

From research to innovation

The case of biotechnical pulp bleaching

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ABSTRACT

The paper studies the emergence and development of a research-based innovation, enzyme-aided bleaching of kraft pulp. The idea of a new bleaching method was formulated in a meeting at the Biotechnical Laboratory of Technical Research Centre of Finland (VTT) in January 1984. The method was based on the use of hemicellulases. The Biotechnology Laboratory has actively studied hemicellulases for several years and they were hence immediately available for experiments. The Biotechnology Laboratory collaborated with the Fibre Chemistry Laboratory of the Finnish Pulp and Paper Research Institute (FPPRI), which knew different kinds of pulps and was skilled in the analysis of their paper technical qualities. With this combination of knowledge the results were achieved without delay. In the summer of 1986 the experimental results were published; they indicated that the hemicellulases helped in bleaching the kraft pulp and decreased the need for using environmentally harmful chlorine.

However, the experimental result was not immediately or without problems converted into an innovation. The pulp and paper industry was not interested in utilizing the results in 1986 - 1988. The public debate on the environmental effects of chlorine used in pulp bleaching in 1987 - 1989 changed the situation. The markets for chlorine-free pulps were formed and the issue of the environmentally friendly image of the products became important for the Finnish pulp and paper producers. As a result most of them tested and implemented the use of enzymes in the beginnings of the 1990's.

The innovation process was not a linear and rationally planned process. The effects of several unanticipated developmental processes and events were timed and accumulated in a way that made the emergence of the innovation possible: fluctuations in oil price, the development of research on dioxin in paper products in 1987 - 1989, changes in the attitudes of paper consumers and the general public, and the formation of chlorine-free pulp markets. Neither was the invention a result of luck or chance. The vision of the researchers of a chlorine- and sulfur-free pulping played an important role in the emergence of the invention. The persistence and ambitiousness of the research program on cellulases and hemicellulases at the VTT Biotechnical Laboratory made possible the formulation of the idea of the new method. The national technology program made continuation of the research on the enzymatic bleaching possible in 1984 - 1989. This underlines the significance of the quality and longevity of research as a criteria in establishing research programs and in fostering innovations.

PREFACE

This work on the enzyme-aided pulp bleaching and enzyme research was carried out in the Group for Technology Studies of the Technical Research Centre of Finland (VTT) 1993 - 1995. The research was financed by the Technology Development Centre (TEKES), which is gratefully acknowledged. The aim of the study was to analyse how an innovation emerges from research work done in a national research centre. The first part of the research covered the emergence of research program on cellulose degrading enzymes at the VTT Biotechnical Laboratory in 1972 - 1984. The results of this analysis were published in 1995 in the report "Biotechnical pulp bleaching in a national innovation network. The formation of conditions" (VTT Research Notes 1643). This publication analyses the invention and innovation phases of the process.

Dr. Liisa Viikari and Professors Tor-Magnus Enari and Matti Linko have been invaluable sources of information for the study. They also critically commented on the manuscript and made many suggestions that improved it and made it more reliable. Several other researchers of the Biotechnical Laboratory and other persons interviewed have contributed to the study. I would like to thank all of them. The Group for Technology Studies have created an supportive environment and work. Sirkku Kivisaari and David Miller helped in putting the finishing touches on the manuscript.

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1 INTRODUCTION

This paper deals with the emergence and development of a research-based innovation, enzyme-aided pulp bleaching. The idea for biotechnical pulp bleaching was formulated in a meeting at the Biotechnical Laboratory of the Technical Research Centre of Finland (VTT) in January 1984. It was applied by the pulp and paper industry in the early 1990s.

The economics of innovation rightly stresses that commercialization makes the difference between invention and innovation. The first transaction in the market can be regarded as the criterion for innovation (Green 1992). Research on innovations has therefore understandably concentrated on the commercialization phase of the innovation process. However, it is also important to understand how new viable ideas and conceptions come into existence. Consequently, in this study the innovation process includes the formation of the immediate preconditions of invention, formulation and early development of the idea and the product development and commercialization of the new method. Using these criteria, the time span for the biotechnical pulp bleaching process was about twenty years, from 1972 to 1992. The process can be divided into five phases.

- 1) The years 1972 - 1982: the research program on cellulose- and hemicellulose-degrading enzymes at the VTT Biotechnical Laboratory (BIO)
- 2) The reorientation of the cellulase research in 1983 - 1984
- 3) The formulation and early development of the idea of enzyme-aided pulp bleaching in 1984 - 1986: from idea to confirming research results
- 4) The latent phase: no interest in application, the research goes on in 1987 - 1988
- 5) The 'innovation phase': the chlorine and dioxin debate, the first plant-scale experiments and application of the method by the pulp and paper industry in 1989 - 1992.

This paper analyzes the first three phases of the process and concentrate on the third phase.¹ It only briefly characterizes the fourth and the fifth phases. Because the analysis focuses on the invention phase of the innovation process, the models of inventions are a relevant starting point for the analysis. In studies of scientific creativity and inventions there is an important methodological demarcation line. Invention was traditionally explained as an individual or psychological phenomenon involving for example the exceptional talents or intuition of the inventor. This is the 'hero' or 'genius' account of scientific and technological development. This conventional view has been criticized since the 1980s by philosophers (Feyerabend 1987;

¹For a more detailed analysis of the first two phases, see Miettinen 1995.

Niiniluoto 1990), sociologists (Schaffer 1990) and psychologists (Gruber 1981; Oeche 1990; Weisberg 1993).

Recent empirical research on scientific creativity has proposed 'systemic accounts' of creativity in which the sociocultural surroundings must be taken into consideration (Csikszentmihalyi 1988; Harrington 1990; Gruber 1989b). This critique has suggested that creativity or inventiveness is social or collective in at least three strong senses. First, the very quality of originality or inventiveness is attributed to a product by communities of specialists or users (Brannigan 1981; Schaffer 1994)². Second, the invention is mainly generated by a network of persons or communities of practitioners who in different ways contribute to the formulation and elaboration of the invention (Fleck 1981). Third, the invention or discovery is based on common, shared cultural resources (Merton 1961 and 1973). This does not deny the significance of the local capabilities nor the significance of the individual. However, the role of the individual is seen more in terms of "projects," issues of persistent interest and long periods of work than of mere ingenuity or exceptional talent (Amabile 1983; Gruber 1989a).

This paper analyzes the invention and innovation process in terms of four issues:

1) The invention is analyzed as a solution to an emerging critical problem of a sociotechnical system or a system of use of technology (Hughes 1971; Constant 1984 and 1989; Weingart 1984)³. In this study the problem was the use of chlorine in the bleaching of kraft pulp. The problem had its own history and developmental trajectory, which essentially influenced the innovation process. There were some 115 kraft (sulphate) pulp mills in the world at the beginning of the 1980s, most of them in northern Europe and America. Most of them used a cheap and efficient bleaching agent, chlorine, to remove the residual lignin from the cooked pulp. The residual lignin makes pulp dark brown and makes bleaching necessary. During the bleaching process residual lignin reacts with chlorine and the reaction produces toxic chlorine compounds.

2) Second, the paper analyzes how the idea of the new method emerged and how it was related to the tradition, know-how and changes in the activities of the inventor, the VTT Biotechnical Laboratory. The development of research on cellulose degrading enzymes will be analyzed in terms of formation of the research object (Engeström 1990; Miettinen 1990), network of investigative enterprises (Gruber 1989b), transformation of object as a result of problems and obstacles faced in research and development (Fleck 1981; Pickering

²In the case of biotechnical pulp bleaching, the new method gained the status of invention only after its usability was proved by plant-scale experiments and it was tested by forest companies in the production of chlorine-free pulps.

³Steven Kline points out that sociotechnical systems can be either systems for creation of technics (manufacturing) or systems of use of technics e.g. a symphony orchestra or an electrical utility (Kline 1977, p. 41). Actually, both of them are collective human activities using cultural artifacts including technical artifacts. Accordingly it can be stated that the critical problems and dilemmas (functional, economical, technical) of these activities form a basis for inventions.

1995) and as a result of the implementation of new methods and technologies. The problems faced by the research, unanticipated changes in environment and the development and implementation of new technologies resulted in a reorientation of the research work and presupposed a new kind of applications. The first of them was biotechnical pulp bleaching.

3) Third, this paper analyzes the cultural conditions of the invention. It analyzes the resources and means used in the solution of the problem (theories, methods and instruments) and how the local network of actors gained access to, combined and transformed these resources. In this case the knowledge on hemicellulose degrading enzymes, practical enzyme technology as well as the capacity to make bleaching experiments with different kinds of pulps were essential.⁴

Evidently many kinds of factors affect the success of an innovation process: contingency and chance, the vision and persistency of the inventors, the nature and quality of collaboration during design and development work and the amount and quality of the cultural and material resources of the innovation network. This paper tries to elaborate the last point. It asks what kind of unique local circumstances, know-how and combination of resources make the invention possible.

David Teece and his colleagues have developed a 'dynamic capabilities' approach to firm strategy and competitive edge. According to this view, the competitive advantage rests on the firm's idiosyncratic and difficult-to-imitate resources (Teece et al. 1994, p. 8). The approach focuses on how the firm first develops specific capabilities and then renews them in response to shifts in the business environment. This local specificity of capabilities can only be analyzed in relation to the capabilities of competitors and in relation to entry time in a field (Teece et al. 1994, p. 35). In this paper the local networks of actors is characterized in terms of the specificity of the capabilities mobilized.⁵

The level and uniqueness of local combination of capabilities and timing in problem solving (and in entry to markets) provide an account of why a local solution will succeed or not. The construction of such an account is complex because of the multiplicity of 'circumstances' and capabilities. Neither can

⁴Robert Merton underlined the significance of common cultural tools for inventions when he dealt with the problem of multiple inventions (1973, p. 371): "Such occurrences suggest that discoveries become virtually inevitable when prerequisite kinds of knowledge and tools accumulate in man's cultural store and when attention of an appreciable number of investigations becomes focused on a problem by emerging social needs, by development internal to the science, or by both." This theory of cultural maturation implies exaggerated determinism. It, however, rightly points out that the local actors are often dealing with common problems and have access to common cultural resources. The solutions of the local actor should be analyzed in relation to the broader cultural backgrounds. As a matter of fact, the particularity of a local activity is better understood when analyzed in relation to other similar activities -i.e. activities with the same kind of object and product. The 115 pulp mills all produce pulp. Several research groups also studied the problem of chlorine in pulp production.

⁵Actor network theory would analyze the network formation in terms of the durability, strength and extensiveness of the network (Latour 1987). The analysis in terms of content, i.e. in terms of historically formed knowledge, know-how and resources of the actors, is a complementary approach.

such an account eliminate the contingency inherent in complex social processes like invention and innovation. However, these factors can be evaluated in the early phases of the innovative enterprise by the actors themselves and hence can help in handling the contingencies of the research work.⁶

4) Forth, the paper analyzes how the invention and innovation process developed as a formation of networks of actors with a common object and complementary know-how and resources. Because the paper concentrates on the invention and development phase of the innovation process, mainly the research collaboration is analyzed. It is analyzed in terms of the complementarity of motives, know-how and the resources of the actors (Tece 1986).

⁶Both historians and sociologists maintain that the explanation of success is always an ex post construction and that success cannot be predicted (e.g. Constant 1989). Even if the asymmetry between explanation and prediction is valid (Bhaskar 1987), it still makes sense to look for meaningful conceptual tools that would help in orienting research and development. The analysis of the combination of capabilities and know-how to be mobilized is one such factor and is closely connected to formation of the network of actors. Of course other points of view could have been selected, for instance the producer-user collaboration or the political approach, the capability of the innovator to mobilize, convince and 'enroll' others and to create a strong network (Callon & Law 1982 and Callon 1986). In this innovation such a strong network, however, was never created. The problem of researcher-user interaction is relevant in the case and I hope to be able to elaborate it in later analyses.

2 THE RESEARCH PROGRAM ON CELLULASES AT THE VTT BIOTECHNICAL LABORATORY IN 1972 - 1983

2.1 THE EMERGENCE OF THE RESEARCH PROGRAM ON CELLULOSE-DEGRADING ENZYMES

The Finnish brewing industry founded Oy Panimolaboratorio (Research Laboratory of the Finnish Brewing and Malting Industry) in 1956. The malting of barley, beer fermentation and brewery yeasts were studied. Later the laboratory was incorporated with the Technical Research Centre of Finland. In 1965 the laboratory changed its name to the Biotechnical Laboratory. It sought to widen its research area to include new biotechnical processes. The management of the laboratory emphasized that the new research should stimulate development of new biotechnical industry in Finland. After doing some research on penicillin, the production and use of microbial enzymes was selected as a new area for study. In 1968 a project on the production of microbial amylases was started. The production of amylases by the bacterium *Bacillus subtilis* was a relatively easy and well-known process. The project resulted to the industrial production of amylases at the Koskenkorva plant of Oy Alko Ab, the Finnish alcohol monopoly. It also helped to form the basic know-how in a new research area.

