Canadian University - Based
Research in Condensed Matter Physics -
a Review and Recommendations
for the Future

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Review Subcommittee:

John Berlinsky
Martin Grant
Thom Mason
Sjoerd Roorda
Mike Thewalt (chair)
Jeff Young

EXECUTIVE SUMMARY

This Review of Canadian university-based research in condensed matter physics (CMP), and its coupled Recommendations, is part of a wider review of all of university-based physics research in Canada, which was initiated as part of the liaison process between the Canadian Association of Physicists (CAP) and the Natural Sciences and Engineering Research Council of Canada (NSERC), the primary funding source for such research. The review, which involved wide consultations with the research community at both the initial and draft stages, was allowed complete autonomy once begun. The analysis and recommendations presented here are therefore those of the review committee alone.

In describing condensed matter physics research activities in Canada, two 'success stories' were used as examples of the impact and recognition which can be achieved when researchers working in areas of existing strength are brought together in a well-organized network aimed at enhancing national and international communication and collaboration. The breadth of activity in Canada was outlined with shorter descriptions of the high-quality work being carried out in departments across the country. In summarizing the results of the review, the committee adopted a format which focused on *strengths*, *weaknesses*, *opportunities* and *threats*, the main points of which are reproduced below.

Strengths

1. The principal strength which is noted in each successful area is a core group of excellent scientists. In areas which have been nurtured in Canada for many years, there are outstanding senior scientists. In these areas we note that the quality of hiring in recent years has also been excellent, so that there is every reason to believe that established strength will be maintained. In new areas, such as (experimental) soft matter physics, the practitioners are predominantly young, and the quality is high.

2. The existence of facilities for materials synthesis and modification at McMaster, UBC, the NRC, U. de Montréal and École Polytechnique, SFU and elsewhere has contributed significantly to the health of Canadian CMP. However, there is much to be gained by further strengthening Canadian capabilities in materials synthesis, modification, fabrication and analysis, and from broadening the range of materials and structures which can be produced.

3. Condensed Matter Physics in Canada has benefited greatly from programs which have fostered interactions between active groups across Canada. In this regard, the Canadian Institute for Advanced Research (CIAR) has played a key role by supporting excellent scientists in both superconductivity and soft matter research, and by promoting networking in these two areas. Similarly NSERC's short-lived Collaborative Grant Program has enhanced interaction in the areas of frustrated antiferromagnets, quantum well disordering, and interdisciplinary studies of biomembranes. We note that the greatest impact has resulted from programs which have promoted interaction in areas of established strength.

4. Two major user facilities, neutron scattering at Chalk River and MuSR at TRIUMF, have acted as magnets for forefront research, and strong user groups have grown up around each facility.

5. Canadian CMP has been dynamic in mirroring the international evolution of the field, both in terms of the hiring of new researchers, for which individual departments have responsibility, as well as in the ability of established researchers to reorient their programs to follow (and lead) new developments. There was little evidence of undue activity in 'older' fields which would need to be de-emphasized.

Weaknesses

1. Subcritical groups and geographical isolation, without compensating collaborations and networking.

2. Shortage of start-up funding; uncertain and often inadequate level of support until long after new faculty arrive.

3. Inability to support even the best programs at internationally competitive levels.

4. Problems in supporting inherently expensive research under the present funding system, particularly if such research does not offer the prospect of short-term economic benefits which would allow supplementary funding to be obtained from the strategic or university/industry programs.

Opportunities

1. Development of new areas of CMP research and enhancement of strong continuing programs.
2. Development of new major facilities for Materials Research.
3. Development of wider collaborations and networks where these can be shown to be of benefit to Canada.

Threats

1. Inadequate infrastructure support for university-based materials research facilities.

2. Inadequacy of major user facilities for research in Materials Science and Engineering.

Indeed, the summary of the Review ends with the following observation:

Overall, the erosion of infrastructure funding of materials research facilities is the greatest single threat to the field of CMP, and to all of Canadian Materials Science and Engineering, and it is the single area of greatest need for corrective action.

Consideration of these issues, in light of the realities of the present overall funding situation, and the feedback received from circulation of the draft Review, led the committee to make a series of suggestions and recommendations, the most significant of which are reproduced below. It should be noted that the feedback from the draft Review demonstrated a strong consensus that excellence and impact should be ***necessary*** requirements for the award of a grant. In this context, we emphasize that 'impact' is neither a code word for applied research or partnerships with industry, nor for the number of Physical Review Letters published - in CMP, excellence and impact are found everywhere along the fundamental to applied continuum. Rather, impact implies that the research is of use to and appreciated by some significant external grouping, as appropriate to the goals of the research itself.

Major recommendations

1. The first and second recommendations of the Bacon Committee, which have already been accepted by NSERC Council, should be implemented without further delay. (*The recommendations of the Bacon Committee are given on page 13; the first two relate to the establishment of national or regional 'clusters' of materials research facilities, and the securing of adequate infrastructure support for these clusters)*

2. The remaining recommendations of the Bacon Committee, dealing with the issue of large-scale facilities for Materials Research, should form the basis of an inter-agency initiative to ensure that they come to fruition.

3. NSERC should appoint a Group Chair for Materials Science and Engineering, in order to better coordinate activities in materials-related areas, and to better evaluate needs and opportunities.

4. NSERC should initiate a thorough review of its current discipline-based Grant Selection Committee (GSC) structure, in order to determine whether a new or modified structure might not be more conducive to cooperation, and to fostering interdisciplinary initiatives. The Materials Group Chair would play an important coordinating role in this review.

5. The increase in selectivity and funding dynamics demonstrated by the GSC for CMP (GSC28), particularly since Reallocation, should be continued, and augmented by the adoption of a set of principles which will guide funding decisions over the next four year grant cycle.

6. Any increase in funding secured by GSC28 as a result of Reallocation should be applied to an initiative dealing with infrastructure and cost-of-research issues associated with high quality programs in materials growth, modification, characterization and fabrication.

VISION STATEMENT

Condensed matter physicists study the electronic, optical, magnetic, thermal and structural properties of materials such as liquids and solids. Their research results in new techniques for observing the properties of matter (such as superconducting quantum interference device (SQUID) magnetometry and scanning tunneling microscopy), as well as the creation of revolutionary devices (transistors, magnetic recording media, laser diodes) and standards (the Josephson volt and the quantum Hall effect ohm) which have impact far beyond their original field of research. Canadian research bridges topics from ceramic superconductors to cell membranes. Condensed matter physics has impact on, and provides a fundamental approach to, topics which are studied in other disciplines, such as biology, chemistry, and materials science and engineering. It provides the basis for understanding, predicting, and improving properties important in the performance of technologically vital materials. The condensed matter physicist has an increasingly interdisciplinary outlook, and can contribute unique skills and approaches to the understanding and solution of the expanding range of phenomena and problems which require such an interdisciplinary approach. Researchers in condensed matter physics have a natural appreciation of the value of possible applications of their research, and recognize excellence anywhere along the continuum joining the most basic to the most applied research. They also recognize the need to redouble their efforts to bridge the gaps which remain between university researchers and Canadian industry, and to explain better the benefits of their contributions to society at large. Condensed matter physicists will play a leadership role in establishing the multidisciplinary and multisectoral partnerships which will see centres of excellence in materials research and engineering established around securely-funded Canadian materials research facilities.

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Acknowledgments **-**

We would like to thank the many individuals who have contributed to this review, both by completing the questionnaires as well as by providing other input and feedback on early drafts. The large volume of detailed and thoughtful comment resulting from the circulation of the previous draft within the community was also a great help in producing a more balanced and comprehensive document. We are grateful to NSERC and to CAP for their ongoing assistance and cooperation, and particularly to Liz Boston of NSERC for cheerfully dealing with what must at times have seemed an almost endless stream of requests for information.

LIST OF ABBREVIATIONS

AECL	Atomic Energy Canada Ltd.
AFM	Atomic Force Microscopy
ANDI	Applied Neutron Diffraction for Industry
APS	American Physical Society
ARES	Angularly Resolved Auger Electron Spectroscopy
BLS	Brillouin Light Scattering
CAP	Canadian Association of Physicists
CAT	Collaborative Access Team
CBE	Chemical Beam Epitaxy
CIAR	Canadian Institute for Advanced Research
CINS	Canadian Institute for Neutron Scattering
CISR	Canadian Institute for Synchrotron Radiation
CLS	Canadian Light Source (proposed)
CMP	Condensed Matter Physics
CRC	Communications Research Centre
CRD	(NSERC) Collaborative Research and Development (grant)
ERD	Elastic Recoil Detection
EXAFS	Extended X-ray Absorption Fine Structure
FCAR	le fonds pour la Formation de Chercheurs et l'Aide à la Recherche
GCM	Groupe de recherche en physique et technologie des Couches Minces
GSC	(NSERC) Grant Selection Committee
GSC28	the condensed matter physics GSC
IMI	Industrial Materials Institute (of the NRC)
IMMCAT	IBM-MIT-McGill Collaborative Access Team
IMS	Institute for Microstructural Sciences (of the NRC)
INRS	Institut National de la Recherche Scientifique
IOR	(NSERC) Industrially Oriented Research (grant)
IRF	Irradiation Research Facility (proposed)
ISAC	Isotope Separator and Accelerator (at TRIUMF)
LEED	Low Energy Electron Diffraction
MBE	Molecular Beam Epitaxy
MOCVD	Metal-Organic chemical Vapour Deposition
MOKE	Magneto Optical Kerr Effect
MRC	Medical Research Council of Canada
MuSR	Muon Spin Resonance
NCE	Networks of Centres of Excellence
NOI	National Optics Institute
NRC	National Research Council of Canada
NSERC	Natural Sciences and Engineering Research Council of Canada
OCMR	Ontario Centre for Materials Research
PDF	Post-Doctoral Fellow
PIXE	Proton-Induced X-ray Emission
PNCCAT	Pacific Northwest Consortium Collaborative Access Team
RA	Research Associate
RHEED	Reflection High Energy Electron Diffraction
SAL	Saskatoon Accelerator Laboratory
SNO	Sudbury Neutrino Observatory
STM	Scanning Tunneling Microscopy
TASCC	Tandem Accelerator Superconducting Cyclotron
TRIUMF	Tri-University Meson Facility
WFA	(NSERC) Women's Faculty Award

I INTRODUCTION

This Review of the state of university-based condensed matter physics (CMP) research in Canada in 1996 is one of three parallel efforts, which are intended to cover the entire field of physics research. While the Review has received generous financial and logistical support from the Natural Sciences and Engineering Research Council of Canada (NSERC), and is to be assessed by a panel of international experts approved by NSERC, the content and recommendations were independently determined by the Review Committee, after wide consultation with the research community, and feedback from the circulation of a preliminary draft. Similarly, while the Canadian Association of Physicists (CAP) was instrumental in initiating the Reviews, in defining their Terms of Reference in consultation with NSERC, and in determining the membership of the Review Committees, it did not influence the efforts of the three committees once the Review process began. Therefore the conclusions and recommendations presented here are those of the CMP Review Committee, although it is hoped that they will be substantially endorsed by NSERC and the CAP.

This is the only review of CMP research in Canada since the publication of "Future Opportunities in Condensed Matter Physics Research in Canada - a Consultative Project" in 1981, which was also initiated by the CAP and supported by NSERC, to which its recommendations were addressed. The primary recommendation to NSERC in 1981 was: "A 100% (or $4M) increase in Individual Operating Grants (IOG) to condensed matter physicists over three years. This addition should be awarded selectively to excellent individuals". In today's era of reduced expectations it takes a real effort to embrace such a bold recommendation, no matter how defensible it may be. In any case, the Research Grants Program is only open to maximum changes of ± 10% per Reallocation cycle, as discussed in detail below. Still, the other much-needed changes which we call for in the area of infrastructure support and provision of new large scale facilities for research in Materials Science and Engineering would have an impact well beyond this 10% limit.

In introducing this Review, there are three main questions to be addressed: ***why*** was it undertaken, and what are the desired outcomes, ***who*** is the intended audience, and ***how*** was the review accomplished?

Aims of the Review

These Reviews of university based physics research in Canada, and the CAP - NSERC Liaison Committee which initiated them, arose out of the 'shock' delivered to the physics community in 1994, when as a result of the first implementation of the NSERC Reallocation scheme, physics (with the exception of space physics and cosmology), together with mathematics, received the largest budget cuts of any disciplines, namely 8.5%. Under Reallocation, this cut applies to a full four year granting cycle and is permanent, in the sense that any change resulting from the next Reallocation (submissions due Jan.1, 1998) would be cumulative. What made this particularly difficult to accept was that the first Reallocation was supposedly based primarily on excellence, but, in the opinion of many, the results could be understood better in terms of the disciplinary bias of the Reallocation Committee (see for example the analysis of John Chadam of the Fields Institute, reproduced in a comprehensive special feature on Reallocation 1994, Physics in Canada, May/June 1995, 1-8), together with long-standing perceptions (or misperceptions) of the relative merits and weaknesses of the competing disciplines. While it is pointless to dwell on the deficiencies of the last Reallocation, as compared to preparing for the next, it is worth reproducing here the total feedback which the CMP and General Physics communities received as the sole explanation for the 8.5% funding cut, and guidance for improvement:

> *The report contained some indications of international excellence in areas such as lasers, atomic and molecular research. However the report did not distinguish sufficiently the contributions of the university sector in a broadly based community. Some contributions made by scientists and engineers from other disciplines were also claimed in this report. Funding was felt to be too dispersed and more focus is required. It was also noted that employment prospects for personnel are weak.*

One of the main goals of the Review is to address these perceptions of Canadian research in CMP by consulting the community and analyzing the level and breadth of research activity, in order to correct the misperceptions and deal constructively with any actual shortcomings. A previous weakness which cannot be denied was a serious lack of political organization, planning, prioritization and lobbying on the part of the physics community. Others have certainly done better in keeping their messages of excellence and priority in the forefront. There have of course been lobbying efforts for individual physics projects, some quite large, but nothing of a more comprehensive and continuous nature. Perhaps we have too naively believed that the funding of science and technology, while subject to external political decisions, could proceed without this kind of internal politics. Certainly the situation is improving with the recent, much more dynamic participation of CAP, and in particular with the initiation of the CAP - NSERC Liaison Committee meetings.

While the Review deals to some extent with issues arising from the previous Reallocation, and is intended as a major forerunner to and input for the next Reallocation Process, it is ***not*** intended to resemble the 10 page document which will be submitted by CMP as the basis for the next Reallocation. Thus it does not focus directly on the issue of how research in CMP benefits Canada, the central issue for the next Reallocation, since these arguments can only be assessed in an interdisciplinary forum. Also, crucial information on employment prospects and economic spin-offs is being collected and analyzed by a separate committee, and will only be available after these Reviews are completed. This Review seeks instead to provide an overview on what CMP research is being pursued in Canada, to highlight areas of excellence and high impact (both individual and collaborative), to analyze the factors which have led to or impeded the achievement of excellence, and to consider the issues surrounding discipline dynamics: is Canadian CMP missing out on emerging fields or too actively pursuing mature fields? are there areas of importance for the economy or for the development of CMP which are not as strong as they should be?

Coupled with this analysis, the Review makes specific recommendations to the CMP community, to NSERC, and to the Grant Selection Committee (GSC) for CMP, that are intended to address both the problems and the misperceptions which have been uncovered as a result of the Review and its wide-ranging consultation with the CMP research community. This is likely the most important contribution of the Review, since while many of the problems and solutions outlined here are not 'new', we have never before been in a situation where the need for implementing change, and the likelihood of change actually taking place, have been higher. In this way the first Reallocation, while seriously flawed, has served as a 'wake up call' for CMP which will hopefully improve the outlook for the future - we can certainly ill afford another across-the-board cut in the next Reallocation, as compared to the much needed increase which we will argue for.

The first Reallocation has set the stage for changes in the way we operate within the funding system. It is our intention that this Review lead to the discussion and implementation of any needed changes. The impetus for change will not come from CAP, for it continues to be an inclusive organization whose central function is to work for and represent ***all*** physicists, rather than to address the question of what approach is best for the health of physics research in Canada, let alone for the health of a specific subfield. There is nothing fundamentally wrong with this - inclusiveness is an appropriate stance for CAP. It is furthermore widely recognized that CAP has recently done important work in lobbying the government regarding the importance of research in physics, and all of science and technology, for the future health of the Canadian economy and society. Still, it should be expected that CAP will steer clear of any move towards higher selectivity in research funding, with its potential for immediate harm to some CAP members and physics departments, just as it will avoid any role in setting funding priorities within physics. However, the corollary to this stance is that funding priorities within physics will of necessity be set from outside the community, without the benefit of CAP input. While we hope that the subdivisions of CAP, such as the DCMP, will in future take up a stronger position of advocacy, they can only argue for, but not decide on, relative priorities.

Similarly, the NSERC CMP GSC has typically not seen itself as an agent of change, even though it usually operates under perceived but ill-defined pressures from the 'system' to increase selectivity, 'discipline dynamics', etc. While there has unquestionably been change in these directions, it has in the past been a gradual and incremental process, with the result that it has gone largely unnoticed outside the physics community. A similar gradualism also characterized the typical way in which individual Research Grants changed with time in the past. This approach is in part explained by the fact that the GSC members are selected by NSERC, via a process which is unclear to outside parties, and serve for relatively short periods of time. The GSC members have therefore had little sense of any mandate to do other than apply their scientific expertise in judging and funding the applications, using the criteria and standards which are already perceived to be in place. The first Reallocation has already had an effect on this, since the GSC saw the need to respond to the factors which had been responsible for the 8.5% cut, to the extent which these could be determined from the very limited feedback. Thus the CMP GSC has since the Reallocation taken a more aggressive stance on selectivity and dynamics, which in our opinion is highly appropriate.

Even before Reallocation, the CMP GSC had done well in attempting to balance the support of excellence with the provision of adequate startup funding for new applicants, under the constraint of an inadequate budget. We believe that CMP now compares quite favorably with other GSCs on the basis of criteria such as startups, selectivity and dynamics. However, the progress has been so gradual (and our efforts to publicize it so minimal) that there has been little change from the 'old' perception (outside of the physics community) of physics as being quite nonselective. Having said all of the above, we must make it clear that we are not in our recommendations dealing only with changing perceptions - there remains considerable room for improvement. In particular, the CMP GSC (together with many other GSCs) has always found it difficult to deal with some cases where criteria other than the recent excellence and impact of the research are difficult to ignore. The possible reasons for these difficulties are discussed in Section VI, together with the issues of selectivity, and the support for research at 'smaller universities'. The point we wish to emphasize here is that the existence of even a handful of such counterexamples, while having a negligible impact on the available funding, can be used with devastating effect when physics attempts to defend its record on selectivity in a forum such as the Reallocation Committee.

After having conducted this Review, with its wide consultations and feedback, and having its claims and recommendations scrutinized by eminent external Assessors, we believe these recommendations will have a sufficient, though of course not unanimous, mandate to produce a significant change in granting practices. This is perhaps the most important long term goal of the Review - to produce an immediate discussion within the CMP research community, the CMP GSC, and NSERC, regarding the analysis and recommendations presented here, followed by a clear acceptance (or rejection) of the individual components. In a sense we wish to 'draw a line in the sand', explicitly stating, as we approach the next Reallocation, clear principles and criteria which the CMP GSC will apply for the next four years, coupled with the uses to which the additional funding will be put. We will then expect to be judged by our adherence to these criteria, and our ability to meet our stated goals, when it comes time for the next Reallocation.

Target Audience

The Review will be of interest to all three groups to which the recommendations are addressed: the CMP research community, NSERC, and the CMP GSC. Beyond this, the element which gives it special credibility is the fact that it will be evaluated by a panel of eminent external Assessors, who have been approved by NSERC. Without this assessment aspect, it is unlikely that NSERC would have provided its significant logistical and financial support, and it is certain that the eventual impact of the Review would be greatly diminished. Therefore, even though the Assessors represent a numerically tiny fraction of the potential audience, the Review has very much been written with them in mind. This entails a considerable amount of background information on research funding and organization in Canada, and in particular those aspects in which the Canadian scene differs most from that in the USA (most of the Assessors coming from American backgrounds). Still, these overviews may be of interest to NSERC and Canadian researchers, since along with factual data they also inevitably reflect a particular point of view, which we believe is representative of that of the Canadian CMP research community.

Methodology

We have already outlined the roles of CAP and NSERC in initiating and supporting the three Reviews. Similarly, the CAP-NSERC Liaison Committee, in consultation with NSERC, set the Terms of Reference of the Reviews. We will henceforth discuss only the procedures followed by the CMP Review, although the Subatomic Physics and General Physics Reviews followed roughly similar paths. The CMP Review was launched with two well-attended Town Hall Meetings at the beginning and end of the Annual Congress of the CAP in June, 1996. In addition, there was considerable discussion of Review issues at the Annual Business Meeting of the CAP Division of Condensed Matter Physics (DCMP), by far the largest division of CAP. Related to the Review, the DCMP meeting sought to settle the contentious issue of how submissions for the 1998 Reallocation were to be made. In 1994, after much debate within the CMP community, the CMP and General Physics GSCs made a joint submission. After the disastrous results of that

Reallocation were announced, there was a greater appreciation within CMP that the joint submission strategy was probably ill advised, not because of any weaknesses or lack of overlap with the General Physics GSC, but because of the limitations it placed on producing a concise and coherent submission.

Still, in 1996 there was a desire from both the General Physics and Subatomic Physics groups, and also from individuals on the CAP executive, to prepare a single, unified physics submission for the next Reallocation. The CMP group, on the other hand, saw this as being a potentially even more serious mistake than was made in 1994, given the new criterion of ‘benefit to Canada’, which it wished to address with specific arguments relevant to CMP, rather than general arguments covering all of physics. After listening to the case for a unified physics submission, ably presented by Gordon Drake, it was clear that the majority of those attending the DCMP Business Meeting were in favor of a separate CMP submission. The issue was settled soon thereafter with the almost unanimous support for the separate submission option obtained via an e-mail ballot of the DCMP. All of this is significant for the Reviews, since it was this desire for separate Reallocation submissions which was in part responsible for the present structure of three Review Committees, each providing input for the later writing of the respective Reallocation Submissions.

The three open meetings at the CAP Congress also provided support for a more explicit recognition of what we do as Materials Science, and for changes in the NSERC GSC structure reflecting such inherently interdisciplinary groupings based on the problems being addressed, rather than which particular disciplines we hold positions in. The implications of this for the fostering of forefront interdisciplinary research will be considered in more detail later.

After the Congress, the three Review Committees drafted a questionnaire designed to collect both factual data and opinions relevant to the Terms of Reference. These questionnaires were mailed out by NSERC to all grantholders and applicants covered by the Reviews, and copies were also sent to all heads of departments, with a request that they be made available to any interested parties. CAP also informed its membership of the need for the Reviews, and the availability of the questionnaire at a common Internet site. The NSERC mailing also included a release form, to be signed and faxed back, which authorized NSERC to release the latest grant application and personal data form of the researcher to the Review Committee. The questionnaires mailed by NSERC to CMP grantholders and applicants also contained a separate list of questions addressing specific CMP issues.

Ninety one completed questionnaires and 130 releases were obtained from the 211 CMP grantholders, with very little input from outside of that group. The number of responses to the supplementary CMP questions was lower, presumably because only the NSERC mailout had these questions appended, while many of the questionnaires which were eventually returned were instead obtained from the web site. The completed questionnaires were copied and distributed to the committee members on the basis of the categories used to subdivide Section IV of this Review. The committee members dealing with these categories then decided which grant applications and personal data forms they required, from amongst those which had been covered by releases returned to NSERC. Eventually, copies of a large fraction of those applications covered by releases were requested by the committee members. A summary of all of the input obtained from the questionnaires is given in Appendix 1.

