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# Economic Considerations Relevant to the Development of New Materials

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The implications of some aspects of current developments in the quantitative evaluation of R & D are explored with particular reference to applied materials research. The return on materials R & D can only be determined by reference to the specific uses for which the research is intended and the apparent worthwhileness of a given programme will depend entirely on the precise role of the evaluating group in the subsequent exploitation of the research and their attitudes to risk. A subjective examination of a wide range of new materials developments suggests that lower material costs are rarely a significant factor in exploitation. The main incentives lie in reduced processing and assembly costs and miscellaneous benefits to the ultimate user. The treatment of uncertainty and risk and setting value to multiple research approaches are discussed.

## 1. Introduction

A considerable proportion of total national R & D activity is concentrated in the "materials" field with individual studies ranging from synthesis or property measurement solely aimed at increasing knowledge, to trouble-shooting programmes aimed at solving immediate practical problems. Since materials have no intrinsic value other than that derived from the benefits which can result from their use the justification for R & D on them can only be related to this prospective use.

In the past, generalised unquantified statements about the aims and potential benefits from R & D have frequently served as adequate justification for its initiation. Thus the author's own studies on the kinetics of catalysed dimerisation [1, 2] were, in his view, at least, justified when undertaken by the claim that increased knowledge of the mechanism of such reactions could lead ultimately to "improvements" in the manufacture and use of polymeric materials. Such generalised claims would still be argued by many to be adequate justification in the basic research field. Greenberg [3] has claimed that the ideology of basic research has held that all unanswered questions are of equal importance; others would argue that no justification is needed for seeking new knowledge, that it should be regarded as an overhead on the remainder of applied science and technology [4] or that it should be judged on the expectation that it will add new dimensions to the environment [5]. All these views have some validity for basic science [6] and may have sufficed in the past in some applied research laboratories where non-technical management has been unable to question critically the merits of research proposals.

Attention in the recent past has been increasingly directed towards quantitative justification of research and development programmes both in the basic [7, 8] and the applied research fields [9-12] and several case studies are available from the public sector [13-17]. Many of the larger industrial research-based companies have also been using similar methods of rational analysis as a guide to levels of R & D investment but their studies are not, in general, published.

The following paragraphs explore the value to be derived from some aspects of materials research and the influence of the criteria and analytical framework adopted on this value.

*There are few identifiable studies on materials cost-effectiveness in the literature; they are either regarded as "confidential" information and jealously guarded by their sponsors, or as unsuitable topics for publication in learned journals, or they may appear as small paragraphs in the "trade" magazines and pass unindexed and unabstracted into obscurity.* For this reason many of the examples cited here are based on the author's own past experience. Similar difficulties in tracing factual information face the technological forecaster searching for reliable data on dated past performance characteristics [18].

## 2. The Path to Exploitation

Since a material only has value in relation to the use that will be made of it, no evaluation of the benefits of materials R & D can be an abstract exercise divorced from application; it must be specifically related to the framework within which the material is to be used or exploited. Successful materials R & D will lead to a chain of manufacture, incorporation into a more complex product, which may involve several steps and manufacturers, and finally to use (fig. 1). For a material to be accepted each

Materials R & D → Materials Manufacture → Incorporation into product → User of product

*Figure 1* Materials exploitation chain.

individual in the chain needs to be convinced that he will derive benefit from its use and each will have different criteria, some of which may be mutually contradictory [15]. For example a manufacturer may be interested in increased sales of a consumer durable and hence favour "planned obsolescence" whilst the user might derive greater benefit from longer life products. In the free competitive market of classical economic theory with full information on costs and useful life available to the user his desires would be the deciding factor, but such a situation rarely exists in practice.

In the simplified model of exploitation presented in fig. 1 the decision to use, or not use, a new material will rest in general with the designers of the saleable product and some of the factors affecting their choice may be discussed by reference to specific examples.

## 3. Factors Affecting Choice

The designer will generally have to consider materials not only from the point of view of their cost but also the costs of incorporating them into his product and their effect on the performance of that product [12]. Material, fabrication route and design are intimately associated, as techniques such as value analysis seek to stress [19], and a complete rethinking of design may be needed to realise the full benefits from a new material [12, 23, 29, 40]. For example, the material cost of resin/porous glass standard diffusion leaks for gas dosing or leak detector calibration [2] may be higher than that of an all-metal membrane system [21] but the cost differential in making the leaks will greatly favour the former. The lower temperature of operation and other operating benefits give further cost savings to the user of the polymer leak.

