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Discovery in the Context of Application: Technological and Organizational Issues in the Case of Hypersonic Aircraft

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DISCOVERY IN THE CONTEXT OF APPLICATION: TECHNOLOGICAL AND ORGANIZATIONAL ISSUES IN THE CASE OF HYPERSONIC AIRCRAFT

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Some research programs, although often oriented towards scientific questions that are well beyond the frontiers of knowledge, include a phase of production dealing with technical tools, research instruments and data, that may be very "rich in innovations". This phase of acquisition of certain technical, and in some sense applied knowledge may precede basic and applied research. We will call the innovation process embodied in this particular phase "discovery in the context of application" [1]. A good example of this is the search for a viable hypersonic aircraft now being undertaken by many nations. The purpose of this paper is to describe such a research program, to show how concretely a process of discovery by application is organized, and to explore some of the specific economic and organizational issues raised by this particular process [2]. The US National Aerospace Plane program (NASP) will be used as an example, and we will concentrate on the organizational form of the program. We will deal with the problem of finding a balance between two organizational priorities: on the one hand, **the necessity to design an organizational system involving multiple decentralized projects**, in order to facilitate experiments in different directions and to decrease the risk of missing the best design; on the other hand, **the necessity of "clubbing together" and forming a single entity**, in order to produce the technologies required to do the research; the so-called "instrumentalities and infratechnologies", which possess a strong public good aspect.

Economic analysis has enabled us to establish a certain number of rigorous propositions, in the area of resource allocation in basic research (Arrow, 1962; Nelson, 1959; Dasgupta and David, 1986), as well as with respect to the economic returns of this activity (Hirshleifer, 1971; David, Mowery and Steinmueller, 1992; Pavitt, 1992) or even with respect to the integration of the research activity into the innovation process (Freeman, 1982; Mowery and Rosenberg, 1989; Foray and Mowery, 1990; Kline and Rosenberg, 1986; Aoki, 1984; Rosenberg, 1990). Nonetheless, the analytical framework so far developed does not yet allow us to study the organizational design for research programs involving processes of discovery in the context of application [3].

1) - NASP Organization: the diversity-standardization dilemma

The purpose of the NASP program is to develop and demonstrate hypersonic and trans-atmospheric SSTO (single-stage-to-orbit) technologies that will support future national security and commercial applications and provide economies in space-launch costs. The NASP program is currently in Phase II of a three-phase research, development, test, and evaluation (RDT&E) program. Phase II is a multiyear technology demonstration effort with the goal of showing that the NASP technologies - including air-breathing propulsion, advanced aerodynamics, materials and structures, fuel systems, avionics, and computational fluid dynamics (CFD) - can achieve maturity adequate to support a Phase III effort that includes development, fabrication, and flight testing of an experimental flight vehicle called X-30 (Augenstein and Harris, 1993).

1-1) The technological target

Scientists have long contemplated the construction of an aircraft capable of attaining satellite speeds, having take- off like a regular airplane, and returning to earth once its mission is accomplished. Space station re-supply would be much cheaper than with systems requiring launching of rockets that cannot be recovered or reused. An aerospace transport vessel, in contrast, could be flown repeatedly. The same project should also eventually lead, with certain adjustements, to the production of a hypersonic transport vessel capable of travelling between two spots on the earth at Mach 8. According to the IIASA' scenario of future air transport (Nakinenovic, 1987 and 1988, Gruebler, 1990, Gruebler, Nakinenovic and Schäfer, 1993), the performance of transport aircraft is estimated to saturate at about 1.2 million passenger-kilometers per hour which is reachable with current aircraft technology and some improvements. However, thereafter aircraft would be required to exceed these levels implying either large subsonic liners (capable of transporting a few thousand passengers) or hypersonic transport with a more modest capacity of a few hundred passengers. Using the quantitative analysis of the historical performance improvement of civil aircraft engine, Gruebler, Nakinenovic and Schäfer (1993) argued that the first alternative appears unlikely since it would require very powerful engines and their rating appears to be saturating in unison with aircraft performance. The second alternative appears more plausible: a new engine could power a hypersonic aircraft of the next century with a performance of a few thousand passenger-kilometers per hour.

