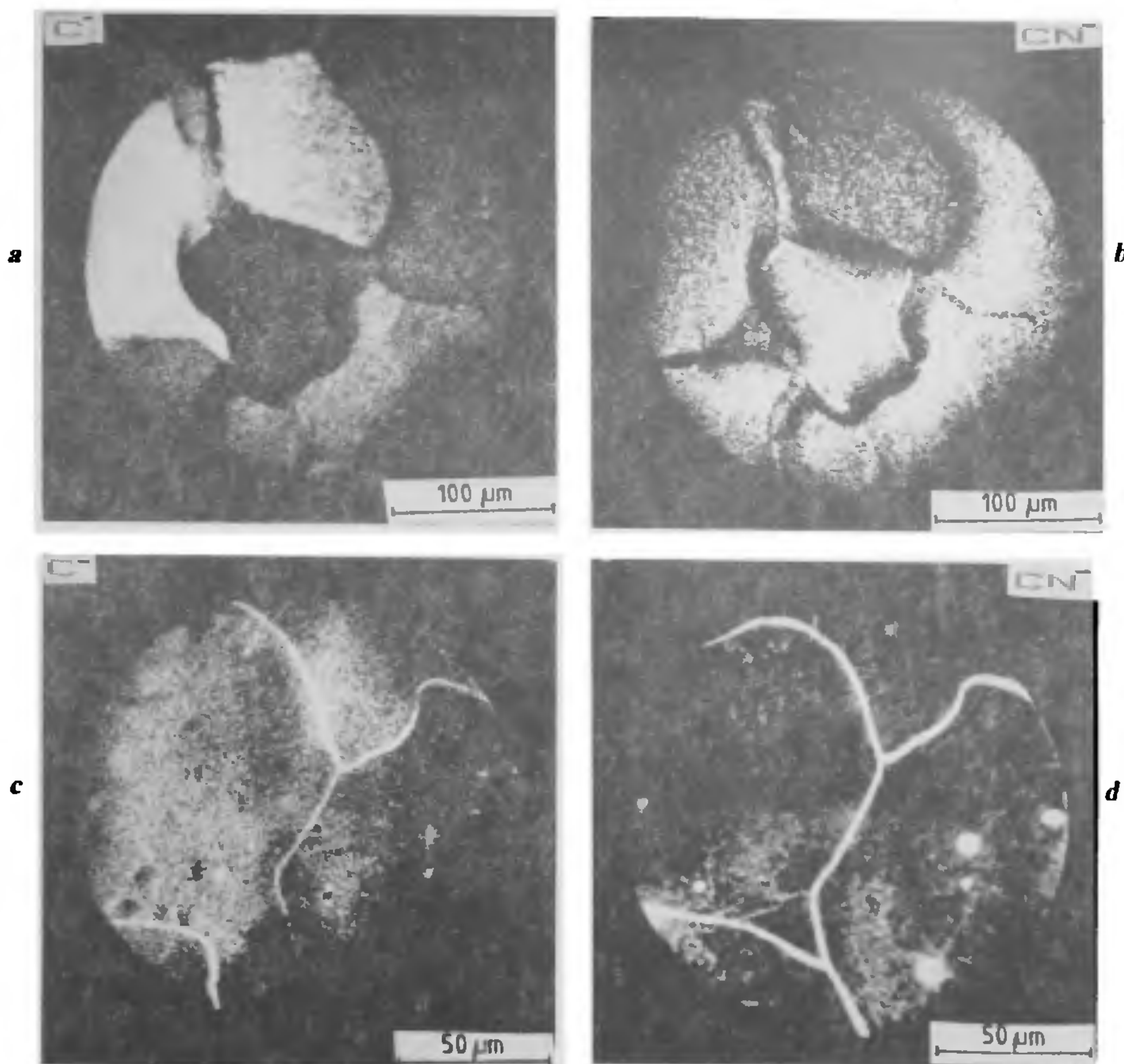


Figure 14. SIMS evidence for carbon segregation in cobalt-containing iron alloy. *a* and *b*, absence of carbon segregation in Armco iron; *c* and *d*, grain boundaries decorated with carbon in Fe-5 wt% Co alloy.

beneficial element in the presence of carbon, has only a marginal effect on the ductile fracture toughness J_{IC} of Armco iron.