For simple products the criterion of selection may itself be simple. When choosing a material for use in process equipment the factors to be considered are environment, physical properties and cost [22]. If the environment is fixed then the necessary physical properties are defined and comparison could be made on a straight cost basis in the simplest cases. Fibre-reinforced materials have been considered on this simple property basis by Scanlan [23] with the criteria of stiffness, tensile strength and shear strength. Scanlan concluded that plastics reinforced with high modulus fibres could be of little economic value in meeting needs for flexural stiffness but omitted from this simplification asbestos fibre bundles, which have specific moduli three times that of steel (table I) and other cheap stiff fibres such as jute [30, 31] which can also produce marked improvements in stiffness at lower cost when compared, for example, with glass fibre.

However, even when stiffness is the predominant requirement, cost per unit stiffness may not be an appropriate economic criterion for comparing composites with conventional materials. In the aerospace field weight savings have value because they permit increases in payload, amongst other benefits, and this has to enter the equation. Simple calculation shows that 0.4 lb of 70 wt % carbon fibre/resin composite can replace 1 lb of glass fibre reinforced resin or a similar weight of aluminium. If weight saving is valued at £10 per lb or more [29] then the carbon fibre-reinforced product should be economic at £10 per lb or more. For this reason the aerospace industry is indeed using increasing quantities of high strength, high modulus materials of low density, despite their apparently high costs [29, 32, 33]. This illustrates the need to define the field of application closely before generalising on the economic viability of a new material.

In practice the criteria on which materials need to be compared may be a complex combination of many factors. Structural plastics in chemical plant need not only have good corrosion resistance but need to have suitable temperature stability, creep characteristics, per-

TABLE I Comparative strengths and moduli

| Material | Ref. | UTS $10^6$ lb in.$^{-2}$ $\sigma$ | Modulus $10^6$ lb in.$^{-2}$ $E$ | Density g cm$^{-3}$ $\rho$ | Specific strength $10^6$ $\sigma/\rho$ | Specific modulus $10^6$ $E/\rho$ |
|---|---|---|---|---|---|---|
| Asbestos | | | | | | |
| (crocidolite) | [24] | 0.85 | 27 | 2.5 | 0.34 | 11 |
| (chrysolite) | [25] | 0.4 | 23 | 2.55 | | |
| Glass Fibre | | | | | | |
| (E) | [24] | 0.25 | 10.5 | 2.5 | 0.1 | 4.2 |
| (HTS Glass) | [26] | 0.4 | 12.5 | 2.5 | 0.16 | 5.0 |
| Carbon fibre | | | | | | |
| RAE I | [27] | 0.30 | 60 | 2.0 | 0.15 | 30 |
| II | [27] | 0.43 | 33 | 1.74 | 0.25 | 19 |
| Steel | [24] | 0.6 | 30 | 7.8 | 0.08 | 3.9 |
| Aluminium | [24] | 0.07 | 10.5 | 2.7 | 0.027 | 3.7 |
| Beryllium | [28] | 0.2 | 45 | 1.8 | 0.11 | 24 |
| Titanium alloy | [29] | 0.15 | 18 | 4.3 | 0.035 | 4.2 |

lb in.$^{-2}$ = 70.3 g cm$^{-2}$

haps fire resistance. For products for sale appearance and feel, scratch resistance etc. may assume importance. Alexander [34] has summarised this by suggesting that the main criteria for engineering materials are cost on the job, strength/rigidity, space-filling and surface behaviour and durability in service. Where multiple criteria apply the decision on a material may require a trade-off between varying desirable and undesirable properties: for example a more rigid thermoplastic may be more difficult to form. One method of doing this is by use of simple ranking procedures [35-38] which attempt to reduce the known facts about an innovation to a single parameter by allotting to each item a merit factor $x$ on a predetermined scale and combining these merit factors arithmetically or geometrically using weighting factors $X$ to allow for the relative importance of the different factors. A hypothetical example which could relate to a choice of material for a machine component is shown in table II. The relative merits of the different materials are then taken to be:

$$\Sigma X x_1\,,\ \Sigma X x_2 \text{ etc.}$$

The problem with all such simplifying systems is that the rankings are only valid for a single application and even then only reflect the subjective biases of the sponsor of the system and may be unacceptable to others. There is a further serious risk that the true significance of specific factors may be hidden rather than highlighted in the evaluation [39]. For this reason the treatment given below is preferred by the author.