The work of the committee was initiated with a one day meeting of all the members, followed by a number of unofficial meetings when circumstances brought committee members together. Most of the discussions and debate have however taken place via e-mail, as has the drafting of this document. The individual sections were drafted by the appropriate committee member, followed by modifications after considerable feedback from the rest of the committee. The exception is Section III.2, the success story on membrane biophysics, for which we are indebted to Michael Wortis of SFU.

After the Draft of the Review had been finalized and approved by the committee, it was released to the community for comment. Its availability, together with the other two Draft Reviews, at the common University of Toronto web site, was widely announced by the CAP, as was the need for timely feedback. In addition, hard copies of the Draft CMP Review were mailed out to all GSC28 grantholders, as well as to other interested parties.

In the three week period set aside for feedback on the Draft, a total of 95 responses were received and forwarded to the members of the CMP Review Committee for consideration. Much of this feedback was supportive of both the content and tone of the Draft, although there were numerous specific suggestions for factual changes or additions. Many of these suggestions were in fact very helpful to the committee in painting a more balanced and comprehensive picture of current research activities in Canada, and have been incorporated into the final version of the Review. It was to be expected that a small committee, with limited time and a less than ideal input of information from the original questionnaire, would tend to focus most on research efforts with which it was more familiar. The Draft/feedback stage of the review process was intended to deal with such inadvertent omissions of important group or individual research efforts.

This is not to say that all such suggestions for additions were acted upon. Section IV was explicitly not intended to be an exhaustive list of all CMP research activity in Canada, and the same criteria used in drafting the original Section IV were also applied to the proposed additions. A number of responses also noted that the references to the awards and distinctions of the grantholders under discussion was very inconsistent in the Draft. These references have been removed from Sections III and IV, and instead an attempt at a more comprehensive listing is made in the new Appendix 3. A listing of interactions between CMP researchers and industrial partners has also been added as Appendix 4.

In addition to addressing inaccuracies and omissions in the overviews of Canadian CMP research activities, the Draft/feedback stage was also intended to foster a debate on the recommendations of the committee. To this end, Sections V and VI of the Draft contained rather lengthy considerations of the central issues, and the recommendations were stated in a provocative and uncompromising way. The committee was gratified by the breadth of the response which was received in the unfortunately short time available for feedback, and the thoughtful, balanced nature of most of the responses.

The CMP Review Committee, together with the Subatomic Physics and General/Space/Atmospheric Physics Review Committees, was guided by a comprehensive planning document which was drafted by the CAP-NSERC Liaison Committee, in consultation with NSERC, which approved the final document. Of particular interest are the 10 goals of the overall Review, which are reproduced on the following page.

Objectives of the Review

1. To survey current and planned areas of Canadian academic physics research activity.

2. To identify current areas of Canadian strengths and weaknesses on an international scale, and how they fit in with the ongoing evolution of the field. Weaknesses could include important or emerging areas needing more emphasis, or areas where less emphasis seems appropriate. While the identification of such areas could assist future GSC deliberations, it is not intended to define areas which GSCs would be constrained not to support.

3. To make recommendations concerning particular areas of focus for the future, while still supporting the diversity and risk-taking which are so essential to a successful research enterprise.

4. To attempt to establish a consensus in the community (within parameters acceptable to NSERC) regarding questions of selectivity, and of concentration versus diversity, in granting practices. This Objective relates to broad principles of ‘how much selectivity’, ‘how much concentration’, etc., rather than to the support to be given to specific areas. However, means should be suggested by which GSCs can take these principles into account.

5. To identify and quantify the employment opportunities for students trained in physics at various levels. If possible, to assess and measure the importance of research to teaching, in the context of Provincial calls for less emphasis on research.

6. To survey and, as far as possible, to quantify the economic benefits of NSERC-supported physics research in terms both of new spin-off companies and of new products and services offered by established organizations.

7. To provide NSERC with the community's views on how NSERC may better encourage (i) risk-taking, (ii) spin-off activities, (iii) communication of the results of research to the public and to other scientific disciplines, and (iv) physics participation in interdisciplinary research.

8. To assess the interactions and impact of Canadian physics research on other disciplines, and to identify means of enhancing them.

9. To review whether the overall health of the discipline in Canada would be enhanced by a major collaborative effort(s) across physics subdiscipline boundaries and/or between physics and other disciplines, and if so to identify that effort(s).

10. To synthesize a "Vision Statement" for Canadian academic physics, according to criteria to be specified by NSERC in accordance with the requirements of NSERC Council.

N.B. Items 5 and 6 from the above list of objectives were the responsibility of a separate committee, which was charged with quantifying the economic benefits of NSERC-funded physics research, and investigating the employment prospects for those obtaining their training in physics research programs. These issues are therefore not addressed in this report, although it is widely accepted that employment opportunities and economic impact are strong points for CMP. This input, which is not yet available, will be an essential component in preparing the CMP submission for the next Reallocation. A preliminary listing of industrial interactions has however been provided in Appendix 4.

II BACKGROUND ON CANADIAN RESEARCH FUNDING

This section is intended to provide an overview of the funding mechanisms which are available for university-based research in Canada. As such it is aimed primarily at the non-Canadian reader, and in particular the External Assessors, whose function it is to assess the claims, arguments and recommendations made as part of this Review. It may also be of considerable use to readers not directly involved in university-based research. Even those involved with the NSERC system may find it of interest, since while the intent is to provide factual information, this information is inevitably presented from a certain viewpoint, which we hope is broadly representative of that of the CMP community.

Constituents

CMP research is done in Canadian universities, in corporations such as Nortel, EG&G, Xerox, etc., and in government laboratories such as the National Research Council (NRC) (in the Institute for Microstructural Sciences (IMS) and the Industrial Materials Institute (IMI)), TRIUMF, Atomic Energy of Canada Ltd. (AECL), the National Optics Institute (NOI), and the Communications Research Centre (CRC). The present Review is specific to university-based research, which takes place in approximately 30 institutions across the country. Most, but not all, of these universities have faculty members active in CMP research.

There are a few cases (6 funded in GSC28) where research employees of the government or industry hold adjunct faculty positions at universities, making them eligible for NSERC grants. These grants to adjuncts are always small, since they are intended only to apply to the support of the graduate student(s) involved, and not to subsidize the research itself. These ‘adjunct grants’, which in GSC28 primarily involve researchers at the NRC-IMS, are widely considered to provide excellent graduate student training at a minimal cost to the NSERC system. It should also be noted that NRC has its own internal programs which help to offset the costs of having externally supervised graduate students visit NRC while participating in collaborative university/NRC research projects.

Approximately 6 % of GSC28 Research Grant support goes to the research programs of professors who are post-retirement (In Canada retirement can be mandatory, typically at age 65, and voluntary early retirement is also not uncommon.). Professors may continue to apply for NSERC grants past retirement, provided they have either lifetime emeritus status, or a term appointment of at least three years duration.

Sources of Support

Canadian university-based researchers obtain support from five principal sources:

i) the Natural Sciences and Engineering Research Council (NSERC) (by far the largest source)
ii) internal university funds
iii) Provincial government programs
iv) the Canadian Institute for Advanced Research (CIAR)
v) industry (often coupled with leveraged NSERC ‘partnerships program’ support)

While NSERC and CIAR programs are national in scope, the other sources vary widely from province to province. Traditionally, NSERC has provided Research Grant support for equipment, personnel, expendables and other direct costs of research, while the universities have provided the majority of support for basic infrastructure (e.g. workshops, technicians, utilities etc.). NSERC's Research Grant program provides the majority of support for university-based research in Canada, and is discussed in further detail below. NSERC also has project-oriented programs; some stand-alone, such as Research Partnerships (which involve partnering with a non-university collaborator - usually industry but potentially also a government lab), and some that they administer on behalf of other government agencies such as the National Research Council.

NSERC also coordinates 14 **Networks of Centres of Excellence** (NCEs) that help support groups of researchers working on specific topics, spanning science and engineering, medicine and the social sciences, which are deemed to be of particular importance to the country. The total budget for the current phase of this program is $197 million over 5 years. The organization and procedures of the NCEs vary, but all are heavily involved with industrial partners, and all coordinate the exchange of information and ideas among participating researchers and industrial affiliates. The two

NCEs most closely related to CMP are Micronet (microelectronics and VLSI, mostly silicon based), and the new Intelligent Sensing for Innovative Structures network, both of which involve, among other things, some electronic and optoelectronic device development. Micronet, for example, lists 20 participating universities, each of which has more than one funded researcher, typically from an Engineering department. While several condensed matter physicists have received strong support through the NSERC Research Partnerships Programs, there has to date been essentially zero CMP participation in the Networks of Centres of Excellence program. There has likewise been no emphasis on advanced materials, by which we mean materials with novel electronic, photonic, magnetic, or other properties which can have an enabling effect on important industries such as telecommunications and computing, and result in high value-added products.

The paucity of Canadian support for advanced materials research is particularly striking when compared with the high profile such research receives in other countries. In Japan, for instance, the Ministry of Education supports "Priority Area Grants", that each receive from $2-$6 M for from 2 to 4 years. There are several of these grants in the area of advanced materials: "Anomalous Metals near Mott Transitions", "Physics of Strongly Correlated Electronic Systems", "Mutual Quantum Manipulation of Radiation Fields and Matter", "Single Electron Devices", "Magnetism and Transport in Nanomagnets", "New Electronic States in Molecular Materials", "New Developments in the Semiconductor Superlattice Structure in Terms of Spin Control", "Complex Liquids", and "Quantum Tunneling in Many-Body Systems". This ministry also supports a major "Center of Excellence" working on "Phase Control and Engineering of Spin-Charge-Photon Coupled Systems". These are in addition to the more targeted programs supported by the Ministry of Science and Technology, and the Ministry of Technology and Industry.

In the United States, the NSF Division of Materials Research has a National Facilities and Instrumentation program (1996 budget $33.4M) that supports such things as state-of-the-art nanostructure fabrication facilities through the National Nanofabrication Users Network. In addition to their support of individual research programs (1996 budget $84.5M), the DMR also supports major collaborative efforts by way of Materials Research Science and Engineering Centers (1996 budget $57.3M). The DOE, in addition to its direct support of materials research at universities through its Basic Energy Sciences program, and its support of the operating costs of materials facilities such as synchrotron and neutron sources, injects an additional ~$7M per facility to strengthen the user programs for university and industrial research through the Scientific Facilities Initiative.

The **Canadian Institute for Advanced Research (CIAR)** is a non-governmental organization that owes its existence to Fraser Mustard, a social and scientific visionary. Since its inception in 1982, the CIAR has supported "research institutes without walls", that have influenced the development of science and technology throughout Canada, as well as public and private policies in health, science & technology, economics and human development. There were 9 separate programs supported in 1996:

1. Population Health
2. Human Development
3. Economic Growth and Policy
4. Cosmology
5. Evolutionary Biology
6. Earth Systems Evolution
7. Artificial Intelligence and Robotics
8. Science of Soft Surfaces and Interfaces
9. Superconductivity

Program 'members' include the top researchers in these nine targeted fields; most are from Canadian universities, but others come from all parts of the world. Members receive financial support from the CIAR that enables them to dedicate more time to research at their home institutions, to visit their colleagues and have their colleagues visit them on a more frequent basis, and to run small, focused workshops on topical subjects on a regular basis. As of June 1996, the CIAR had raised more than $62 million, (34%) from the private sector, (27%) from provincial governments, and (39%) from the federal government, or an average of ~$4.5 million per year.

A small but very significant subset of the CMP community has benefited greatly from participation in the CIAR Soft Surfaces and Interfaces and Superconductivity programs. In addition to the obvious advantage of having more time to devote to research, the networking and regular meetings have had a very positive effect on establishing a sense of community in these areas, and in enhancing their international impact. It is no coincidence that the two "success stories" discussed in Section III are both connected with these programs.

The provinces of Ontario and Quebec have special programs that support groups of researchers working on related topics (the **Ontario Centres of Excellence** and le fonds pour la Formation de Chercheurs et l'Aide à la Recherche (**FCAR**) respectively). These two programs differ a great deal in their organizations, but both have a significant impact on CMP research in those provinces, and demonstrate an emphasis on materials research which has no apparent national counterpart. Some of the other provinces have smaller programs that typically require very direct industrial participation, and offer little prospect of funding continuity.

Direct industrial support for university-based CMP research is small in comparison to NSERC support. Nortel, formerly known as Bell Northern Research and Northern Telecom, is by far the largest company in Canada with technological interests in common with the CMP community. They have infrequently provided in-kind or cash support for CMP researchers seeking funds from NSERC's Research Partnership Program, but in the past have not been seen as particularly supportive of university-based research in Materials Science. There is growing evidence that this situation is changing, as budgets for longer-term materials research within the company come under pressure, and the desirability of partnering with university researchers in these areas becomes more apparent. Nortel also sponsors several **NSERC Industrial Research Chair** positions, but these are mostly in Engineering or Computer Science departments, and are not related to Materials Science. Other Canadian industries fund the two CMP researchers who now hold such NSERC Industrial Research Chair positions: Mike Thewalt, whose chair at SFU, supported by Crystar Research, Bomem and EG+G Optoelectronics, has just been renewed for a second five years, and Jeff Dahn, who has recently taken up a new chair funded by the 3M corporation at Dalhousie.

There are a number of smaller companies that collaborate with university-based researchers on targeted projects. NSERC has several programs that will match both cash and in-kind contributions from industrial partners. These include **Industrially Oriented Research (IOR) Grants ,** and **Collaborative Research and Development (CRD) Grants**. Two examples of CMP participation in these programs are the collaboration of high T_c superconductivity researchers with CTF Systems, a manufacturer of SQUID-based imaging instruments, and of semiconductor laser researchers with Rogers Cable, a cable television company. NSERC also has a **Strategic Grants Program**, which funds projects in predefined areas of strategic interest. This program does not require cash or in-kind support from industry, but does require strong indications of interest and participation from an industrial partner or partners. For a minority of researchers, the total support from industry plus the NSERC matching and strategic programs can be comparable to or greater than their basic Research Grant funding. However, this type of funding typically does not have the continuity and predictability which are widely seen to be among the most positive aspects of the Research Grants program.

There are three other NSERC-administered programs that should be mentioned, before focusing on the Research Grants component, which is the primary source for funding academic research in CMP. The first is the **NRC/NSERC Research Partnerships Program**, which is funded by NRC. Its objective is to support the university component of collaborative projects involving NRC, the university group(s), and small (< 500 employee) companies. As it covers the entire NRC and NSERC mandate, there will likely be at most one CMP project funded per year.

The **Technology Partnerships Program** has similar goals, but it is funded by NSERC, and it does not necessarily involve the participation of government laboratories. The specific purpose is to help transfer university-generated technology to small and medium sized Canadian companies. Finally, there is also a **Research Networks Program** that involves partnering with at least one non-university collaborator (while industrial participation is not a formal requirement, it can be assumed to be near-essential). It is specifically for research opportunities where there is a demonstrable benefit to a network approach that links at least 5 researchers from 3 different institutions. As will be discussed later, there may well be excellent opportunities under this program for enhancing CMP efforts in areas which are currently lacking in national cohesion and planning, but which have a clear strategic, economic importance for Canada.

The NSERC Research Grants Program

As mentioned above, some researchers in CMP obtain support for specific projects related to the more applied aspects of their research through the NSERC Research Partnership Program, but the overwhelming majority of NSERC support for CMP comes through the Research Grants and the Scholarships programs. NSERC provides a limited number of scholarships for post graduate students and post-doctoral fellows. Some provinces and/or universities also have graduate student scholarship programs. Together, this means that approximately 30% of graduate students have some sort of scholarship that effectively augments their supervisor's Research Grant. A small number of post-doctoral fellowships are also awarded, but these are often held outside of Canada. The Research Grants program therefore funds a large portion of the stipends/salaries of all research personnel (excluding professors themselves), major and minor equipment, and the direct costs of research (excluding utilities etc.).

An important aspect of the program is that a researcher may only be a principal investigator in one single Research Grant at any given time, whether it is an individual grant or a team grant. There is no specific limit on how many other grants, networks etc. a researcher can hold or be part of in addition to the Research Grant, although the *need* for additional funding is, in principle, a requirement always to be addressed.

The Research Grants program is designed to support high quality research regardless of any direct or short term economic justifications. It is a flexible program that emphasizes the quality and impact of past and proposed work, and puts few constraints on how the awards are used to achieve these goals. Research Grant applications do not require milestones, and there are no penalties for fruitful changes in research direction in the middle of a grant (which normally lasts four years). When applying for the renewal of a Research Grant (funding under this program has a high degree of continuity), the success over the previous grant period is not judged against the goals of the previous grant application, but rather by attempting to evaluate the achievements (publications, impact, excellence, training) on their own merits. At least in CMP, for established applicants the track record is much more important than the details of the research proposal, which encourages changes in research direction and the undertaking of novel or ‘high risk’ projects.

Research Grant applications are reviewed by a number of discipline-based **Grant Selection Committees** (GSCs) that cover a wide range of subjects, from psychology to sub-atomic physics. The most recent available breakdown of NSERC Research Grant and Equipment expenditures by GSC are listed in Table 1. Each GSC is comprised of academic, industrial and government researchers from Canada and abroad. The CMP GSC (GSC28) has 8 members: currently these include 4 from Canadian universities, 1 from a Canadian company, and 2 from foreign research institutions (one of the foreign researchers having left the committee for health reasons). The GSC28 budget for Research Grants is ~ $ 6.35 M/yr, out of a total NSERC Research Grant budget of $ 186.3 M/yr (1996 data).

As discussed in the introduction, starting in 1994, the distribution of the total Research Grant budget among GSCs is adjusted every four years through a **Reallocation Process**. In the first Reallocation, this consisted of placing 10% of each GSC's budget into a pool, and reallocating the pool based on the **Reallocation Committee**'s review of written submissions from all the GSCs, where the supposed primary criterion was research “excellence”. The CMP and General Physics GSCs made a joint submission, and together with Subatomic Physics and Mathematics, received the maximum 8.5% reduction resulting from Reallocation.

There is insufficient space here to go into the details of the previous Reallocation, and the responses to it. The little feedback that was received from the Reallocation Committee (the 5 lines of text, bottom of page 1) indicated that the committee felt our community suffered from a lack of focus, and that the job opportunities for graduates were not the best. The present Review of Physics is timed so that the results can be used as input for the next Reallocation exercise (submissions due Jan. 1, 1998). The criteria for the next exercise will be very different from the first. Rather than focusing on generic issues of quality, discipline dynamics etc., the submissions will have to specifically address how their community would use any new resources for the "benefit of Canada". It has already been decided that the CMP community will make a submission in 1998 which is independent from that of the General Physics and Subatomic Physics communities.

There are 217 principal investigators who are funded by GSC28 (1996 numbers). Most hold **Individual Research Grants**, largely for historical reasons associated with the importance of the existence and size of one's Research Grant in career progression at the universities. NSERC has long argued against the prevalence of this interpretation of the

Research Grant within the community, but not surprisingly, with little success. NSERC also recognizes that in many, but of course not all cases, it would make more sense for a group of researchers to share a **Team Research Grant**, and they encourage researchers to apply as teams. There may be a very slow trend in this direction, but until the situation in the universities changes, or much clearer messages and incentives are provided by NSERC and/or individual GSCs, it is unlikely that Team Grants will become as common as they perhaps should be. At present there are five Team Grants in CMP, having 11 principal investigators. A listing of all of the GSC28 Research Grants is provided in Appendix 2. For GSC28 the size of these grants ranges from $5,000 to $101,000 per year, with an average of $29,182 that differs little between experiment and theory ($29,644 vs. $28,266, respectively). The nominal grant cycle is 4 years, but there are exceptions ranging from 1 to 5 years.

There is a separate **Equipment Grant** competition each year, open to all Research Grant holders (not only those with Research Grants under current consideration), which occurs in parallel with the Research Grants competition, but is essentially decoupled from it, except for new applicants. There are three categories: minor equipment ($7,000-$150,000), major equipment ($150,000-$325,000), and major installations (above $325,000). The GSCs have sole discretion on minor equipment funding and relatively direct control of most major equipment applications, while major installation applications are usually adjudicated by ad-hoc committees. At present, approximately 25% of the dollar value of these equipment requests are funded. Equipment grants are not coupled with any ongoing support for the operation and maintenance of the equipment; it is assumed that this will be provided by the researcher(s), the university, or by fees for external users.

The GSCs operate within their budget envelopes with a fair degree of freedom. They are constrained by the NSERC regulations and guidelines, but there is substantial flexibility based on the interpretation of these guidelines. The four criteria for evaluating Research Grant (and equipment) proposals are:

1) Scientific or Engineering Excellence of the Researcher(s)
2) Merit of the Proposal
3) Need for Funds (or equipment)
4) Contribution to the Training of Highly Qualified Personnel

Research Grant applications consist of two forms. The first contains the budget, plus a 5 page description of the progress made during the last grant cycle, and the work proposed for the next cycle. The second, or personal data form, summarizes and quantifies the applicant's research contributions over the previous six years. Equipment Grant requests include the same personal data form, and an application form that describes the equipment, and budget, and explains the intended use. Minor equipment applications are limited to 2 pages of text, major equipment applications to 10 pages, and major installation proposals are open-ended.

GSC28 funds experimental and theoretical research in the following, broadly defined areas:

i) metals and magnetic materials,
ii) highly correlated electronic systems,
iii) soft/biological/polymer materials,
iv) electronic/optical materials, and
v) nonlinear systems/fluids.

(a breakdown of the relative size of the research effort by subfields is given in Appendix 1)

The work represented in this list ranges from abstract theory to prototype device development, and covers most of the ground in between. In some cases a researcher funded by the GSC28 may also work in related areas, such as optics, lasers, general statistical mechanics etc., areas that are covered by the General Physics GSC or one of the engineering GSCs. More details about these various efforts are provided below, and in Appendix 2.

As mentioned above, the Condensed Matter, General Physics, and Subatomic Physics GSCs did not do well in the first reallocation process. One topic that is often discussed in this context, both within the community and with NSERC representatives, is the level of '**selectivity**' exercised by various GSCs. There exists a perception that physics GSCs have not been as selective as some others. There is much debate as to what, if any, hard evidence for this exists, but certainly there is the flexibility within the system to vary the degree of selectivity.

University Support

Canadian universities have a quite different relationship to research funding as compared to, for example, those in the USA. In Canada, the universities provide full 12-month salaries for all their faculty, even though most only offer two full terms of courses. Faculty salaries are infrequently augmented through consulting fees, but not through Research Grants or contracts. The universities can collect overhead only on research contracts, but not on NSERC Grants of any kind. Thus the universities provide full salaries to the faculty, whether they are active in research or not, and must cover from their own resources some of the costs inherent in research (buildings, utilities, technical support) The universities also often provide significant startup support for new faculty, depending upon their financial resources and their willingness to hire competitively. Many universities have some form of internal operating support for research, but these sources tend to be of minimal size.

The **NSERC General Grant**, an amount equal to some small fraction of the total NSERC grants at an institution, which in past years was transferred to the university administration to partially offset the costs inherent in pursuing research, was eliminated some time ago. Thus Canadian universities, under increasing economic pressure, inevitably begin to see the winning of Research Grants, and even more so large Equipment and Installation Grants, as a significant cost rather than a benefit to the university, offset only by the intangible prestige which a vigorous research program can bring. In this environment, university support for existing facilities, and the willingness to commit to support in order to win new facilities, becomes an ever greater problem.