The ultimate success of this project depends, therefore, on solving the problem of propulsion generated by aerobic motors [4]. Aerobic propulsion technology has significant advantages, notably:

- An improvement in mass ratio of the order of 3 to 5 in comparison with the mass placed into orbit by anaerobic propulsion. This is because aerobic motors utilize air as a combustive agent, obviating the need for the oxygen mass loaded for combustion in rockets.
- The possibility of reutilization thus eliminating costly replacement (or in the best case - as in the case of the shuttle - re-configuring and re-qualifying after each flight).

- The ability to take off and land horizontally as well as the elimination of auxiliary solid-fuel rockets and other types of launch support.
- Maintenance is closer to airplane maintenance than rocket maintenance.

However, at the sought-after flight speeds (beyond Mach 6) supersonic combustion becomes necessary [5], requiring the difficult merger of the aerobic principle and hypersonic speeds in the perfectioning of a supersonic ramjet (otherwise called a "scramjet"). This demands a change in the technological paradigm.

Five countries have launched projects in this direction: the USA (NASP), France (PREPHA), the UK (HOTOL, currently in abeyance), Germany (Sänger), and Japan (HOPE). The former USSR also possesses significant scientific and technological capabilities in this areas, but current information on those programs is lacking. Note that the French and Russians are now negotiating an expansion in their joint efforts into more hypersonic technology areas.

The weight of technological inheritance requires that we distinguish among countries according to the history of their research efforts in aerobic propulsion. On the one side, the USA, France and the UK have pursued military research programs on aerobic propulsion for missiles at supersonic speeds. These countries therefore have infratechnologies emerging from the old paradigm (the ramjet). Military research permitted the maintenance of a research direction abandoned by the civil sector in favor of rocket propulsion (Berton, 1991). On the other side, Germany and Japan do not have the scientific and technological bases of the preceding paradigm.

1-2) The NASP organization: a topic of debate

Cohen, Edelmann, and Noll (1991) described the NASP organization as being similar to the great Japanese government-industry collaborations. NASP was extracted from the American industrial-government fabric, a new entity which incorporated private and public expertise previously isolated and dispersed throughout the system.

The objective of this new entity was to share all technical results and to formulate a single design incorporating features of each firm's past work (Cohen, Edelman, and Noll, 1991, p.51) [6].

Also notable is the desire to rapidly render the new entity irreversible by producing specific codes and specific informational channels. Thus an electronic communication team was immediately created with the objective of developing networks within the contracting system [7]. This prioritization brings to mind Arrow's ideas (1974) that codes and information channels are forms of irreversible organizational capital. Thus, the rapid creation of codes and informational channels within the emerging entity, composed of subgroups of independent firms, imposes an irreversible character upon organizational investments.

A third organizational characteristic is noteworthy: the unprecedented level of integration of public laboratories in the research project. For the laboratories, this integration process (known as "mainlining") involves going beyond generic tasks to include research and experimentation instruments [8].

According to Cohen *et al.*, NASP's organizational form (classified as an "innovative team approach") has two drawbacks. First, the grouping together of all available forces into a single entity narrows the range of alternative paths of development that are explored and could also cartelize the industry. Second, the institutional concentration makes it difficult to stop the project if it fails. According to Cohen *et al.* "the innovative team approach makes the program more difficult to kill if NASP becomes nothing more than an expensive toy". In short, this organizational form not only increases the risk of missing the best design, it also raises the cost of a possible failure. This leads to reduced resource-allocation efficiency in the given research sector. Cohen *et al.* suggest that this organizational form, more a reflection of political pressure than of technical and economic optimization, increases the likelihood of failure.