## 4. Generalised Treatment

Wherever possible the use of cost/benefit

TABLE II The subjective ranking method

| Parameter \ Material | Parameter weighting $X$ | Mat. 1 $x_1$ | Weighted value $Xx_1$ | Mat. 2 $x_2$ | Weighted value $Xx_2$ | Mat. 3 etc. |
|---|---|---|---|---|---|---|
| Material cost | A | $a_1$ | $Aa_1$ | $a_2$ | $Aa_2$ | |
| Fabrication cost | B | $b_1$ | $Bb_1$ | $b_2$ | $Bb_2$ | |
| Ease of maintenance | C | $c_1$ | $Cc_1$ | $c_2$ | $Cc_2$ | |
| Durability | D | $d_1$ | $Dd_1$ | $d_2$ | $Dd_2$ | |
| Heat stability | E | $e_1$ | $Ee_1$ | $e_2$ | $Ee_2$ | |
| Appearance | F | $f_1$ | $Ff_1$ | $f_2$ | $Ff_2$ | |
| Noise | G | $g_1$ | $Gg_1$ | $g_2$ | $Gg_2$ | |
| Reliability | H | $h_1$ | $Hh_1$ | $h_2$ | $Hh_2$ | |
| Summed ranking | | | $\sum Xx_1$ | | $\sum Xx_2$ | |

$X$ are subjective weightings of the relative importance of the parameters.
$x$ values are rankings on some arbitrary scale 0 to $n$ which need not be identically quantised for the different parameters.

methods for evaluation of the merits of a proposed new material are to be preferred. As a practical illustration, consider two alternative forms of a product, one using one material for some component part and the second using an alternative material. If the cost of material needed to produce the component is $c_m$ (including allowance for wastage and, if applicable, scrap recovery), the cost of fabrication $c_f$ and the cost of finishing (e.g. painting, assembly etc.) $c_l$, each for a single unit, then the cost differential to the manufacturer of using one material rather than the other will be

$$\Delta(c_m + c_f + c_l) = c_2 - c_1 = \Delta c\,.$$

(All the $c$ terms are assumed to incorporate their share of overheads.) The annual benefit to the manufacturer in a fixed market where the two forms of the product have a selling price differential $(p_2 - p_1) = \Delta p$ will be $(\Delta p - \Delta c)m$ where $m$ is the number of units sold per annum.

The user of the product may incur differential running costs $\Delta k_r$ per annum (for power and lubrication, say), differential maintenance costs $\Delta k_m$ per annum (painting, cleaning etc.) and the life of the product $l$ may change. From the user's standpoint the discounted present worth cost of buying and using the one product as opposed to the other will be $\Delta K$ where

$$\Delta K = \sum_{t=1}^{T}(\Delta k_r + \Delta k_m)(1+d)^{1-t} + \Delta p + p_2 \sum_{z=0}^{n}(1+d)^{-zl'} - p_1 \sum_{z=0}^{n}(1+d)^{-zl}\,.$$

$d$ is the discount rate regarded as appropriate by the user, normally equated with the opportunity cost of capital to him, and $n$ the number of product life cycles needed to cover the period $T$ years of interest to the user. $n$ will be a function both of obsolescence and of the discount rate $d$; a high discount rate rapidly diminishes the value to be attached to future expenditure in relation to current outlay; $l$ and $l'$ are the lives of the product with the old and new material respectively.

The benefits to the user can take a wide variety of forms depending on the nature of the product. His own capacity to make a profit may increase through increased productivity, lower costs at similar throughput etc.; also he may avoid duplication of equipment through improved reliability; he may benefit by reduction in the number of accidents, reduced noise etc. Attempts can be made to set values to such economic and social gains (see, for example [6, 16, 17, 39]) but for the purposes of the present paper it will suffice to value the benefit to the user at the extra sum he would be prepared to pay for the new version of the product relative to the old, $\Delta B$. The user's estimate of his net benefit will then be $\Delta B - \Delta p$, where $\Delta p$ is the actual price differential, each time he buys the product.