A major project on the use of cellulose-rich wastes as raw material for the production of fermentable sugars was carried out in 1972 - 1975 at the laboratory. One of the options of treating cellulosic materials was the use of cellulose-degrading enzymes. These enzymes were technically more demanding to produce and a less known group of enzymes than the amylases.⁷ The prices of soya and fish-meal - used as animal feed - rose steadily in 1973 on the world market. The goal of the project was to study the possibilities for producing an alternative protein, single cell protein (SCP) from the cellulosic waste materials of the food industry. The waste materials were first hydrolyzed by cellulose-degrading enzymes. Molds to be used as food were grown in the hydrolysates. This project failed for many techno-economic and social reasons. The conditions for the study of production and use of cellulases were, however, created. In 1974 the Biotechnical laboratory obtained a strain of the fungus *Trichoderma viride* from the US Army's Natick laboratories and research on the production of cellulases was initiated.

The decisive factor behind research on microbial cellulases was the energy crisis. The rising price for oil paved the way for research on alternative fuels.

⁷Wood, cotton, straw and hay are lignocelluloses. The lignocellulose structure is composed of three fractions: cellulose (40 - 45 %), hemicellulose (30 - 35 %) and lignin (20 - 25 %). Cellulose and hemicellulose fibers are composed of chains of sugar molecules. The lignin molecule is a large, web-like molecule. Lignin ties the fibers together and make the structure durable. In pulp making, the lignin is degraded by cooking the wood chips in chemicals to separate the wood fibers. The trivial names of enzymes refer to the substrates in which the enzymes catalyze reactions. They are formed with the ending *-ase*. The enzymes that degrade cellulose are called cellulases, enzymes that degrade hemicellulose are hemicellulases and enzymes that degrade lignin are ligninases.

One option was to produce ethanol from wood or other cellulosic materials. Lignocellulose is the most abundant renewable natural resource on the earth. Visions of limitless renewable energy sources during the oil crisis were tempting. It was also natural interest for the VTT Biotechnical Laboratory. Finland has large forest reserves and a strong forest industry. The laboratory requested funding for the ethanol project from the Finnish National Fund for Research and Development (SITRA). The project was started with the participation and financing of two Finnish companies, the Finnish alcohol monopoly Alko and a paper and pulp producer, Metsäliiton Teollisuus. This research, "*The hydrolysis of cellulose and the production of ethanol*," lasted from 1975 to 1981. It established the structure and nature of cellulose research. The years 1972 - 1982 can be regarded as a period of research on cellulases at the Biotechnical Laboratory with an established research object.⁸ During this period the overall concept of the aims of the research remained the same; the object was the total hydrolysis of wood cellulose and hemicellulose (or other cellulosic material) into sugars and the production of ethanol or other products from the sugars. This research object was conceptualized with the model of total wood utilization. A version of this model, formulated in 1979 is presented in Figure 1.

This overall object of research presumed several complementary research enterprises, which could be called a network of enterprises. This concept was originally formulated by Howard Gruber in his study of the work of Charles Darwin (1981). Gruber shows that the eminent scientist had several interrelated although independent research enterprises going on simultaneously. The concept stresses three aspects of research work: the open-ended nature of research, the persistency of certain research problems and the dynamic interrelationships between the enterprises. This concept can be applied to collective research work as well. The network of enterprises of the cellulase research at the VTT Biotechnical Laboratory are presented in Figure 2. Typically, each of the enterprises is composed of a series of succeeding research projects with specific goals. For instance the fermentation process was optimized in a series of six projects with different names between 1975 - 1983. This gives lends continuity to research work.

⁸ Seppo Raiski (1990) has analyzed the "problem patterns" of Finnish dissertations of technology by studying to what extent they were connected to practical values of use contexts (functionality, economy) and to what extent they aimed at creating general models and methods in a theoretical context - usable in multiple-use contexts. The idea of studying the matrix of problems as reflecting the transitions between practical and theoretical contexts has inspired my analysis of the research object of cellulose research.

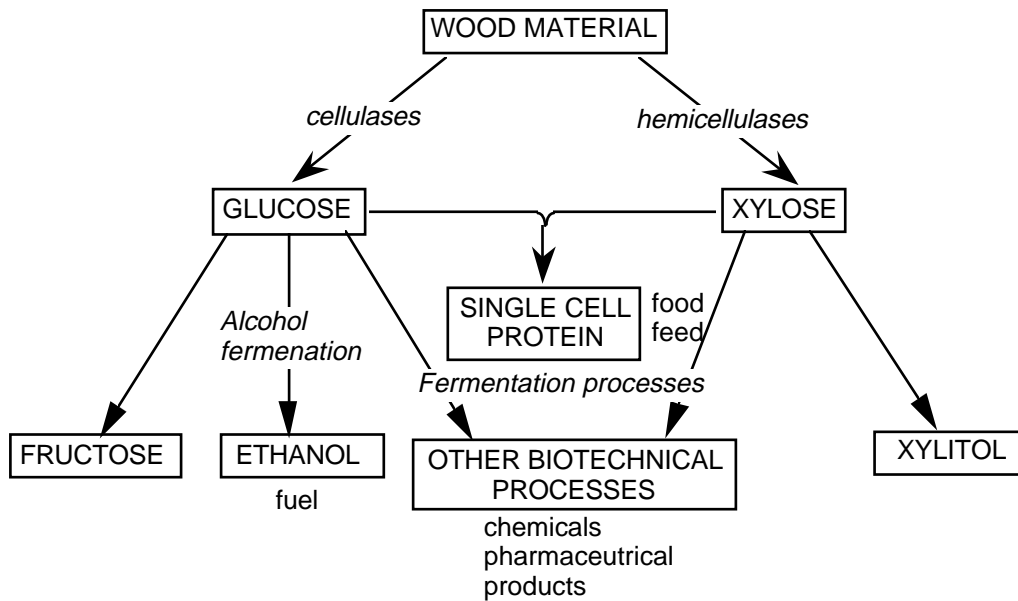


Figure 1. The model of total utilization of wood carbohydrates (Project plan for Academy of Finland, October 10, 1979).

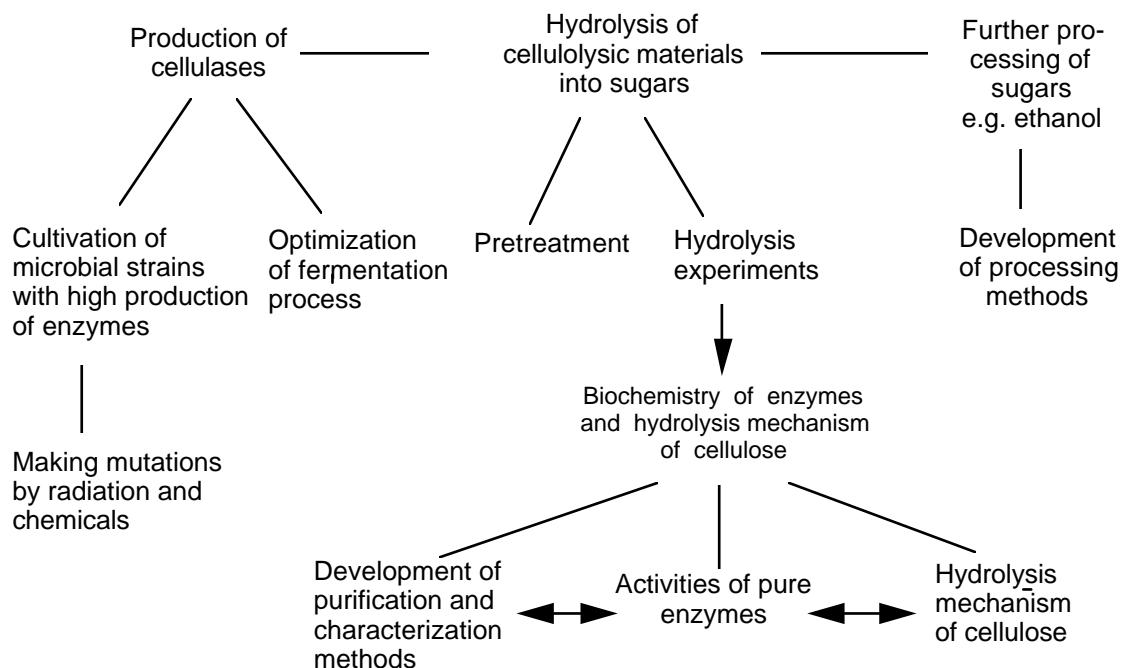


Figure 2. The network of investigative enterprises in cellulase research program of cellulases at the VTT Biotechnical Laboratory in 1972 - 1982.

Each of the enterprises was related to the overall object. The total hydrolysis of wood presupposed production of great quantities of enzymes. That is why increasing production by mutating microbial strains and by improving the fermentation process were of central concern in the research program. The enzymatic hydrolysis of cellulose into sugars was the core of the prospective technology.

On the other hand, each of the enterprises was relatively independent, and had its own research object. The researchers in charge of the projects represented different fields of science and technology and were also situated in different sections of the VTT Biotechnical Laboratory (see Table 1). Each of the enterprises also had its own network of collaboration. The fermentation process of the pilot fermentor was carried out together with the process engineers of the Helsinki University of Technology. Full scale hydrolysis and production experiments were carried out with the rawmaterial and equipment of the industrial partners. Pretreatment was studied with the wood chemists working at a research center in Hamburg (see section 4.4).

The research enterprises were interconnected with each other through common procedures, methods and people. The biochemical characterization of cellulases, e.g. the identification of pure enzymes and their effects, supplied the knowledge necessary for the improvement of the hydrolysis experiments. The production of a considerable amount of cellulases was necessary for extensive hydrolysis experiments. Problems in hydrolysis experiments raised problems for the study of the hydrolysis mechanism of cellulose. The division of duties did not follow the boundaries of project groups and sections. Many of the researchers participated at the same time in several projects, which secured an effective transfer of knowledge between the investigations.

The network of investigations can also be characterized in terms of transitions between contexts or activities. The network involves a transition from the industrial context to the natural scientific context. The three complementary research issues on the top row of Figure 2 correspond to the structure of the production chain: the production of enzymes by microbes, the hydrolysis of cellulosic materials into sugars and the refining of the sugars into an end product (ethanol, xylitol, SCP). These three were the subprojects of the main application project of the 1970s, the "Production and use of cellulases." They also reflected - although in a generalized form - the structure and state of the industrial biotechnical processes being studied and developed in Finland at the beginning of the 1970s.

The three tasks are converted into a series of engineering problems to be solved in technical research and development work, which is presented on the second row. The third level represents natural-scientific context. The connection between the levels can be characterized in terms of context transitions. First, a practical societal problem (e.g. a need for an alternative fuel) is transformed into vision of alternative product (e.g. ethanol from cellulosic raw material). This is converted into a series of technical problems (e.g. enzymatic hydrolysis of cellulosic raw materials) and finally into a natural-scientific problem (e.g. the hydrolysis mechanism for cellulose).

Table 1. Investigations, projects, some results and the disciplinary background of the researchers involved in the cellulase research at the VTT Biotechnical Laboratory.

Issue of investigation	Example of a project	Result	Disciplinary background of the responsible researcher	Section
Cultivation of high production microbial strains	One of the three subprojects of "Production and use of cellulases" 1975-1980,	New <i>Trichoderma reesei</i> -strains with radically increased cellulase production	Microbiologist	Section of process technology
Optimizing the fermentation process	"Control and optimization of fermentation" 1974-1976; "Computerised control of fermentation" 1978-1980 , ect.	Models of control, new control equipment for pilot fermentor	Biochemical engineer with process engineers	Section of process technology
Pretreatment	"Steaming pretreatment and hydrolysis of wood" 1982-1984	Knowledge of the hydrolysis of birchwood xylan and of the difficulty of creating an economic pretreatment method	Biochemical engineer with wood chemists	Section of process technology
Hydrolysis experiments on laboratory,- pilot- and mill scale	One of the three subprojects of "Production and use of cellulases" 1975-1980	Cumulative knowledge of the (practical) conditions of hydrolysis	Biochemical engineer	Section of process technology
Further processing of sugars	"Fermentation of ethanol from pentoses" 1980-1984	Knowledge on conditions of the production of ethanol	Biochemical engineer Microbiologist	Section of process technology
Hydrolysis mechanism of cellulose	"Biochemistry of cellulases" 1980-1985	Methods of analysis, Purification and characterising of <i>Tr</i> -cellulases, A model of the hydrolysis mechanism of cellulose	Biochemist	Section of biochemistry

The interaction of the investigation also had a chronological order. First the hydrolysis of cellulose was studied directly, with hydrolysis experiments. In 1979 a research project on the hydrolysis mechanism of cellulose was started with financing from the Academy of Finland. This project studied the biochemistry of distinct cellulases to uncover their role in the hydrolysis mechanism of cellulose. This project meant a transition from a direct approach to an 'indirect strategy'⁹. The aim was now the modelling and

⁹Another important feature in the research was the enlargement of the research object from cellulose to the other main elements of wood, first to hemicellulose in 1977 and finally in 1984 to lignin. The hemicellulose and lignin studies had much the same structure as the cellulase studies; production, use and the hydrolysis mechanism were studied.

understanding of the hydrolysis mechanism of cellulose. Professor Enari, the researcher in charge of the project regarded this order problematic:

"We started from the wrong end when we first began to develop the production and use of cellulases. We should have started by studying what cellulases are and how they function. The basic knowledge necessary for the development of the applications lagged behind all the time."