What can we say in response to the above evaluation? The critique is, of course, relevant: a unified organizational form increases the risk of missing the best design. It also increases the cost of a possible failure regarding the selected evolutionary trajectory. Uncertainty about the performances and functionalities of a large number of possible "canditates" to be selected as the technological standard calls for incremental development, flexible management schedules, and the ability to explore many technical paths before commitment is made to a particular system design (Cohen, Edelman, and Noll, 1991, p.53).

NASP does not fulfill that set of necessary organizational conditions. Currently, there are also several reasons why the formation of a single entity would be advisable. One of the reason is associated with the necessary production of a collective research infrastructure (standards, infratechnologies, instrumentalities). The production of this infrastructure, which enables measurement, comparison, and collective experimentation, must occur despite great uncertainty as to the potential returns from projects based on the infrastructural knowledge generated. Here we find a justification for "clubbing together", i.e. the formation of a single entity grouping together all agents in a particular sector and the rapid creation of irreversible organizational capital, with strong participation from public agencies in the production of infratechnologies and instrumentalities [9]. There is no doubt that there is a rationale behind NASP's organization. This rationale resolves the organizational conflict stemming from the tension between diversity and standardization. NASP therefore attaches greater importance to the production of a collective research infrastructure than to the broad exploration of the technological and functional spectrum. This orientation manifests itself as a preference for a unified organizational form -- the innovative team approach -- as opposed to the management of multiple decentralized experimentation and exploration projects.

* * *

We try here to investigate the manner in which it is possible to find a balance between these two organizational priorities. After successively examining what would be the economic rationale for both organizational forms in the case of NASP, we will explore how to manage the tension between standardization and diversity in the organization of the program.

2 - Uncertainty about the technological infrastructure and the necessity for organizational standardization

The accomplishment of the program's mission necessarily implies **a change in the technological base** [10]. Such a radical change creates a situation of structural uncertainty [11] which in turn implies a need for knowledge acquisition on the very structure (data, methods, instruments) of the problems considered . This in turn directs the program toward the production of infratechnologies and research instruments. As a result, the appropriate organizational form should be subject to the requirements of collective production of infratechnologies and instrumentalities.

2-1) Presumptive anomaly as the engine of paradigmatic change

Applying Constant's (1973) idea of, "a presumptive anomaly" underlies paradigmatic change, which in this case arises from the scientific evidence that conventional aerobic propulsion systems cannot function at hypersonic speeds. The presumptive anomaly joins the functional anomaly as a factor of paradigmatic change. However, in contrast to the latter, the presumptive anomaly is deduced from science before a new paradigm has been formulated, so that scientific deduction is the sole reason for creating the new paradigm as it is the only guide. There is no functional failure; one presumes the existence of an anomaly, hence the term, presumptive anomaly.

Such a paradigmatic change implies discontinuities, scientific as well as technological. The two traditionnal supports for the elaboration of new technological concepts (scientific models and designs of preceding technological generations -- the supersonic "ramjet") cannot be used well here, and only permit certain highly limited indications.

In the following paragraphs, we show that, in the case of hypersonic technologies, the state-of-the-art does not yet permit the development of predictive models. Furthermore, old concepts (especially the "ramjet") only supply very limited indications and therefore do not compensate for the absence of predictive models.

2-2) The weakness of available scientific evidence

In the case of supersonic combustion (Mach 5-6), the first difficulty is that it is almost impossible to produce on-the-ground scientific data that is needed in order to validate the "scramjet" concept and predict its performance. Indeed, on-the-ground test capacities and experimental installations do not yet exist for vessels beyond Mach 8. There are no installations capable of reproducing the combination of speeds, pressures, and temperatures necessary to simulate hypersonic flight. Experiments on the ground are extremely short. For example, the hypersonic wind tests generally last less than a few seconds because of the great quantities of energy required. There is a clear lack of suitably sized installations needed for the experimental verification of propulsion and aerodynamics concepts beyond Mach 8 (US Space GAO, 1988). This weakness in experimental apparatus is partially overcome by mathematical simulation methods. Here, however, there are also immense difficulties. The resolution of supersonic combustion equations would require nearly unlimited calculation times. The simulations therefore comprise significant approximations. Another crucial problem is the absence of a predictive law for turbulence.