This work and the associated information from the literature^{13,14} encouraged us to embark upon the development of a low alloy, relatively much less expensive steel, to match the mechanical properties of the highly alloyed maraging steel.

A high-silicon steel, made and investigated for the first time by Garrison¹⁵, was chosen as the base material. Cobalt was deliberately added to raise the

toughness level. The composition was balanced to maintain the required strength levels. The result is the development of a NiSiCrMoCo steel (total alloying addition less than 7%) with a strength toughness combination comparable to the value obtained in industrially produced M250 maraging steel (Figure 15). Auger electron spectroscopy suggests that carbon segregation occurs (Figure 16) to the extent of ~ 30% of monolayer in the steel containing cobalt and cobalt + molybdenum. On the other hand, the base steel did not reveal carbon segregation.

Table 4. Effect of cobalt and nickel additions on the tensile, impact and fracture toughness properties of Fe-0.2C alloy

Alloy	YS (MPa)	UTS (MPa)	El (%)	n	CVN impact energy (J)	DBTT (K)	Fracture toughness J_{IC} (kJ/m ²)
Fe-0.2C	244	370	44	0.24	16	300	130
Fe-0.2C-5Co	242	410	47	0.25	15	300	232
Fe-0.2C-5Ni	297	467	37	0.19	120	193	153