He, however, immediately reassessed the issue, calling for a simultaneous, interactive model of basic research and applications:

"On the other hand there is such a contradiction that had we started merely with basic research, we wouldn't have been on the edge of the development, because it is such a slow process after all. You should carry out both side by side."

2.2 THE INTERNATIONAL AND THE LOCAL IN RESEARCH ON CELLULASES

The cellulose and ethanol research at the VTT Biotechnical Laboratory was from the beginning connected with international developments and other groups in the field. After the oil crisis in 1973, several research programs on the production of ethanol from cellulose were started in different countries. In a review made in 1981 by a researcher at Alko, 11 international symposia on the hydrolysis of cellulose were mentioned (Nurminen 1981). A consortium of Finnish firms collected a list of 23 hydrolysis methods for wood under research and development. Half of them were in the United States, although Canadian, Australian and Swedish methods were also mentioned. The Canadian Government supported an "ethanol from cellulose program" that aimed at constructing a pilot plant based on enzymatic hydrolysis. The problem of developing an alternative fuel from cellulosic materials was common to all countries with substantial cellulosic raw materials and dependence on oil imports.

The Finnish group saw from the beginning that international collaboration was necessary for success. Without knowing what is being done in the field it is impossible to create something new or find one's own niche. The VTT Biotechnical Laboratory together with the Finnish National Fund for Research and Development organized an International Symposium on Enzymatic Hydrolysis of Wood at Aulanko, Finland in summer 1975. The aim was to ask the most prominent cellulose research groups to attend the symposium. This aim was achieved.¹⁰ The group could connect itself with the international web of groups studying the enzymatic hydrolysis of cellulose. The symposium also reviewed what was known about enzymatic hydrolysis and what different

¹⁰ Representatives of six institutions from U.S.A. (including six researchers from US Army Natic Laboratories and four from US Department of Agricultural Research), four from Scandinavia, five from England, two from Japan, one from France, Hungary, the Soviet Union and India participated in the symposium. 22 foreign institutes or research groups attended, among them the leading research groups of the field from the USA and Sweden.

groups were studying (Bailey et al. 1975). This underlines the shared, global aspect of the research work.

Every group contributes to the emerging field on the basis of its tradition and local resources. Cellulase research provides an example. In the hydrolysis of cellulose an enzyme mix produced by a micro-organism degrades cellulose into sugars. In industrial scale processes a great amount of enzyme is needed. The production of enzymes becomes a key issue. The problem is to find a micro-organism with a high production of these enzymes and to increase its production capacity. The best known producer of cellulases was the fungus *Trichoderma reesei*. It was found during the Second World War. It was noticed that tents and clothes made of cotton used by the U.S. Army rotted in tropical climates. When the phenomenon was studied at the U.S. Army's laboratories, it turned out that it was *Trichoderma reesei* that degraded the cellulose in the cotton. In the 1960s the U.S. Army's Natick Laboratories began to study the enzymes of *Trichoderma reesei* as a possible solution to the waste problem. The organism could be used to destroy community wastes containing considerable amounts of cellulose.

In 1974 a researcher from the VTT Biotechnical laboratory wrote to Doctor Mary Mandels and asked whether their group could have the *Trichoderma reesei* strains developed at the US Army's Natick Laboratories. Doctor Mandels sent the strains as she had done for several other groups in the world. Later on, the VTT group developed mutant strains that were four times more productive than those received from the Natick Laboratories (Nevalainen et al. 1980). Another reason for their success was the history and equipment of the VTT Biotechnical Laboratory. Since it was originally industrially oriented, it had studied the production of amylases in fermentors. Like most research-oriented laboratories, the Natick Laboratories used shake-flasks in production experiments. *Trichoderma* produces not only cellulase but also organic acids in the flasks. When the pH of the cultivation reaches 2.6, the micro-organism dies and the enzymes are destroyed as well. The results of the production of cellulases were based on that fact. The researchers at VTT had worked extensively with fermentors in which the pH level could be controlled. With this instrument considerably higher production of cellulases compared with laboratory experiments with the shake-flash method was achieved. The historically formed local know-how - the use of a fermentor - made it possible to redefine the conditions of enzyme production. Local differences of this kind in the make-up of instruments, know-how and tradition can evidently explain many achievements in research.

2.3 THE BACKGROUND OF THE INVENTION: REORIENTATION OF THE RESEARCH PROGRAM

At the beginning of the 1980s the cellulase research program with its conception of the "total hydrolysis" of cellulolytic materials into sugars experienced a crisis. After ten years of research the 'bulk production'-orientation faced difficulties which gradually led to redefinition of the objects of the research. Several economic, technical and scientific reasons were involved (see Table 2.) These factors can be divided into three groups: the long-term price fluctuations of raw materials (1 and 2), the resistance, i.e. obstacles to the enzymatic hydrolysis of cellulose that became evident during the research work (3), and the development of new theories, research methods and instruments that open new possibilities (4).

Table 2. Factors contributing to reorientation of the research program.

1.	The oil crisis recession
2.	The great economic value of cellulose fibres compared with a cheap final product-ethanol
3.	The technical and scientific limitations became evident during the research
2.1	Lack of an adequate and cheap pretreatment method
2.2	Low specific activity of cellulases and the limits of enzyme production - too much enzyme is needed
2.3	The waste materials of forestry and agriculture industry are resistant to hydrolysis. They are dispersed - collection and transport make them an expensive raw material
2.4	The hydrolysis is slow and often incomplete
4.	New potential created by research
4.1	The biochemical research at VTT BIO purified and characterized the most important cellulases
4.2	Gene-technology and molecule biology provided new tools for studying and producing of pure enzymes

The most obvious external reason for the decline of the research program was the oil crisis recession. Oil prices began to fall in 1983. The projects for producing an economically viable alternative fuel declined. Four Finnish companies interested in production of ethanol from wood had made a cost estimate for an ethanol producing plant in 1982. The calculations showed that production would be unprofitable (memo of the working party of firms April 28, 1982). It was clear that interest in research on ethanol production declined as well. Funding for ethanol research was cut, which called for new applications.

Several problems in research work contributed to the gradual reformulation of the research object. Enzymes cannot enter the structure of the wood, and the

structure must somehow be broken to make it accessible to cellulases. The researchers tried to remove or eliminate the obstacle by studying a pretreatment method that would brake the structure and make wood accessible to enzymatic attack. One of the methods, steam explosion, was studied at the VTT Biotechnical Laboratory together with a German research institute. This method, however, uses a great deal of energy and was expensive, thus significantly raising the costs of enzymatic hydrolysis (Nevalainen 1987). The problem of pretreatment remained unsolved.

An economically feasible utilization of wood and other cellulosic materials - implied an efficient hydrolysis of substrate. This proved not to be the case. The capacity of one weight unit of cellulase to degrade a substrate in a given time is called the specific activity of the enzyme. It measures the efficiency of the enzyme. This capacity varies greatly among different enzymes. Some can degrade tens of thousands of molecules in a second; others only a few. The research program gradually revealed that cellulases had low specific activity. Amylases, the enzyme used in degradation of starch and studied at the VTT Biotechnical Laboratory at the beginning of the 1970s, were the natural frame for comparison. The specific activity of cellulases was hundreds of times less than that of amylases.¹¹ Consequently, large amounts of cellulases would have been needed for the hydrolysis of cellulose. Moreover, cellulases were - and still are - relatively expensive enzymes. This made the possibility of a large-scale industrial process unlikely and contributed to the reformulation of the research object.

"One gram of amylase degrades a cubic meter substrate. But we need almost as much cellulase as substrate. Naturally we didn't know that at the time"

Trichoderma reesei has played a central role in world-wide endeavors aimed at biotechnical utilization of cellulose materials. (...) A few general facts should be pointed out, both good news and bad news. First the good news (...). Trichoderma reesei mutants are efficient producers of a variety of enzymes, including those necessary for the hydrolysis of cellulose and xylan (...) Then the bad news. The specific activity of T reesei cellulase is low (Linko et al. 1983, p. 372)."

The most natural raw material for enzymatic hydrolysis was the abundant waste wood originating from forest harvesting, saw and pulp mills. This material comprised bark, branches and sawdust. It was very resistant to hydrolysis. Second, it is dispersed and hence collection and transportation would make it expensive.¹²

¹¹ This difference has a natural evolutionary explanation. Starch is a reserve nutrient of the plant, cellulose a component of the cell walls and structures that strengthens the plant. Biotechnologists aimed at efficient hydrolysis (production of sugars) of both of the materials, irrespective of these differences.

¹² The limitations of the aim of total hydrolysis were recognized quite early. An article written by the researchers of the VTT Biotechnical Laboratory in 1978 recognized almost all the technical problems and limitations mentioned in table 2 (Linko & Nybergh 1978, pp. 64 - 65). However, it was argued that in the long run they can be solved. It was the oil crisis recession that ultimately frustrated these hopes and made the complex of limitations insurmountable and a new approach and new application necessary.

"The ideal starting point in ethanol research was to make ethanol from residual wood - it was a still born idea. We didn't know it then. The starting point was that the roots and branch parts would be used. But they are the most difficult to be degraded. There is a lot of bark that must be removed. Roots are rich in lignin, phenol and all kinds of trash. And everything that won't do for the paper industry won't do for enzymes either. If you could use pulps used for paper making, it would be easy to produce ethanol from it. But it is not profitable (...). Ethanol is too cheap from today's perspective - its production does not pay. Some additional benefit is needed. Technically it would be possible to do it from pulp. The consolation of the time was that if a bad energy crisis comes, or a war starts or something, then it would be possible to produce it from cooked pulp."

It was evident that the cellulose fibre used in the production of pulp, paper and other products was too valuable to be hydrolyzed into sugars (Enari 1985, p. 66):

"Cellulose is of course so valuable as fibre, that the macromolecules should not be hydrolyzed. Current pulping processes are inefficient in that they make use only half of the raw material and also cause pollution. The pulping process should therefore be developed to allow profitable use of all wood components."

All these interrelated factors called for a gradual reformulation of the research object. The idea of total hydrolysis of lignocellulose was no longer an economically and technically viable aim. The situation can be characterized in terms of the contradiction between the established research object and the means of accomplishing it. The resistance of the structure of wood against enzymatic attack as well as the low specific activity of the prospective main agent of hydrolysis, the cellulases, did not represent an economically viable and realistic means for industrial scale hydrolysis of lignocellulose and hence for the production of ethanol.

A new object gradually begun to develop in the mid 1980s. It was the idea of selective use of cellulases in the modification of cellulose or hemicellulose fibres for specific industrial purposes. The specific effect of an enzyme or mix of enzymes becomes important. The decisive new means for the reorientation was the emergence of recombinant-DNA (rDNA) technology, later known as gene technology. This technology makes it possible to transfer the gene encoding the production of one pure enzyme to another organism that would produce it. It also makes it possible to tailor the composition of enzyme mix produced by a micro-organism. This made it possible to use enzymes selectively. A rDNA group was founded at the Biotechnical Laboratory in 1980 and the genes of *Trichoderma reesei* cellulases were the first object of research (Knowles et al. 1983). Professor Enari explained the significance of genetic engineering for cellulase research as follows (1985, pp. 60 - 61):

"The availability of cloned cellulase genes opens a number of new possibilities. In the first instance, it is an important tool for studying these enzymes. Secondly, the encouraging finding that at least fungal cellulases are efficiently secreted into the growth medium by yeast suggests that new organisms can be constructed for the

*production of single cellulolytic enzymes. Single cellulases, free from interfering activities, can be used in various processes to modify cellulose when total hydrolysis is not desired. (...) Recombinant DNA technology opens the way to more exciting possibilities in the future. By means of protein engineering using in vitro mutagenesis of cellulase genes, the properties of the enzymes themselves could be modified. Thus, new cellulases with higher specific activities or improved properties such as temperature tolerance and pH optimum, could be constructed.*¹³

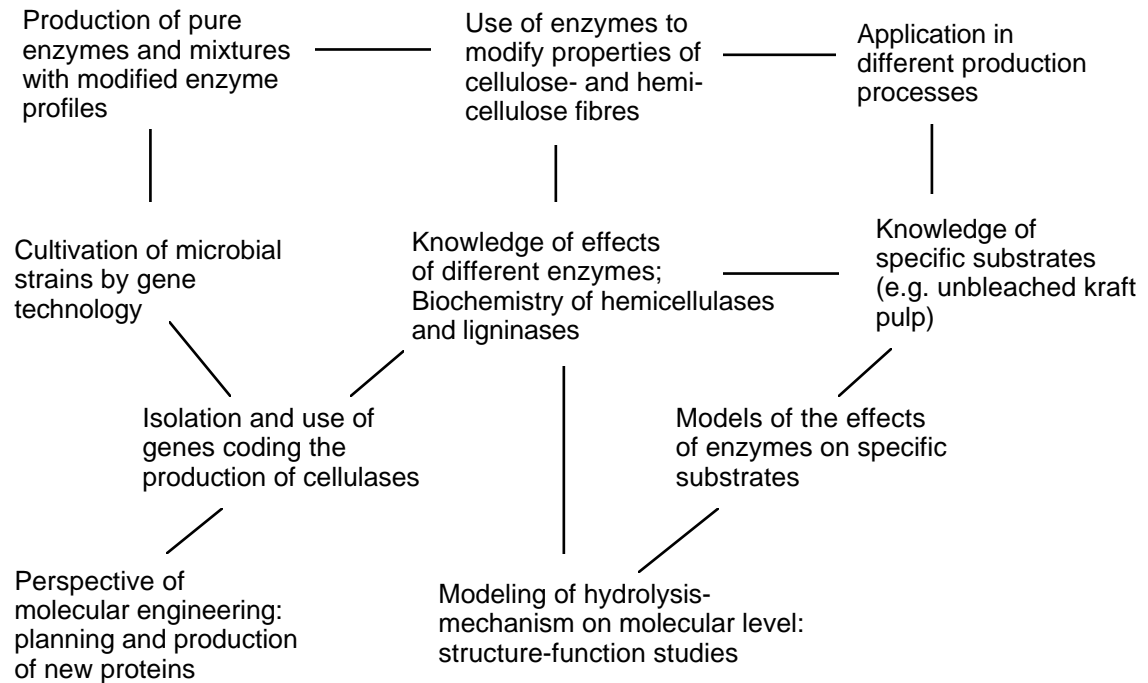


Figure 3. The network of enterprises in cellulase and hemicellulase research at the VTT Biotechnical Laboratory in 1985 - 1991.