The Growing Crisis in Infrastructure Support

In Canada, the provincial governments are responsible for and control education, but the financial resources come primarily from the federal government in the form of "transfer payments". These transfer payments are the principal source of university budgets, a portion of which has traditionally been used to support research, through such things as technician's salaries, workshop equipment, startup funds etc. Transfer payments have been substantially reduced over the past 5 years, resulting in continuing budget cuts to the universities. Institutional support for research is thus constantly declining, as shrinking resources are concentrated more and more on the direct costs of teaching. The federal government has also reduced the NSERC budget over the past 5 years, forcing NSERC to cut all of their "non-core" programs. The net effect is that the Research Grant budget has remained almost constant, in absolute dollar units, while the pool of eligible researchers continues to grow. Worse, the support for infrastructure, undergraduate summer fellowships, and new programs such as the Collaborative Project Grants has either been substantially reduced, or completely done away with. In particular, while the infrastructure requirements for research in CMP have been steadily increasing, the sources for appropriate funding are rapidly drying up. Unfortunately the provincial governments, in spite of their responsibility for funding and operating the higher education system, have shown little interest in even contemplating the infrastructure problem, perhaps out of fear of being saddled with the full responsibility.

We have already referred to the continuing reduction in infrastructure support provided by the universities for the type of smaller, university-based Materials Science and Engineering facilities which have long been associated with successful materials research. NSERC also has recognized that access to large facilities with high-quality infrastructure support is a major concern of researchers in Materials Science. It recently funded a review committee (the **Bacon Committee**) to make recommendations on major materials research facilities. They concluded that " ‘**clusters of equipment**’ play a key role in materials research, but that stable infrastructure support for these clusters is seriously inadequate, and rationalization of the management, operation , accessibility and financing of such equipment ‘clusters’ is necessary". They also concluded that, "as a modern industrial nation, Canada needs access to both neutron and synchrotron radiation facilities, but that this will effectively be denied unless improved facilities and equipment are available". The committee made the following six recommendations.

Recommendations of the **Bacon Committee:**

1. NSERC should play a leading role in the process of facilitating and accelerating initiatives to co-ordinate resources for materials research and establish national or regional ‘clusters’ of facilities.

2. When national or regional clusters of facilities are established, the infrastructure necessary to operate each cluster must be provided through appropriate co-operation of federal and provincial agencies, and of industry, for the useful lifetime of that cluster.

3. Canada should make an immediate commitment to develop a fully equipped reactor-based national source for neutron beam research. (*We note that in the body of the report the Bacon Committee explicitly endorsed a dual-use reactor, combining neutron beams with an AECL irradiation test facility.)*

4. Canada should make an immediate commitment to develop a fully equipped dedicated national source for synchrotron radiation research.

5. Immediately upon acceptance of Recommendations 3 and 4, proposals for the construction of both national research facilities should be requested and peer reviewed, and a cash flow plan for construction of the two facilities should be designed.

6. NSERC should initiate co-operative efforts among parties drawn from Industry Canada, Canadian universities, AECL, CINS, CISR, NRC, MRC, and other interested parties, to explore neutron beam and SR sources.

In October of 1995 the NSERC Council accepted recommendations 1,2 and 6. A committee was established to suggest ways of implementing recommendations 1 and 2, but nothing has come of this as yet. More details on the status of recommendation 6 are provided in Section IV. Previous NSERC infrastructure programs (covering all NSERC-funded areas, not just materials research) were replaced by a **Major Facilities Access (MFA) program** in 1996. This effectively served to consolidate related infrastructure grants into a much smaller number of larger grants, but **the net result was an overall reduction in infrastructure support by approximately a factor of two**. CMP researchers receive direct infrastructure support from 6 MFA grants (listed in Appendix 2), but the total support for CMP is less than what was previously received under the infrastructure grant program.

The most recent federal budget announced that a new Canada Foundation for Innovation (CFI) would be formed, with funding totaling 800M$ over five years. This is to be used to upgrade research facilities in universities and teaching hospitals, but explicitly excludes any support for the operation of these facilities. The federal component of any project will be 40% of the total cost, with the rest coming from non-federal sources (provinces, universities, or industry).

Clearly this represents a major opportunity to improve outdated research laboratories and develop new capabilities. However, it will not in and of itself solve the problem. The matching funds requirement, given the state of affairs of most provincial and university budgets, will inevitably require industrial contributions to any successful project. This will be a challenge even in disciplines close to the marketplace such as engineering and medicine. For CMP there will no doubt be selected cases where viable industrial partnerships can be forged, however, the long term nature of any basic research may make it difficult to obtain significant access to these funds for much of the infrastructure required by condensed matter physicists, despite the demonstrated importance of the field as the fundamental underpinning of any materials oriented technology. Furthermore, simply building up equipment is not sufficient, it is also necessary to have in place the resources to operate it. The cumulative effects of years of erosion of the university infrastructure have been accompanied by a general decrease in the technical support which is essential to efficiently exploit any new facilities that may be built. It is not at all clear where adequate operating funds for these new facilities will be found, given the ongoing cuts to NSERC, and the explicit exclusion of operating expenses from the CFI program.

Other useful statistical data on CMP in Canada is given on the following three pages.

TABLE 1: NSERC RESEARCH PROGRAM GRANTS AWARDED IN 1996 COMPETION ($1,000)
(taken from NSERC Contact, vol.21, No. 2, Summer 1996, p. 7)

Grants Selection Committee	Research Grants[1]		Equip. Grants[2]		MFA Grants[3]		Total Funding	
	N	k$	N	k$	N	k$	N	k$
Animal Biology	235	5,899	19	530			254	6,429
Animal Physiology	200	6,627	15	428			215	7,055
Cell Biology and Genetics (02)[4]	1	51					1	715
Cell Biology	265	8,589	23	664			288	8,786
Molecular and Developmental Genetics	171	6,644	11	197			182	6,841
Plant Biology and Food Science	305	9,728	39	1,002			344	10,730
Evolution and Ecology	451	12,573	28	596			479	13,170
Psychology	346	8,966	24	394			370	9,360
Solid Earth Sciences	299	8,880	17	708			316	9,588
Environmental Earth Sciences	333	7,998	30	1,177			363	9,175
Inorganic and Organic Chemistry	270	11,421	31	2,490			301	13,911
Analytical and Physical Chemistry	299	10,767	27	2,252			326	13,019
Space and Astronomy[4]	155	4,842	13	247	2	125	170	5,214
Condensed Matter Physics	215	6,489	25	1,156			240	7,645
General Physics	129	3,870	13	620			142	4,490
Pure and Applied Mathematics (16)[5]	4	92					4	92
Pure and Applied Mathematics A	299	4,273	2	77			301	4,350
Pure and Applied Mathematics B	223	3,167	7	167			230	3,334
Statistical Sciences	242	3,128	12	229			254	3,357
Computing and Information Science	502	11,342	21	719	11	668	534	12,728
Communications, Computers and Components Engineering	300	6,819	11	454			311	7,273
Electromagnetics and Electrical Systems Engineering	255	6,261	17	602			272	6,863
Industrial Engineering	223	4,484	11	273	2	100	236	4,858
Chemical and Metallurgical Engineering	424	12,154	32	1,891			456	14,045
Civil Engineering	504	11,201	30	875			534	12,076
Mechanical Engineering	485	11,077	30	1,180			515	12,257
Interdisciplinary[6]	39	940	2	57	50	3,690	91	4,686
Selection Committee on Research Grants[7]			9	4,969	1	30	10	4,999
Selection Committee in Life Sciences			7	867			7	867
Total (excluding Subatomic Physics)[8]	**7,174**	**188,283**	**506**	**24,820**	**66**	**4,612**	**7,746**	**217,912**
Subatomic Physics	160	11,501	10	482	13	5,009	183	16,992

1 - Includes individual, team, and project grants and grants to holders of Women's Faculty Awards.
2 - Includes Equipment, Major Equipment, and Major Installations Grants; some equipment grants were paid with 1995 funds.
3 - Includes phase-out of Infrastructure Grants.
4 - Space science is also funded by the Canadian Space Agency
5 - Remaining installments of grants from GSCs which have been eliminated by reorganization
6 - Has only a small number of Research Grants, but handles all interdisciplinary (i.e. multi-GSC) Equipment and MFA Grants
7 - Final authority on Major Installation Grants
8 - NSERC has historically followed this format due to the unique importance of Project Grants to subatomic physics.

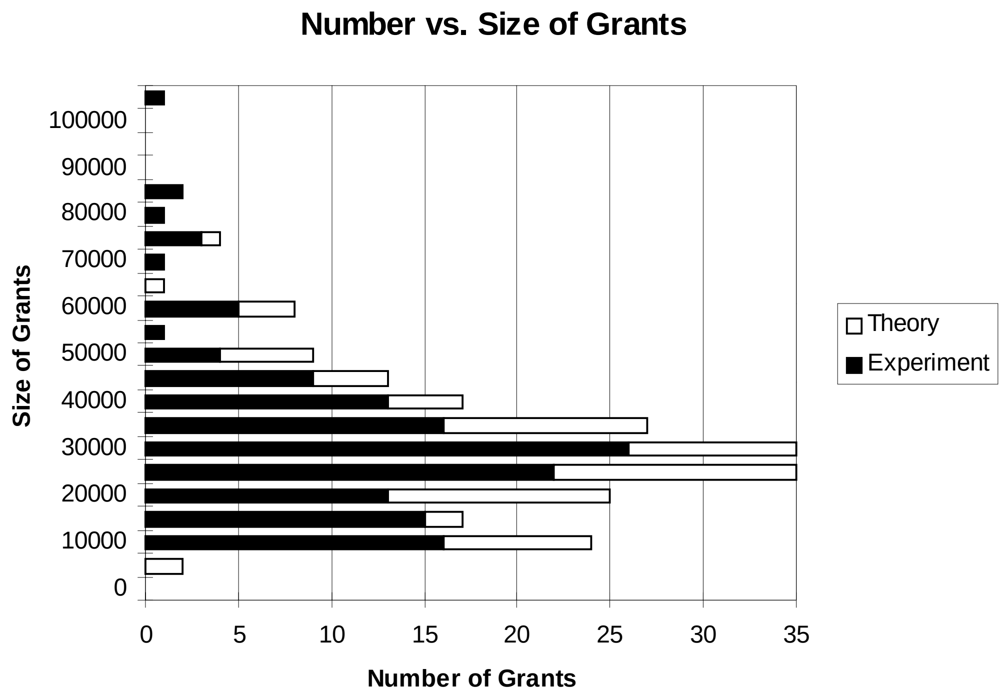

Fig. 1: Number of Research Grants per $5K bin in GSC28 for 1996, with experimental and theoretical components separated out (team grants divided by no. of funded investigators). Note that one third of the lowest-funded group of experimentalists is accounted for by adjuncts, who qualify only for small grants directly related to the added cost of supporting a graduate student. The first nonzero bin on the vertical scale indicates that there were two grants of between $5,001 and $10,000/yr., etc.

No. of experimental grants - 142 (67%)	Average experimental grant per investigator - $29,644
No. of theoretical grants - 69 (33%)	Average theoretical grant per investigator - $28,266

Size of CMP in Canada vs. USA:

	CAP	APS
Total 1996 membership (individuals) -	1628	39882
1996 membership in DCMP -	226 (14%)	5433 (14%)
APS Materials Physics Division -		1953 (5%)

Table 2: 1996 Research Grant funding under GSC28 by university, ranked in descending order of total amount (includes CMP-related WFA grants). Note that last column is per investigator, not per grant.

University	No. of Grants	Grant Total ($)	Average Grant per Investigator ($)
SFU	21	769,400	36,638
UBC	14	703,400	50,243
McMaster	14	515,300	36,807
Toronto	14	482,300	34,450
McGill	10	409,600	40,960
Queen’s	11	355,100	32,281
Sherbrooke	12	330,000	27,500
Western	11	300,100	27,281
Waterloo	13	262,700	20,207
Ottawa	13	261,500	20,115
Memorial	6	219,500	31,357
U. de Montréal	8	209,021	26,128
U. Manitoba	7	206,400	29,485
Guelph	7	201,300	28,757
U. Alberta	6	197,500	32,916
Dalhousie	8	189,600	23,700
École Polytechnique	5	150,523	30,104
Brock	6	124,100	20,683
Concordia	4	99,000	24,750
St. Francis-Xavier	3	94,700	23,675
Lakehead	5	58,500	11,700
New Brunswick	1	58,000	58,000
Trent	2	46,000	23,000
U. Winnipeg	1	40,000	20,000
Brandon	1	32,000	32,000
Moncton	1	30,000	10,000
Trois-Rivières	2	27,000	9,000
Calgary	1	24,000	24,000
Acadia	2	23,000	11,500
PEI	2	22,600	11,300
Wilfrid Laurier	1	22,500	22,500
York	1	22,000	22,000
U. Northern B.C.	2	20,000	10,000
Regina	1	5,000	5,000

III TWO SUCCESS STORIES IN CANADIAN CMP

The following two programs have been singled out for special discussion because they are widely recognized as successes within the Canadian community, as evidenced by the many times they were referred to as such in the questionnaire responses. While they are certainly not our only successes, they also merit special consideration because of the common factors associated with the achievement of their success, and the related high international impact. Consideration of these factors is important for any discussion of ways to improve the overall impact of Canadian research in CMP. Put simply, the common factors in these two success stories were the existence of a group of talented scientists across Canada, who had already made significant contributions in their fields, brought together to work as a coherent group on a set of well-defined problems under a scheme which emphasized networking and communication on both the national and international levels.

Since this Review forms part of a wider effort covering all of Canadian physics research, we should also note that a considerable number of researchers in CMP listed the Sudbury Neutrino Observatory (SNO) and cosmology as two other areas of Canadian strength in physics. It is interesting to note that in common with our two CMP ‘success stories’, cosmology is supported by a CIAR network.

III.1 *High Temperature Superconductivity*

High Temperature Superconductivity is the most dynamic research topic in the history of Condensed Matter Physics. The field took off like a rocket at the end of 1986, after confirmation of the original result of Bednorz and Mueller of superconductivity above 30 K in LaSrCuO, and shortly afterward was boosted into orbit by the discovery of a 90 K superconductor, YBCO, by Paul Chu. An army of workers from many disciplines joined the field in 1987 in hopes of discovering even higher T_c’s, of uncovering the mechanism driving this new phenomenon, or of producing novel superconducting devices which would revolutionize technology. The field continued in high gear for the next few years, generating an unprecedented number of papers and conferences and then gradually stabilized. Equilibrium was restored in the early 90’s by the realization that further progress in this extraordinarily competitive field required a high level of commitment of resources, personnel, and expertise. In particular, the most successful groups were ones with the ability to produce extremely high-quality samples, well characterized by a variety of methods, using techniques in which they were the acknowledged world experts.

In spite of the high stakes, high temperature superconductivity research has thrived in Canada and is presently our most successful and visible condensed matter physics program. This section will highlight one particularly successful part of the Canadian high T_c program, the UBC/TRIUMF/McMaster collaboration on the microwave, MuSR and infrared properties of high quality YBCO crystals grown at UBC. However it is important to recognize that high temperature superconductivity is a major strength of Canadian Condensed Matter Physics, and that excellent programs exist at universities across the country. A more comprehensive description of the full Canadian high T_c program is presented in Sec. IV.1, whereas here the focus is on only one component, a single, very successful inter-university collaboration.

YBCO crystals produced at UBC are among the best in the world and are studied by experimental groups across North America and in Europe. The microwave lab at UBC, MuSR at TRIUMF, and the far infrared lab at McMaster each dominate their field. The single most influential result of the Canadian program was the discovery of the linear temperature dependence of the low temperature penetration depth in high quality, optimally-doped YBCO crystals by Hardy, Bonn and coworkers at UBC. The impact of this highly cited result was to turn the tide of opinion toward the possibility that the order parameter in high temperature superconductors has d-wave symmetry, unlike conventional superconductors which are s-wave. The d-wave symmetry of the gap is a major clue for solving the mystery of why T_c is so high.

Canadians have had a disproportionately large influence on this field, and their program is still in high gear. The field itself will continue to flourish in the future because the kind of “strong correlation effects” which give rise to high temperature superconductivity will continue to be found in other materials, providing a wealth of useful new electronic properties for the technology of the 21st century. Strong correlation effects also arise in other contexts, such as magnetism, organic conductors and the two-dimensional electron gas. There is significant Canadian work in all these areas, as is made clear in Sec. IV.1 below.

For the purpose of this section on Success Stories, it is relevant to consider just why it was that Canadians have been able to contribute so effectively to such a dynamic, competitive, and resource-intensive field of research as high T_c . We argue that there were four main ingredients for this success:

1. As always, success was heavily dependent on the involvement of a small number of very talented individuals. Their presence is the result of good hiring decisions, in some cases dating back to the '70s, and to the nurturing of excellent researchers.

2. Specialized facilities and infrastructure, again dating back to the '70s, including the materials preparation and characterization facilities of the Brockhouse Institute for Materials Research at McMaster and the MuSR Facility at TRIUMF.

3. The flexible funding of research in Canada which, in 1987, allowed researchers the freedom to rapidly redirect their programs, and which was also then able to infuse critically needed extra funding to ramp up the new program. In this regard, the responsiveness exhibited by NSERC's Strategic Grant Program in the late 1980's was particularly crucial.

4. The creation of the Superconductivity Program of the Canadian Institute for Advanced Research (CIAR), which provided release from teaching, and catalyzed interaction among the leading Canadian groups.

The membership of the CIAR program illustrates both points 1 and 4. Members include Walter Hardy, Doug Bonn, Rob Kiefl, Jess Brewer, Ian Affleck, and Philip Stamp at UBC, Tom Timusk, John Greedan (a Solid State Chemist), Jules Carbotte, John Berlinsky, and Catherine Kallin at McMaster, Thom Mason at Toronto, Louis Taillefer at McGill, André-Marie Tremblay and Claude Bourbonnais at Sherbrooke, and Bill Buyers and Frank Marsiglio at Chalk River. These members receive varying amounts of teaching relief, and, in addition, the CIAR provides an interaction budget and sponsors annual meetings of the group.

Two established facilities, the MuSR facility at TRIUMF and the Materials Preparation and Characterization facilities in the Brockhouse Institute at McMaster, each spawned a high level of activity in the early stages of high T_c research. It was immediately clear in 1987 that MuSR would be an important technique for characterizing even the low quality ceramic samples which were initially available. There was substantial demand for access by external users (such as the MuSR Group from AT&T Bell Labs) and a high level of interest by the local group. This in turn led to the development of a materials synthesis effort at UBC, led by Walter Hardy, as the importance of high quality samples became apparent.

Later on, in collaboration with Doug Bonn, Hardy began to apply his own technique, microwave spectroscopy, to the crystals that he and his collaborators produced. Studies of the microwave surface resistance of YBCO showed a peak in the surface resistance and substantial low temperature dependence which could not be understood if one assumed the existence of an s-wave gap as was then believed to be the case. Catherine Kallin and John Berlinsky of McMaster worked closely with the UBC microwave group, helping to provide the theoretical basis for analyzing the unusual low temperature dependence of the microwave properties. The enormous drop of the inelastic scattering rate and the residual temperature dependence of the low-T microwave conductivity cast serious doubt on the conventional s-wave picture. However it was the discovery of the linear low-T temperature dependence of the penetration depth which really put things into perspective, providing strong evidence for line nodes in the gap function as one would expect for a d-wave superconductor. These results were credible because of the manifestly high quality of the YBCO crystals produced at UBC and because of the exquisite sensitivity and precision of the microwave measurements. As a result, they had a substantial impact on the evolution of the field. The paper describing this work, by Hardy, Bonn and co-workers, was among the Top 10 most cited current Physics papers for most of 1994/95 and was the most cited for July and August 1995. Bonn was subsequently appointed to a faculty position at UBC.

The availability of high quality crystals has played an important role in the usefulness of MuSR as a probe of high T_c superconductivity. Early misleading results on ceramic samples had suggested that high T_c superconductivity was conventional in nature. However more recent work on crystals clearly confirms the low temperature dependence of the penetration depth that was discovered by Hardy and Bonn. The sensitivity of the MuSR technique has improved dramatically over the past few years, through the efforts of Rob Kiefl, Jess Brewer and the NSERC-Infrastructure-supported MuSR Facility. This group took a severe blow when NSERC Infrastructure funding was contracted and redistributed through the inadequately-funded Major Facilities Access (MFA) Program.

Along with far-infrared measurements, MuSR is one of the few methods for measuring the absolute value of the penetration depth (microwaves only measure the change of the penetration depth with changes in temperature). In addition, MuSR has the unique capability of determining both the penetration depth and the coherence length in the same experiment, by measuring the magnetic field distribution both between vortices (the saddle point in the field distribution) and inside the vortex cores (the high field cut-off). In 1992, MuSR measurements were used to place a very low limit on the on the breaking of time-reversal symmetry in high T_c superconductors thus effectively eliminating a mechanism based on fractional statistics quasiparticles (anyons). Planning is underway to use Muons to test the new SO(5) theory of high T_c superconductivity which predicts antiferromagnetic vortex cores in underdoped samples.

McMaster University was able to become a major player in high T_c because of its long-standing investment in materials research, involving faculty in several Science and Engineering departments and shared facilities, jointly supported by NSERC, the University and, over the past 10 years, by the Ontario Centre for Materials Research (OCMR). McMaster high T_c researchers benefited from the extensive materials preparation and characterization facilities of the interdisciplinary Brockhouse Institute for Materials Research, which led to the early availability of good high T_c samples as well as new materials for substrates for superconducting films. The most significant results came from Timusk's far-infrared lab, which produced accurate measurements of the real and imaginary parts of the conductivity, in the normal and superconducting states, for a wide variety of pure, doped, and radiation-damaged high T_c crystals. Infrared studies of UBC crystals determined the absolute value of the low temperature penetration depth, supplementing microwave measurements of the change of the penetration depth with temperature.

Timusk's work anticipated much of the current interest in the so-called pseudo-gap in underdoped high T_c compounds, and now forms the basis for our understanding of the optical properties of the underdoped state. The work of the McMaster infrared group benefited from the high level of theoretical activity and interest at McMaster, particularly from a close interaction with the group of Jules Carbotte, Director of the CIAR Superconductivity Program. Over the years Carbotte's program has evolved from definitive calculations of the strong-coupling properties of conventional superconductors, through a critical analysis of the possibility that high T_c superconductivity could arise from a conventional mechanism, to studies of d-wave superconductivity and its relevance to the transport and optical properties of high T_c materials.

In some ways, an equally important product of the McMaster program has been the training of excellent new physics faculty. Over the past several years, these include former Ph.D. students Thom Mason (Toronto), Maureen Reedyk (Brock), Elisabeth Nicol (Guelph), Doug Bonn (UBC), and Frank Hegmann (Alberta), as well as Dimitri Basov, a post-doc of Timusk, who is joining the faculty at UC San Diego at La Jolla and Chris Homes (a product of UBC, McMaster and SFU) who will develop the far infrared spectrometer at the Brookhaven Synchrotron.