Finally, we must remember that simulations do not eliminate the need for real tests, which are still required in order to verify the results. Calculations may nonetheless minimize the quantity of experimental work necessary. They enable researchers, for example, to limit wind-tunnel tests to those precise areas where simulations are too difficult or do not provide sufficiently precise results.

In the final analysis, the current difficulty of ensuring synergy between calculations and real tests reveals that science is still far from being able to provide predictive models for innovation and analytical design. This weakness is not overcome by the existence of other sources of information, such as concepts inherited from preceding technological generations.

2-3) The weakness of lessons from old concepts

The paradigmatic change described above is reflected in the fact that the results obtained at the threshold of Mach 5 are no longer valid beyond Mach 5. Certain physical-chemical laws are even reversed once one passes from the supersonic domain to the hypersonic [12]. It is useful here to use the terminology established by David, Mowery, and Steinmueller (1992) to assess the potential of transferability of knowledge generated by a basic research program.

First, the "homotopic correspondences" [13] between the concepts developed at different levels of speed are weak. There is therefore a definite discontinuity between the supersonic and the hypersonic domains which precludes an evolution based on modest additional investments in installations and human resources.

Second, the "analogical links" between aerobic propulsion and rocket propulsion are relatively insignificant [14]. They only allow for a slightchance of transferring knowledge from one domain to the other [15].

Finally, with respect to the weakness in homotopic correspondences and analogical links, this research domain will have a relatively high degree of "lumpiness", as much on the material plane as on the informational one. This will greatly affect expected economic returns [16].

2-4) First priority: the production of infratechnologies

The change in the technological base therefore creates a situation of structural uncertainty which in turn implies a need for information on the very structure of the problems considered. A change in the technological base thus means that a critical lack in "infratechnologies" [17] and "instrumentalities" [18] has to be overcome. In other words, the instrumental basis for R&D within the new paradigm is completely lacking: "lots of things need to be measured that we do not know how to measure" (De Mice, 1990).

Analysis of the content of research carried out enables us to define the hypersonic programs as "oriented toward the production of adequate infratechnologies and instrumentalities" [19]. This research phase precedes basic and applied research and contains a strong technological dimension:

> "The important thing about these techniques of science is that they are not of themselves part of the knowledge system of science. They are clearly technology, an understanding of the way to do things, and often in their beginning, as with the telescope or the voltaïc pile, no one properly understands how and why they do work as they do, but only that they work" (De Solla Price, 1984).

It is clear that the NASP program is now in this preliminary phase, with its strong technological composition. How then does one produce infratechnologies and instrumentalities appropriate to the new technological base, given the weakness of scientific support, and the discontinuity marking the passage from the supersonic to the hypersonic domain? The first objective is to push back the frontier of experimentation on the ground [19]. Second, it is necessary to develop a computer simulation for fluid dynamics to predict the performance and flight characteristics at speeds beyond ground-experimentation capacities. However, performances thus calculated can vary greatly according to the hypotheses expressed in the codes. Thus the first task is the verification of vehicle design methods using the correlation between simulation and experimentation. As a result, the NASP engine (the experimental vehicle X-30) will not (yet) be a prototype or a "R&D instrument". Instead, this will merely be a demonstration vehicle or "basic research instrument" enabling the production of infratechnologies and instrumentalities necessary for further research and development.

No possibility for incremental research and step-by-step approaches exist: the weakness of homotopic correspondences and analogical links reveal lumpy technological and research projects. The production of infratechnologies and instrumentalities is based on the experimentation-simulation relationship and should result in the design of demonstration vehicles for the production of flight data. It is only on the basis of such data that the subsequent research and development phases can be undertaken with a minimum of acceptable efficiency in resource allocation.