Bleaching studies begun in 1984 with experiments that by 1986 showed that hemicellulases promoted the bleaching of kraft pulp and decreased the need for chlorine in the process. After attaining these experimental results the research oriented to the biochemical characterization of hemicellulases and to discover how the enzymes affected the unbleached pulp. A model of the mechanism in enzyme-aided bleaching was formulated at the turn of the decade. According to the model hemicellulases hydrolyze the reprecipitated xylan on the surface of the pulp fibres and render the pulp more permeable, thus facilitating removal of the residual lignin (Kantelinen et al. 1991). To study it further, new kinds of phenomena like the accessibility of enzymes into the structure of fibres was to be studied.

¹³The fact that the researchers speak in a natural way of the construction of new organisms and planning and production of new proteins confirms a central theme of recent science studies; science is not only a process of representing nature. It is also - like other human activities - a process of transforming it and a process of constructing phenomena in the laboratory (see Hacking 1983).

Table 3. Enterprises, projects, some results and disciplinary background of researchers involved in cellulase research at the VTT Biotechnical Laboratory in 1984 - 1992.

Investigation	Example of project	Result	Disciplinary background of the responsible researchers	Group/ section
Development of microbial strains by gene technology	"Development of new cellulolytic organisms" 1986-1988	<i>Trichoderma reesei</i> strains with novel cellulase profiles	Geneticist together with microbiologist	Gene technology group in microbiology section
Use of enzymes to modify the properties of cellulose fibres	"Biotechnical pulp bleaching" 1984-1987	Use of hemicellulases decrease the need of using chlorine about 25 %	Biochemical engineer	Section of process technology
Different enzymes and their effects; Biochemistry of hemicellulases and ligninases	"The production, biochemistry and use of ligninases 1984-1991	Isolation and characterization of hemicellulases and ligninases	Biochemist	Section of Biochemistry
	"The use of hemicellulases in pulp industry" 1988-1992	Model of the bleaching effect of xylanase on unbleached Kraft pulp	Biochemical engineer together with wood chemists	Section of process technology
Models of effects of enzymes on specific enzymes	"The use of hemicellulases in pulp industry" 1988-1992	Model of hemicellulases acting on Kraft pulp fibres	Biochemical engineer	Section of process technology
The isolation and use of genes controlling the production of cellulases	"Molecular cloning of cellulase genes from <i>Trichoderma reesei</i> " 1982-1985	Isolation of the genes of the major cellulases of <i>T reesei</i> and their expression in bacterial hosts	Geneticist	Gene technology group in the microbiology section
Study of enzymatic mechanism of cellulases on molecular level		Molecular model of the CBH I molecule and hypothesis of the function of its tail part on cellulose fibre	Geneticists together with biochemists specialising in molecular biology	Gene technology group in the microbiology section
Perspective of protein engineering	"Mechanism of action of cellulases using site-directed mutagenesis"			Group for molecular modeling

The recombinant DNA technology supplied means for the elaboration of the idea of selective use of cellulases. It also opened new perspectives for enzyme research. The genes coding the production of the *Trichoderma*

cellulases were cloned (Teeri et al. 1983) and transferred to a yeast that produced the pure enzymes. The genes of the production strains were manipulated to increase production or to change the profile of enzymes mixtures. At the end of the 1980s the researchers of the VTT Biotechnical Laboratory and the enzyme producer ALKO created several production strains with an altered profile of enzymes suitable for different industrial purposes (Mäntylä et al. 1990). The future oriented projects aimed at totally new technologies (depicted on the lowest row of Figure 3) were started in the laboratory in 1984 - 1985. A new level of studying the effects of cellulases was the structure-function studies of cellulase molecules using the methods of molecular biology (Kraulis et al. 1989). The molecular modeling group was formed in 1986. Gene technology, site directed mutagenesis¹⁴, and computer-aided molecular design opened the perspective of molecular engineering, i.e. planning and constructing of new enzymes for specific purposes. Several projects aimed at the creation of the know-how necessary for molecular engineering were started.

The change in the object of research was accompanied by a change in collaboration within the laboratory. Instead of two groups in the late 1970s (see Table 1), four groups were now involved: process technology, biochemistry, genetic engineering and lastly, at the beginning of the 1990s, the molecular-modeling group (see Table 3). Each of the groups has its own scientific ambitions and international communities. The change in cellulase research at the VTT Biotechnical Laboratory conforms closely to the recent characterizations of change in activity as an expansive cycle (Engeström 1987) or open-ended cultural extension (Pickering 1995). All the elements of the activity have interactively undergone a change: the research object was transformed, the knowledge of the object phenomena, methods and instruments as well as the social basis of the research. In addition to cellulases and hemicellulases, ligninases were now studied. More people with more extensive disciplinary background were involved, the methods are more varied and more elaborated, the instruments more expensive. This expansion has also made activity more complex thereby causing difficulties in coordination of the interconnected activities of the different groups.

How was the idea of biotechnical pulp bleaching related to this expansive change? After 1983 it was increasingly difficult to find financing for research on the production of ethanol from wood. There was no other clear-cut or major application in sight. At the same time the study of cellulases and hemicellulases was developed clearly as the scientific core of the research agenda of the laboratory. Research on cellulases was beginning to gain an international reputation. New applications had to be found to use and further develop this know-how. The enzyme-aided pulp bleaching was the

¹⁴It is a technology with which only a one pair of bases of the DNA coding the production of protein is changed to cause a very specific change in the order of aminoacids of the protein - and hence in the activity or other qualities of the protein. pH- and temperature resistance are important qualities for the enzymes used in pulp and paper industry.

first and most important of these applications. It, in turn, oriented the research to seek application more broadly in the pulp and paper industry. Actually, the name of the project in 1987 - 1990, following the biotechnical bleaching project, was "The applications of hemicellulases in the pulp industry."

3 THE INVENTION PROCESS IN 1984 - 1986

3.1 THE EMERGENCE OF THE IDEA OF BIOTECHNICAL PULP BLEACHING

The idea of the biotechnical pulp bleaching was formulated in a meeting at the VTT Biotechnical Laboratory on January 19 in 1984. Five researchers were present.¹⁵ In the minutes of the meeting written by one of the researchers the idea was named the "enzymatic degradation of residual lignin and hemicellulose." The idea was formulated in the minutes of the meeting as follows:

"Research on the degradation of residual lignin and hemicellulose will be started with a preliminary study. First, the feasibility of the idea will be investigated. Research on 1) the effects of xylanases, 2) the effects of "ligninases", and 3) the co-effects of the two will be carried out."

In kraft pulping a small amount of lignin remains in the pulp, causing its dark brown color. In bleaching this residual lignin is removed from the pulp. The meeting formulated two possible ways of using enzymes to make removal possible. First, the use of lignin-degrading enzymes would be studied. This idea was stimulated by a recent discovery by Tien and Kirk (1983) of an extra cellular enzyme of a white fungus that could degrade lignin. However, virtually nothing was known about the production and use of ligninases. However, the laboratory did have much experience with hemicellulases, especially xylanases that degrade xylan, the main hemicellulose of hardwoods. According to the participants of the meeting, it was known that the residual lignin is somehow connected with the hemicellulose in unbleached pulp. Consequently the second idea was presented. By degrading hemicellulose selectively, the residual lignin could more easily be extracted from the pulp. This later, secondary idea, eventually proved successful and formed the basis of the innovation. It was the "inventive" aspect in the idea formulated at the meeting.¹⁶

Who invented the idea? The question is futile. It was developed and elaborated in a discussion. Two of the participants are ready to take the honor, although in a very modest way:

¹⁵ Research director Tor-Magnus Enari (VTT BIO), Research prof. Allan Johansson (VTT Chemical Laboratory, the convener of the meeting), Prof. Jonathan Knowles, director of the r(DNA) group of VTT BIO, Professor Matti Linko, Director of VTT BIO, and Dr. Liisa Viikari, who took the minutes of the meeting. I interviewed the participants, except Prof. Knowles who eventually left VTT and no longer lives in Finland.

¹⁶Afterwards it is impossible to know what the participants knew about the linkages between lignin and hemicelluloses. When the project started the relevant literature was naturally reviewed. All later learning has no doubt influenced by the way in which the interviewees remember what was discussed and proposed. In the first project plan (16.4.1984) the relation was formulated as follows: "With the aid of an enzyme that specifically degrades xylan the bonds between residual lignin and hemicellulose can be weakened and the need for bleaching chemicals diminished."

"We didn't know much about ligninases. If we decide to study them, it will take a long time(...) Instead a question was raised - I think it was me who asked it - where is lignin attached to the wood? The answer is that it is attached to the hemicellulose. I also suggested that we should degrade the hemicellulose to the extent that the lignin comes off. We know how to degrade hemicellulose. We have the enzymes for that. This was the basic idea. The research started to evolve from this idea. Later it turned out that the mechanism is different. The basic conception is wrong but the idea works"

"It came to mind that the residual lignin is somehow attached to the hemicellulose. (...) This led to the idea that it might be worth while to use the hemicellulases of the Biotechnical Laboratory to split off a part of it and maybe the fragments of lignin would come off easier. If you make it very specifically you don't lose much hemicellulose and the quality of the fibre does not suffer in the process (...) this was the idea which - as far as I can remember - I presented at the meeting. (...) If I made any contribution, it was the idea that gentle removal of the hemicellulose might be a feasible solution."

The third account by a participant was depersonalized and includes a longer time perspective.

"We got the idea that if we couldn't affect the lignin, then what is the other enzymatic possibility? We dealt with it in different discussions. Little by little the basic idea crystallized. The lignin is so tightly attached to the hemicellulose - it was even proposed that there are covalent bonds between lignin and hemicellulose - what would happen if we degrade the hemicellulose a little? Some provisional experiments were carried out - without knowing in any exact way whether it would work or not."

This account even suggests that the idea had been discussed before the meeting. It was the formulation that was worked out at the meeting. The idea of using hemicellulases was the secondary idea of the meeting. The primary option was to study the possibility of using ligninases. The hemicellulase solution proved to be an innovative idea only afterwards - after a long process - as we will see.¹⁷

The formulation of the idea of enzymatic pulp bleaching is an example of a distributed invention. No single person can be considered the inventor. It is impossible to trace who first raised the issue in the meeting and how it was elaborated in the discussion. Probably both of the persons claiming to have presented the idea, made their own contributions. This possibility will become more evident when the cultural and organizational conditions of the invention are studied more carefully. This invention fits the conception developed by the theory of cultural preparation. It was 'in the air' - the cultural conditions were present. However, the highly local conditions, the motives of the actors and

¹⁷ The primacy of ligninase option is expressed in the documents in many ways. The minutes of the second meeting on pulp bleaching (6.2.1984) were entitled "The biological degradation of lignin." In the first articles on the research project (Viikari & Ranua 1986) the significance of lignin research was greatly emphasized. The ligninase project received FIM 6 million for 1984 - 1987, whereas the bleaching project (with hemicelluloses) FIM 3 million. It later turned out that the enzymatic degradation of lignin is a very difficult problem and applications were unlikely in short period. Ligninase research at the VTT BIO was - for the time being - stopped in 1992.

combination of resources basically made it happen at VTT. These two are in no way mutually exclusive.

3.2 THE CULTURAL AND SOCIAL CONDITIONS OF THE IDEA

I have collected the relevant cultural elements of the invention in Figure 4. It depicts the 'general' cultural preparation of the idea, the motives and resources of the local actors and the social mechanism through which the idea was born.

The background: research on biotechnical pulp bleaching

The idea of biotechnical pulp bleaching was not new. Several research groups had studied methods for degrading the residual lignin present in unbleached pulp in the 1970s. The groups of Kent Kirk at the Forest Product Laboratory of the US Department of Agriculture and Karl-Erik Eriksson of the Swedish Forest Products Research Laboratory had studied the effect of white-rot fungi on the degradation of kraft lignin since the beginning of the 1970s (Hiroi & Eriksson 1976; Lundquist et al. 1977). Kirk had defined the problem of present bleaching methods very clearly (Kirk & Yang 1979, p. 347):

"Wood pulp produced in the kraft ('sulfate') process generally contains 5 to 8% by weight of residual, modified lignin, which gives the pulp a characteristic brown color. This residual 'kraft' lignin is removed commercially by bleaching with chlorine and chlorine dioxides. Chlorinated products derived from the kraft lignin during these bleaching procedures have been recently shown to be mutagenic (Ander et al. 1977) and they obviously represent a waste treatment problem, both because of their toxicity and their dark color, which resist classical biological methods. Alternative methods are needed for bleaching pulp."