The history of the development of the Canadian high T_c program provides a unique perspective on the effectiveness of various Canadian funding programs over the past decade. Canadian high T_c research funding got off to a good start in 1987 with an infusion of fast-tracked funding through NSERC's Strategic Grant Program. This funding, together with the flexible nature of NSERC's Research Grant program, allowed the Canadian effort to ramp up quickly. For example, it allowed Walter Hardy to make the radical shift from studying atomic hydrogen gas at temperatures below 1K, to studying superconductors above 90K. A major proposal was prepared at that time, involving essentially all Canadian high T_c researchers, and submitted to the first round competition for the Federal Networks of Centres of Excellence (NCE) Program. This proposal was successful in the peer-reviewed competition, but it was refused funding (and lower-rated proposals were funded) for political reasons, reportedly having to do with regional distribution. The failure of the National High T_c Network proposal was a major setback, since it delayed stable funding, and also because it required the Network to break up into local groupings to generate smaller proposals which could be funded through other programs.

NSERC's Strategic Grant Program continued to be the main source of supplementary funding for high T_c during a four year period coinciding approximately with the first four year round of the Federal Networks. After that, the guidelines for Strategic Grant funding evolved in a way which made it difficult to fund high T_c research. Also, the second round competition for the Federal NCEs was so tightly focused that high T_c was effectively excluded. This led to a break in federal high T_c funding which was particularly damaging for the UBC group. McMaster was less seriously affected because of stable support from the Provincial Centres Program through the OCMR. Last year, following an initial failure, an NSERC Collaborative Grant was funded involving UBC, McGill, and McMaster, providing some resources for new initiatives. In addition, both the UBC and McMaster groups were able to obtain smaller, and narrowly targeted NSERC Strategic Grants. The other major ingredient in high T_c support, which was already described, has been the CIAR Superconductivity Program, which supplements conventional funding by providing release time for key researchers and by organizing annual national meetings.

The Canadian high T_c experience provides a striking illustration of Canadian Science at its best. An extraordinary discovery and research opportunity captured the imagination of talented scientists across Canada. Spurred by international competition, endowed (for once) with significant, although somewhat intermittent resources, including two key Major Facilities Access Grants for TRIUMF MuSR and the Brockhouse Institute, and with the help of a uniquely Canadian institution, the CIAR, Canadians staked out a leadership position which they currently still hold. This example should remind us that there is no need to limit our aspirations in Science (or elsewhere), and that sustained investment in excellence inevitably pays off.

III.2 *Membrane Biophysics* - a case study in interdisciplinary Materials Science

Lipid molecules are amphiphilic in water solution, and under appropriate conditions self-assemble into bilayer sheets, a geometry which is driven by the hydrophobic interaction and effectively shields the hydrocarbon “tails” of the molecules from water exposure. These sheets are remarkably flexible. While somewhat permeable to water, they are quite impermeable to ions and to larger molecules like proteins. In their high-temperature fluid phase (liquid-crystalline, L_α), they behave as two-dimensional fluids, with zero shear rigidity, high compressibility modulus, and large in-plane diffusive mobility. At lower temperature they typically undergo a weakly first-order transition (the “main” transition) to a so-called gel (hexatic) phase, in which the membrane is thicker, supports shear, and exhibits much lower molecular mobility.

Nature uses these materials, characteristically in the fluid phase, as membrane separators between cellular compartments of different chemical composition, as in the cell plasma membrane or the bounding membranes of intracellular organelles. Biomembranes are typically composite, including a phospholipid bilayer and an associated protein-based cytoskeleton—a combination which preserves the flexibility of the bilayer but adds additional toughness. Because of their ability to accommodate hydrophobic units in the bilayer interior, membranes act as substrates for complex proteins with specific, properly calipered hydrophobic regions (the “mattress model”). When dissolved in or segregated to the membrane, such integral membrane proteins are forced to organize into shapes which make them functional as pores, pumps, signal transducers, etc.

Canadian workers have made several key contributions in this important area of science, which crosses the boundaries of physics, biology, biochemistry, biomaterials, and bioengineering. Myer Bloom (with his many students and postdocs: Jim Davis, Ed Sternin, Jenifer Thewalt, and others) has in many ways been the leader of this enterprise in Canada. Following Charvolin and Seelig, he was one of the first people to look seriously at the application of NMR techniques to biological membranes, and to measure carefully the orientational order parameter as a function of distance along the hydrocarbon tail. In particular, his group developed the quadrupolar echo technique, now widely used, which makes possible “high-fidelity” spectroscopy, as has been necessary in studying lipid-protein interactions and verifying the “mattress” model. He and his students studied the role of cholesterol in phospholipid membranes, especially the way a new fluid phase appears above about *25%* cholesterol in which the main transition is suppressed, so that the membrane remains fluid at temperatures well below the main transition of the pure-lipid system. He has also helped to focus attention on the importance of this kind of study by speculating on issues of evolutionary “design”, e.g.: Why does nature often (but not always) choose to adjust lipid composition so as to set the operating point of biomembranes close to but slightly above the main transition? Why does nature use so much cholesterol in the plasma membrane? (To fluidize the membrane and make it more robust). And, how might the behavior of these crucial encapsulating materials have affected the course of cellular evolution?

David Pink, Martin Zuckermann (with Ole Mouritsen (Copenhagen)), John Whitehead and Mark Whitmore have done pioneering work in modeling the role of the conformational degrees of freedom of the hydrocarbon tails in the “main” transition, including the dependence of the transition temperature on chain length and the weakly first-order character of the transition. Such models have helped in understanding the behavior of lipid-cholesterol mixtures, as described above. Related work has clarified the role of the head-group conformations, and that of quasi-critical fluctuations near the (weak) transition, in promoting the solubility of small impurity molecules, such as anesthetics.

Evan Evans (UBC Physics), who is funded by the NSERC Cell Biology GSC, together with coworkers Mohandas Narla (Berkeley), Erich Sackmann (Munich) and others, developed the now-widely-used techniques of micropipette manipulation and phase-contrast microscopy applied to micron-scale vesicular objects, both natural/biological and artificial/prepared. These techniques have been enormously successful in probing biomechanical properties at this difficult length scale. Applications have included the first detailed microscopic determinations of elastic moduli of complex biomembranes, such as that of the red-cell, which has a composite structure including a fluid membrane (the plasma membrane) with an attached elastic protein network (the cytoskeleton). In a program of ground-breaking work, these techniques have been used in novel ways in Evans' lab to understand membrane fluctuations, membrane adhesion, the forces between membranes and proteins, the strength of biological bonding, etc. They have also led to technological applications such as the construction of a force-balance apparatus with sensitivity in the piconewton range, and the possibility of controlled phospholipid-based "microplumbing" with tube radii down to 10 nm.

Evans and Michael Wortis (co-workers Udo Seifert (Teltow), Ling Miao, Hans-Günther Dobereiner, and others), in a classic collaborative interaction between theory and experiment, have developed a new theory of the shapes and shape transitions of vesicles in aqueous solution. This theory includes an important new effect, omitted in Helfrich's original bending-energy description (1972), and allows for the first time a quantitative predictive comparison between theory and experiment, including understanding of the occurrence of "budding" transitions, which mimic in a purely physical way the kind of shape changes seen in biological processes like endo/exocytosis.

These successes have given Canadian efforts a considerable visibility in this active area of science. A recent review (J. Tobochnik and H. Gould, "Lattice Simulations of Biological Membranes", Computers in Physics **10**, pp. 542-547, 1996) reads like a 'who's who' of our soft matter theorists, with 10 out of 19 references being to Canadian work. It is useful to analyze the organizational context in which these successes took place. First and foremost, as always, is the key role of important individuals. Here, one should highlight Myer Bloom's huge and interdisciplinary network of friends, colleagues, ex-students, ex-postdocs, etc., which has allowed him both to inspire and to draw inspiration from many people across the scientific spectrum. Similarly, Evan Evans' biological and engineering background has given him a broad perspective on what are the right interdisciplinary questions to focus on and where the insights of physics can usefully be brought to bear on these questions, a perspective which he has been generous in sharing with those of his colleagues having more "mainline" physics backgrounds.

NSERC, although its discipline-based GSC structure often left interdisciplinary labs like Evan Evans' sadly underfunded, has given freedom to many of the above contributors via the flexibility of its Research Grant program to work in these initially "unconventional" areas of condensed-matter/materials physics. NSERC/NRC has also provided key equipment at crucial times. For example, an NRC grant funded the original NMR spectrometer used by Bloom's group, when opening up this area in the mid-1970's. A critical grant ($ 30K), funding three postdocs for interdisciplinary work, was provided by the Killam Foundation in this early period.

The Canadian Institute for Advanced Research (CIAR) through its program in "The Science of Soft Surfaces and Interfaces," with rather modest funding ($50--$100K/year since 1991), has been instrumental in giving this group of Canadian workers a kind of coherence and international presence which they would otherwise have lacked. Myer Bloom is a Fellow in this Program, which also has supported both Canadian Associates (Terry Beveridge, David Boal, Pieter Cullis, Evan Evans, Jan Noolandi, Theo van De Ven, Martin Zuckermann and Michael Wortis) and non-Canadian Associates (Alice Gast (Stanford), Ole Mouritsen (Copenhagen), Mohan Narla (Berkeley), Adrian Parsegian (NIH), Jacque Prost (Paris), Erich Sackmann (Munich), David Tirrell (U. Mass.)), including, in addition to physicists, biologists, biochemists, chemical engineers, etc. The funding has mainly supported travel and accommodation related to interactions between the various "nodes", including an annual meeting and a summer school in 1993.

The success of these programs has been directly tied to the ability of the core group to reach out and include other disciplines in serious, working collaborations. The international component has been crucial in keeping the group in touch with the best work going on elsewhere. In addition to their direct positive impact on the quality of the science, these two features—interdisciplinarity and internationality—have also ensured that this Canadian work has had an impact and visibility which it might not otherwise have enjoyed.

IV DETAILED REVIEW OF CANADIAN RESEARCH ACTIVITIES IN CMP

This section is intended to provide an overview of the CMP research being undertaken in Canadian university laboratories and funded primarily by NSERC. It is not intended to be an exhaustive list, but rather to focus on programs of sufficient excellence, impact or importance that we feel confident in having the Assessors validate our assertions that such work is well worth funding, and that in fact Canada obtains an excellent return on its relatively small expenditure for this research. A complete list of present CMP grantholders along with the titles of their projects, the annual funding, and their home institutions is contained in Appendix 2.

IV.1 *Strongly Correlated Electronic Systems*

Strongly correlated electronic systems are ones where the traditional band theory of electrons breaks down completely. For example, the short range Coulomb interaction between nearby electrons is very important in narrow band systems: For solids with one electron per site, it can generate an insulating state where band theory would predict a good metal. Simple quantum mechanical arguments then suggest that the electron spins will order antiferromagnetically, as happens in the ‘parent compounds’ of the high temperature superconductors, which are antiferromagnetic insulators. Doping such compounds with mobile holes can lead to spin glass behavior, and, with further doping, to high temperature superconductivity.

One-dimensional systems represent the most striking example of breakdown of the usual Fermi liquid ideas used to treat electron-electron interactions in conventional solid-state systems. Indeed, the Luttinger liquid concept is the appropriate framework for the description of such unconventional systems, and it manifests itself clearly, for example, in the paramagnetic state of quasi-one dimensional organic conductors. The same challenge of finding alternatives to Fermi liquid ideas is present in the field of high-temperature superconductors.

In heavy fermion compounds, electrons move with effective masses which are tens or hundreds of times larger than those of normal band electrons. They can exhibit superconductivity of an unconventional but low temperature type, which is also associated with antiferromagnetism. Antiferromagnetism arising from strong electronic correlations may be destroyed by the presence of mobile holes, or it may be frustrated on lattices, such as triangular lattices, which are not suited to antiferromagnetic order. This can lead to other types of ground states, with more complicated order, or alternatively to a ground state, called a ‘spin liquid’, with no order at all. One such liquid, the chiral spin liquid, is predicted to exhibit quasiparticles with fractional statistics (anyons) and a different, yet undiscovered, kind of high temperature superconductivity. Experimentally it is found that known “geometrically frustrated antiferromagnets” undergo a very low temperature transition to a spin-glass-like phase, even for systems with a high degree of atomic order. The origin of this glass-like phase is a topic of great interest to which Canadian researchers are making major contributions.

Canadians have in fact made important contributions to all aspects of the field of strongly correlated electronic systems. There is a substantial effort in the area of high temperature superconductivity, some of which has already been described in Sec. III.1. In addition, there is significant activity in the areas of heavy fermion superconductivity, one and two dimensional organic conductors, one dimensional quantum spin chains, and two and three dimensional frustrated antiferromagnets.

In the area of high T_c superconductivity, in addition to the work described in Sec. III.1, Chuck (J.C.) Irwin's Raman scattering measurements at Simon Fraser University, done partially in collaboration with the UBC group, have provided considerable insight into the coupling of lattice vibrations to the superconducting state. Of equal importance is his beautiful work on the electronic continua, in several high T_c materials, which yielded clean measurements of the anisotropy of the d-wave gap. Jurgen Franck at the University of Alberta has been studying the technically difficult but important question of oxygen and copper isotope effect in high T_c superconductors since 1987. His research, along with that of Alex Mueller, is generally considered to be the definitive work in this field. Thom Mason at Toronto continues to be involved in systematic neutron scattering studies (in collaboration with Aeppli, Mook and others) of magnetic excitations and fluctuations in high T_c superconductors and their antiferromagnetic parent compounds. Bryan Statt of Toronto performs elegant NMR experiments which, for example, have elucidated the properties of different CuO_2 layers in multi-layer high T_c materials. S. Jandl of Sherbrooke, in collaboration with M. Cardona (Stuttgart), has developed a unique optical spectroscopic tool for studying the magnetic properties of a class of these compounds.

Louis Taillefer of McGill uses thermal conductivity, in a particularly productive way, to study YBCO crystals produced in his own lab, which are comparable in quality to UBC crystals. His most recent results demonstrated, for the first time, the existence of a "universal limit" in the low-temperature heat transport of d-wave superconductors, as predicted by Patrick Lee, Jim Sauls and others. The McGill crystals have also been used by M Aubin of Sherbrooke to study vortex motion in the mixed state, revealing several novel phenomena.

On the theoretical side, André-Marie Tremblay and his group at Sherbrooke, in particular Y. Vilk, have combined quantum Monte Carlo and analytical approaches to gain unprecedented insight into the Hubbard model from weak to intermediate coupling. This model was proposed, at the outset, by P.W. Anderson as a paradigm for the origin of the correlations which give rise to high-temperature superconductivity. Tremblay developed a non-perturbative approach that satisfies a number of exact constraints not usually obeyed by standard many-body theories. Their results give the best agreement, of available analytic theories, with numerical Monte Carlo simulations. Their work sheds light, in particular, on spin fluctuations and on the possible role of thermal fluctuations in the formation of the pseudo-gap observed by photoemission experiments.

Philip Stamp at UBC has also studied the breakdown of Fermi liquid theory and has used the "eikonal expansion" to handle the singular interactions in the problem. Ian Affleck at UBC, who is a CIAR Fellow and a member of both the Cosmology and Superconductivity Programs, made substantial early contributions to the understanding of strongly correlated electronic systems through his work with Brad Marston on flux phases.

John Berlinsky, Catherine Kallin and their group at McMaster were the first to elucidate the internal structure of vortices in $d_{x^2-y^2}$ superconductors using Bogoliubov-de Gennes and Ginzburg-Landau theory. Later, with Marcel Franz, they applied the techniques that they had developed for inhomogeneous superconductivity to the problem of the effects of impurities in d-wave superconductors on the localization of quasi-particles, on the superfluid density, and on T_c. Recently Franz and Affleck have derived a London-type theory for the d-wave vortex state which is much more tractable than B-dG and G-L theories and applicable over a wide range of field and temperature.

At Toronto, Michael Walker has studied the relationship between Josephson tunneling experiments and the symmetry of the superconducting order parameter as well as the oblique structure of the Abrikosov lattice. Allan Griffin, who is best known for his expertise in the area of Bose-Einstein Condensation, has also contributed to our understanding of the collective modes in weakly-coupled, layered superconductors, such as the high T_c materials.

Bob Gooding of Queen's has focused mainly on low and intermediate doping states and the spin texture induced by impurities. He also works on the problem of phase separation and the formation and properties of stripe phases, a topic that has become particularly prominent in the past year. John Harrison has established a millikelvin facility at Queen’s, and has been involved in a number of collaborations studying dissipation in high T_c materials. His main contributions have however been in the area of quantum fluids, in particular thermomechanical effects and superfluidity of ^{3}He in porous media and thin films.

Although the applications of high T_c superconductivity are not yet widespread in Canada or elsewhere, the Canadian high T_c program does have significant industrial interactions. The SFU group (Heinrich, Irwin, and Curzon) became involved in an industrial cooperation with CTF Systems to develop an all high T_c SQUID magnetometry system. CTF Systems, a Port Coquitlam based manufacturer of SQUIDs for biomagnetic imaging systems, created the High T_c Alliance together with Industry Canada, the BC Provincial Government and the Furukawa Corporation. From 1992 to 1995 an NSERC CRD grant allowed the SFU group to further enhance their contribution to the High T_c Alliance. A 3-axis high T_c SQUID magnetometer was successfully developed at CTF for operation at 77K with a sensitivity of 250-350 fT rms/Hz above 10 Hz. Materials studies by Heinrich and Frindt in 1988 substantially sped up the development of Nb/Al_2O_3/Nb based CTF SQUID devices, resulting in a new generation of a large three dimensional array SQUID sensors for biomagnetic studies in neuroscience and clinical applications. CTF Systems is presently marketing a multichannel SQUID system for whole-cortex measurements.

John Preston at McMaster produces high quality high T_c thin films by laser ablation on novel, McMaster-grown, dielectric substrates. He and Timusk are involved in OCMR- and NSERC-sponsored projects to grow large-area substrates of these new materials for ComDev, an Ontario-based company that produces compact high T_c microwave filters for satellite communications. The UBC group is supporting this effort, by providing measurements of the temperature-dependent dielectric constant and loss for both standard and new dielectric materials. Another project involving applications is that of M. Aubin in Sherbrooke who collaborates with J. Cave of Hydro-Québec in the study of ac losses in high T_c ribbons and cables.

Much of the Canadian activity in heavy fermion metals arose, in the early 1980's, from the ability of one of the professional crystal growers in the Brockhouse Institute at McMaster to produce crystals of these materials. This allowed several McMaster researchers, Tom Timusk (far-infrared), Ross Datars (magneto-transport), and Malcolm Collins and Bruce Gaulin (neutron and x-ray scattering) to compete effectively in this dynamic field. McMaster crystals were studied by neutron scattering at Chalk River by Collins and Gaulin as well as by AECL scientist Bill Buyers. In a tour de force experiment, Gaulin has used resonantly enhanced magnetic x-ray scattering to measure extremely small antiferromagnetic moments in heavy fermion compounds at the synchrotron at Brookhaven. In a similar vein, the materials expertise of McMaster Solid State Chemist John Greedan in the subject of pyrochlores led to the timely study of geometrically frustrated antiferromagnets by neutron scattering and MuSR, as further described in Section IV.3

Louis Taillefer, who established his reputation in studies of the heavy fermion compound UPt_3 at Cambridge and Grenoble, is continuing this work at McGill. Taillefer grows the world's best UPt_3 crystals, and his recent measurements of the anisotropy of the thermal conductivity in the anisotropic superconducting phases of UPt_3 represent a major step in determining the symmetry of those phases. Both Doug Bonn at UBC and Thom Mason at Toronto have contributed to this field in the past, and are continuing their work using microwave spectroscopy and neutron scattering.

Organic conductors have been studied in Canada since the early 1970's. Today, the main effort is at Sherbrooke, which has become one of the leading Centres worldwide on this subject, particularly for theoretical studies, but also because of the experimental work of Poirier, Jandl, and Beerens. Bourbonnais and Caron have developed a renormalization group approach to quasi-one dimensional correlated fermions that gives a detailed understanding of the overall phase diagram and electronic properties of the class of organic conductors known as Bechgaard salts. It is in these salts that organic superconductivity was discovered in 1980 by the group of Jerome in Orsay. Sherbrooke has been collaborating closely with this group since the 1970's.

John Eldridge of UBC has a long-standing program on the infrared properties of organic conductors, an area in which Timusk at McMaster has also contributed. Although the properties of these materials were originally interpreted in terms of conventional superconductivity, it now appears that organic superconductors are better thought of as strongly correlated systems like the high T_c and heavy fermion superconductors. In addition, the group of Poirier has performed microwave experiments, analogous to those of Hardy and Bonn, that suggest that quasi two-dimensional organic conductors of the BEDT class are also d-wave superconductors, since they have a linear temperature dependence in their low temperature penetration depth. This is one of the numerous ways in which there has been cross-fertilization between the organic and high-temperature superconductor fields. Another example, drawn from the theoretical side, concerns the question of the stability of Luttinger liquids raised once more by Anderson. It is well known that interacting electrons in one dimension are in the Luttinger liquid universality class, instead of the Fermi liquid one. The question of the stability of the Luttinger liquid to transverse hopping has been one of the most debated issues worldwide in the context of correlated electrons. The pioneering work of Bourbonnais and Caron had addressed this issue a long time ago. More recent work with Tremblay and Boies has corroborated that, at sufficiently low temperature, the Luttinger liquid develops either one or two-particle instabilities.

Important work on quantum spin chains was done by Ian Affleck, shortly before moving from Princeton to UBC in the mid-1980's. This work was related to Haldane's conjecture of a gap in the excitation spectrum of a spin 1 antiferromagnetic chain, which was first observed in neutron scattering at Chalk River by Bill Buyers and Robin Armstrong (then at Toronto). Affleck found distinctly different behaviour for half-integer spin , and at UBC developed a field theoretic treatment of excitations of the spin 1 antiferromagnet, followed by work together with Buyers on the experimental consequences of this theory. Related work has been done by D. Sénéchal in Sherbrooke who, in addition to being the co-author of the first extensive textbook (900 pages) to date on conformal field theory, has produced a number of original contributions.

Affleck's continuing interest in spin chains is also connected with the breakdown of Fermi Liquid Theory. New finite temperature renormalization group tools for this problem have been developed by Sénéchal and Chitov, extending previous work of Bourbonnais and Shankar, while the peculiarities due to two-dimensional critical fluctuations have been elucidated by Tremblay and Vilk. On the numerical front, Steve White's real space renormalization group technique is a widely acclaimed breakthrough that has now been extended to fermions and to finite temperature thanks to the work of Caron and Moukouri in Sherbrooke. Important applications include those by Affleck, Caron and Moukouri to problems ranging from the Kondo Necklace to higher spin systems.

One area of strong correlation physics which has not flourished in Canadian universities is experimental studies of the quantum Hall and fractional quantum Hall effect physics of the two dimensional electron gas. The reasons for this gap are discussed in the section on electronic and optoelectronic materials. They are basically that, at the time when this field began to open up, the threshold costs for setting up and maintaining the required materials preparation facilities were higher than what was available through NSERC. As a result, Canadian condensed matter physics 'missed the boat' on a very exciting area, which laid an important part of the groundwork for modern strong correlation physics.

Although high T_c superconductivity is the most dynamic subarea of modern metals physics, and the area where the best Canadian work has had the most impact, the broader topic of strong-correlation physics represents the current frontier in the study of the electronic properties of solids. Canada is fortunate to have a strong foothold across this broad frontier. Furthermore, although excellent people are the key to any successful program, experience has shown that, in the materials business, the ability to make high quality new materials provides a tremendous advantage. The importance of materials preparation capabilities, which is largely an issue of infrastructure support, is amply demonstrated by the Canadian experiences described above. Any future plan for Condensed Matter Physics must recognize this essential issue, and provide for stable, high-quality facilities for materials growth, modification and characterization.