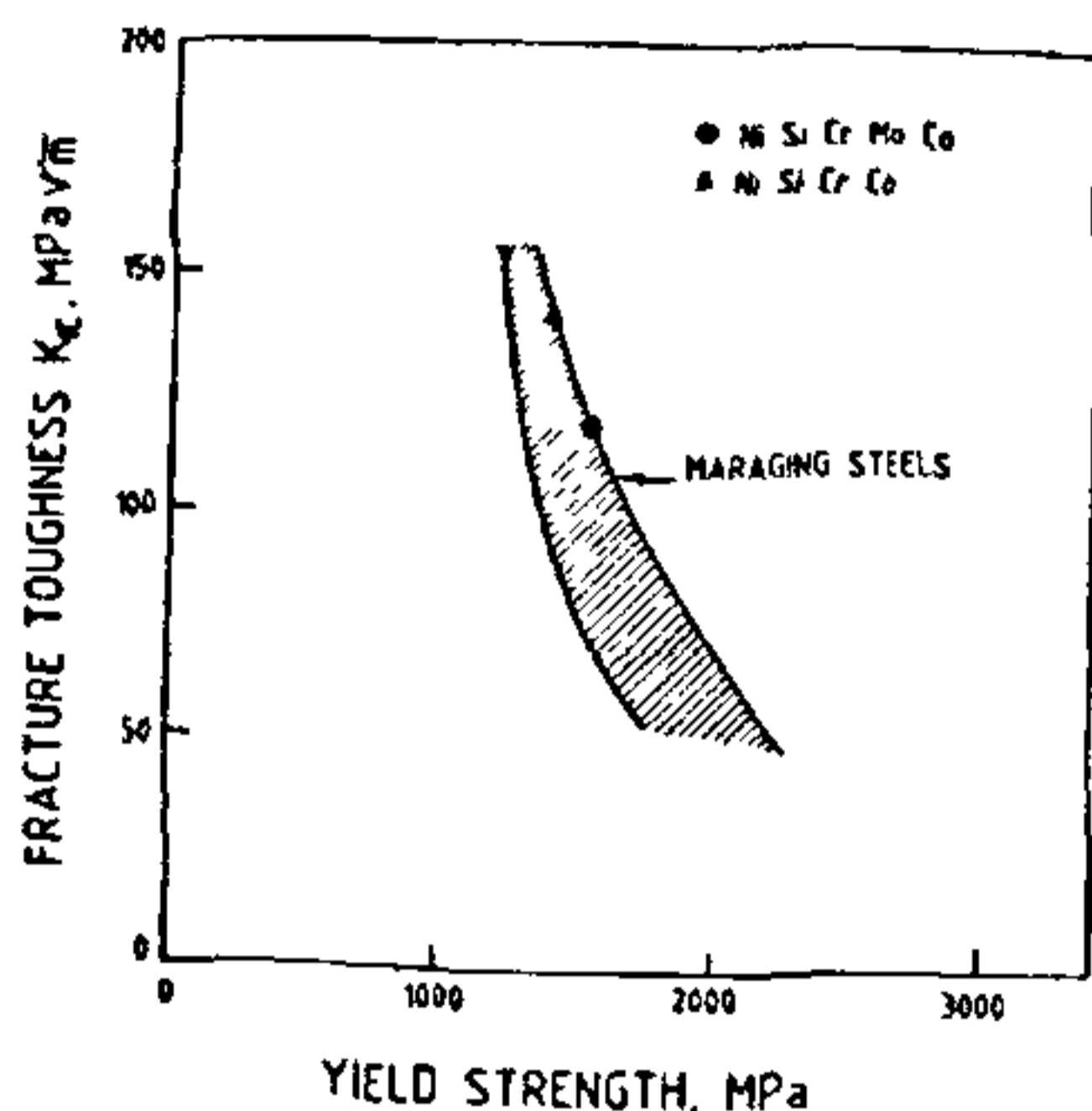


Figure 15. K_{IC} versus yield strength for high-strength steels.