Kirk's group cultivated the fungus *Phanerochaete chrysosporium* on pulp. Compared with control treatments, 27% less chlorine was needed in the bleaching experiments with this pulp and the brightness of the pulp achieved was considerably higher (1979). These studies were well known and evidently contributed to the formulation of the idea at the VTT Biotechnical Laboratory. The organisms cannot be directly used in the industrial bleaching processes. The revolutionary discovery of Kirk's group was a lignin-degrading enzyme excreted outside cells in 1983 (Tien & Kirk 1983). The possibility of producing and using ligninases raised great expectations and hopes.

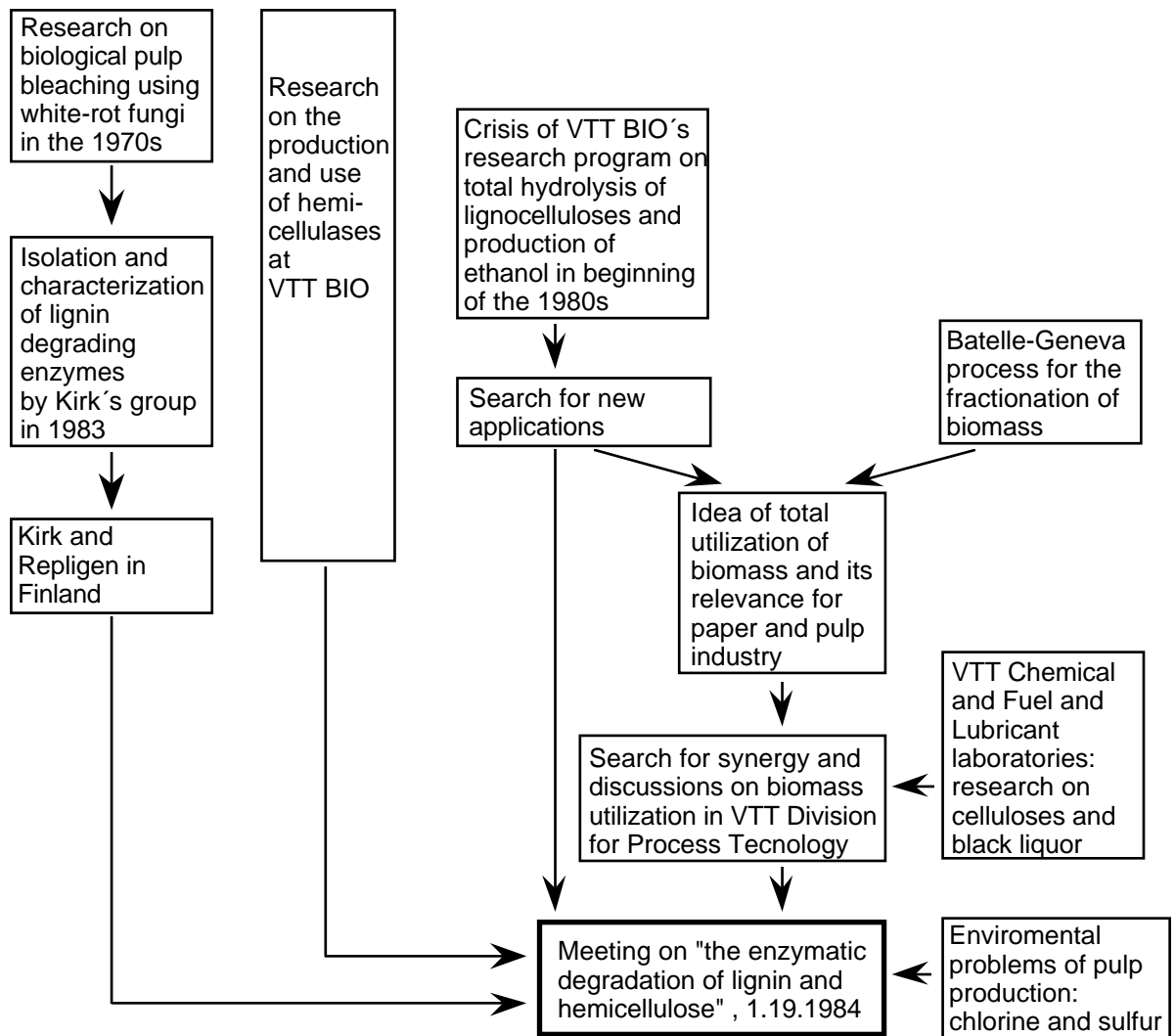


Figure 4. The elements of the emergence of the idea of enzymatic pulp bleaching.

"There was tremendous enthusiasm. We all thought that everything can be done with this, for instance removing the residual lignin from the fibre."

"Kirk's observations combined with the work of Eriksson created new spirit and everybody started to dream of biotechnical pulp production. So did we in the same rush of enthusiasm."

"In 1982 - 83 research results were published on the biological degradation of lignin. This raised general interest in what could be done with biotechnical methods. Everybody of course thought that the pulp industry is the new area in to which we should go. This was evidently the background for the discussions we had."

These statements illuminate in an interesting way the significance of the 'discovery' of Kirk's group. Kirk's results opened a wholly new perspective for research on degradation of lignocellulose: the possibility of degrading and modifying the most complex of the fractions of wood, lignin. It hence gave a new means of applying the vision of "total wood utilization," covering all the fractions ¹⁸. It was the 'promise' or signal of possibility included in these results that reoriented the activity of several research groups in the field, not the facticity of the results. These results also directed the research toward pulp and paper industry.

Kirk also visited Finland. The Repligen biotechnology firm sold services based on Kirk's group's results. A Finnish construction company Partek has a holding in Repligen and was active in organizing collaboration between Repligen and the Finnish forest industry. The research manager of the Metsä-Serla Company explains how Repligen contacted him:

"They eagerly offered us their ligninases. We were building the Äänekoski pulp mill and we said okay. We'll send a sample in two weeks. Let's see what you can do with it. They tried to do something with it, but nothing happened. It turned out that they had done their experiments with old Canadian pulp, which had a double lignin content compared with our pulp. There is even waste liquid in pulp like that. We call it salted pulp. It is obvious that lignin would degrade in stuff like that. But it had no effect on our pulp."

The decisive factor: hemicellulase research at the VTT Biotechnical Laboratory

The general idea of biological pulp bleaching was not new. What was new was the idea of using hemicellulases in bleaching. The precondition for the idea was 'local,' the fact that hemicellulases had been produced and used at the Biotechnical Laboratory and hence could be used easily and immediately in bleaching experiments, in contrast to the long-term perspective of studying and producing ligninases. The idea was closely connected with the research tradition of the laboratory. The production and use of hemicellulases were actively studied around the time of the meeting in several projects, 'on a broad front,' as one of the researchers expressed it. Of course the hypothesis of the attachment between hemicellulose and lignin in the pulp was also required to formulate the idea.

Research on hemicellulases was a direct outgrowth of research on the cellulose. One of the first objects of enzymatic degradation experiments in the 1970s, waste liquid from Savon Sellu, contained a considerable amount of xylan, the most important hemicellulose of hardwoods. Another raw material,

¹⁸The basic phase in pulp production is 'cooking' in which the lignin is dissolved to separate the cellulose and hemicellulose fibers at high temperature (170 grades) and pressure (12 bars) with 'hard' chemicals (NaOH, Na₂S). Consequently, the discovery of the lignin-degrading enzyme opened the revolutionary vision of a biological, environmentally sound and low-energy pulp production method.

peat, also contains large amounts of hemicelluloses. Research on the production of hemicellulases began in 1976. The organism used in the production of cellulases, *Trichoderma reesei*, also proved to be a good producer of hemicellulases (Linko et al. 1977; Viikari et al. 1978). In 1978 the need for studying the production of xylanases was justified as follows (Viikari et al. 1978, p. 147):

"Important potential industrial uses for hemicellulases, especially xylanases, include enzymatic hydrolysis of waste materials of plant origin to fermentable sugars. As hemicellulose and cellulose, the main components of most plants, are usually present in close association, the hydrolysis of both polymers may be necessary for an economic process. Research in this field has so far been mainly concerned with the production and use of cellulases."

In the beginning of the 1980s hemicellulases were studied in several projects. They were studied in a project for producing ethanol and feed protein from surface peat at the VTT Biotechnical Laboratory. The use of hemicellulases was also studied in a project on pretreatment of cellulosic materials started in 1982 and conducted together with the Biotechnical Laboratory and the Institute for Wood Chemistry of the Federal Research Centre for Forestry and Forest Products of the Federal Republic of Germany (Hamburg). Production and use of hemicellulases was also studied in a project on utilization of pentoses (hemicelluloses) started in 1984 by the VTT Chemical and Biotechnical Laboratories.

Hemicellulase research was conducted mainly in the context of ethanol production. Both cellulose and hemicellulose were to be degraded into sugars for the production of ethanol to make the process economic (Linko et al. 1983). In the beginning of the 1980s several related problems were studied at the Biotechnical Laboratory: organisms and methods capable of hydrolysing hemicelluloses to pentoses and fermenting them to ethanol (Viikari 1983), pretreatment of wood materials to make them accessible to enzymatic hydrolysis (Poutanen & Puls 1984) and the simultaneous enzymatic hydrolysis of lignocellulose and ethanol fermentation (Linko et al. 1983). As a result of this research activity, several types of hemicellulases were produced and used in tests to hydrolyze xylan by 1984.

The concept of total utilization of wood and its connection with the forest products industry

The central concept used as an argument in the project plans and review articles about research on degradation of lignocellulose was the *total utilization of biomass or wood*. This concept was based on two arguments. First, lignocellulosic materials are the most abundant renewable raw material on earth. However, its utilization for the production of food and energy is not economically feasible. If all the fractions of cellulosic waste materials

originating in industrial processes could be utilized, the processing could become economically feasible.¹⁹ This general model was modified when new knowledge of the hydrolysis of different fractions was obtained. Figure 5 describes one of the versions of the concept presented by Professor Enari in 1986. The model now covers the two main types of hemicelluloses, xylan and glucomannan. The former is the main hemicellulose of hardwood, the latter is dominant in softwood.

Also the hypothesis of the possible applications changed according to the social and economic problems that were faced. In the late 1960s it was believed that production of single cell protein would resolve the problem of hunger. In the 1970s - as a result of the oil crisis - cellulosic materials were thought to be the raw material for an alternative fuel. In the early 1980s there was another major redefinition.

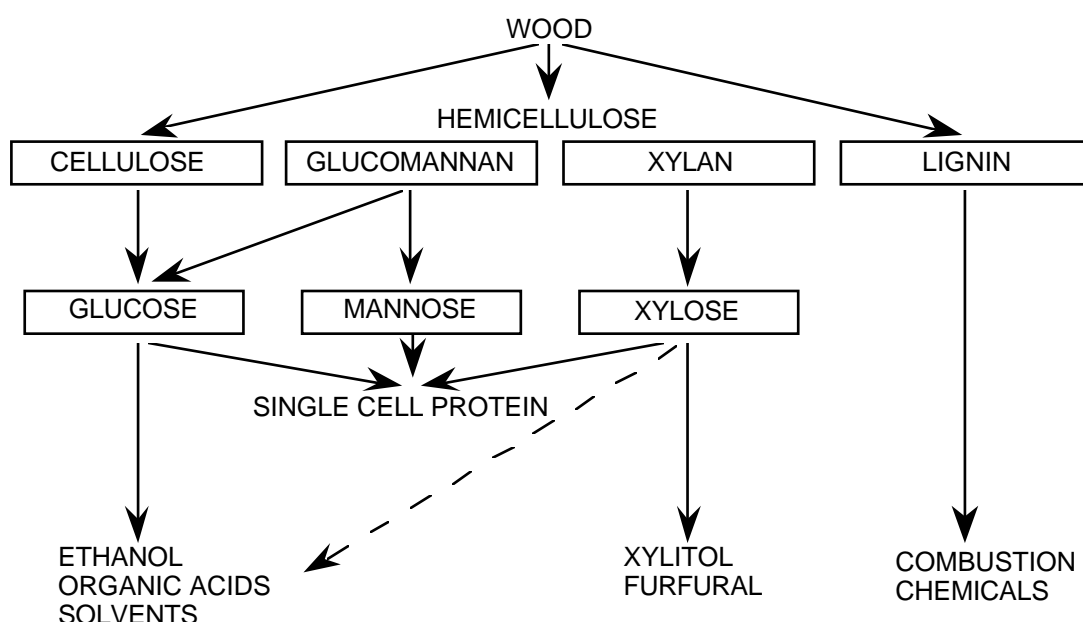


Figure 5. The model of total wood utilization (Enari 1986).