IV.2 *Electronic and Optical Materials*

Electronic and optical technologies pervade our society. The group IV semiconductor Si forms the basis of microchips that can be found in everything from $2 calculators to $200,000,000 satellites. Group III-V semiconductors such as InP, GaAs and related alloys form the basis of optoelectronic devices that drive the information superhighway, which itself is based on high-purity, doped silica glass. Canada is home to one of the world's most successful communications equipment suppliers, Nortel, and the Ottawa area is often referred to as "Silicon Valley North", because of its exploding population of high-tech companies, that are all based one way or another on electronic and/or optical materials. Research on these materials therefore offers the condensed matter physicist the opportunity to work on highly relevant subjects that are evolving at a dizzying pace. It also provides a level of comfort for the researcher to know that there is a large demand for graduates trained in these areas.

Approximately one quarter of the condensed matter community (~ 50 faculty) devote all or part of their research efforts to electronic or optical materials, primarily semiconductors. While there is some GSC28-funded work on optical glasses at the Université de Montréal (J. Brebner, R. Leonelli), and at the Université de Sherbrooke (S. Jandl), the majority of optical-fibre, glass waveguide, and laser crystal research in Canadian universities is funded through the Engineering or General Physics Grant Selection Committees. A number of universities have several condensed matter faculty members working on different aspects of semiconductor research (Moncton, Sherbrooke, École Polytechnique, Montréal, Toronto, McMaster, Western Ontario, Lakehead, Simon Fraser and UBC). Four universities, UBC, McMaster, Western Ontario, and the University of Toronto have MBE growth facilities, while Simon Fraser University, École Polytechnique and Sherbrooke have MOCVD reactors. This group of ~ 50 researchers is primarily comprised of people under ~45 years old; historically there was relatively little semiconductor research carried out in Canadian universities, with early exceptions including J. C. Woolley's work on III-V alloys, Bob Barrie's theoretical work on transport, R. Parsons' silicon spectroscopy, and the theoretical and experimental work of the Groupe de recherche sur les semiconducteurs et les diélectriques by L. Caron, M. Aubin, C. Carlone and A. Caillé in Sherbrooke.

With the exception of a group in the early sixties lead by P.H. Simpson, there was also little semiconductor research activity at the National Research Council in Ottawa prior to the mid eighties. NRC now includes the Institute for Microstructural Sciences (IMS), which represents the largest government-funded semiconductor research group in Canada, with ~ 60 researchers, and extensive growth, characterization and fabrication facilities. While there are a number of individual examples of university-NRC collaborations in the semiconductor area, there is as yet no coordination of activities on a larger scale (other than with the Micronet NCE, based on Si materials, which has no CMP involvement), reflecting the present lack of any unifying collaborative initiatives or networks in the areas of semiconductor or photonic materials.

The university research can be broken down by sub-discipline, or area of expertise as follows. There are roughly equal numbers of those with primary expertise in i) spectroscopy, ii) growth and surface studies, iii) nonequilibrium dynamics, iv) development of device technologies, and v) theory. Magneto-transport experiments, which have been responsible for some of the most recognized discoveries in semiconductor physics over the past 20 years, are conspicuously absent from this list. There is some high-quality activity in this area, notably Robin Fletcher's thermopower work at Queen's, and Jean Beerens' far-infrared studies at Sherbrooke, but there are not as many university-based researchers in this field as one might expect. Fletcher and Beerens have established very fruitful collaborations, both internationally, and with Andy Sachrajda, Marie D'Iorio, and Peter Coleridge of the Institute for Microstructural Sciences at NRC.

Sachrajda and D'Iorio hold adjunct appointments at universities, and receive small Research Grants from NSERC for the support of their grad students. They enjoy strong support from the growth and nanofabrication groups at NRC, and they have made well-recognized contributions in mesoscopic transport (particularly in systems with artificial impurities), and in characterizing the insulating state of the 2D electron gas observed at low densities in silicon MOS structures. The relative absence of Canadian university-based experimental participation in the explosion of worldwide activity on 2D electron gasses, the quantum Hall effect, mesoscopic transport, etc. has already been mentioned in Section IV.1. This resulted from the lack of adequately supported facilities for heterostructure growth and fabrication in the early days before strategic nature of such research was more apparent - indeed, most of our university based heterostructure growth capabilities are of fairly recent origin, and even now are not well supported. Another example of Canada's lack of an adequately supported infrastructure in materials preparation, which would allow the rapid pursuit of new initiatives, is the striking absence of significant experimental work on wide-band-gap materials such as II-VI semiconductors, nitrides, and SiC, which has recently exploded elsewhere.

On the theoretical side, there is considerable work on mesoscopic problems. Kirczenow at Simon Fraser, Guo at McGill, Zaremba at Queen's, Vasilopoulos at Concordia and Singh at Western, are all active in developing theories to describe the electronic and optical properties of quantum dots, wires, and devices based on gated two-dimensional electron gases. Kirczenow in particular has made very significant contributions to the understanding of how scattering affects quantum conductance in these systems. A part of his work in this area has been in collaboration with the experimental group at NRC, resulting in a nice tying together of theory and experiment on systems with artificial impurities. Guo has made numerous contributions in developing realistic models for quantum transport in mesoscopic structures and devices. His recent work on the destruction of universal conductance fluctuations in 'dirty' quantum wires is of particular note. Like Kirczenow, Guo enjoys a fruitful collaboration with the experimental group at NRC.

The semiconductor physics group at Simon Fraser is building upon Mike Thewalt's work on spectroscopic identification of light emission processes in a variety of bulk semiconductors and heterostructures. Recent highlights include the leading work on the identification of optical processes in SiGe heterostructures, much of which was done in collaboration with NRC/IMS. The effort at Simon Fraser has expanded to include Simon Watkins, who recently used his MOCVD apparatus to produce the best thick InAs epitaxial layers ever reported, and Colombo Bolognesi, who is establishing a device fabrication laboratory for novel electronic and opto-electronic devices. Several students from this group are now established semiconductor researchers in Canadian universities, government laboratories, and companies. It is worth noting that the growth and fabrication facilities referred to above were obtained with funds from the provincial government of British Columbia.

While at Exxon, Tom Tiedje made several seminal contributions to our understanding of amorphous semiconductors, including the Tiedje-Rose model for dispersive transport, and the pioneering of amorphous superlattices. Since moving to UBC in 1987, he has developed novel, in-situ optical diagnostics for MBE growth, and studies of surface morphology and kinetic roughening during thin film growth. His optical temperature monitor has now been commercialized by Thermionics N.W. Tiedje collaborates with Jeff Young, formerly of NRC/IMS, on the development of semiconductor photonic bandstructures. Tiedje also works with Jochen Meyer, who is developing novel semiconductor switches for producing femtosecond pulses in the mid infrared (~ 10 μm). Rob Kiefl's use of MuSR to study the muon as an analog of hydrogen impurities in silicon and other semiconductors (see Section VI.6.3) have received international acclaim, although most of his efforts are currently devoted to correlated electrons and exotic magnets.

Henry van Driel spearheaded semiconductor research in the physics department at the University of Toronto. Although his substantial international reputation is also based on the development of novel optical sources and nonlinear optical probe techniques, he is very well known for his work on pulsed-laser interactions with semiconductors. His papers on the "phonon bottleneck" problem are heavily cited, as is his work (in collaboration with John Sipe) on explaining the symmetry of laser-induced surface melting morphologies. Most recently he has applied his optical parametric oscillator developments to study ultrafast laser-semiconductor interactions in the 1 - 2 μm spectral range so important for optical communications technologies. Toronto now has a formidable ultrafast group interested in condensed matter, with the recent hiring of P. Smith (formerly of AT&T), and D. Miller (formerly at U. of Rochester). On the theoretical front, Sipe collaborates with van Driel on nonlinear optical properties of bulk semiconductors (most recently involving coherent control of photo-currents). Sipe also collaborates with many other groups around the world; his work with E. Mendez on understanding excitonic Stark ladders in superlattices is perhaps one of the outstanding examples. Sajeev John, one of the co-inventors of the photonic bandstructure concept, continues to lead this field by identifying and describing a host of novel phenomena that should be observed when one introduces electronic resonances in these materials. The Toronto group has received substantial financial support from the Ontario Provincial Government through the Ontario Laser and Lightwave Research Centre (OLLRC), which is one of the provincial Centres of Excellence.

The Groupe de recherche en physique et technologie des Couches Minces (GCM), a group funded in part by the Quebec government's FCAR program (see Section II above), brings together several researchers from the physics department at the Université de Montréal, and Engineering Physics faculty from the École Polytechnique in Montreal. They collaborate extensively, both with each other and with local industry. III-V MOCVD material grown by Remo Masut is used to study optical properties of heterostructures (John Brebner and Richard Leonelli), and to study the stability and strain relaxation of new strain-balanced multilayer structures (Masut). Their clean room and electronic materials fabrication equipment is among the best in the Canadian university system, having been largely funded with the help of industrial contracts. A large fraction of the clean room activities are devoted to the fabrication of novel sensors and actuators (J.F. Currie). The work on self-assembled arrays of InAs quantum dots grown on off-axis InP wafers is of particular interest. The group has recently modernized their ion-beam accelerator facility (Sjoerd Roorda), which is used for ion-implantation and near-surface crystal modification/analysis of materials including amorphous and crystalline semiconductors (Roorda, Yelon), and optical waveguide materials (Brebner with Albert (Communications Research Centre)). The GCM also studies other types of materials, as described in Sections IV.1 and IV.7.

Ion beam interactions are also a focus for the group at the University of Western Ontario. Ian Mitchell (formerly of the AECL accelerator group at Chalk River) oversees a large surface science facility that includes several beam lines used for semiconductor research. Mitchell's own work is further described in Section IV.6. Others involved in ion beam-semiconductor research at Western include W.M. Lau, W.N. Lennard and M. Zinke-Allmang. All of the Western researchers have significant interactions with NRC/IMS, and with industry. One focus has been the use of ion probe techniques to provide new insights into the nature of passivation processes on III-V semiconductor surfaces. Zinke-Allmang has recently developed an on-line MBE machine, unique in its ability to carry out in-situ ion scattering analysis of epitaxial growth processes.

McMaster University also has a substantial semiconductor effort, based largely in the Engineering Physics Department. The research in the CBE growth program (Dave Thompson), and the optoelectronic device fabrication and testing groups (John Simmons and Paul Jessop) could easily be considered within the framework of the CMP GSC, but for historical reasons these groups are funded elsewhere. Again, a large part of the funding for this facility, including clean rooms, growth and fabrication equipment, came from provincial sources (an Ontario Centre of Excellence, the Ontario Centre for Materials Research). Other members of this department are funded from GSC 28, including John Preston, whose semiconductor work involves high speed characterization of optoelectronic structures, and Peter Mascher who studies defects in semiconductors and semiconductor devices.

J. Beerens is the leader of the microstructures group in Sherbrooke. In addition to high magnetic field studies (J. Beerens), activities of this group include femtosecond spectroscopies (D. Morris) and nanofabrication (J. Beauvais, in Electrical Engineering). Fabrication facilities include class-100 clean rooms fully equipped for VLSI circuit fabrication. At Moncton, a Team Research Grant to Vo-van, Bader and Girouard has helped to establish the Groupe de recherche sur les couches minces et l'energie solaire, which has established a number of international collaborations in the area of thin films for smart window and solar energy applications.

Others who have established strong national and/or international collaborations include Alastair McLean at Queen's University, Emery Fortin at the University of Ottawa, and Laurent Lewis at the Université de Montréal. McLean has done some elegant surface physics experiments that reveal a new surface reconstruction on pure InP(100) that challenges the conventional wisdom that surface reconstruction occurs predominantly by the formation of surface dimers. He has also measured surface bandgaps and reconstructions on S-passivated InP(100) surfaces, which is of particular technological relevance to companies such as Nortel. Actually, several Canadian groups are making important contributions to the surface passivation problem, including that of Laurent Lewis. He recently proposed a novel, temperature-dependent sequence of reconstructions for the S-passivated InP(100) surface, based on ab-initio calculations. These were found to be in excellent agreement with Raman and core-level shift spectroscopy measurements. Fortin has received considerable attention of late for his optical transport studies of a possible excitonic Bose condensate in Cu_2O.

Another highly successful research program based upon the efforts of a single, outstanding investigator is that of Jeff Dahn, who studies materials associated with energy storage, and in particular the materials physics of Li-intercalation battery systems. Dahn has always maintained a close cooperation with Canadian and foreign industry, and recently left SFU for Dalhousie, where he occupies what is only the second NSERC Industrial Research Chair in CMP, supported by the 3M corporation. Some of Dahn's publications on new electrode materials for intercalation batteries are 'citation classics' in Materials Science. It is worth noting that Dahn, and his Ph.D. supervisor Rudi Haering, created a new industry and many new jobs in B. C. based on this Li-intercalation battery technology which was a direct spin-off from CMP research at UBC.

Two recurring themes are apparent from the preceding summary: first, the majority of funding for what growth and fabrication equipment exists in the Canadian university system has come from provincial and industrial sources, whereas most of the NSERC contributions have been for analytic equipment, and second, many of the university groups owe at least some of their success to collaborations with the Institute for Microstructural Sciences (IMS) at the National Research Council, and with Nortel.

To put things into perspective, the number of semiconductor materials researchers at Nortel, IMS and in the Canadian university system are comparable, but there is very little in the way of formal linkages between university researchers and either industry or IMS. Existing university links are almost all on an ad hoc, personal level. The physics-oriented semiconductor community has not been successful at establishing national networks (such as the CIAR, or Networks of Centres of Excellence), partially due to a lack of perceived industrial support for such a network in the past. As a consequence, there is little coordination of the overall investment in semiconductor research. One analysis would be that given the individual talents that exist, and given the number of universities with clear commitments in the semiconductor area, the overall impact of semiconductor research in Canada could be increased by establishing some sort of Network of Centres that could better coordinate activities both within the university community, and between the Network and the other major players. The NRC IMS, with its strong orientation towards industry, could play a central role in helping to bridge the gaps between university-based CMP research and Canadian industry.

In particular, and consistent with the recommendations in the Bacon Report, the condensed matter community must have access to state-of-the-art fabrication facilities and epitaxial semiconductor films. The corresponding capital and infrastructure support costs must be acknowledged and budgeted for, perhaps in coordination with NRC and industry.

IV.3 *Metals and Magnetic Materials*

Magnetic materials and metals (including metallic magnetism) span a diverse field ranging from fundamental studies of the statistical mechanics of quantum spin chains (where Affleck at UBC has made important contributions) to studies of the magnetic and magnetoresistive properties of thin films and multilayers (there are strong groups working in this field at McGill, U de M, SFU, and Manitoba, with linkages to McMaster and the neutron scattering facilities at Chalk River). The so-called giant magnetoresistive effect and colossal magnetoresistive effects are being widely pursued not only because of their intrinsic interest, but also due to their potentially enormous technological (and financial) impact in the fields of magnetic data storage and sensing.

An area of magnetism which has been particularly exciting in recent years is the study of the novel properties of geometrically frustrated systems (as opposed to frustration due to randomness occurring in conventional spin glasses). There has been active Canadian research on this topic from the outset, strongly influenced by the materials preparation facilities at McMaster, as mentioned in Section VI.1. The work was bolstered by an NSERC Collaborative Grant to a team spanning McMaster (Gaulin, Collins, and Greedan), UBC (Kiefl and Brewer), Waterloo (Gingras), Columbia (Luke and Uemura), and more recently Toronto (Mason) and Edinburgh (Harrison). The team combines the sample preparation and characterization facilities at the Brockhouse Institute for Materials Research, the muon beams at TRIUMF, and the neutron beams at Chalk River, to study the static and dynamic properties of a variety of materials which develop unusual frozen magnetic ground states due to the lattice frustration inherent in, for example, materials having the pyrochlore and Kagome lattices, where antiferromagnetic interactions dominate on structures built up out of triangular subunits. This work couples to similar studies at Toronto (Mason, in collaboration with Harrison at Edinburgh), and makes use of some of the additional experimental facilities there for transport and thermodynamic measurements at high magnetic fields. Related earlier efforts at McMaster included far-infrared (Timusk) and magnetotransport (Datars) experiments, together with theoretical work on the Kagome system (Kallin and Berlinsky).

At Sherbrooke, Caillé, Plumer and Poirier have made important contributions to the question of a possible new universality class for geometrically frustrated Heisenberg antiferromagnets, while Poirier and Bourbonnais are credited with making the first contribution to the question of quantum and classical fluctuation effects in the newly discovered inorganic and organic spin-Peierls compounds.

Southern at Manitoba has studied frustration effects on vortex unbinding and the relation to the non-linear sigma model for the 2D classical Heisenberg triangular antiferromagnet. Manitoba has also had an ongoing and very successful program of experimental studies in magnetism - G. Williams has been pursuing the interplay between superconductivity and magnetism, particularly in the borocarbides, while A. H. Morrish is internationally known for his magnetic studies of novel materials, using Mossbauer spectroscopy as well as other techniques, which have resulted in numerous industrial collaborations.

Another extremely active field is that of magnetism in engineered structures such as ultrathin metallic films, magnetic multilayers and superlattices, and amorphous magnets. There are active groups at Simon Fraser (Heinrich, Cochran, Arrott) and McGill (Strom-Olsen, Altounian, Ryan) as well as Montréal (Cochrane) and McMaster (Gaulin) studying the linkage between structure, magnetic, and transport properties. The study of ultrathin 3d transition metals was initiated in the early eighties. The resulting discovery of giant perpendicular anisotropies and giant magnetoresistance effects were very quickly incorporated into magnetic devices and computer memory applications. The progress in this field has been steadily accelerated by a rapidly increasing influx of scientists from various disciplines of physics, chemistry and materials science. Applications deriving from an understanding of the physics of thin film magnetism have resulted in a new branch of materials science directed towards the development of a new generation of magnetic sensors, magnetic recording media, and microwave devices.

The SFU group (Heinrich, Arrott, Cochran) has been involved in this field from the beginning, and Brett Heinrich has established himself as a world leader, complementing the long-established reputation of Tony Arrott, who is now on a post-retirement contract. They have used Molecular Beam Epitaxy (MBE) techniques to prepare well-characterized single crystal ultrathin magnetic films. These superior specimens were used to demonstrate clearly that the broken symmetry at magnetic interfaces causes giant uniaxial anisotropies with the easy axis often oriented perpendicular to the film surface and resulting in giant perpendicular anisotropies. They have also been involved in pioneering studies of the exchange coupling between ferromagnetic ultrathin films separated by non-ferromagnetic spacers. The SFU group pioneered the use of Reflection High Energy Electron Diffraction (RHEED) intensity oscillations to monitor the growth of ultrathin metallic film structures. They also demonstrated that ferromagnetic resonance (Heinrich) and Brillouin light scattering (BLS) (John Cochran) could be successfully used to measure the magnetic properties of ultrathin metallic magnetic structures. The local expertise in EXAFS (Crozier) has also been used extensively to characterize these structures.

The SFU in-house experimental techniques have been further complemented by numerous collaborations involving spin polarized neutron reflection studies (T. Bland, Cambridge), synchrotron low and high angle X-ray diffraction studies (E. Fullerton, and P. Bontano, Argonne National Laboratories), and Mossbauer studies using a single layer of ^{57}Fe (Schurrer, Royal Military College, Kingston). The SFU group has been for many years the sole supplier to the magnetic community of nearly perfect iron single crystal whiskers prepared by chemical vapor deposition. These Fe whiskers have been used as very smooth templates for the growth of metallic thin films by the SFU group and other groups (notably NIST) in studies that have played a pivotal role in the development of essential concepts of interface anisotropies and exchange coupling in strongly spin correlated systems, such as Fe/Cr/Fe(001). The SFU studies of nearly perfect Fe(whisker)/Cr/Fe(001) structures using RHEED and angular resolved Auger electron spectroscopy (ARES) (in cooperation with Venus, McMaster) revealed the presence of topographically smooth interface alloying at the Fe/Cr interface, and the BLS and magneto-optical Kerr effect (MOKE) studies have shown that this alloying leads to profound changes in magnetic coupling through the spin density wave in Cr.

A long-standing emphasis of research by Altounian, Ryan, and Strom-Olsen of McGill involves the study and fabrication of advanced non-equilibrium materials, such as metallic glasses, and related nanocrystalline magnetic systems. This work involves excellent fundamental research as well as potential applications to the marketplace. The group's emphasis on direct control of microstructure by fabrication techniques has led to novel materials. Metallic glasses, which act as soft magnets, are made typically by rapid solidification, high-energy ball-milling and DC/RF sputtering. Rapid solidification technology is also being used to manufacture ceramic fibers of a few microns in diameter. By using high temperature oxide ceramic fibers dispersed in conventional ceramics, their high temperature toughening properties are improved. In addition, films of alternating layers of magnetic and non-magnetic metals (e.g., Cu-Co) are being made. These exhibit giant magnetoresistance and, for small saturation fields, the films can be used as magnetoresistance sensors. Also of interest is the potential supermagnet Sm_2Fe_{17}. A unique process has been developed where both nitrogen and/or carbon atoms are introduced into the host Sm_2Fe_{17} alloy. The resulting lattice expansion is accompanied by a dramatic increase in the Curie temperature and the development of uniaxial magnetic anisotropy of the carbonitrides of this alloy. Finally, work on magnetic materials, with particular emphasis on those with frustrated or competing exchange interactions is being done by Ryan, primarily by Mossbauer spectroscopy, although in recent years neutron scattering (e.g., at Chalk River) has played an increasing role in his research. A typical alloy being studied is a-$Fe_x Zr_{1-x}$. As the iron content is increased, the alloy evolves from a weakly frustrated ferromagnet to a spin-glass, thereby providing a clean and controllable system for the investigation of this phenomena. Also being investigated are alloys such as RFe_6Ge_6 , where a cancellation in the R-Fe exchange leads to a two order-of-magnitude difference in the rare-earth and Fe sub-lattice ordering temperatures. The availability of polarized neutron facilities at Chalk River, particularly the new polarized reflectometry instrumentation developed by Zin Tun, has augmented the in-house capabilities of the above groups.

Interesting new physics can also emerge when magnetic systems are reduced in size, for the same reasons that mesoscopic electronic systems display novel behavior. Stamp (UBC) has been pursuing the theory of quantum mechanical tunneling in nanometer sized ferromagnets, as well as engineered magnetic molecules. The field is now at a point where important predictions of the theory (of domain wall tunneling, and of tunneling in magnetic macromolecules, with significant nuclear spin effects) have now received experimental support. It will be very interesting to see future experiments which will begin to make the connection to the magnetic recording industry. The direct study of such systems is allowed by scanning probe techniques. Grutter at McGill is developing and studying magnetic force microscopes, which can simultaneously measure magnetic dissipation and magnetic force, thereby determining magnetic anisotropy and coercivity on the nanometer scale. Furthermore, Grutter's lab now has a combined field-ion, STM, and AFM microscope, which is unique in the world. It has the ability to completely characterize the atomic structure of the tip, so that one can make absolute measurements of the tunneling current as well as distance versus force curves. This provides a unique tool to directly measure forces related to adhesion and friction. In addition, Grutter is using scanning probe techniques to study magnetic reversal in model systems of patterned magnetic films and nanometer Fe particles, as well as to study multilayer metallic thin films. This method permits not only the observation of structure, but its manipulation as well, which is of potential value for applications, since some such systems demonstrate the effect of giant magnetoresistance, which may be useful for magnetic storage, sensors, or switches.