The present worth costs and benefits to producer and a single user are summarised in table III and apply for a fixed need fulfilled by one of two versions of a defined product. The "national" costs and benefits are determined by adding the user and producer benefits and costs and neglecting transfer payments (i.e. the profit to the producer). The definition of $\Delta B$ in the preceding paragraph leaves a small price term in the national benefit equation (table III) which would disappear if the life of both product versions were the same ($l = l'$).

**TABLE III** Present worth differential costs and net benefits*

| | Cost | Benefit |
|---|---|---|
| Producer | $c_2\Sigma(1+d)^{-zl'} - c_1\Sigma(1+d)^{-zl}$ | $(p_2 - c_2)\sum_0^n (1+d)^{-zl'} - (p_1 - c_1)\sum_0^n (1+d)^{-zl}$ |
| User | $\sum_{t=1}^{T}(\triangle k)(1+d)^{1-t} + p_2\sum_{z=0}^{n}(1+d)^{-zl'} - p_1\sum_{z=0}^{n}(1+d)^{-zl}$ | $(\triangle B - \triangle p)\sum_0^n (1+d)^{-zl'}$ |
| National | $\sum_{t=1}^{T}\triangle k(1+d)^{1-t} + c_2\sum_{z=0}^{n}(1+d)^{-zl'} - c_1\sum_{z=0}^{n}(1+d)^{-zl}$ | $\triangle B\sum_0^n (1+d)^{-zl'} - c_2\sum_0^n (1+d)^{-zl'} + c_1\sum_0^n (1+d)^{-zl} + p_1\left\{\sum_0^n (1+d)^{-zl'} - \sum_0^n (1+d)^{-zl}\right\}$ |

*For each users requirements to time $T$

It will be seen that the costs and benefits to the producer and user are quite different and differ from the overall national benefit. The value of using a new or improved material will appear different to the producer, to the user and from the overall national standpoint, hence the justification for developing new materials for future use will appear different to different people in the exploitation chain.

It is quite feasible for the producer to make a cheaper longer-lived product which, in a fixed market, will decrease his present worth profit and act contrary to his own short term interests, i.e.

$$(p_2 - c_2)\ \Sigma(1 + d)^{-t'} < (p_1 - c_1)\ \Sigma(1 + d)^{-t}.$$

He may still develop the product as a means of increasing his market share or guarding against a competitor producing it. Thus there are additional benefits to the manufacturer related to his views on the actions of his competitors.

If the original price $p_1$ was only marginally above the costs $c_1$ but the new costs $c_2$ are well below the price the producer sets, $p_2$, calculated to increase his market share, then his profit will increase in relation to the hatched areas in fig. 2.

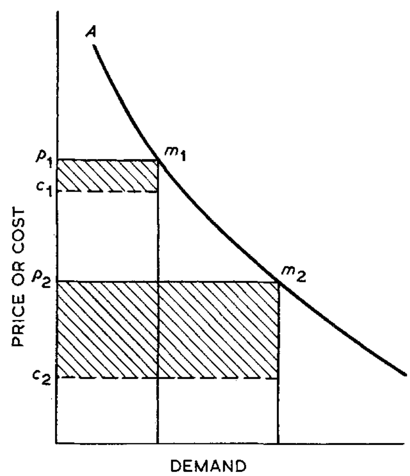


*Figure 2* Demand curve.

To set a value on such a benefit demands knowledge of the producer's policy and competitor's abilities to respond. The national benefit for constant market size is independent of the profit levels since profits are transfer payments in the economic sense. In fig. 3, $A$ is the demand curve as a function of price and if the market is fixed at $m_1$ then the rectangular shaded area is the benefit to the user at zero profit level. If the market expands to $m_2$ then the user benefit is the whole shaded area. However, prices are higher than costs in practice so that the market size and the overall benefits will both decrease as the manufacturer increases his profit levels [12] for a demand curve of the type in fig. 3.

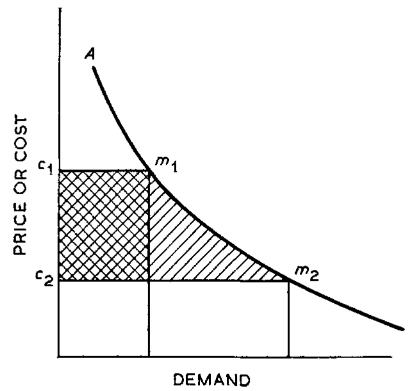


*Figure 3* Effect of cost savings on benefit level.