¹⁹ Arthur Humphrey of the University of Pennsylvania was one of the researchers who developed the concept in the 1970s. In 1975 he stated the following (1975, p. 439): "There is no doubt in my mind that in the long term cellulose as the major renewable resource must become a viable source of food, energy and consumer goods. General schemes for achieving this are fairly clear. Their practicality is only a matter of time." In 1979 he was more cautious and explicit (1979, p. 26): "Based on present technology cellulase utilization through hydrolysis processes does not appear economical for the production of sugar syrups or alcohol fuels, particularly if biomass costs are greater than \$30/ton. However, there is reason for optimism. If ways can be found to improve yields, especially to achieve total biomass utilization and to improve the values of process byproducts, then process feasibility will emerge." The concept of total utilization of biomass is a kind of metaconception that combines social, ecological, technical and economic aspects of using the major renewable material on earth. It also includes a strong tension between what would be sensible, just and technically possible and what is economically feasible. It was formulated by several authors in the late 1970's. Its versions formulated (Viikari et al. 1981; Enari 1986) at the VTT Biotechnical Laboratory were based on know-how, raw materials and processes available in Finland. This is another example of the interpenetration of the common cultural and the local.

When ethanol research lost its funds and viability, this concept was reformulated in a way that led to the idea of the enzymatic pulp bleaching. Cellulose is a valuable fibre and should not be degraded into sugars. Instead, it should be used in the pulp and paper industry. Enzymes could be used to improve and modify the quality of fibres for different purposes. Moreover, the forest industry does not use the other fractions of wood in the best possible way. In conventional pulping processes more than half of the raw material is dissolved into the waste liquid (called black liquor) and is subsequently burned to produce energy. New uses that add more value should be found for these fractions (Report of the working party on technology programs, 1984).

"Cellulose is of course so valuable as fibre, that the macromolecules should not be hydrolyzed. Current pulping processes are inefficient in that they make use of only half of the raw material and also cause pollution. The pulping process should therefore be developed to allow profitable use of all wood components" . (Enari 1985, p. 66)

Professor Enari outlined the new pulping process presented in Figure 6. This model was an application of the principle of total wood utilization to the pulp production process.

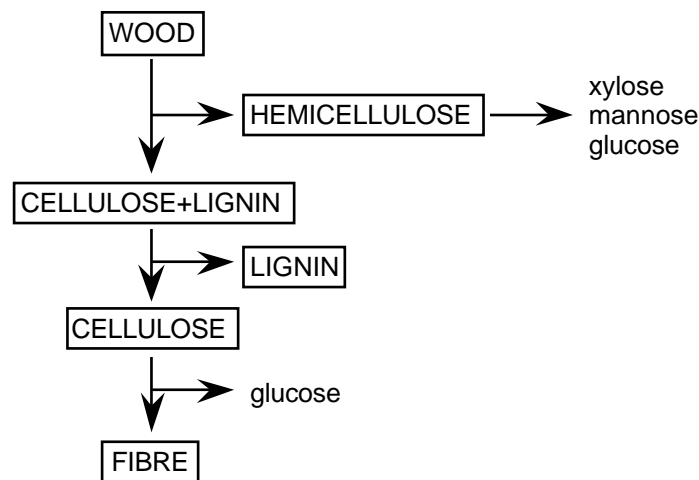


Figure 6. Outline of a new pulping process (Enari 1985, p. 66).

The problem of the raw material oriented the cellulose research toward pulping process. The idea of the first projects on cellulase research was to utilize cellulosic waste materials of the food industry as raw materials for the production of sugars. It soon turned out that the amounts were all too small for any productive purposes. The second idea was to use the most abundant cellulolytic material, the waste material from forest production. As was mentioned before, it proved to be too scattered and too resistant to enzymatic hydrolysis. Consequently the question arose of whether the

enzymatic hydrolysis could somehow be used as a part of the pulping process, using the fractions of raw materials processed in it.

The pulp and paper industry is the most important industry in Finland, accounting for some 40% of Finnish exports. The research tradition and industrial know-how in paper and pulp production - basically modification of cellulose fibres - is strong. The raw material source for enzymatic processes was in the hands of the forest industry. Hence the transfer from ethanol production - energy use - to total utilization implied collaboration with the forest industry and the related research field, classic wood chemistry.

One of the factors that contributed to the reorientation of the pulping processes was the recruitment of a new researcher with a strong background in forest production, fractionation, and the use of biomasses. In the early 1980s Dr. Allan Johansson and his colleagues developed a fractionation method for biomass at the Batelle Institute in Geneva. The scheme of the process is presented in Figure 7. In this method phenols are used to dissolve lignin, the cellulose fraction is separated by filtration, and the remaining liquid is cooled. During cooling the phenol portion with dissolved lignin separates spontaneously from the aqueous phase containing pentose (hemicellulose). Each of the three fractions can be processed further. This system included a version of the idea of "total biomass utilization" in a materialized form.

The central idea of this approach is to use a solvent with which the lignin in the lignocellulosic material can be extracted leaving the cellulosic fraction undisturbed (Johansson et al. 1982, p. 9):

"The Batelle-Geneva fractionation process possesses the unique feature of allowing a separation of the three main components of biomass into separate fractions which can be valorized independently without the need for regeneration of chemicals. In contrast to other methods of biomass upgrading such as pyrolysis, gasification or even complete hydrolysis in which both the lignous and fibrous structure of the original matter is totally or partially destroyed the components are by this method recovered virtually in their original form (with the exception of the hydrolyzed hemicellulose fraction)."

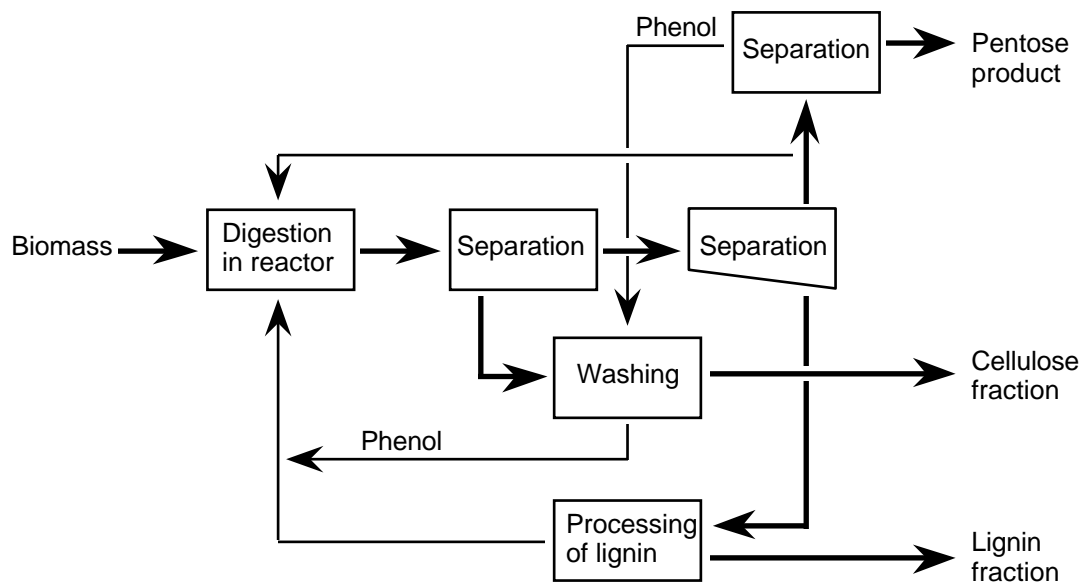


Figure 7. Batelle-Geneva system of biomass fractionation (Johansson et al. 1982, p. 4).

Dr. Johansson brought the idea of "biomass refining" and his knowledge on pulp and paper production to the Chemical Laboratory of the Technical Research Centre of Finland. These ideas contributed to and concretized the idea of development of total use of cellulosic materials and helped to connect it with the context of the pulp and paper production.

In 1983 the Ministry of Trade and Industry appointed a committee with the task of suggesting national technology programs. Professor Enari prepared one of the programs called "The use of wood as a raw material of the chemical industry." The aim of the program was more efficient use of biomass by developing fractionation methods and utilization of lignin and pentosan fractions. The user of the results was supposed to be the Finnish pulp and paper industry (Report by the working party on technology programs, 1984). The idea behind the program was later expressed by the organizer of the program as follows (Enari 1985, p. 7): "Enzymes can play a key role in the development of a new sulfur- and chlorine-free pulping process which makes optimal utilization of all main wood components possible."

The social mechanism of preparation: search for synergy at the VTT Division for Process Technology

A year before the meeting on the enzymatic hydrolysis of pulp, a series of discussions concerning biomass refining and synergy were held by the laboratories of the VTT Division for Process Technology. All five laboratories of the division conducted some uncoordinated research on biomass. The Chemical Laboratory studied solubilization of celluloses used in the production of viscose. The Fuel and Process Technology Laboratory studied

alternative fuels and was initiating research on the utilization of waste liquid from the sulfate pulp process, black liquor. The Combustion and Thermal Laboratory studied peat and combustion processes. The declining funds for ethanol research also hit other laboratories studying alternative fuels and energy forms. An attempt was made to form a synergistic program on biomass that would interest all the laboratories.

"We tried to link these attempts to the Biomass program at VTT (...) We had some seminar-type discussions on how to link up the existing know-how and needs in some way without knowing exactly what to do. This is a very important market area - at least potentially - in Finland. An organization began to develop around biomass: discussions, idea generation, etc. We were quite open to new ideas."

It was in these discussions that the different points of views and arguments were linked together and refined. As a result of these discussions a four-year VTT research program called "Sustainable Technology" was initiated in 1984. One of the projects of the program was concerned the utilization of pentoses (hemicelluloses) directed by Dr. Johansson together with a researcher from the VTT Biotechnical and Chemistry Laboratories. This project studied the production and use of xylanases. The issues essential in the idea of enzymatic bleaching of cellulose - environmental impacts and utilization of waste materials (including hemicelluloses) using hemicellulases - were prominent in the discussions and activities of the VTT Division for Process Technology in 1983 - 1984.

The meeting that formulated the idea of biotechnical pulp bleaching was a part of this search for new directions. The convener of the meeting was the organizer of the discussions. There were also "strategic planning discussions" initiated by the management of VTT. A consultant who had worked with the pulp and paper industry participated in these discussions and contributed by insisting that the biotechnical know-how should be connected to problems of the forest products industry.

3.3 EARLY PLANNING OF THE PROJECT: MOBILIZING RESOURCES AND ACTORS

The two meetings (January 19 and February 6, 1984) on enzymatic degradation of the residual lignin and hemicellulose of pulp immediately began to in organize a preliminary project to get the work started. The seven-month preliminary project was financed by the VTT Biotechnical and Chemical Laboratories. The main content of the minutes of the meetings concerns how to acquire the material means and methods necessary for the project. Three elements were needed: 1) organisms that produce enzymes and the enzymes used in the experiments, 2) substrates, i.e. different kinds of lignin compounds to be degraded in the experiments, 3) methods of analysis of the results of the degradation experiments. Because the Biotechnical Laboratory had not studied lignins the enzymes, organisms and substrates needed in lignin research would be acquired from outside,

from other research groups and persons with which the researchers had previously collaborated.²⁰ This task of mobilizing resources is presented in Table 4. A list of elements or necessary resources is presented first and then the person who could supply it. The person responsible for contacting these 'resource' persons was then chosen.

The idea of biotechnical pulp bleaching, the material elements necessary in the experiments and social networks of researchers and research groups are indistinguishable in the draft for the project. This kind of co-evolution and interdependency of the material and the social was analyzed by Callon in his early version of the sociology of transformation or the actor network theory (1980).²¹ The content and the network of actors are planned as indistinguishable parts of the same process. The principle of co-evolution, or mobilizing social, material and intellectual resources as aspects of one and the same process, seems to characterize the organizing of bleaching research.

Table 4. The material resources needed to start experiments on biotechnical pulp bleaching and researchers/research groups having and potentially supplying these resources.

Organisms and enzymes**Hemicellulases**

- Those produced at VTT Biotechnical Laboratory
- Commercial hemicellulases

Ligninases

- Matti Leisola (ETH, Technical University of Zürich)
- Paul Broda (Department of Biochemistry, Manchester University)
- Annele Hatakka (Department of Applied Chemistry and Microbiology, University of Helsinki)

Ligninase producing organisms

- Annele Hatakka (Department of Applied Chemistry and Microbiology, University of Helsinki)

Lignin model substrates

- Gösta Brunow (Laboratory of Organic Chemistry, Department of Chemistry, University of Helsinki)
- Jürgen Puls (Federal Research Centre for Forestry and Forest Product, Institute for Wood Chemistry, Hamburg, FRG)

Method of analysis of lignin degradation

- An indirect method recently developed by Kent Kirk (Forest Production Laboratory, US Department of Agriculture)
 - Methods that are available and will be developed at the VTT Chemical Laboratory.
-

²⁰This can be characterized as mobilization of existing "latent" relationships and is one expression of the strength of weak ties, not constantly and frequently active relationships (Granovetter 1973).

²¹Callon studied a plan for a energy research program in France. He indicates in the form of a table how the content and research themes, the research groups interested in these themes and financing are planned at the same time in the proposition for the research program. From the beginning the relationship between the cognitive and the social is analyzed in terms of power: whose definition will dominate (1980, pp. 197 - 198). However, an analysis of the research traditions and material resources of each of the actors is also needed to understand the relationship.