Of course, a complete understanding of the interaction between the tip of a scanning probe device and a substrate can be quite subtle, particularly when the probe is actually being used to modify that substrate. Guo of McGill is using first-principles quantum molecular dynamics to simulate the influence of impurities on the adhesion between two metallic surfaces. He is also calculating the force versus distance curves of the loading-unloading cycles when two surfaces - for example, a surface and a tip - are approaching each other. These predictions will be useful in understanding surface structures, the bonding phenomena, the hysteretic behavior of the surface adhesion process, and the coupling to bulk elasticity. They can also be directly compared to experimental data obtained from STM, or other surface probes.

Mark Freeman recently moved from IBM Yorktown Heights to the University of Alberta, bringing much of his laboratory with him. He is a recognized pioneer in the development of novel time-resolved optical probe techniques, specifically as applied to the study of magnetic relaxation phenomena, and more recently, to atomic-scale dynamics. As recently reported in Science, he has achieved picosecond time-resolved STM images by integrating a customized STM with a repetitive picosecond optical pulse train. This work is likely to have a huge impact on the STM community, especially given the recent developments in pulsed optical source technologies. His forefront work on time-resolving spin dynamics is not only of great fundamental interest, but it is also of direct relevance to the large magnetic recording industry with which he collaborates.

IV.4 *Soft Materials: Biological, Polymeric and Complex Fluids*

Newspapers often report new discoveries in astronomy, when an unusual velocity of a distant galaxy is measured, or in high-energy physics, when the mass of a submicroscopic particle is measured using an accelerator. Sometimes, however, the most interesting physics can be right under our noses, not microscopically small or macroscopically far away. For example, the classic problem of the flow of ketchup slowing down, the harder it is pushed, is an example of the shear thickening of a polymeric melt. When flow is forced, the sheared polymers near the walls are coherently knotted up, completely changing the rheology of the process. This example of collective nonlinear phenomena in the kitchen is only one of many similar ones that physicists are beginning to address. As physicists we have a tradition of expanding our domain of activity into new areas where our unique viewpoint - our unquestioned ability to ask and answer clear questions in a sophisticated technical and mathematical way - is of value. In particular, CMP research has often served as the bridge from physics to other sciences, such as biology, chemistry, and engineering. Indeed, unlike other areas of science, research in CMP bridges an incredible diversity of topics from ceramic superconductors to cell membranes. As such, CMP has impact on, and provides a fundamental approach to, topics and systems studied in many other disciplines, such as biology and chemistry, as well as many of the applied science disciplines, including electrical, chemical and metallurgical engineering.

An excellent example of this interdisciplinary impact is the current research in soft materials, where Canadian work is amongst the best in the world. This research is motivated by the actual and potential novel properties of these materials, which occupy a middle ground between liquids and solids. Not surprisingly, Mother Nature already makes widespread use of these handy materials, for example to form cell membranes, and so research in this area is highly interdisciplinary. The first-class work of Bloom, Evans, Wortis and coworkers on model and natural membranes was described in Section III.2 above. We describe below other Canadian contributions which are at an internationally competitive level. Indeed, in addition to the work mentioned in Section III.2, Canada has every reason to expect continued excellence in this broad area. This is partly because we now have a track record of achievement, with talented senior scientists leading the effort. More so, it is because this is an area of unquestioned research promise and potential, as is borne out by the simple fact that it includes many of Canada's best young scientists.

For example, John Bechhoefer of Simon Fraser is internationally well regarded for his experimental research on kinetic phenomena, such as pattern formation during crystal growth, and the phase behavior of liquid crystals. His research is interdisciplinary, and creatively addresses projects in the areas of engineering and biological materials. Many of his contributions are `deeper' than the norm, because he simultaneously does (and is good at) experiment and theory. His clear and definitive work on the Faraday instability in parametrically driven surface waves is noteworthy. This is an area where less rigorous experiment and theory had been competing for some time, but Bechhoefer's work is of a different standard. He clearly explains the origin, mechanism, and - most importantly - the larger significance of this phenomena with his beautiful experiments. Some other promising young experimentalists with similar interests are listed under IV.5 below.

The Vancouver area has become a regional hub for this activity. In addition to Bechhoefer and the research discussed in Sec. III.2, Simon Fraser has another very promising young experimentalist, Barbara Frisken. She is using light scattering to study the phase separation of binary fluid mixtures in silica gels, as well as shape transformations in vesicles. Furthermore, David Boal of SFU has been modeling the mechanical properties of biomembranes, which has helped to explain the properties of red blood cells.

In addition to the intrinsic interest of the phenomena, this work leads to the development of new instruments, and new applications of existing experimental apparatus, a common factor across experimental CMP. This is well borne out by Canadian ultrasound work on phase transitions in porous media, as well as on glassy systems and viscoelastic fluids, by John Beamish of Alberta, and John Page of Manitoba, respectively. These works address fundamental issues concerning the nature of phase transitions in confined regions, and the localization of phonons in disordered media. Perhaps as important as these, however, is the development of new high-precision uses of ultrasound, and the resulting ability to do rheology on the micron scale "at the speed of sound". Another very promising young scientist, with a novel experimental approach, is Stefan Idziak, who has just been hired at Waterloo. Prior to returning to Canada, he had worked as a postdoc with C. Safinya of Santa Barbara, on nanoscale tribology. Idziak's research combines x-ray structural analysis (he will be using the Canadian beamlines at the APS), with scanning probe techniques, to study the small-length-scale structure of polymers under large-length-scale shear and bulk stress. This unique combination of instruments gives access to important nonequilibrium structural properties of such systems. Indeed, one of the clear contributions of condensed-matter physics to other scientific disciplines is evident in the way instruments developed here - for the non-destructive evaluation of specific materials - are later used in chemistry, biology, engineering, industrial, and medical settings.

In fact, as one would expect, some of this work, although motivated by fundamental issues in physics, has some rather direct connections to industry, particularly related to medicine. For example, Slater of Ottawa has been applying physical principles to the electrophoresis technique of separating large molecules, such as DNA, which is an important focus of research in analytical biochemistry. Slater's work has shown how the concepts of reptation, self-diffusion, and the morphology of polymers in confined spaces has implications for, e.g., the separation of polymers by molecular weight. Some of his work is done in collaboration with the equipment manufacturer Perkin-Elmer. The interdisciplinary nature of his research is demonstrated by the fact his work, while excellent physics, was until recently funded by the NSERC GSC responsible for chemical engineering.

Another example of an excellent researcher whose work has wider implications is Mike Sayer of Queen's. He uses his vast experience in film deposition, and the surface-analysis techniques of condensed matter physics, for the development of physical and chemical sol-gel deposition techniques which have led to novel ferroelectric piezoelectric coatings and new artificial bone surfaces. The work on both piezoelectrics and biomaterials has been part of significant technology transfer to industry. The biomaterials work is carried out with John Davies of the Toronto Centre for Biomaterials.

Jim Davis of Guelph has been using NMR to analyze lipid-protein interactions and the structure of membrane proteins, particularly gramicidin. He has an international reputation for his efforts in developing new techniques of NMR analysis for the identification of such structures. It should be noted that, though a renowned physicist in this area, Davis is funded through the Cell Biology GSC, rather than the CMP GSC at NSERC (but is well-supported by that GSC). Also at Guelph, Ross Hallett is doing light scattering studies of lipids, while Ken Jeffrey is experimentally studying the effect of sugars on the hydration of lipid bilayers, which has some implications for the commercial freezing of food. The interest in membrane research in Canada has been the stimulus for the construction of a dedicated biomaterials diffractometer at Chalk River.

Atlantic Canada constitutes another regional centre of concerted activity in soft materials. At Memorial University, Mike Morrow's experimental expertise in NMR is used to determine the phase behavior of lipid bilayers, while large scale numerical work on polymers, lipids and complex fluids is being done by Lagowski, Whitehead, and Whitmore. Morrow's work is done in concert with related theoretical studies by David Pink at St. Francis Xavier University. Pink is also involved with work by Manfred Jericho of Dalhousie using STM and AFM methods to study soft materials. "Hopping mode" scanning probe imaging of soft biological specimens was invented at Dalhousie by Jericho, Blackford and Dahn as an extension of scanning tunneling microscopy. This group was one of the first to apply scanning probe techniques to biological specimens, a field which has seen a high level of activity subsequently. Hopping mode operation is now a standard capability in commercial atomic force microscopes for imaging soft surfaces.

Given the strength of soft materials research in Atlantic Canada, it is perhaps worth noting here that these researchers suffer from a relative lack of university infrastructure and provincial support, and have therefore been disproportionately affected by the recent NSERC cutbacks and from its cancellation of the Summer Undergraduate Research program (St. Francis Xavier, for example, does not have a graduate program). Such local problems can have a wider impact, as it is generally recognized that these universities provide many of the best graduate students attending our larger, and more research-intensive universities (many of whose best undergraduates tend to do their graduate work outside of Canada). Indeed, there are a large number of physicists in Canada who can trace their roots back to Atlantic Canada, such as Peter Poole, who was an undergraduate at St. F. X., and is now pursuing theoretical studies of metastability at Western.

Despite such bright young theorists as Poole, and polymer physicist Z. Y. (Jeff) Chen of Waterloo, it is an historical curiosity that this is a field consisting of young experimentalists and established senior theorists. Indeed, a number of these senior Canadian theorists have made strong contributions. Rashmi Desai of Toronto has studied Langmuir monolayers and block copolymer phases, and is currently investigating the elasticity of soft stressed solids. He has recently studied the stability of ordered phases in diblock copolymer melts, in collaboration with colleagues at Xerox Mississauga, wherein he makes use of a deep analogy to the theory of Bloch states in crystalline solids to identify phase behavior. Donald Sullivan of Guelph has been using first-principle techniques to explain microemulsions, thermotropic and lyotropic liquid crystals and liquid interfaces. His work characterizes the phase behavior as well as the structure of defects in, for example, lamellar phases. At Sherbrooke, Alain Caillé has been leading the effort to understand discotic (columnar) liquid crystals. In particular, he has suggested that quasi-long range order is possible along the columns in analogy with similar predictions that he is known for in connection with Smectic A liquid crystals. At McGill, Martin Zuckermann has been continuing his internationally renowned work on the ordering properties of lipid bilayers, and other soft biological materials. In collaboration with colleagues in Denmark, he has recently characterized new phase structures in pure lecithin bilayers. Guo and Zuckermann of McGill have been studying the formation and structure of polymer brushes through large-scale simulation methods, as well as the behaviour of complex fluids such as microemulsions. Laurent Lewis, at the Université de Montréal, has been investigating a simple model of the fragile glass-former ortho-terphenyl, experimentally one of the most studied materials. While the validity of the mode-coupling theory of supercooled liquids cannot be assessed from these simulations, they have revealed the role of the coupling between translational and rotational degrees of freedom in the dynamical behavior of the system.

Martin Grant of McGill, in collaboration with Piché of the Industrial Materials Institute of NRC, has recently been studying the extrusion of polymer melts from capillaries. Plastic molding, and applications of polymer melts as glues, involve such extrusion at the fastest possible rates. However, the extrudate shows texturing and large scale structure at flow rates beyond some critical value. Grant argues this is due to a transition in morphology of the polymer at the walls, giving rise to a first-order stick-slip transition, an idea based on one of de Gennes'. Grant gives a complete numerical solution, incorporating the hydrodynamic-like flow of a visco-elastic fluid, and recovers the instability and the texturing. He is also able to make predictions for the morphology, and implicitly, how to control it, which opens up obvious practical applications.

Over the last ten years, this field has progressed from an emerging area of promising research, to a mainline area of physics, and, in particular, a Canadian scientific strength. However, it cannot be said that this work has been nurtured by the current NSERC GSC structure, and indeed it can be argued that this structure has mitigated against success. Work in soft materials is highly interdisciplinary, and has, until recently, tended to 'fall between cracks' in the current GSC structure. Much the same can be said of research in other areas related to advanced materials. Indeed, the way that work in these areas has developed serves as a lesson for future emerging areas. Simply put, NSERC needs to develop appropriate mechanisms to react to the development of emerging interdisciplinary fields. We make recommendations for such mechanisms, such as a new GSC structure or an NSERC Group Chair responsible for materials science and engineering, later in this Review.

Research in this area is currently considered to be one of the relatively strong areas in Canadian physics, and it is therefore now well supported by the CMP GSC (whether it is similarly well supported when the grant happens to be dealt with by other GSCs has already been questioned in Section III.2). It is therefore natural for Canada to build on this success by strengthening our materials physics efforts, especially in the area of new materials, including polymers, composites, and biomaterials.

IV.5 *Nonlinear Phenomena and the Statistical Mechanics of Materials*

A striking fact of everyday life is the complexity of commonplace phenomena: A plume of smoke rises steadily with hot gases around a cigarette, and then suddenly becomes random and turbulent; moisture freezes on a window into spectacularly complex branched patterns. Even when one looks at most materials with near-atomic resolution, one does not see a regular array of atoms, as one might expect from a text on solid state physics: instead, materials display complex granularity and domain structures, as well as defects and dislocations, on scales of microns or less, which are due to the history-dependence of their processing. The paradox is that, under equilibrium conditions, systems should generically be structureless. Since this is manifestly untrue in nonequilibrium conditions, such as the ones just described, it is a fundamental issue in physics to explain how such complex structure arises, and thus to learn how it may be predicted and controlled. The notable thing is that many of the properties of such apparently disparate systems can be understood in common, that is they share universal features. Physics, with its history of engaging such issues - by identifying common principles with mathematical sophistication, and through the creation of controllable model experimental systems - has much to contribute to the understanding of these phenomena.

Furthermore, the understanding of these processes is an important issue for applications: microstructures formed under nonequilibrium conditions are central to the physical and mechanical properties of most materials. Failure rates of materials, and important properties including tensile strength, reactivity and magnetic coercivity, depend crucially on the dynamically-tuned morphology, which often has a length scale of microns or less. For example, airplane wings, swords, and other strong alloys are made by creatively constructing a coherent microstructure on the scale of microns to stop the propagation of cracks. This is done by subjecting an alloy to heat treatments (some prescription for raising and lowering the temperature), and cold working. Indeed, much of the recent progress in materials science has come about by understanding these phenomena, and thereby developing processing techniques to control this microstructure. What is produced is far from an equilibrium phase - it is a nonequilibrium material with a purposely tuned microstructure.

An understanding of how nonlinearity leads to complexity in materials, and the exploitation of this understanding for applications, is an important current research topic in Canada. There is some behavior which is similar and presumably universal, as mentioned above, but there are myriad differences, and issues to be resolved. Consider the prototypical heat treatment used to strengthen a binary alloy, mentioned above. The heat treatment creates a microstructure of interconnecting, interlocking domains through the kinetics of a first-order phase transition. The structure scales to the size of those growing domains, so that at any time the system looks invariant, provided lengths are measured in units of that domain size. On the other hand, consider a fluid heated from below. Above the threshold of an instability, the fluid exhibits a regular periodic array of convection cells. However, under only moderately increased heating, a new, complex dynamical state, called “spatio-temporal chaos”, emerges. In this research, the underlying materials themselves are not the main focus of research, but rather the more-or-less ordered dynamical states that the macroscopic patterns exhibit. Such studies have links to the many disciplines across the natural sciences in which complex dynamics are important.

Research has made progress in this area by focusing on model systems wherein different ideas can be tested with rigor, as described in Section IV.4 above, and indeed there is a smooth continuum between the work described there and in this section. Canadian research in this interdisciplinary area is marked by the notable work of promising young scientists. The ability of these talented young experimentalists speaks well for the future of this area. An excellent example is John de Bruyn of Memorial, who is experimentally studying spatial and spatio-temporal patterns in systems that are far from equilibrium. His excellent work is noteworthy for the novelty of the systems he studies, and the simplicity and clarity of his experimental methods. This work involves a generalization of ideas from nonlinear dynamics, such as chaos, to systems with many degrees of freedom. He has worked on Rayleigh-Benard convection in gases, one of the prototypical systems for the study of spatiotemporal chaos. He has also studied instabilities at driven fluid-air interfaces, including fingering in fluids running down an inclined slope, and the related but more complex printer’s instability. Furthermore, he has been studying the growth of rough surfaces by electrochemical deposition. The complex behavior of these relatively simple laboratory systems has implications for many real-world systems, ranging from the industrial coating of paper to the formation of icicles.

Stephen Morris of Toronto is similarly talented. He was involved in the key discovery of spatio-temporal chaos in Rayleigh-Benard gas convection while a postdoc with Ahlers in Santa Barbara. In addition to continuing those studies, Morris is investigating Marangoni convection on the surface of fluids. He is also studying certain autocatalytic chemical reactions in solution, which proceed by propagating convection fronts, somewhat like flame fronts. Morris and de Bruyn also collaborate closely on electrically driven convection in liquid crystals, and on crack patterns in brittle materials. Also in the same area of pattern formation is the promising young experimentalist James Gleeson of Calgary. His particular systems of current interest are dendritic growth in liquid crystals, as well as directional solidification, and electro-hydrodynamic convection. He has also studied the related issue of front propagation.

Most of these problems involve, in some way, the investigation of interfaces between separate phases. John Dutcher of Guelph is using Brillouin light scattering, which can probe both magnetic and elastic properties, to study a variety of such surfaces. These include ultrathin magnetic films, corrugated surfaces, and thin-film polymer interfaces. This has led him to use this probe to investigate metallic superlattices, as well as the glass transition in freely-standing polymer films, where he finds very large reductions in the transition temperature. Piercy of Ottawa is also studying surface structure and dynamics via low energy electron diffraction (LEED).

Talented theorists are also working in this area in Canada. Michael Plischke of Simon Fraser is studying growth instabilities and roughening during molecular beam epitaxy (MBE). Unlike much of the theoretical work in this area, Plischke has been making clear contributions with experimental relevance. He has predicted and explained not only the universality class for MBE roughening, but also predicted kinetically driven surface reconstructions during growth. Rashmi Desai of Toronto, mentioned in Section IV.4 above also has interests in rough surfaces, and has recently given a unified approach to the kinetics of phase separation and phase ordering for systems with long range repulsive interactions, e.g., Langmuir monolayer films and uniaxial ferromagnetic films. At St. Francis Xavier, N. Jan and D. L. Hunter are using computational physics techniques to study a range of nonlinear systems, including spin glasses, dynamic critical phenomena, and other complex systems. At Ottawa, I. l’Heureux is studying nonlinear dynamics and chaos, and particularly its relevance to geological systems, and the formation of oscillatory zone instabilities, such as Liesegang rings.

Not all experimental work in this area is done on a tabletop in a small lab. Excellent work using both neutron scattering, by e.g. Bruce Gaulin at McMaster, and x-rays is also being done. For example, Mark Sutton at McGill is using x-ray reflectivity and glancing incidence diffraction to study the structure of thin films and their interfaces. The x-ray measurements are also possible on buried interfaces, and diffuse x-ray reflectivity is sensitive to the interface roughness. In addition, both Sutton and Marsha Singh of Queen’s are making use of the fact that x-rays are ideally suited to studying both the crystal structure and the microstructure of materials by combining both small angle scattering and wide angle powder diffraction. So far this has been most heavily used to study crystallization kinetics.

An exciting spin-off from the conventional x-ray diffraction technique, x-ray fluctuation spectroscopy, has been developed by Sutton of McGill, with collaborators at MIT and Argonne National Labs. This technique makes use of coherent x-rays to measure the kinetics of systems both in and out of equilibrium, and is, arguably, a new probe of matter. The latest results have been the measurement of time correlations in copolymer melts of polystrene-polyisoprene diblock in a polystyrene matrix. The success of this and related work has led to Sutton and Singh being the Canadian component of the IMMCAT beamline, now under construction at the Advance Photon Source at Argonne National Labs. This beamline has a more than one thousand fold increase in photons compared to the beamline on which the previous time resolved measurements were done, potentially permitting the measurement of a diffraction pattern with nanosecond time resolution. The IMMCAT beamline will be further optimized to perform intensity fluctuation spectrometry with greater flux and higher time resolution than has been done to date.

Sutton's work is closely coupled to theoretical efforts at McGill of Grant, who is studying nucleation and growth, crystallizing eutectics, spinodal decomposition, and related topics. In Grant's work on eutectic crystallization, all standard features of this process (tilt wave instabilities, competition between nucleation and phase separation, dynamic contact angles) were recovered. Furthermore, 'fingerprints' of different growth processes - such as primary and secondary crystallization - were identified, which can be verified experimentally by, for example, scattering probes.

Martin Zinke-Allmang of Western has made notable contributions to the understanding of surfaces and interfaces, particularly under nonequilibrium conditions, through the use of scanning electron microscopy. One of his interests concerns the coalescence of clusters on surfaces. This is a long-standing problem in materials science, and one where experimental work of the quality of Zinke-Allmang's has been sorely lacking. His work provides strong tests of ideas in this area, and he has raised several important issues which had been unappreciated, despite the fact that droplet growth by evaporation and condensation has been studied since the seminal work by Ostwald in 1901. The creative and original style of his research is evident in his work on clustering. Zinke-Allmang, on close examination of clustering on surfaces, found that craters are caused by clusters, with commensurate diffusion and dissolution below the substrate. This was quite unexpected, and is of potential importance for applications, since surface clustering is one method now being touted for making quantum dot devices. Further, he found a fascinating example of "shape-cycling", where cluster shapes cycle between rectangular and spherical shapes. The cycling is attributed by him to a subtle diffusional coupling to the substrate. These are fascinating observations, which pose a severe challenge to the theoretical understanding of self-similar droplet growth.

Nucleation and growth is a common mechanism for the formation of nanocrystallites, particularly with regard to applications. For example, Strom-Olsen of McGill is studying how the defects and grain boundaries between crystallites act as diffusive "highways" for the storage of hydrogen in magnesium based hydrides. Hydrogen diffuses easily through the interfaces allowing faster charging and discharging. In addition to these diffusional properties, nanocrystalline materials can have novel magnetic properties, when made of ferromagnetic alloys: Since their structure is disordered, they act as soft magnets, and in addition they often have negligibly small magnetostriction. Indeed, all elastic distortions and decrepitation are reduced due to the small domain sizes in these systems. Much of this excellent fundamental research has strong potential for transfer to applications and the market place.

As discussed in Section IV.4, this entire area is an exciting, dynamic and highly interdisciplinary field, where some of Canada's best young scientists work. Provided these talented people can be given the research support they need, Canada has every reason to expect continued excellence in this area.

IV.6 *Materials Research Requiring Large Facilities*

Canadian physicists make use of a number of large scale facilities for research in condensed matter physics: neutron scattering at Chalk River, x-ray scattering and spectroscopy at foreign sources, muon beams at TRIUMF, and ion beams at a variety of installations. Condensed matter physicists and, increasingly, scientists and engineers in other materials related disciplines, exploit these techniques to obtain detailed information about structure and dynamics that cannot be accessed by other probes. In the present context large facilities can be taken to refer to experimental facilities of sufficient cost and complexity that they are not normally available at universities (typically with >$50M capital cost).

As the exploitation of these techniques has increased there has been a trend, in many countries, away from shared use or parasitic programs to dedicated sources optimized for materials research. In Canada, this has not occurred, partly due to circumstance of history and geography, and partly due to the relatively small size and geographic dispersion of the research community. Large materials research facilities were the topic of a recent NSERC sponsored review (the Bacon Committee), already discussed in Section II, which produced a report covering much of this area. Although not specific to condensed matter physics, most of the issues raised are of direct relevance.