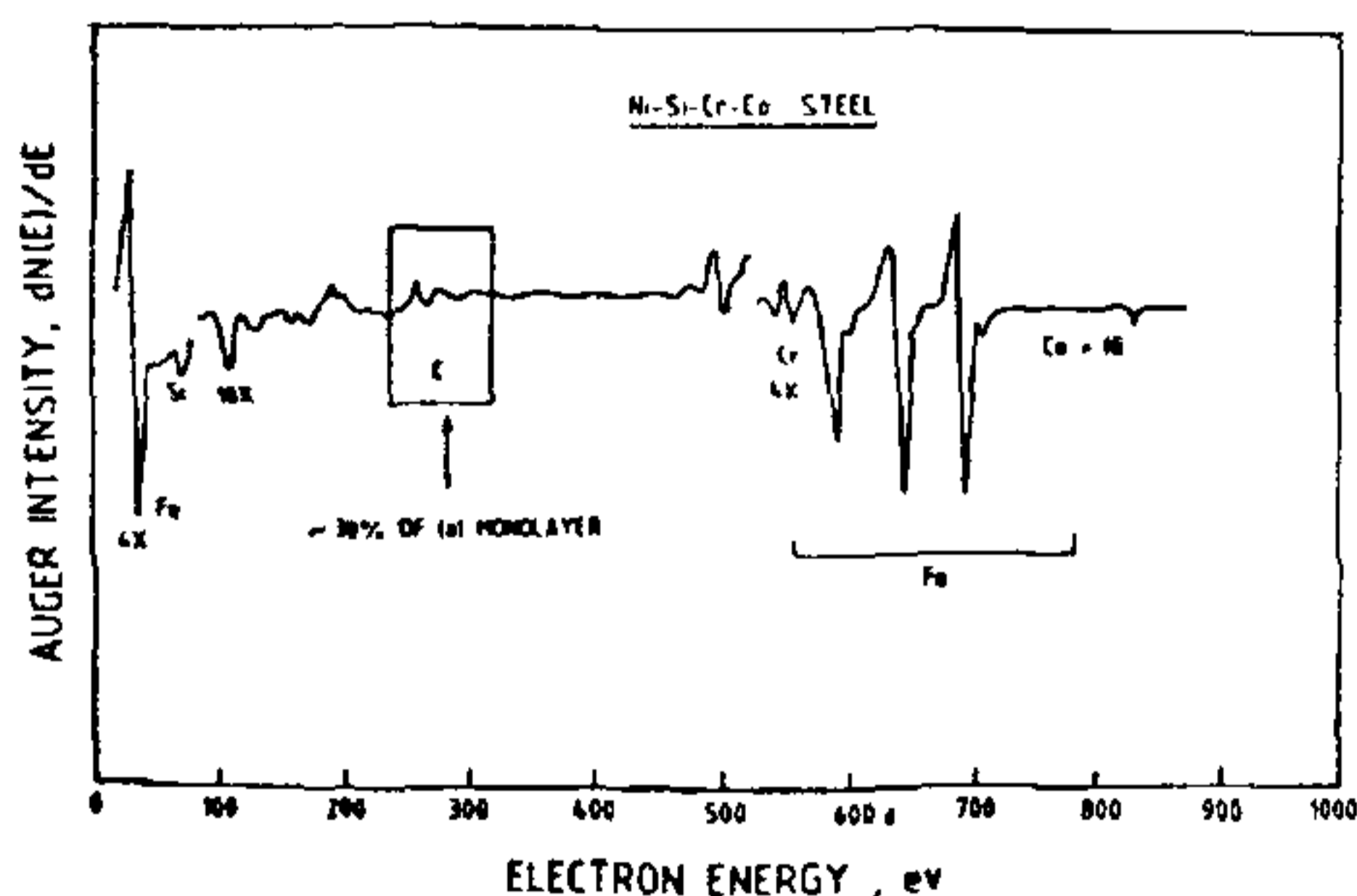


Figure 16. AES of NiSiCrMoCo steel showing grain boundary carbon.

The steel in the spheroidized condition can easily be rough-machined or formed before finally subjecting it to the hardening + tempering treatment. The steel in the softened condition has a hardness of HB230. The cupping test showed good formability. Preliminary studies have revealed that the weldability of the steel is quite satisfactory.

With strength-toughness combination comparable to the maraging steel, the NiSiCrMoCo steel, at nearly 20% of the cost, can be an attractive cheaper substitute to maraging steel in several applications.

Cubic zirconia for artificial diamonds—substantial benefit to domestic economy

In conclusion of this lecture, I wish to consider the case of cubic zirconia¹⁶, a ceramic alloy of ZrO_2 and Y_2O_3 , in the context of our growing diamond industry. (India covers nearly 50% of the world market employing over 700,000 skilled artisans.) Finished natural diamonds are a major export earning (> Rs 5000 crores annually) product of our country. However, about eighty per cent of the foreign exchange earning is offset by the need to import diamond roughs. Our major diamond mining as of today is only in one location in the state of Madhya Pradesh. The enterprising gem industrialists have in recent years taken up production of artificial diamonds (sometimes called American diamonds) and marketing jewellery using these new materials. The success is noteworthy. Zirconia and yttria needed for the artificial diamonds are imported. There is considerable room for upgradation of the various operations involved in the making of the cubic zirconia crystals and their subsequent handling.

India is richly endowed in regard to zircon, the mineral resource from which zirconia is extracted. Owing to Professor Brahm Prakash and his pioneering efforts, India possesses world-class capability in the Department of Atomic Energy in the area of extraction of nuclear-grade (hafnium-free) zirconium as part of the programme of zircaloy development for fuel-cladding applications. This capability can easily be deployed for production of gem-grade zirconia (see Table 5 for a comparison of nuclear and gem-grade zirconia) in

Table 5. A comparison of nuclear and gem-grade zirconium oxide

Impurity	Maximum allowed, ppm	
	Nuclear-grade*	Gem-grade
Iron	750	0.7
Hafnium	100	1960
Aluminium	50	100
Sodium	50	75
Titanium	50	420
SO ₃	500	700
Silicon	20	230

*Nuclear-grade specifies in addition the maximum levels for Ba, Ca, Co, Cr, Cu, Mg, Mn, Mo, Ni, Pb and V