3.4 CONSTRUCTING NETWORKS FOR RESEARCH AND DEVELOPMENT

The network of actors outlined in the first meetings was never realized. A new factor emerged and the social basis of the enterprise was extended. A new technology policy organization, the Technology Development Centre, was founded in Finland in 1984. Its primary task was to organize and finance national technology programs. One of the first programs was "*The use of wood as a raw material of process technology.*" This program included the idea of developing new chlorine- and sulfur-free pulping methods. Biotechnology would contribute to this aim (Enari 1986). The research on enzymatic pulp bleaching integrated with this program was one of its projects.

Its social basis also changed. As a part of the preparation for the new programs, discussions were held by the VTT Biotechnical Laboratory and the Fibre Chemistry Laboratory of the Finnish Pulp and Paper Research Institute (FPPRI), owned by the Finnish pulp and paper industry.²² It was agreed that FPPRI would participate in the pulp bleaching project. What motivated the Fibre Chemistry Laboratory to participate in the project? The laboratory resumed its activity in 1981 and started to study soluble pulps and viscoses. In 1983 the owners and management of the FPPRI urged the laboratory to reorient its activity to the main area of the institute, the paper celluloses. In devising a transformed object of research, the laboratory decided to focus on environmentally sound paper production techniques, more exactly chlorine-free and sulfur-free production of chemical pulp. The use of enzymes and the organosolv methods were the most interesting alternatives available. The laboratory concentrated on the latter and in 1984 - 1986 it developed a pulping method called MILOX, based on the use of peracids and hydrogen peroxide (Sundquist 1986). But as the use of enzymes was continuously relevant for diminishing harmful chemicals in pulping, it was natural for the Fibre Chemistry Laboratory to participate in the project on biotechnical pulp bleaching. By participating it could follow up and evaluate the enzyme option. It was the 'chlorine- and sulfur-free pulping' that was the common object of the VTT Biotechnical Laboratory and the Fibre Chemistry Laboratory.²³ Both of them had their own research object (biobleaching and MILOX) within this larger aim. Because these objects were noncompetitive and the know-how and analytical resources clearly distinct and complementary, and the division of labour was clear, the collaboration was relatively efficient.

²²Professor Enari, one of the organizers of the the program, proposed collaboration to the director of the Fiber Chemistry Laboratory of the FPPRI, Professor Sundquist, after a meeting related to another project. They knew each other well, because Prof. Sundquist had worked at VTT in the 1970s. The laboratories of the FPPRI and the VTT Biotechnical Laboratory are situated near each other in Otaniemi.

²³ This 'shared' aim appeared in the texts and speeches of the representatives of both laboratories. It was also the central theme or ideology in the national technology program entitled "Wood as a raw material for process industry." This object united these two laboratories against the rather conservative conceptions of the pulp and paper industry and the traditional wood and cellulose chemistry.

The FPPRI has a half century tradition in producing and analyzing the paper technical properties (brightness, strength, etc.) of pulps and in bleaching experiments. The division of labor was clear. FPPRI provided the Biotechnical Laboratory with the pulps used in the hydrolysis experiments. The Biotechnical Laboratory acquired the enzymes, conducted the hydrolysis experiments and sent the hydrolyzed pulp to FPPRI. FPPRI did the bleaching, analyzed the pulps and compared their characteristics with the reference pulps. The resources and instruments were clearly complementary.

*"Somehow I wanted to stay out of biotechnology. We did only the bleaching. The pulps traveled back and forth. VTT did the enzymatic treatment. We did the bleaching here."*²⁴

"Of course collaboration is easiest with partners who do not conduct the same kind of research at all and both know their own specialty."

In the expansion of collaboration outside VTT, the VTT Chemical Laboratory was superseded. This was based on the view that the VTT Chemical Laboratory could not create the capabilities for producing and analyzing the pulps necessary in the project. However, the national technology programs favored collaborative projects with representatives of several institutions. Thus this collaboration also represented a move towards more extensive collaboration with the Finnish forest products industry.

The VTT Biotechnical Laboratory also developed scientifically significant collaboration with the Institute for Wood Chemistry of the Federal Research Centre for Forestry and Forest Product of the Federal Republic of Germany (BHF Hamburg) in the early 1980s. The institute had advanced capability in the analysis of carbohydrates important in the analysis of the activities of the enzymes. Collaboration of the VTT Biotechnical Laboratory and BHF began in 1982 when a researcher of the Biotechnical Laboratory visited BHF. Doctor Jürgen Puls and the Institute of Wood Chemistry and Technology of Wood were interested in the enzymatic hydrolysis of wood. A co-project on enzymatic hydrolysis of cellulose and hemicellulose after pretreatment was initiated in 1983 (Poutanen & Puls 1984). This research did not directly influence the early pulp bleaching experiments of 1984 and 1985. In the following years, when the mechanism of hemicellulose hydrolysis was studied, this collaboration became important and contributed crucially to basic research on the biochemistry of xylanases (Poutanen 1988). One of the researchers characterizes the basis for collaboration as follows:

"In the beginning of the 1980s our laboratory began to have a sound knowledge of enzymes, on their activities, possibilities and also their effects. Especially when

²⁴ Actor network theorists would say at this point that "pulp" is a central mediator, a real material connection between the actors; something that moves between them (Callon 1992). However, apart from the object of research and research programs of the actors, this is not very informative. Basically, it is the knowledge of how enzymes effect unbleached pulp and help in the degradation of lignin (the object) that is important for the actors, not the material flow of samples nor even the separate sheets of results ('inscriptions').

working with hemicellulases we realized that we know enzymes, but we don't know substrates. We didn't understand wood and its structure very well. Puls had an adverse situation. He was - and continuously is - a talented wood chemist who knew wood well. He had also tried something with enzymes but not succeeded. Since he didn't know enzymes very well it was an appropriate situation; Kaisa Poutanen was an excellent specialist in enzymes, Puls an excellent specialist in substrate and together they did excellent work."

Another researcher characterized the relation as follows:

"They utilize our enzymology. We produce enzymes - they don't have any production systems. Their analytical appliances are superior to ours.(...) We send samples to them to be analyzed. Somebody from Hamburg comes here to study the purification of enzymes, because they have no purification system there (...) We also send enzymes when needed. (...) In fact, no money has been exchanged between us for a long time."

This scientific collaboration has been productive. The groups wrote 28 co-authored papers in 1985 - 1991. Doctor Puls has been an opponent in dissertations written by the researchers of the VTT Biotechnical Laboratory. A professional relationship has developed into friendship. The collaboration was also a learning process. The biochemists of the VTT Biotechnical Laboratory have learned much about wood chemistry. The collaboration also constantly produced ideas on alternative methods and research designs for experimental work.²⁵

The basis of the co-operation can be analyzed in terms of the complementarity of tools and methods as well as in terms of the research objects of the partners. In the first case, the partners clearly had their own research objects that were linked to a broader common object - chlorine- and sulfur-free pulping. In the second case, the common object was on a more generalized level - understanding the degradation mechanism of the different fractions of wood and lignocelluloses. Within this common object both partners had their special knowledge and corresponding objects (enzymes, carbohydrates of wood) which, however, were clearly connected through the enzyme-substrate relation. This facilitated continuous common projects, co-learning and co-creation as well as extensive co-publication possible.

I think that this approach - analysis of the complementarity of know-how, capabilities and resources of the the partners in relation to the common object - is more fruitful in the analysis of collaborative networks than the characterization of "mediators" that move between the actors proposed by some of the actor network theorists (Callon 1992; Vinck et al. 1993).

²⁵ The VTT group started to study hemicellulases called mannanases in 1988 when they were optimizing the enzymatic bleaching process. One of the researchers describes how a discussion with the partner oriented the experiments: "As a matter of fact it was Jürgen Puls who in a meeting told us that not all the mannanases are equal. We had a bacterial mannanase. And we have tried it and it didn't have any effect. Then we started to look for the mannanases of the *Trichoderma* (...) It was purified and we discovered that it was completely different from bacterial mannanase and indeed increased the bleachability of the pulp."

Substrates, samples, enzymes and result sheets of analyses move between the actors. Non-material processes such as consultations and discussions, comments and suggestions on plans and papers and evaluation of thesis can be characterized as learning processes. They are extremely important for interaction. The value of both kinds of artifacts becomes understandable only on the basis of the common object of the groups: understanding the degradation of wood.

3.5 FIRST EXPERIMENTS AND THE RESULTS

The project was organized into two research groups. One started research on ligninases. The ligninase group had to study the production of ligninases and characterize the enzymes to be used in the bleaching experiments. The other group started the bleaching experiments with hemicellulase preparations. In the first experiments the pulp became brighter as a result of the enzyme treatment. However, the pulp was of lower quality than that used in conventional bleaching. This was the enzyme preparation also contained small amounts of enzymes that could degrade the cellulose fibres and made them weaker. As a result, too much hemicellulose was degraded. This decreased the pulp yield and adversely affected the bonding ability of the fibres in the paper making process thus weakening the paper.

In 1985 the researchers looked for new enzyme preparations with lower cellulase activity. Experiments were carried out with new preparations and adjusted enzyme doses.²⁶ In these experiments it turned out that the pulp treated by a hemicellulase preparation was more easily bleachable and the need for chlorine declined. The results were published in the Third International Conference on Biotechnology in the Pulp and Paper Industry in Stockholm in June 1986 (Viikari et al. 1986, p. 69):

*"In order to study the effect of the enzymatic treatments on the chlorine consumption and to achieve a more efficient delignification, a (DC)E prebleaching was applied. Using the bacterial hemicellulase preparation for pretreatment, a kappa number of 5.5 was obtained, with a concomitant reduction of 25% in the consumption of chlorine chemicals."*²⁷

These experimental results subsequently led to a new bleaching method. In 1986 it was, however, just one experimental result for the researchers. This particular result was not discussed in the conclusion of the paper. The conclusion stated that promising results were obtained both with hemicellulases and ligninases acting directly on lignin. "However, the

²⁶This difficulty reflects the transition from the program of "total hydrolysis of cellulase" to the selective use of enzymes. The first experiments still followed the model developed in the hydrolysis experiments.

²⁷The bleaching process is composed of a series of phases, each of which is designated with a letter referring to the chemical used in the phase: C=chlorine. D=chlorine dioxide, E=alkali. The Kappa number is the measure of pulp brightness.

application of ligninases offers the greatest potential for future development," it concludes.

The result was defined as a discovery only afterwards. This experimental result was not important - only potentially and in the context of growing environmental concern. In 1986 it was not shocking in terms of the aim of the research, "the elimination or significant reduction of chlorine chemicals used for the bleaching of unbleached pulps." The result was not important for the paper and pulp industry. Chlorine was an efficient and cheap bleaching agent. The participants from the Biotechnical Laboratory and the FPPRI uniformly recollected that representatives of the pulp and paper industry and wood chemists considered the project insignificant or even irrational; why degrade hemicellulose if lignin is to be removed from the pulp? They also said that the result was not patented by the authors because the representatives of the pulp and paper industry deemed it insignificant. The method was patented later by Cultor, a Finnish enzyme producer. The researchers of the VTT Biotechnical Laboratory regarded this as intellectual theft. From the point of view of Cultor it evidently was a rational measure because it was oriented to the production of cellulases and it collaborated with a Finnish forest production firm, Enso Gutzeit.

4 SUBSEQUENT DEVELOPMENTS: A LATENT PERIOD AND CHLORINE AND DIOXIN DEBATES AS MIDWIVES OF THE INNOVATION

The Finnish pulp and paper industry was not particularly interested in the application of the research results. The Enso Gutzeit company made the first plant-scale experiments at the Uimaharju Pulp Mill in March 1989. The indifference of the pulp and paper industry was clearly expressed in the preparation of another national technology program related to the forest product industry in 1987. Biotechnical pulp bleaching was no longer included. The VTT Biotechnology Laboratory participated in the program with a more general project, "Enzymes in the pulp and paper industry." Within this project the degradation mechanism of hemicellulose was studied without clear reference to pulp bleaching. This however, gave the research group an opportunity to study the mechanism of bleaching and characterize different hemicellulases and their activities, thus creating the basis for optimizing the use of enzymes in the bleaching process.

During 1990 and 1991 enzymes were tested and used at several Finnish pulp mills. The reasons lay in environmental issues. Several interrelated developments turned the experimental results into an innovation. First, there was a discussion of dioxins, the highly toxic chlorine compounds also called 'super poisons.' They received wide publicity as a result of an accident of a chemical plant at Soveso, Italy in 1973. In the United States it had been discovered that the paper products bleached with chlorine also include small amounts of dioxins. The results of these studies were made public in the New York Times in September 1987 and in several other newspapers and journals during the following months. In the conference on dioxines in Toronto in 1989 results were published on the migration of dioxine from paper packages to foodstuffs.

In Germany, the environmental authorities launched their own studies on the issue and prepared to set strict limits on the dioxin content of paper products. The Finnish forest company Enso Gutzeit was the biggest producer of liquid packaging boards in Europe. It was in danger of losing its main markets in the Federal Republic of Germany. This was one reason why Enso Gutzeit was the first to make plant-scale experiments with enzymes at its Uimaharju plant in March 1989. The ultimate reason for implementation of enzyme-aided bleaching was the emergence of ECF (Elementary Chlorine Free) and TCF (Totally Chlorine Free) pulps. The clients - printing and publishing companies - began to request chlorine-free papers because readers began to prefer chlorine-free products. This change of attitude was also a result of the campaigns of environmental groups, first of all Greenpeace. Another related reason was that enzymatic bleaching was progressive and 'green,' and could be used in advertising and in improving the image of pulp producers, thereby confronting the criticism of environmental movements. Using enzymes became a part of image-building and a tool of competition on the emerging markets.