Whilst all benefits to the user are embraced by the definition of $\Delta B$, the nation, like the producer, can derive additional benefits from such factors as improvements in the trade balance or increased public welfare which do not enter into the calculations of industry, so that table III should be regarded as illustrative rather than definitive.

One may conclude that the apparent benefits from the use of new materials and hence justification for applied R & D on materials will differ enormously with the viewpoint of the sponsor of the research and that normal market forces may not be adequate to guarantee maximum benefit to the nation when the prime beneficiary and the risk-taking organisation are not under the control of a single decision-taker [12].

## 5. Nature of the Benefits from Materials R & D

Table IV summarises the areas in which benefits from the use of new materials may arise for a wide spectrum of end-products. The benefits from market share effects etc. are excluded. It will be seen, even from this short list, that lower material costs are rarely the incentive behind a development; indeed material costs are likely to be significantly higher in many instances. The chief manufacturing benefits arise from pro-

**TABLE IV** Nature of the benefits from materials R & D

| Item | Derived from reference | Manufacturer | | | User | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Lower material cost | Production costs savings | Finishing and assembly savings | Reduced maintenance costs | Reduced operating costs | Longer life | Other economic user benefits | Non-economic user benefits (greater safety, better appearance etc. less noise |
| Plastic rainwater pipes | — | + | √ | √ | √ | | ? | | |
| PVC coated steel | [41] | + | | √ | √ | | √ | | ? |
| Reinforced materials (aerospace) | [30, 42] | + | + | + | | | | √ | |
| Plastic engineering components | [43, 44] | + | √ | √ | ? | | √ | √ | √ |
| Plastics for chemical plant | [22] | | √ | √ | √ | | √ | | |
| Radiation cured paints | [45] | ? | √ | | | | √ | | ? |
| Plastic diffusion leaks | [20] | | √ | | | √ | | | |
| Material for $T(n, 2n)$ studies | [46] | | | | √ | | | | √ |
| Fused salt reactor fuels | [47] | ? | √ | √ | ? | | √ | √ | √ |
| Cryogenic materials for power transmission | [48] | + | + | | | √ | | | √ |
| Semiconductor materials | — | + | √ | √ | | √ | √ | | |
| Pollution free fuels | [49] | + | | | ? | √ | | | √ |
| Directionally cast alloys and special alloys | [33] | + | + | | | √ | | √ | |
| Neutron source targets | [50] | ? | | | | | √ | √ | |

√ indicates claimed benefit
? possible benefit in some instances
+ indicates probable penalty

duction and finishing savings, whilst the user can benefit equally via a number of routes.

## 6. Other Types of Materials Research

Not all materials research is aimed at the development of new materials; some may be aimed at improving the properties of existing materials by improved processing techniques, or avoiding losses in time and money by studying material compatibility or other properties on the laboratory scale prior to adopting materials for specific uses. Again, from personal experience, the former might be typified by studies on the removal of hydrogen from beryllium aimed at making it more ductile [51] whilst the latter might be exemplified by exploring the corrosion of container materials [47] or the radiolytic behaviour of greases and gasket materials for tritium-handling systems [52, 53]. The benefits from such researches arise from the savings made (or avoided losses) or the wider utilisation of the improved materials, and whilst the benefits may be different in kind they can be treated in much the same way as in the preceding section, except that the user and prime beneficiary of such research will often be the sponsoring organisation itself.

## 7. Delays to Attainment of Benefits

The benefits achievable from materials R & D will not arise for some time after its initiation and this delay or lag is taken into account by the discounting of both costs and benefits to convert all sums to present worth, as in section 4. Whilst the delays in deriving benefit from trouble-shooting or trouble-avoidance studies of the type described in section 6 may be short, the lags in introduction of new materials to commercial use even after invention are often lengthy. Penicillin took 15 years, Krilium soil conditioner $12\frac{1}{2}$ years, semiconductor transistors 15 to 16 years, nylon 13 years and general developments in the chemical industry 4 to 6 years [18, 54, 55]. Lags of this length are sufficient to reduce significantly the present value of benefits in relation to R & D costs and over-optimism about chances of rapid exploitation needs to be guarded against.