IV.6.1 *Neutrons*

In Canada, neutron scattering has the longest history as a major facility for Canadian condensed matter science, centred on the availability of the highest flux neutron source (at the time) at Chalk River beginning in 1957. Because the Canadian nuclear program was centred on heavy water reactors at inception, Canada was a major player in the development of the techniques which are now commonly employed at neutron sources worldwide. The Canadian role in the development of inelastic neutron scattering was recognized with the awarding of the 1994 Nobel Prize for Physics to Prof. B.N. Brockhouse for his ground breaking work, carried out in the 50's and 60's at the NRU reactor at Chalk River. NRU continues to be a workhorse neutron source serving both the neutron beam community and AECL's own reactor development needs. This shared use aspect has meant that Canada has for many years enjoyed a competitive medium flux neutron facility for materials research at a very low cost compared to most other countries. There are currently six neutron spectrometers (valued at over $20 M), optimized for a variety of purposes, serving a user community of about 100 that spans physics, chemistry, engineering, and biology, the most recent addition being the biomaterials diffractometer. The CMP component is about 30% of the user program, with non-physics based Materials Science and Engineering representing another 40%. This serves as an indication of the success in exporting the techniques developed by condensed matter physicists to the wider materials science community.

Nearly all of the young scientists in the Chalk River group obtained their PhD's in condensed matter physics at Canadian universities, where they were part of GSC28 supported research programs. The Chalk River group has led the world in the application of neutron scattering techniques to industrially relevant materials. The Canadian ANDI (Applied Neutron Diffraction for Industry) program is now being emulated by other neutron laboratories. It has stimulated a growth in materials science and engineering related experiments which employ the techniques developed by condensed matter physicists, often involving interdisciplinary work. Examples include the Chalk River collaboration with McGill on steels and metal-matrix composites (Canadian Steel Industry Research Association, Professors Yue and Drew), with Queen's on gas pipeline sensors (scientists David Atherton and Clapham, with industrial partner Pipetronix), with UBC on processing of aluminum and steel (industries Alcan and Alta Steel, scientists Brimacombe, Samarasekera and Hawbolt) with an Ontario Centre for Materials Research funded program involving scientists at Chalk River, Canadian industry, and university researchers, Mason (Physics, Toronto) and Wang (Materials and Metallurgy, Toronto).

In addition, the neutron facilities are used with particular success by scientists studying magnetic materials -Gaulin and Collins (McMaster), Mason and Fawcett (Toronto), Altounian, Ryan, and Strom-Olsen (McGill), Kiefl (UBC), Steinitz (St. F. X.), and Tindall, (Dalhousie), superconductors - Gaulin and Collins (McMaster), Mason (Toronto),and Taillefer (McGill), and ordered structures in biological membranes - Epand (McMaster), Hallett and Jeffrey (Guelph). The polarized beam capability of the DUALSPEC triple axis instrument has been extended to reflectrometry studies, which have been very productive in studying magnetic ordering in metallic multilayers (McGill and McMaster groups - see related discussion in Section IV.3) The Canadian university research community participates in the majority of the over 150 experiments per year carried out as part of the Chalk River user program. NSERC has recognized the importance of the neutron scattering facilities by funding ancillary equipment such as superconducting magnets, cryostats, etc., and 50% of the cost of DUALSPEC which consists of a high throughput powder diffractometer and a polarized beam capable triple-axis spectrometer.

In response to budget cuts announced in last year's budget AECL decided to withdraw from all research not directly related to its CANDU (power reactor) mission. AECL funding for the Neutron and Condensed Matter Science Branch (which operates the neutron scattering program) terminated on March 31, 1997 at which time the National Research Council assumed responsibility for a scaled down neutron scattering laboratory based at Chalk River. This interim funding has been secured for three years, at the end of which NRC is expected to include the program in its long-term planning provisions. A permanent solution must be put in place, or Canada runs the risk of losing this highly successful program, which would directly impact research at Canadian universities in a number of subfields of condensed matter physics, chemistry, biology, and materials science. In addition, access by Canadians to international facilities could be lost since, in the past, this has occurred at no cost to Canadians on the basis of reciprocal access for foreign researchers at Chalk River. Typically 20% of Chalk River users are from outside of Canada and roughly 20% of Canadian neutron experiments are carried out abroad, when specialized capabilities not available at Chalk River (such as cold neutrons or pulsed beams) are required.

Over the longer term the challenge is to secure a successor to the NRU reactor, which will likely only operate a few years beyond 2000. AECL is planning to build two reactors for isotope production only, and then a new research reactor, the Irradiation Research Facility (IRF), a 40 MW heavy water reactor with neutron beams. If this goes ahead, the beam research community will again be able to benefit from the reduced cost of a shared use facility and utilize its present suite of six thermal spectrometers. To bring the new facility to modern standards the community plans to raise approximately $60M to build a cold neutron laboratory consisting of a cold source, guide hall, and neutron spectrometers. This would significantly enhance Canadian neutron scattering by providing a much higher flux of cold neutrons, which are particularly suited to high resolution spectroscopy and structural work at long length scales (1-1000 nm), as occurs in many soft condensed matter systems - biomaterials and polymers for example. Although the capital cost represents a significant investment for the materials research community in Canada, it is much less than the cost of a dedicated neutron beam reactor. The shared aspect also means that the annual operating cost for a user support group would be much less than for a dedicated source, and all its funding would go to the research and not the source.

A moderate but significant Canadian investment will therefore be essential to maintain access for Canadian researchers in Materials Research and Engineering to both a national facility as well as to the much larger pool of neutron research facilities available worldwide, and at a cost much less than a buy-in to a share in a foreign facility. If such shared use of the IRF should not be possible, a dedicated reactor-based source is not the only solution for mounting a viable Canadian program in neutron-based Materials Science. A completely different approach to the Canadian need for a neutron source would involve the extension of TRIUMF to provide a spallation neutron source. As discussed in Section IV.6.3 below, this could result in a Canadian materials research facility bringing together both an enhanced MuSR capability and neutron scattering, which would provide a strong core for a Centre of Excellence in Materials Science, building upon the existing strengths already present in the Vancouver area.

IV.6.2 *X-Rays*

Although x-rays have been employed as a structural probe of condensed matter since the outset of modern solid state physics, it is only relatively recently, with the dramatically increased source brightness possible at synchrotrons, that large scale x-ray sources have become important tools for the condensed matter community. Since Canada does not have a synchrotron source, the Canadian effort in this field has of necessity been based at foreign sources.

Currently soft x-ray experiments use the Canadian Synchrotron Radiation Facility (CSRF) at Aladdin (Wisconsin), NSLS, the Daresbury source in the UK, the Advanced Light Source in Berkeley, LURE in France, and the source at Lund in Sweden. Those requiring hard x-rays use the Stanford Synchrotron Radiation Laboratory, NSLS at Brookhaven, CHESS at Cornell, the Advanced Photon Source at Argonne, the Photon Factory in Japan, Daresbury, HASYLAB in Germany and the European Synchrotron Radiation Facility in France. The CSRF soft x-ray beamline, implemented through the support of the Ontario Centre for Materials Research (OCMR), is ideally suited to work on Si, much of which has been done by T. K. Sham (UWO), who has many collaborations with other groups at universities and the NRC.

Canadian researchers are involved in two Collaborative Access Teams (CAT's) building beamlines at the Advanced Photon Source at Argonne National Laboratory in the U.S. Under an agreement with NSERC, two years after the operation of the first beamline, other Canadian scientists and engineers will be able to apply on a competitive basis (peer-reviewed) for access to all the IMM-CAT and PNC-CAT facilities, the amount of beamtime being in proportion to NSERC funding. IMMCAT stands for IBM-MIT-McGill Collaborative Access Team, reflecting its initial membership. The Canadian component involves Singh (Queen's) and Sutton (McGill). Their expertise is in high resolution diffraction, small angle scattering, time resolved scattering and coherent x-ray scattering (intensity fluctuation spectroscopy). Sutton has also had experience designing and building a beamline at NSLS.

The research program of IMMCAT consists of several related and overlapping areas in materials science and condensed matter physics, with a focus on dynamic phenomena. The experiments planned fall primarily into four areas listed roughly in order of priority: studies of dynamics by x-ray intensity fluctuation spectroscopy and related coherent x-ray methods, time-resolved x-ray scattering studies of bulk phase transition kinetics, grazing-incidence scattering studies of surface structure and kinetics, and scattering studies of the structure and kinetics of buried interfaces.

There is much in common between these topics, both in the techniques used and the systems studied. Since the nature of phase transitions depends strongly on spatial dimension, the kinetics of bulk phase transitions should be compared with the kinetics of surface phase transitions. Because growth of one phase in another occurs at their common interface, studies of buried interfaces can be extended to studies of growth dynamics, since the x-ray diffraction techniques applied to surfaces are equally applicable to buried interfaces. Finally, intensity fluctuation spectroscopy can measure dynamics not only in non-equilibrium systems but also in equilibrium systems. It provides a completely new probe to study novel aspects of kinetics. As can be seen from this list of topics, the emphasis of the CAT is on various types of scattering measurements with high resolution in wavevector (angle) and time.

The Pacific Northwest Consortium Collaborative Access Team (PNC-CAT) is a consortium of Canadian and American institutions formed to build a multipurpose insertion device (undulator) and bending magnet beamlines. The lead institutions are Simon Fraser University, University of Washington, and Battelle Pacific Northwest Laboratory. They are responsible for the design, construction, installation and daily operation of the CAT. The Director of the PNC-CAT is Prof. E.A. Stern, while D. Crozier (SFU) is the Associate Director and Dr. S. Heald (PNL) is on-site at the Advanced Photon Source (APS) as Director of Construction. The other Canadian faculty who will share the initial beamtime are Heinrich (Physics, SFU), Tiedje (Physics, UBC) and Mitchell (Chemistry, UBC).

The protein crystallography groups at the University of Saskatchewan and the University of Alberta are also current members of the PNC-CAT. However, if the Canadian Light Source at the Saskatchewan Accelerator Laboratory is funded, they will build a beamline in Saskatoon. If it is not funded, they will pursue options with the PNC-CAT or the National Synchrotron Light Source.

The PNC-CAT will conduct fundamental studies in condensed matter physics, chemistry, materials science and environmental science. They are emphasizing two primary capabilities: microbeams and spectroscopic (energy scanning) applications. A capillary focusing microprobe is being developed with a spatial resolution smaller than 1 micron. The high spatial resolution will permit pump-probe experiments on the microsecond time scale. Initially it will provide a monochromatic beam over the energy range from 3 keV to 40 keV. Techniques will include x-ray absorption fine structure (XAFS), reflectivity, x-ray standing wave (XSW), x-ray scattering, and imaging. The x-ray scattering will include application of the diffraction anomalous fine structure (DAFS) technique. Magnetic and non-magnetic atoms at interfaces will be distinguished with spin-dependent XAFS (the polarization state of the x-ray will be changed using x-ray waveplates). A significant portion of the PNC-CAT research will involve surfaces and/or buried interfaces. These include the liquid-solid interface, of vital importance in many environmental processes, as well as problems in surface science such as epitaxial growth.

The soft x-ray community has been less content with the use of foreign x-ray sources, perhaps because Wisconsin, the first formal Canadian presence at a foreign synchrotron radiation facility, is a less powerful second generation source. This has led to a proposal for a Canadian synchrotron, the Canadian Light Source (CLS) to be sited in Saskatchewan (as a result of a recent site competition coordinated by NSERC). The present estimate for the cost of constructing this facility is $116M, including contingencies. The proposal would see a compact ring utilizing the latest insertion device technologies, built at the Saskatchewan Accelerator Laboratory. It would be ideally suited to the needs of the UV community and, in addition, would be better than the NSLS for harder x-rays. The proposed intensities are highly appropriate for the vast majority of x-ray scattering and spectroscopy uses. The few experiments that require higher brilliance will then be able to go to ESRF (Europe), SPRING 8 (Japan) or APS (in fact, we should add here that the latest thinking is that with small-gap undulators the CLS could be competitive with the APS in brightness even for hard x-rays!). While it is likely that those scientists already directly involved in CATs at the APS will have all of their needs met for the immediate future, if the usage of x-rays grows to exceed the UV usage by three or four to one at steady state (roughly the ratio in the U.S.), the current APS lines will not be able to satisfy the Canadian needs, reinforcing the case for the CLS.

IV.6.3 *Muons*

For a number of years the proton beams produced by the TRIUMF cyclotron for research in subatomic physics have also been used to produce muons for condensed matter science. This is a relatively small field but Canadians have played a major role in both the development of the technique and its exploitation. In condensed matter physics there has been a highly visible effort to measure the penetration depth in type II superconductors, most notably high temperature superconductors, through the sensitivity of the muon spin to magnetic field inhomogeneities. This has been a component of the CIAR Superconductivity Program, and has complemented the UBC measurements of the temperature dependence of the penetration depth by microwaves, which are only sensitive to changes in penetration depth and not its absolute value. Another area where muons have had important impact is in the low frequency dynamics of frustrated magnets, where the UBC group has been part of an NSERC Collaborative Project with McMaster and Columbia University. There has also been important Canadian research on the use of muons as a more readily studied analog of hydrogen in semiconductors, and as a probe for the study of anomalous diffusion.

Elsewhere in the world new muon beams have been developed in consort with the proton beams needed for spallation neutron sources (Paul Scherrer Institute in Switzerland and ISIS in the UK) at dedicated materials research facilities. A similar opportunity exists at TRIUMF - by adding an accumulator and booster ring to the cyclotron; CW and pulsed muon beams could coexist with a powerful pulsed spallation neutron source. This would be very attractive to the neutron community, particularly if the proposed IRF does not materialize or does not include neutron beams. The scientific capabilities of such a pulsed neutron source would differ from the proposed IRF - exceeding it for applications that can make efficient use of the time structure, such as powder diffraction, and possibly falling short in some cold neutron applications (although that is a topic of much current debate worldwide). Overall, a new medium flux neutron source of either type (reactor or spallation) would meet the bulk of Canada's needs.

Such an initiative at TRIUMF would imply a significant change in the laboratory's mission, similar to what occurred at the Rutherford Laboratory, when the UK subatomic physics effort shifted to CERN, and the pulsed neutron/muon source ISIS was dedicated to materials research. The present initiative at TRIUMF, the isotope separator and accelerator (ISAC), which involves the production of a wide variety of radioactive isotope beams, will allow the development of new techniques involving the implantation of light, spin polarized nuclei into materials, and using them to study local magnetic fields in much the same way MuSR or NMR does. This may open a window into the dynamics of small structures, epitaxial layers, and surfaces, which is currently inaccessible. It should be noted that another route to the study of the magnetic properties of surfaces and near-surface layers could be based on the development of a cold muon source. The ability to work with isotopes with lifetimes longer than that of the muon will permit studies of spin relaxation to lower frequencies, so that $1/T_1$ can be easily measured in metallic and superconducting samples. While the new capabilities of ISAC are as yet unproven, it seems likely they will augment the existing muon beam techniques by extending the range of condensed matter problems that can be tackled.

The subatomic physics mission of TRIUMF has not in the past prevented the lab from assisting substantially in helping to establish a viable MuSR program. However, the study of materials is still to some extent a peripheral interest at TRIUMF, despite the internationally recognized success of the MuSR program. There is considerable potential to further develop the already very successful TRIUMF materials research program, and it is quite possible that condensed matter physics will become an even more important part of the local program in the future.

IV.6.4 *Ion Beams*

Ion beams, from keV to MeV energy, have been used in CMP research for several decades and are gaining in importance. Canada has traditionally been a strong player in this field, with major contributions in the 70's, 80's and 90's. MeV ion beams are used to modify or to analyze materials. "Modify" includes ion implantation, an essential technique that is widely used (at somewhat lower beam energies) to dope semiconductors. Research on ion beam modification covers much more, including optical and magnetic materials. "Analyze" includes Rutherford backscattering, channeling, recoil spectroscopy and particle induced x-ray emission spectroscopy.

Depending on the beam energy and number of beam lines, ion beam equipment qualifies as anywhere from "large equipment" (say, comparable to an SEM) to "Major Facility" (e.g. TASCC, where only a small fraction of the research was in CMP). All ion accelerators, and especially older installations, are expensive to maintain and operate. Most small and mid-sized systems were previously supported through the NSERC infrastructure program. In recent years, three major facilities (Queen's, McMaster, and TASCC) have closed. The recently modified beam line for high energy ERDA at TASCC will move to the Tandem at Université de Montréal, where it will continue to be used by Jim Forster. However, it is not clear whether the maximum energy of the 6 MV tandem is sufficiently high. A 70 keV radioisotope implanter at AECL has also been decommissioned.

On a brighter note, two MeV tandem accelerators have been installed (one about 8 years ago at UWO, one this year in Montréal) which consolidated the existing installations at UWO and U. de M. Both installations are well supported from a variety of sources including NSERC and provincial grants, as well as from user fees. Canadian research in CMP with accelerators has had, and continues to have, a very significant, truly international impact. To illustrate Canada's impact, we should begin with John Davies' (Chalk River, McMaster) contribution to the discovery of the channeling effect in the early 70s. This discovery led the way to bulk and surface analysis techniques capable of identifying exact lattice locations of atoms. Both elastic recoil detection (ERD) and ERD with time-of-flight (ERD-TOF) were invented in Montreal, by L'Ecuyer with Therrault (INRS), and by Gujrathi and others, respectively. With the exception of L'Ecuyer, all are still active in ion beam analysis. The strong showing of Canada in ion beam analysis techniques continues today with the recent developments of surface-PIXE at UWO (W.N. Lennard), of high-energy ERD (Davies and Forster, AECL), and of the very elegant stopping power measurements by Therrault and Ross at INRS.

The research emphasis at the two newest tandem accelerators has moved from materials analysis to materials modification. Mitchell at UWO is collaborating with Charbonneau (NRC-IMS) and others to control optical emission wavelengths in quantum wells. Ion beam mixing, which can be patterned using masks, is used to blur the interfaces of a layered semiconductor structure and thus to locally change the transition energies. These studies will not only lead to new devices and device processing techniques, but can also add new information on the mobilities of point defects in different III-V alloys. The ion beam facility at UWO is completed by two variable energy positron accelerators (P.J. Simpson), one being used for defect studies in solids, the other for supporting fundamental positron and electron interaction studies in thin films. Another well-recognized program using positrons to study defects in semiconductors is that of Dannefaer and Kerr at Winnipeg.

At the U. de Montréal, Roorda is studying point defects in Si on two fronts: differential scanning calorimetry combined with standard defect spectroscopies yields new information about divacancies, a study which was done using the old 6 MV accelerator, whereas the new accelerator will be used to develop novel defect engineering techniques for impurity gettering in Si. The recent discovery in his group of macroscopic material displacement due to transfer of momentum from the ion beam to the target material puts high energy ion beam damage in a new light. The power and appeal of energetic ion beams in CMP is the ability to adjust the embedded ion range distribution through selection of ion energy, the concentration through dose, and the kinetics and dynamics through target temperature and flux. The possibility to move far from equilibrium is a powerful attribute of ion beam modification. The interplay between defects and the implant species, or with the lattice structure and its composition, gives rise to rich possibilities for basic and applied physics. As a recent example of ion implantation for medical application, one could mention the implantation of beta-emitting 32-phosphorous in stainless steel stents (Stents are expandable, slotted stainless steel tubes which are permanently implanted in arteries during coronary angioplasty.). Such stents are expected to reduce the restenosis rate after balloon angioplasty and stenting, and have recently been used in pioneering trials at the Hôpital Notre Dame in Montréal. The use of ion implantation to impregnate the stents with the radio-isotope is ideal because of its dose control, and to circumvent problems with adhesion of deposited layers.

Other Canadian ion beam installations that should be mentioned because of their application in CMP are the medium energy ion implanter for semiconductor work at Sherbrooke run by J. Beauvais (see also IV.2) and the focused ion beam facility at NRC/IMS in the group of T. Jackman. With this machine, ion beam modification at small feature sizes can be explored. E. Knystautas at Laval has a vertical van de Graaff accelerator which is used for ion beam mixing and ion beam analysis. Installations that will not be discussed in this report include ion beam facilities for applications outside of CMP, such as mass spectrometry and isotope dating (Isotrace at U. of T.), Campbell's micro-PIXE at Guelph or TRIUMF's ion beam facility for particle physics (however, the applications of TRIUMF's muon beams for CMP are discussed in IV.6.3)

V SUMMARY

The following summary of the issues discussed in the previous sections, as well as in the questionnaires, is based on a so-called **SWOT** analysis: Strengths, Weaknesses, Opportunities and Threats. It thus leads directly to Section **VI**, Recommendations.

Strengths

1. The principal strength which is noted in each successful area is a core group of excellent scientists. In areas which have been nurtured in Canada for many years, there are outstanding senior scientists. In these areas we note that the quality of hiring in recent years has also been excellent, so that there is every reason to believe that established strength will be maintained. In new areas, such as (experimental) soft matter physics, the practitioners are predominantly young and the quality is high.

2. The existence of facilities for materials synthesis and modification at McMaster, UBC, the NRC, U. de Montréal and École Polytechnique, SFU and elsewhere has contributed significantly to the health of Canadian CMP. However, there is much to be gained by further strengthening Canadian capabilities in materials synthesis, modification, fabrication and analysis, and from broadening the range of materials and structures which can be produced.

3. Condensed Matter Physics in Canada has benefited greatly from programs which have fostered interactions between active groups across Canada. In this regard, the CIAR has played a key role by supporting excellent scientists in both superconductivity and soft matter research, and by promoting networking in these two areas. Similarly NSERC's short-lived Collaborative Grant Program has enhanced interaction in the area of frustrated antiferromagnets, quantum well disordering, and interdisciplinary studies of biomembranes. We note that the greatest impact has resulted from programs which have promoted interaction in areas of established strength.

4. Two major user facilities, neutron scattering at Chalk River and MuSR at TRIUMF, have acted as magnets for forefront research, and strong user groups have grown up around each facility.

5. Canadian CMP has been dynamic in mirroring the international evolution of the field, both in terms of the hiring of new researchers, for which individual departments have responsibility, as well as in the ability of established researchers to reorient their programs to follow (and lead) new developments. There was little evidence of undue activity in 'older' fields which would need to be de-emphasized.

We have not attempted any detailed bibliometric studies justifying our claim that there are many outstanding CMP researchers and groups in Canada, and that Canada obtains an excellent return in terms of research productivity from its expenditure in CMP. This is largely because we feel that a sufficient case is presented here for the Assessors, being expert in their fields and having broad experience, to accurately judge these issues.

Weaknesses

1. Subcritical groups and geographical isolation, without compensating collaborations and networking.

2. Shortage of start-up funding; uncertain and often inadequate level of support until long after new faculty arrive.

3. Inability to support even the best programs at internationally competitive levels.

4. Problems in supporting inherently expensive research under the present funding system, particularly if such research does not offer the prospect of short-term economic benefits which would allow supplementary funding to be obtained from the strategic or university/industry programs.

Canada's provincial governments maintain an extensive system of small, medium and large universities, distributed uniformly across the country's populated regions. This national, province-run system operates under a strongly egalitarian philosophy which mitigates against the concentration of expertise and resources in a few elite institutions. It has frequently been argued that this system is inefficient and that the country would benefit from the cultivation of a few elite institutions, since the competition for first-rate students and faculty is with such institutions in the U.S. and elsewhere (the perception that many of our best students pursued their graduate studies outside of Canada, sometimes with the assistance of an NSERC scholarship, was a worry raised by many respondents). On the positive side, the Canadian system of having less dispersion in university quality (as compared to the US, for example) is responsible for the fact that even our smaller physics departments are in fact quite good. Given the present system, mechanisms for improved communication and networking are greatly needed. Any differentiation between institutions and departments which arises solely from selectivity based on excellence and impact, should on balance be seen as positive.