The pilot plant experiments were planned and realized in complete independence from the Biotechnical laboratory and the FPPRI by Enso Gutzeit in collaboration with Cultor, one of two Finnish enzyme producers. In the case of biotechnical pulp bleaching the technology was not realized or 'stabilized' by one network of actors. It happened through several loosely connected networks. Enso Gutzeit, one of the key actors in the conversion of the experimental results into an innovation, later largely gave up the use of enzymes.

In 1990 - 1992 - along with the formation of markets for ECF and TCF-pulps - enzymes were tested at most Finnish pulp mills. However, the method was an auxiliary solution to the chlorine problem. The problem was immediately resolved by replacing chlorine with chlorine dioxide, a less harmful chlorine chemical. The future method will probably be closed circulation, which presupposes elimination of chlorine. Enzymes are a good solution for many existing mills because they can be added to the old bleaching equipment without significant investments. The researchers summarized the status and significance of the innovation in 1994 as follows (Viikari et al. 1994, p. 346): "It is clear that the xylanase-aided bleaching offers a low investment and flexible technology at least during the transient stage bleaching technology at many mills." Bleaching enzymes have not yet developed into a significant business for the two Finnish producers, Alko and Genencor International²⁸.

The pulp bleaching project also contributed to two more general issues. First, it contributed in raising research on cellulases and especially hemicellulases to a high level at the VTT Biotechnical Laboratory.²⁹ Second, it has been important in fostering integration between biochemistry and enzymology and the pulp and paper industry. It contributed to a nationally important "boundary crossing" phenomenon in Finland: dialogue and collaboration between biochemists, traditional wood chemists and paper engineers. The researchers at the Biotechnical Laboratory said that when research on pulp bleaching began, they had to study wood chemistry to learn about pulps and fibres, the objects of enzymatic treatment. Moreover,

²⁸Genencor International is one of the major enzyme producers in Europe. It is owned by the Finnish company Cultor and Eastman Chemicals. Genetic research and development of the organisms is carried out in the Research Center of the Company in San Francisco. The enzymes are produced in Finland at the plants in Hanko and Jämsänkoski. Roal Oy, a joint venture of Alko Ltd and Röhm GmbH, Germany, started up a new fermentation plant at Rajamäki, Finland at the end of 1993. The plant produces industrial enzymes including hemicellulases used in bleaching of pulp. According to a review made of the literature, by August 1994 more than hundred mill trials were reported, half of them in Europe and the rest in Canada, the USA and Japan. Ten mills reported the use of commercial bleaching enzymes (Viikari et al. 1994).

²⁹ The VTT Biotechnical Laboratory and Alko have studied the production and use of *Trichoderma reesei* enzymes. Two Canadian researchers wrote a review article on *Trichoderma* xylanases (Wong & Saddler) in 1992. The article makes 282 references, 36 of which are (12%) to the papers written by the Finnish groups. The VTT group is regularly asked to write about the use hemicellulases in collections of articles.

paper engineers have increasingly approved biotechnology as a potential tool in the pulp and paper industry. New, more intensive collaborative projects have been started with the participation of biochemists and paper engineers. Enzymology has provided new tools for studying the structure of fibre and cellulose.

5 SUMMARY AND CONCLUSIONS

The invention of enzyme-aided pulp bleaching was a process that took many years. It took only two years from the formulation of the idea in January 1984 to the publication of the results of experiments confirming the idea in June 1986. It took, however, several additional years before these results gained the status of an invention and were transformed into an innovation.

The emergence of the invention was at first analyzed in terms of the problem of a use activity. The 'critical problem' that called for the invention was related to the use of chlorine gas in the bleaching of kraft pulp. Chlorine is a very efficient and cheap bleaching agent, which have been used for half a century in the bleaching of kraft pulp. The results of environmental research and analysis gradually created a chlorine problem. It was discovered that the chlorine compounds produced in reactions between chlorine and lignin were harmful; some of them were mutagenic. The chlorine problem was redefined many times. It was first a problem of waste water. This problem was primarily solved in Finland by constructing and developing biological treatment plants.

The research results published in 1987 according to which small amounts of the most harmful chlorine compound, dioxin, are also left in the paper product were a turning point in the development of the problem. This suggested that dioxin migrates from the food containers to the food and then to the human body (Ryan et al. 1988). No agreement about the health risks of the small dosages of dioxins in paper products was reached in the public discussion. The pulp and paper industry, most paper and pulp researchers and even enzyme researchers regarded the amount of dioxin in paper products as insignificant and thought that the whole problem was a result of the use of new, supersensitive methods of analysis. The reactions of the Finnish pulp and paper industry towards the dioxine discussion was first very abrupt. The publication of the Finnish paper exporters, Finnpap Wold, commented on the dioxine discussion in 1989 as follows:

"The current discussion of chloro-organic compounds and dioxines has gone badly astray into the jungle of emotions and political and commercial opportunism. These compounds have become the prime focus of regulation, regardless of their ecological insignificance, and have diverted abatement efforts from the essential to the trivial."

Toxicologists instead calculated that the risk of excessive dioxine concentration to the human body was real. Paper product users resolved the controversy. A senior researcher expressed this as follows:

"It makes no difference whether the risk is real or not. If German housewives want to read their Ellos from chlorine-free paper, the paper producers change their bleaching system."

The problem was included in public environmental discussion and markets for environmentally friendly non-chlorine pulps emerged in central Europe, first of all in Germany.³⁰ At this point the chlorine problem turned out to be a full-fledged economic problem to the pulp and paper producers and led rapidly to the abandonment of chlorine in pulp bleaching.

The chlorine problem was doubtless global in the sense that the compounds are surely formed in all the bleaching processes using chlorine gas. However reservations must be made concerning the globality of the problem. First, the problem has a different meaning to the pulp producer, depending on the end products of the producer. What is fatal for liquid packaging boards, foodboards and filter papers can be insignificant for wallpaper or boxboard. Secondly, different markets have different demands for chlorine-free pulps. Environmentally sensitive central European consumers often prefer non-chlorine paper products. In England the issue has not received such wide publicity. In economically constrained Russia the issue has hardly been raised at all. Hence, while the chlorine problem in the sense of producing dioxin and other harmful chlorine compounds surely concerns all pulp mills using chlorine in bleaching, the socio-economic and cultural conditions influence the extent to which it is a problem and how it is reflected in the market.

In spite of these reservations the problem is global in the sense that the gradual elimination of chlorine chemicals in pulp bleaching within the next ten years is a foregone conclusion. No new pulp mills using chlorine bleaching systems are under construction, at least in the industrialized countries. Enzyme-aided bleaching emerged to help in solving the problem of using chlorine in bleaching of kraft pulp. In defining the aim of the production of chlorine- and sulphur-free pulp in 1984, the researchers anticipated the significance of the problem. In 1984 no perspectives for economically viable application were in sight.

The invention was not only the solution to the problem of pulp production. It was a solution to a problem in the activity of the main actor, the VTT Biotechnical laboratory. The laboratory was losing its main object of application, the production of ethanol from wood. At the same time, the whole related research strategy, total hydrolysis of wood components into sugars was fading away for economic and technical reasons (see table 1). The invention was an attempt to resolve of this problem by introducing a new application, which contributed to the redefinition of the research objective and research strategy based on selective use of enzymes in the modification of cellulose and hemicellulose fibres.

The study of enzymatic pulp bleaching had begun in Sweden and in the U.S.A. before the chlorine problem was well known. The immediate impulse for the invention was the discovery of a lignin-degrading enzyme outside the cell by Kirk's group in 1983. The novelty of the idea of the Finnish group was

³⁰For instance Der Spiegel, a German magazine with a circulation of 1,4 million copies decided to transfer to chlorine-free paper in December 1992, as did another German magazine, Stern, immediately after Der Spiegel.

to use the other type and less evidently workable enzyme, hemicellulase, in bleaching. This idea arose directly from the preceding research activity of the laboratory; the hemicellulases had already been produced and they were immediately available for experiments. Extensive discussions on the utilization of biomass, including hemicelluloses and the aim of chlorine- and sulphur-free pulping, paved the way for formulation of the idea.

The successful confirmation of the idea was due to the local combination of resources. The VTT Biotechnical laboratory had a strong tradition in the enzymatic hydrolysis of lignocellulosics. Probably the most obvious local 'strength' of the laboratory was the early dedication to the hemicellulase studies. The VTT group was evidently one of the first groups to study the production of *Trichoderma* hemicellulases. At the beginning of the 1980s hemicellulases were studied in several projects at the VTT Biotechnical Laboratory, thereby creating the basis for formulation of the idea. They were also immediately available for experiments.

The Finnish Pulp and Paper Research Institute had strong capabilities in pilot-scale pulp production, bleaching and analysis of paper technical properties of pulp, which made rapid advance in experimenting possible. A new funding organization, the Finnish Technology Development Centre, was founded in 1984. Immediately the first national technology programs were formed for the years 1984 - 1987. The bleaching project was integrated with one of the national programs with considerable public financing (see footnote 14), thereby securing the continuity of the research and experimentation. In 1988 the project was incorporated with another national research program for 1988 - 1991. This kept the research and development on laboratory-scale active until the pulp and paper producers in response to the pressure of chlorine discussion and the formation of the new chlorine free pulp markets at the beginning of the 1990s implemented it.

The Finnish group was not the first to enter the field of enzymatic bleaching. It, however, managed to find the first feasible solution, the use of hemicellulases in bleaching. However, the idea and the discovery arose "too early." The potential users did not attribute to the experimental results the status of invention nor did they believe in their significance. It was the environmental concern of the consumers and the formation of chlorine-free markets that resulted in re-estimation of the significance of the use of enzymes in bleaching. The status of 'invention' was publicly attributed to the enzymatic bleaching when the method received an award from the Ministry of Environment for being the most significant environmental invention in 1990. Since then, the method has been extensively used as an example of inventive activity at the Technical Research Centre of Finland. The social construction of the invention took at least six or seven years.

The innovation process can be characterized as a transfer of knowledge on the degrading enzymes from one problem area to another: from production of ethanol (solving the fuel problem) to the treatment of cellulosic materials. Independent global processes stimulated the invention of enzyme-aided pulp

bleaching: fluctuations in oil prices and the emergence of the chlorine problem in kraft pulp bleaching. Both processes had their own time scale and dynamics. The 'oil' crisis lasted about ten years (about 1973 - 1983) and influenced the orientation of research on cellulases at the VTT Biotechnical Laboratory. The results of environmental and toxicological research gave rise to the chlorine problem. The environmental movements and public opinion reacted to the research results and demanded the elimination of chlorine from pulping. The Finnish pulp and paper industry and cellulose engineers never believed that the small amounts of dioxin in paper products were a real problem. But the image of consumers was decisive. It was the formation of markets for chlorine-free pulps and paper products that ultimately created the innovation.

The aim of chlorine- and sulphur-free pulping and bleaching formulated by the researchers in the beginning of the 1980s proved to be a far-reaching vision. It would be, however, erroneous to maintain that the invention was a result of any rational, calculative decision making or that it was planned in advance. The vision of the biotechnical bleaching emerged and developed in the form of two ideas, both of which were hypotheses. Professor Enari characterizes the hemicellulase alternative as follows:

"When we had that meeting, no experiments had been conducted. It was a hypothesis on the basis of which we started to work (...) We didn't know how it happened. But it worked. It does not matter whether a hypothesis is right or wrong. What is important is that it leads to experiments that solve the problem."

The use of ligninases in pulp bleaching proved to be a difficult problem scientifically and technically and the idea did not develop into a workable method. The idea of using hemicellulases was proved by the experiments and it turned into an invention. All the events and factors that decisively influenced the emergence of the invention were not and could not have been anticipated: the oil crisis recession, the results of Kirk's group in 1983, the development of research on dioxin in paper products in 1987 - 1989, changes in the attitudes of paper consumers and the general public and the formation of chlorine-free markets. There was a strong element of contingency in the process. The effects of several unanticipated developmental processes and events were timed and accumulated in a way that made the emergence of the invention possible.

Neither was the invention a result of luck or chance. The know-how and persistence of cellulase and hemicellulase research made the formulation of the idea possible. Neither would it have happened without the idea of sulphur- and chlorine-free pulping. The necessary presence of contingency, vision and persistence in invention and discovery was excellently formulated by Louis Pasteur; chance favours a prepared mind. This can be formulated on a more collective level. It was the persistence and ambitiousness of the research program on cellulases and hemicellulases that made possible the formulation of the idea for enzyme-aided pulp bleaching although the status of invention

was attributed to it by others only later and due to a series of unanticipated events in the environment.

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THE ARCHIVE MATERIAL USED

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The personal archive of Dr. Liisa Viikari. The minutes of the meetings formulating the idea of biotechnical pulp bleaching and the project plans of biotechnical pulp bleaching from 1984 to 1991.

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