## 8. Uncertainty

Research necessarily carries a risk of failure: partial failure resulting in products that only produce marginal improvements over existing ones, or complete failure due to unforeseen natural barriers. Even technically successful projects may fail to reap any benefit because commercial exploitation fails or a competitor gets into the market first. Any economic justification of applied research must take this uncertainty into account and this is usually done by attaching subjective probabilities of success to the various stages of research, development and exploitation [6, 12]. Where comparisons are made between project proposals it must be remembered that both the benefits and costs will be affected differently by uncertainty and the expected benefits, defined as estimated benefit if successful times probability of success, should be compared with the expected costs. It is well known that in the chemical/pharmaceutical industry only a relatively small proportion ($\sim 1\%$) of projects undertaken result in marketable products and the use of probabilistic estimates is intended to reduce the risk of over-investment in research.

The use of subjective probabilities for essentially non-repetitive events is still a matter for debate and an alternative criterion called "credibility" has been proposed by Allen [56, 57] as more appropriate for the high uncertainty situations applying in R & D. This criterion itself has a number of shortcomings and has not proved useful in practice [58, 59].

## 9. Risk

If the costs and benefits associated with development of a new material have been computed and due allowance made for uncertainty, the outcome in the ideal case would be presented as a probability distribution of net present worth benefits (benefits less costs) of the type shown in fig. 4 [16]. The sponsor has then to weigh the risks of loss against the chances of benefit for this project and against the other options open to him, including doing nothing and non-R & D options [16]. He may choose to apply the classical concepts of decision theory [10, 60] or to make a

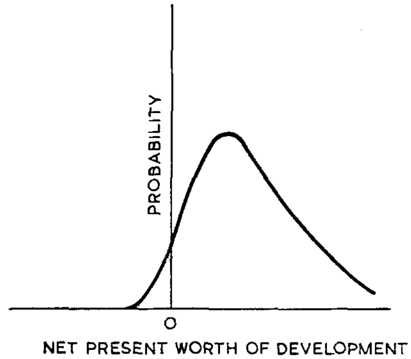


*Figure 4* Distribution of outcomes.

completely subjective judgement based on the potential penalties following loss outcomes, the cash flow from the project etc. A high expected net benefit will not be an automatic passport to acceptance in all environments.

## 10. Multiple Approaches

Where materials problems are sufficiently serious to demand urgent solutions or where the potential rewards are high but the chances of achieving them low, it may pay to pursue several R & D routes in parallel. The criterion for so doing is still one of comparison of the extra expected benefit from the additional lines of approach with their expected costs [39, 61] and the relation borne by these to the returns on alternative forms of investment of resources.

## 11. Fundamental Research

Fundamental research with no immediately apparent application cannot be treated in the same way as applied work. Some will have economic value [9] as precursor to new inventions; it is a useful (though not necessarily optimal) way of training scientists in research techniques which can later be exploited in the applied field [7]. In a corporation the research may be justified as providing the basis for avoidance of, or rapidly overcoming, technical problems. It can also be argued that basic science should be supported for the aesthetic satisfaction it provides. No one expects research in the arts or archaeology to produce an economic return, it is sufficient that it increases man's knowledge and appreciation of his past and his environment [6].

## 12. Conclusions

This paper has surveyed some aspects and implications of current practices in the quantitative justification of R & D and more especially applied materials research. The quantifiable value of materials R & D is entirely related to the use to which the materials can be put or the mis-uses that can be avoided and will look different depending on the viewpoint, role and risk attitudes of the assessor, so that unqualified generalisations on the value of a materials development are meaningless and no guide to the likelihood of their ultimate exploitation.

Across a wide spectrum of material developments known to the author, materials cost reductions rarely appear to be the main incentive to exploitation. Reduced processing, assembly and finishing costs are of greater significance to the manufacturer employing the material. For this reason, material appraisal can only be done using a systems approach and exploring the whole cost involved in material use and the whole benefit accruing.

Having appraised the benefits of successful exploitation, the probability of reaching this state, the delays and the risks involved need to be considered if an estimate of the true economic return on the R & D is to be obtained. Fundamental research aimed solely at gathering knowledge clearly cannot be treated in the same way. Other approaches would have to be adopted if the level of such work is to be related to its value to the nation and universally applicable techniques for doing this are not yet available.

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