2-5) Production of infratechnologies and the need for an unique organizational entity

The production of structural information requires the elaboration of necessary infratechnologies and instrumentation. Certain specific organizational forms are the result. It is clear that an "infratechnologies-focused" program should be equipped with a particular organizational form, linked to the very nature of the element produced: infratechnologies constitute the basic standards which enable measurement, comparison, and collective research. They therefore represent the positive demand side for economies of scale. That is, they have no significance outside of collective usage (Kindleberger, 1984). Their generalized diffusion and adoption constitute their very mode of existence. In other words, infratechnologies possess some public good features:

> "Just as individual proprietary transportation vehicles utilize the same non proprietary highway, individual proprietary and processes utilize the same pool of basic research and the same pool of nonproprietary measurement or test methods. (..) Just as the highway is part of the economy's infrastructure, the measurement method or the verified database is part of the economy's infratechnology -- a public good provided by a government laboratory" (Tassey, 1991, p.164).

The public good (or at least the collective good) aspect of infratechnology implies the necessity to form a single "learning entity" to produce the necessary structural knowledge. Thus, the program must follow an organizational rationale requiring the formation of a technological club, which incorporates private and public expertise previously isolated and dispersed - in order to develop the technological infrastructure.

3 - Uncertainty about the best design and the necessity for organizational diversity

The NASP program considered above will now be reexamined to demonstrate that structural uncertainty also concerns the services and functions that the hypersonic and trans-atmospheric technologies are likely to assume in the future. This uncertainty about functions makes it necessary to investigate what could be the best design and how one should use it? [21]. A phase of exploration and experimentation covering the full functional and technological spectrum must therefore be undertaken before selection of a particular set of performance criteria and the attendant unique trajectory are made.

3-1) Uncertainty about functions and performances

In the case of the hypersonic program, the objective discussed above lies beyond the limits of those performance criteria that have hitherto governed the technological evolution of aerospace engines (Nakinenovic, 1987, Gruebler, 1990). During the development of spatial technologies, criteria associated with cost and industrial implementation have gradually become evident and, in the case of rocket engines, have marked the end of a "stable" orientation for technological progress. This orientation - the so called "standard operating procedures to generate technological change" - is derived from the need to deal primarily with the problems of acceleration, speed, and orbital access, thereby ignoring the issues of reutilization, operability, and payload mass. The orientation thus neglected the industrial potential of aerospace transport systems (Brooks, 1983; Macauley, 1986).

The new research objective is to try to reconcile the contradictory performance requirements that were previously applied exclusively, either to aeronautic or to space projects. This involves uniting in a single engine, the economic advantages of airplane engines (cost, ratio to mass, operability, maintenance) with the performance criteria of rockets, in terms of flight speed and orbital access.

3-2) Option generation and the necessity of organizational diversity

A change in technological orientation implies a structural uncertainty with respect to the design and utilization of the new product. Thus, there is no consensus today on the best design for a space engine equipped with a supersonic combustion ramjet. Moreover, it is not yet known whether the missile, the launcher or the plane will represent the best application of the scramjet. The construction of a functioning pre-identified engine is therefore not at issue.

This structural uncertainty as to the best design and utilization implies a certain organizational diversity. This diversity facilitates experimentation in different directions and option generation. According to Ergas (1994), option generation refers to the process by which alternative design approaches are developed, tested, and selected. As a learning process, the efficiency of option generation can be greatly affected by the range of alternatives being explored and by the speed and integrity with which the results of exploratory efforts are transmitted within the technological community involved. In other words, one should create a system involving multiple, decentralized projects, being the only way to explore the totality of the technological and functional spectrum. Such a system must include also mechanisms and procedures for exchanging and distributing information produced in the course of these projects, and a centralized procedure of assessment to decide upon the timing of the switch and the standard to be selected. The final orientation of the entire program toward a single, predetermined area should only be decided after the completion of many pilot projects and broad experimentation [22]. Such an organizational design is, however, rather difficult to establish. First, it is necessary to plan some financial compensation for those projects not selected (selection ultimately results in technological orphans). Second, the information generated by the different experiments must be shared. Only when this is the case does the experience of one agent reduce the uncertainties of other agents, and play a part in cross-fertilization. But if it is known that such information is to be widely shared, there will be an incentive for agents to free-ride, thus avoiding the cost of participating in any of the experiments.