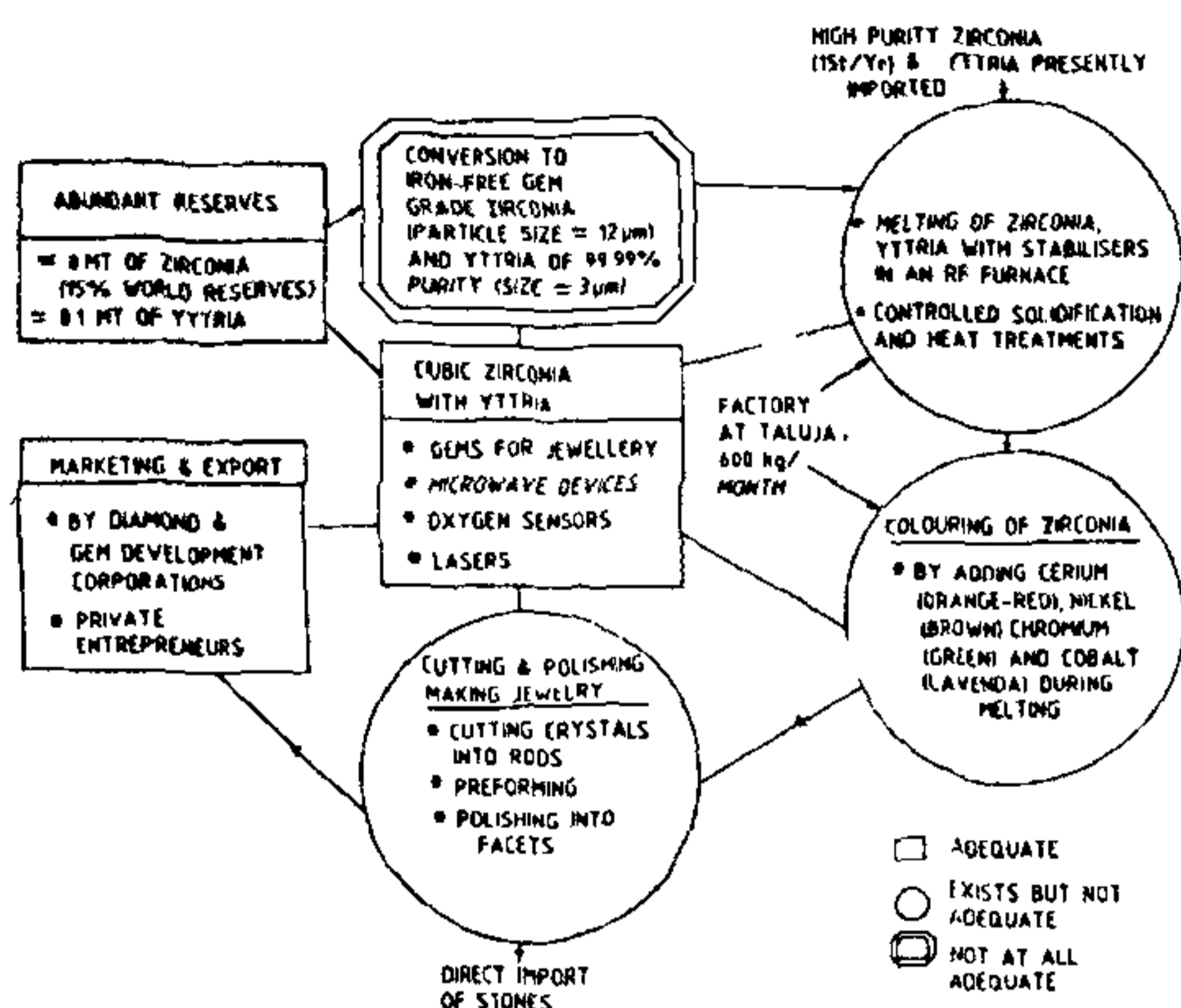


Figure 17. Indigenous situation in regard to cubic zirconia for the gem industry.

tonnage quantities. Indian Rare Earths (a public sector undertaking in the Department of Atomic Energy) are also in a position to make high-purity (better than 99.9%) yttria required for making transparent cubic zirconia crystals. The scenario with regard to cubic zirconia for the gem industry is depicted in Figure 17.

The important thing to note is that, unlike in the case of natural diamonds, we do not have to incur expenditure in foreign exchange for import of the raw material for making artificial diamonds. Indigenous production in tonnage quantities of gem-grade zirconia and yttria for the artificial diamond industry will be a major foreign exchange saving to the extent of several crores of rupees. DAE are entirely capable of making this possible. We can also utilize our materials science capability to upgrade downstream operations, e.g. improved solidification technology in the making of the crystals, heat treatment, gem identification and characterization, modernization of machines for crystal cutting and polishing and computer aided gem design. This industry deserves the fullest support of the materials science community not only because of the enterprise that has

been amply displayed but also that it provides employment to several hundred thousand people who are skilled but unfortunately are not well-to-do. Here is one product in the making of which the materials engineer does not have to bother about the tasks that pertain to component making, integration with a system or even marketing. Our jewellery people have taken care of these aspects. We need just to concentrate on the materials aspect. There is an urgent need to take rapid strides in this respect which will be an excellent tribute to late Professor Brahm Prakash who started it all.

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