4 - Managing the organizational tension between diversity and standardization and creating common pools of knowledge

Langlois' (1984) typology, which distinguishes parametric and structural uncertainty, enables us to catagorize NASP as research characterized by a double structural uncertainty relating to infratechnologies and research instrumentation (how does one carry out this research?) as well as to the best design and mode of utilization of the outcome (what does one do with this research?). From an organizational point of view, this means that a compromise has to be found between standardization and diversity, i.e., between the necessity to form a club, in order to produce the collective infrastructure for research (data, experimental procedures) and the need to diversify organizations in order to reduce the risk of bypassing the best design or utilization. How can this conflict of organizational objectives be dealt with within the NASP framework?

One could suggest that it is a matter of timing: after a period of experimentation, during which many variants of a technology are tried (organizational diversity), one variant is selected as the standard (organizational unity). According to Cowan and Foray, 1994 and 1995), such a timing is based on the existence of two kinds of learning: the first is extensive learning or learning from diversity, which involves experimentation with a wide variety of options and, through the results of the experiments, leads to the elimination of certain avenues of development. The second type of learning can be called intensive learning, or learning from standardization, which concentrates attention on one technological variant, making it easier to identify empirical irregularities that point to underlying structural conditions deserving further investigation (See Cowan and Foray, 1995).

We argued, however, that the phase of production of infratechnologies and instrumentalities, i.e., the production of the standards, precedes basic and applied research. In other words, some standardization work precede (or at least run in parallel with) the experiments.

The difficulty is to build simultaneously infrastructural knowledge of two types: the first type deals with the production of infratechnologies and instruments associated to the change of paradigm. To be infrastructural, this type of knowledge must be collectively used and, thus, has to be public and diffused in well-documented forms. The second type deals with the information generated by the different experiments. To be infrastructural, this second type of knowledge must be shared in being incompletely appropriable and persistent [23].

Thus, the coexistence of the following features -- the expansion of measurement, standards, and testing activities of public institutions on the one hand, and the design of organizations involving multiple, decentralized, high-tech consortia on the other hand -- might be an unique way to manage the tension between diversity and standardization in the organization of the research program [24].

Notes

1 The expression *"discovery in the context of application"* was suggested by Prof. Michael Gibbons, who used it to characterize the organization of the innovation process in the case of hypersonic aircraft. An excellent summary of the case is provided in Chapter 1 of the book *The New Production of Knowledge* (Gibbons *et al.*, 1994).

2 In another paper in this series, Thomas Schelling (1995) describes and analyses another class of discovery that he termed "research by accident": a sequence of unanticipated discoveries which subsequently reveal properties and characteristics of the technology not expected initially.

3 Some pioneer, althoug recent, contributions from Cohen and Noll (1991 and 1992) deal with the issue of assessing the organizational forms of big federal projects.

4 The aerobic principle is distinguished by the utilization of oxygen from air (taken up from the atmosphere) as the combustive agent, whereas rocket propulsion requires the loading of both fuel and combustive agents (anaerobic principle).

5 Hypersonic speed is obtained from supersonic combustion, just as supersonic speed is obtained from subsonic combustion.

6 The members of the club are McDonnel Douglas, General Dynamics, Rockwell, Pratt & Whitney, and Rocketdyne. The National Program Office assumes the function of program coordinator.

7 "The team has already developed an unclassified network to develop scheduling and other plans, and it is now working on a classified system to handle electronic transfer of drawings and other data" (Wright-Patterson, 1990a).

8 "But mainlining brings the government-run facilities into positions often played by contract research labs or subcontractors" (Wright-Patterson, 1990a).

9 For example, government efforts led by NASA-Ames have provided an understanding of how to safely contain hydrogen, especially during the NASP's high-temperature flight (Wright-Patterson, 1990b)

10 The notion of technological base is used in a narrow sense. It includes the products and processes of production, as well as the ideas, concepts, and modes of enquiry that are necessary to generate a particular revealed performance (Layton, 1974).

11 Uncertainty can be either **parametric or structural**. Parametric uncertainty means that the structure of the problem is clear and the uncertainty only affects certain specific parameters (the chances of various outcomes). Structural uncertainty concerns the very structure of the problem (what outcomes are possible) (Langlois, 1984, p.29).

12 Beyond Mach 5, air no longer behaves as a perfect gas; beyond Mach 8, properties dependent upon temperature and even dissociation become dominant (Barthelemy, 1989): "as a result of kinetic chemical phenomena of increasing significance, simple extrapolation parameters no longer exist which can be applied to the domain of supersonic combustion".

13 See David, Mowery, and Steinmueller (1992): the methods and results may or may not be extrapolated to every size of range. The notion of "homotopic correspondence" comes from topology: two correspondences are said to be homotopic if one of them can be deformed continually within the other. Thus, in mechanics, a theory predicting the reaction of a physical object to attraction by an external force will be true for any object of greater mass. The relationship between force and mass is unaffected by changes in the mass parameter.

14 See David, Mowery, and Steinmueller (1992): the analogical links are important because nature is conservative in its usage of concepts and structures. The concept of symmetry, applied in mathematics and physics, as well as chemistry and crystallography, is a good example of an analogical link allowing for the extension of theoretical results from one domain to another.

15 "The installation requirements for aerodynamic experimentation and propulsion systems appear to be quite different depending upon whether they concern the development of a shuttle or a scramjet demonstrator" (Harsha and Aldman, 1989).

16 See David, Mowery, and Steinmueller (1992): the property of "lumpiness" is derived from the fact that the production of new results requires the prior resolution of a greater or lesser number of subproblems in the research area. This lumpiness may be either informational (the minimum of subproblems to solve) or material (the minimum of required experimental installations). This property is no doubt particularly pronounced where the homotopic correspondences are weak.

17 Following Tassey (1991), we will define infratechnologies as the instrumental basis of R&D, including: "the scientific data necessary for operations of measurement, test, control, and trial; methods and research instruments, techniques, and knowledge. Infratechnologies are the bases of technological development in that they enable precise measurements and furnish scientific and technical data, evaluated and organized, necessary to the understanding, characterization, and interpretation of pertinent research results. Infratechnologies are linked to the basic units of measure. In addition, infratechnologies incorporate the concepts and techniques of measurement and testing which allow for increased quality".

18 According to Derek de Solla Price (1984, p.13), instrumentality carries "the general connotation of a laboratory method for doing something to nature or to the data in hand".

19 Thus, according to Rosenberg (1992): "Scientific instruments may be usefully regarded as the capital goods of the scientific research industry. That is to say, the conduct of scientific research generally requires some antecedent investment in specific equipment for purposes of enhancing the ability to observe and measure specific categories of natural phenomena".

20 After determining that existing Air Force, NASA, industry and university engine test facilities were not capable of testing scramjets above speeds of Mach 8 for sustained periods, the NASP program awarded two contracts in October 1986 totaling US $9.6 million for two engine test facilities. These facilities are expected to provide the capability to test full-scale scramjets up to speeds of Mach 8 (GAO, 1988).

21 The existence of what Hummon (1984) termed as "the standard operating procedures to generate technological change", may result in a reduction of this kind of uncertainty. These standard operating procedures constitute a structure of mutually consistant expectations on the rate and direction of innovation, which in turn facilitates industrial coordination.

22 According to David and Rothwell (1990), Cohen and Noll (1991, p.42), and Cowan and Foray (1994 and 1995).

23 Knowledge that plays an infrastructural role in industry needs to persist long enough that it can be recognized and exploited by the organizations not directly involved in its creation (see Steinmueller, 1995).

24 In this area, the work of D.Collingridge (1990) on the establishment of a principle of incrementalism in the management of large research programs very likely indicates the way for additional fruitful research.

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