It must be conceded that GSC28 (and most other GSCs) has in the past used a small fraction of its budget to fund researchers in isolated situations, where for whatever reason the critical mass and connectivity that could help to ensure excellence and impact were missing. If researchers in such situations cannot achieve excellence and impact within the limits of their available resources, then we must seriously consider whether they should have to choose between linking with a larger effort (local, national or international), which would allow them to contribute in a more significant way, or losing their NSERC support. This in no way indicates a belief that researchers and groups in isolated situations cannot achieve excellence and impact on their own - there are indeed a number of examples showing they can - and it is understood that they should be funded as well as anyone when they do so. It should also be noted that examples of isolated, subcritical efforts can also be found in large, research-intensive departments.

University resources for starting up new faculty have been seriously depleted in recent years, at least in part due to the demise of NSERC's General Grants to universities. NSERC's Major Equipment and Major Installation Grant Programs can be an excellent source of start-up funding, but they also frequently require two or even three applications before one is successful. Such delays, together with a conservative approach to funding some new researchers of demonstrated excellence, are extremely wasteful and demoralizing for new faculty. They can also lead to 'horror stories' which make it more difficult to hire exceptional new faculty members in Canada. Related to the issue of start-ups is the time taken for new researchers to reach a funding level, which while not adequate in an absolute sense, is at least appropriate in comparison to other activities supported by the GSC.

The GSC system, in its present underfunded state, has difficulty in dealing with cost-of-research issues. There is a tendency for grant size to correlate more with the excellence and impact of the program under consideration than with the actual costs inherent in maintaining that program. This results in part from the perceived pressure on the GSC to demonstrate that it is supporting excellence, within its inadequate budget. Of course it is true that for many research programs which are able to access Strategic Grants or Research Partnerships funding, the Research Grants are not the only, or even the largest, source of support, and that these other sources must be taken into account when assessing the need for funding in deciding on the level of the Research Grant. However, even research which is well-suited to the goals of the strategic and partnerships programs can be difficult to initiate under the present scenario, since the Research Grant level will likely assume the availability (or necessity) of additional funding, while Strategic Grants and partnerships involving industry are often significantly delayed for beginning researchers by the need for them to first 'prove' themselves.

The situation is more serious for those who wish to pursue an inherently expensive experimental program (or even worse, one that is both expensive and high-risk) which does not have significant apparent short-term economic benefits, and therefore has little possibility of supplementary funding through Strategic Grants or partnerships. This is perhaps one of the inherent weaknesses of the NSERC system, except in areas such as astronomy and particle physics, where the connection between expenditures and future economic benefit are understood to be much less direct.

While only a minor factor compared to the above weaknesses, the problem of convincing our very best undergraduate physicists to pursue their postgraduate studies in Canada was of concern to many, since it has a direct effect on the quality (and cost) of Canadian research, and leads to an increasing reliance on foreign graduate students. This problem can be dealt with, at least in part, by emphasizing that excellent, world-class research training in most areas of CMP can in fact be obtained in Canada, which is coupled to our recommendations of a more absolute and prominent focus on excellence and impact as funding criteria, together with more competitive funding levels for the best programs. More must also be done by researchers, CAP and the DCMP to highlight Canadian achievements in a visible and credible way.

Opportunities

1. Development of new areas of CMP research and enhancement of strong continuing programs.

2. Development of new major facilities for Materials Research

3. Development of wider collaborations and networks where these can be shown to be of benefit to Canada.

The field of Condensed Matter Physics is evolving at a tremendous rate and Canadian CMP is changing with it. 25 years ago, Canadian CMP consisted largely of classical metals physics and superconductivity, a small amount of work in bulk semiconductors, and mature programs in phonons and magnons based on neutron scattering. There was little work in statistical mechanics and virtually none in soft matter. Today, bulk metals physics has been displaced by the study of ultrathin and nanostructured magnetic materials, and strongly correlated electronic systems, including high T_c; a large fraction of semiconductor work is on the two-dimensional electron gas in heterostructures, ballistic transport, or other effects of reduced dimensionality; there are strong programs in both equilibrium and non-equilibrium statistical mechanics; and there is substantial interest in both polymer physics and membrane biophysics. These last two fields in particular have only recently begun to make their way up the growth curve, and there are tremendous opportunities for departments to develop strong programs in these areas. Both polymer physics and biophysics are strongly interdisciplinary, and both provide opportunities for physicists to demonstrate the power of the techniques which CMP can bring to bear on ‘new’ problems.

Canada has traditionally been strong in areas of communications technology, beginning of course with Alexander Graham Bell. Some of the most significant components of our high technology sector, of which Nortel is only the largest example, are in this area. CMP is of major importance to the long-term future and direction of these technologies - in the miniaturization, increasing speed, and decreasing power requirements of electronic devices, in optoelectronic materials and devices, in fiber transmission, in the application of high T_c materials to communications, and, most significantly, in the search for revolutionary new approaches to the fundamental limitations of existing technologies. This should be seen as a golden opportunity for the establishment of new interdisciplinary networks of direct national relevance.

There are a number of current opportunities in the area of major facilities. The resolution of the fate of the neutron scattering facilities at Chalk River, by placing them under the NRC, stabilizes the situation for at least the next three years. The challenge now facing the neutron community is to build a compelling case for the construction of neutron scattering facilities in AECL’s new research reactor, the IRF, or, failing that, possibly a pulsed neutron facility at TRIUMF. The MuSR User Facility at TRIUMF, now a well-established program, suffered a serious blow from the cut-back of NSERC infrastructure funding. The opportunity exists to continue to develop MuSR at TRIUMF as a world-class facility if a way can be found to maintain the user support program at a viable level. There are opportunities for Canadian synchrotron users to obtain access to foreign x-ray sources by forming and obtaining funding for Collaborative Access Teams (CATs). More significantly, there is now the opportunity to provide for the majority of Canada’s synchrotron needs through the construction of a dedicated Canadian synchrotron source, the CLS, as has been endorsed by NSERC for Saskatoon. These new neutron and photon sources should form the foci around which national centres of excellence in interdisciplinary Materials Science and Engineering can be established.

Threats

1. Inadequate infrastructure support for university-based materials research facilities

2. Inadequacy of major user facilities for research in Materials Science and Engineering

Modern Condensed Matter Physics is particularly sensitive to impediments to the support of infrastructure. More specifically, a successful CMP program, or to put it in a broader context, success in Materials Science and Engineering, requires stable long-term support for:

a. materials preparation and modification facilities,
b. operation and maintenance of large analytical facilities at universities
c. user support at major facilities.

In recent years, cutbacks of infrastructure funding by NSERC have posed a serious threat to CMP research. As was already mentioned, the importance of infrastructure to the materials community was a major emphasis of the Bacon Report. However, the impact of budget cuts and the reorganization of infrastructure under NSERC's MFA Program was effectively to cut infrastructure support in half.

The key role of material preparation facilities has been emphasized throughout this report. The ability to make new materials of the highest quality is the most important competitive advantage that a good materials group can have, and pass on to its collaborators. This applies equally to all sub-areas—high T_c and strongly correlated electronic systems, epitaxial and nanoscopic semiconductor structures, ultrathin and nanostructured magnetic materials, soft and biomaterials systems, etc.

Technical and user support is important to ensure the effective utilization of expensive, sophisticated equipment. Equipment must be maintained, students trained, and safety standards maintained. Outside users should have access to equipment which is not fully utilized locally. Users should not have to be expert practitioners in order to access major facilities, such as neutron, muon and synchrotron beams. Instead, there should be on-site instrument scientists to train new users, to collaborate with them, or, in some cases, to run the experiments as a service.

We should also note here that ¾ of the theorists in CMP stated in the questionnaire that the availability of large-scale computing facilities would be beneficial for their research, and a considerable number complained of the competitive disadvantage posed by the lack of such facilities in Canada. The availability of such large-scale computing facilities, together with broad band networks connecting them and the universities, is an issue which goes well beyond research in CMP, and may be an ideal initiative for the Innovation Foundation to address.

The shortfall in infrastructure support can certainly not be addressed by the Research Grants Program alone, nor for that matter, by NSERC alone. We believe that the importance and special requirements of research in Materials Science must be recognized in Canada, as it has been in the U.S., Europe and Japan, and new programs put in place to address these crucial issues.

Overall, the erosion of infrastructure funding for materials research facilities is the greatest single threat to the field of CMP, and to all of Canadian Materials Science and Engineering, and it is the single area of greatest need for corrective action.

VI RECOMMENDATIONS

The following recommendations are based upon the input received through the questionnaires and other submissions, as well as many discussions with various interested parties, and within the Review Committee. They have furthermore been modified as a result of discussions resulting from the feedback received after circulation of the draft of the Review. These recommendations do not assume an ideal world, in which it would be fruitful to argue that the direct funding for academic research should be doubled (as is in fact happening in Japan), and in which granting agencies had sufficient resources to cover the ***full*** costs of funded research and facilities. They represent instead our best effort at planning how we can work most effectively within the present circumstances, and if possible improve them, for the benefit of the future of Canadian research in CMP and in the wider area of Materials Science and Engineering, and for the benefit of Canada.

Our major recommendations are listed below, followed by a discussion of the rationale behind them, together with a number of secondary recommendations. Other issues raised by the Terms of Reference and the planning document for the Review, which did not lead to any specific recommendations for change, are mentioned in Appendix 1.

Major Recommendations

1. **The first and second recommendations of the Bacon Committee, which have already been accepted by NSERC Council, should be implemented without further delay.**
   (The recommendations of the Bacon Committee are given on page 13; the first two relate to the establishment of national or regional 'clusters' of materials research facilities, and the securing of adequate infrastructure support for these clusters.)

2. **The remaining recommendations of the Bacon Committee, dealing with the issue of large-scale facilities for Materials Research, should form the basis of an inter-agency initiative to ensure that they come to fruition.**

3. **NSERC should appoint a Group Chair for Materials Science and Engineering, in order to better coordinate activities in materials-related areas, and to better evaluate needs and opportunities.**

4. **NSERC should initiate a thorough review of its current discipline-based GSC structure, in order to determine whether a new or modified structure might not be more conducive to cooperation, and to fostering interdisciplinary initiatives. The Materials Group Chair would play an important coordinating role in this review.**

5. **The increase in selectivity and funding dynamics demonstrated by GSC28, particularly since Reallocation, should be continued, and augmented by the adoption of a set of principles which will guide funding decisions over the next four year grant cycle.**

6. **Any increase in funding secured by GSC28 as a result of Reallocation should be applied to an initiative dealing with infrastructure and cost-of-research issues associated with high quality programs in materials growth, modification, characterization and fabrication.**

VI.1 *Major Recommendations Addressed Primarily to NSERC*

Infrastructure - It is clear from this Review that the overriding concern for the future of internationally competitive CMP and Materials Research in Canada is the growing gap between the sophisticated equipment and facilities needed to pursue this research, and the shrinking infrastructure budget, which is inadequate to maintain and fully utilize even existing installations, let alone to cover the cost of the new facilities which are needed to bring Canada up to the level of any of the industrialized economies. Much of this analysis is already well documented in the 'Bacon Report'. The NSERC response to date, pressed by reduced budgets to focus on its 'core' programs, has been the replacement of the Infrastructure Grants with Major Facilities Access Grants, resulting in a substantial ***decrease*** in the total infrastructure support. The concept of "regional clusters of equipment for Materials Science" appears to have been put on hold. We therefore recommend that NSERC proceed immediately with implementing recommendations 1 and 2 of the Bacon Committee.

The magnitude of the existing infrastructure problem, and the need for new facilities such as neutron and synchrotron sources which will require major additional infrastructure and operating support, clearly make this a problem which NSERC alone cannot solve within its present budget. Still, NSERC has an important role to play as a highly credible authority in arguing for the urgency of having this issue addressed by the Federal and Provincial governments. We would also hope that NSERC could play a central role in determining how any new infrastructure program would adjudicate the disbursement of funds. While the new Innovation Foundation may be good news, there remains the well-founded fear that excellent and much-needed new facilities will be provided without the long-term operating and infrastructure funding required to maintain and properly utilize them. Again, NSERC is well situated to explain the severity of this problem to government.

GSC Structure - We recommend that NSERC undertake a serious reevaluation of the existing discipline-based GSC structure, which can often pose a structural impediment to the initiation and funding of interdisciplinary research, and in particular the kind of forefront research which is often too new to be recognized as a desirable component of an existing disciplinary GSC. Furthermore, it seems evident that the importance of Materials Research and Engineering as both a thriving area of interdisciplinary activity, and a critical source of enabling technologies, is not well recognized within the current NSERC structure, or for that matter by any Federal initiatives, especially in comparison to the proliferation of such initiatives and support mechanisms found in the USA, Japan and Europe (a few of which are listed on page 8).

Our recommendation for the immediate appointment of a Materials Group Chair would address this deficiency at two levels (in the NSERC system the Group Chair is an unpaid position, usually but not always held by an NSERC-funded researcher, who acts as a liaison between a group of GSCs and the NSERC staff, council, and standing committees). First, the Group Chair could coordinate materials-related activities between existing GSCs. This would be particularly valuable in considering applications for major facilities, such as neutron or synchrotron sources, or for major interdisciplinary initiatives such as Networks of Centres of Excellence or Research Networks involving materials.

The Materials Group Chair would also provide an important coordinating role in any reevaluation of the GSC structure, since we believe it likely that some form of materials 'umbrella' would naturally result from any new GSC structure which was more 'goal oriented' and less 'discipline oriented'.

The present proposal for an interim solution involving the Materials Group Chair, instead of a more direct move towards a new GSC structure (which would in any case take considerable time), resulted from new input and considerations resulting from the circulation of the draft, as well as other input sought out by the committee. There was considerable worry, which seems justified considering related developments in the USA, that the move to a 'materials' focus carried with it a considerable threat to the support of theory in CMP, and to the support of long-term research, or research which had no evident short-term applications. This is not a development which we would wish to see - the existing CMP GSC contains about the right combination of interests and expertise to adjudicate the funding of materials physics, and to set the priorities between long-term and short-term (or, fundamental and applied) research, especially in light of the fact that the Research Grants are the sole source of support for fundamental research.

VI.2 *Major Recommendations Addressed Primarily to the CMP GSC:*

Excellence, Impact, and Selectivity - From our consultations, the questionnaire results, and particularly the feedback received after the circulation of the initial draft, ***it is clear that the vast majority of Canadian CMP researchers endorse the principle that excellence and impact should be necessary criteria for the awarding of all Research Grants.*** This is not to say that a small number of respondents did not argue that the emphasis on excellence and impact should be relaxed in order to support research activities in geographically diverse departments. The committee certainly recognizes the value of having active research programs in ***all*** physics departments, and more specifically recognizes the considerable contribution to the overall research effort which many of these institutions make, by providing excellent students who go on to pursue research elsewhere in Canada. However, the Research Grants Program and its GSC structure, together with the peer review process, and the implicit 'reward' structure of Reallocation, is not well suited to dealing with such important but 'second-order' considerations, as compared to the primary issues of excellence and impact. These issues are further dealt with in Section VI.3.

As has already been discussed, it is apparent that GSC28 has become increasingly selective with time, and especially since the results of the first Reallocation were announced. We believe that there is still room for improvement in this regard, and most definitely a need for the GSC to communicate its stance of high selectivity to the outside world. We therefore recommend that GSC28 adopt a set of clear principles and procedures. It should be emphasized that the recommendation of such principles is not meant to imply that the practice of GSC28 does not at present substantially fulfill these goals, but rather to provide a concise and easily understood set of statements against which performance can later be judged. In particular we emphasize that these requirements should be ***necessary*** ones - a surfeit of training, for example, should not compensate for research which is mediocre, or without impact of its own.

We therefore propose the following principle for funding:

> ***A recent history of demonstrated excellence and impact are necessary requirements for the award of a Research Grant. For start-up grants, there must be evidence leading to an expectation of the same.***

The GSC must be competent to judge excellence and impact, but we emphasize that these criteria cannot be allowed to 'slide'; the GSC must feel comfortable that it can defend every funded grant to outside critics on the basis of these criteria. Similarly, the GSC is best positioned to interpret the requirement for a ***recent*** history of achievement, as discussed in the following section on dynamics.

There was some concern expressed in the feedback that the term 'impact' might have some hidden meaning, prejudicial, for example to, fundamental research. This was not our intention, nor is it the way in which GSC28 has judged impact in the past. 'Impact' covers a wide range of research outputs, and can only be evaluated with reference to the nature of the research being pursued. It includes publications, citations and other recognition of the work, training of students and other research personnel, evidence that these students are finding positions which benefit from their training, collaboration with industry, technology transfer and the starting of new enterprises, evidence of leadership roles in national or international collaborations, etc. It is up to the GSC to strike a balance in weighing these components for a given application, and there is no evidence that it has had problems in doing so in the past.

We should point out here that the questionnaire results indicated that 60% of the respondents felt that selectivity should remain "more or less the same', while 36% supported higher selectivity and 4% lower selectivity. Additionally, 71% agreed with the concept of a minimum grant level, with proposed amounts ranging from \$10 K to \$40 K. We believe that these results are consistent with our recommendation for a moderate increase in selectivity, and in particular with the elimination of any counterexamples of nonselective funding. The issue of minimum grant size is a complicated one, and it would be a mistake to tie the GSCs hands with a recommendation for a 'hard' lower bound on grant size. The need for funding, and the availability of other sources of funding, must first be taken into account - it would be foolish, for example, to eliminate all adjunct grants by setting a minimum grant size which ignored the fact that they did not require any support other than for the graduate student involved.

Still, the surprising strength of the response on this issue, and the frequent argument that while very small grants may be much-appreciated, they are unlikely to be essential for the pursuit of the project, leads us to propose the following principle for adoption by GSC28:

All grants should be both necessary for the pursuit of the project, and sufficient, considering all available funding, to provide a reasonable expectation of excellence and impact.

As a corollary of and support for the above principle, and in recognition of the support for the concept of a minimum grant level, we further propose the adoption of the following practice by GSC28:

The GSC will justify all grants below $15 K with a 'special case' argument.

Dynamics - The second aspect of our recommendations to GSC28 deal with the dynamics of the granting process. Again, GSC28 has shown evidence of an increasingly dynamic granting practice since Reallocation, and has for even longer been active attempting to provide a reasonable level of start-up grant to new researchers, if not in absolute terms, at least in relation to the generally underfunded CMP grant level. This is a very positive stance, which needs to be continued. For new applicants there is usually not an extensive track record, but rather evidence which promises excellence and impact in the future. These researchers must be given adequate operating and equipment support to be able to demonstrate this promise.

Continuing applicants (and 'senior new' applicants), on the other hand, usually have a sufficient track record for the GSC to judge the likely significance of their contributions over the next grant period. However, while GSC28 dynamics have improved, there is still evidence for a correlation of renewal grant size with previous grant size, or 'time in the system', rather than with recent achievements and future promise. This can be demoralizing for younger researchers who are striving to be internationally competitive, and is wasteful of potential and resources. Particularly harmful is any perception by the community that the funding of yesterdays 'high flyers' is not being renormalized if they cease to perform at levels commensurate with their funding.

This is the rationale behind a more zero-based funding model; the size of the previous grant should only be of interest in judging the level of achievement over the past funding cycle, while the size of the next grant should be determined by both the recent achievement of impact and excellence, as well as by the promise of these during the next grant. We therefore propose the following principle for adoption by GSC28, which again is not meant to imply any failure of the GSC to move in this direction in recent history.

Where a sufficient track record exists, funding level should be determined by need, and by the recent record of excellence and impact, and not by the previous grant level.

In this context 'recent' would normally be interpreted as meaning over the past six years, but the GSC should not be restricted from using its good sense in interpreting this.

Implementation - In connection with the issues of selectivity and dynamics, we proposed that the GSC consider the advisability of moving to a two-pass method of adjudicating grants. In the first pass, applications would be sorted into categories such as outstanding, excellent, good and dubious, without any particular regard to the budgets. Then the outstanding grants would be funded at a level, considering other sources of support, which the committee felt would make them internationally competitive. Following this the excellent applications would be discussed, and funded at a level which made them at least viable, and then the best of the 'good' applications could be similarly funded, as the GSC28 allocation permitted. It was also proposed that the likely increase in nil grants need not be seen as negative, if the present stigma associated with a nil award was lessened, and these applicants were not discriminated against in following competitions.

While we continue to stand by this analysis, many misgivings about this proposal were expressed as part of the feedback. One was that this model would lead to a continual narrowing of the research base until there were only a few very large grantholders left. This was certainly not the intention of the proposal. In order to be as clear as possible, we reiterate that GSC28 has already moved to a more selective stance, and this committee does not believe that a drastic narrowing of the research base would be in the best interests of CMP research in Canada. Our call for a moderate increase in selectivity envisions a reduction in the number of research grants (all else being equal) of roughly 10%.

This proposal is also not intended to move our program-based granting practice to a project-based model; the program-based model has clearly served Canada well in the past, and must be maintained in light of the lack of other funding sources for this research.

Finally, considerable feedback on the question of nil grants was received pointing out the hardships resulting from a nil grant, when most of the grant went to manpower support, which could not be supplemented from other sources in the interim period before a new grant could be applied for. This is certainly an important consideration, given the lack of alternate funding sources, and the inability of most universities to come up with bridge funding under such circumstances. Thus the GSC might be ill-advised to award a nil grant to a renewal proposal which had a significant manpower component, unless it felt that the likelihood of an improved, fundable proposal was small. In such situations the GSC already uses the option of awarding a one year grant, which can be reduced to a nil grant if the next application is not sufficiently improved. It would then be essential to communicate the precariousness of the situation to the applicant, along the lines of “this would have been a nil grant, but….”.

Use of a 10% Increase - One of the specific issues which the Review Committees were charged with making recommendations on was what the GSC should do with an overall 10% increase (or decrease, see the following section). This recommendation is also of direct relevance for the drafting of the next Reallocation Submission.

After considerable thought and discussion, and reviewing the input from the questionnaire, we have concluded that it is more important to be realistic in answering this question than it is to come up with a package which sounds exciting but cannot be implemented. One message which is clear from the questionnaires was that no one wished to see the GSC setting predefined areas which were to receive extra (or less) support, as compared to dealing with the excellence, impact and promise of proposals on a case by case basis. We agree with this - while the GSC is certainly competent to judge whether a proposal is in an exciting area which needs bolstering in Canada, or is perhaps a run-of-the-mill proposal in an area already over represented, and deal with it accordingly, the setting of predetermined areas of focus can only dilute any drive towards excellence, and raises the specter of ‘locking in’ the importance of mature fields as compared to a dynamic response to new developments. It also ignores the pivotal role of the universities, through their hirings, in determining the future directions of CMP research in Canada.

Furthermore, the GSCs are very poorly positioned to implement new collaborative initiatives having any focus or coherence, as much as these are required. The Research Grants program is simply not suited to this function, among other reasons because of its 4 year cycle, which will be staggered for the various partners of any such collaborative effort, together with the limitation, set by NSERC, of being party to only one Research Grant at any given time. This situation might be different if Project Grants were available to disciplines other than Subatomic Physics, but this is not a recommendation we wish to make at this time. Instead, these much-needed collaborative projects, both within CMP and of a more interdisciplinary nature, should be vigorously pursued through more appropriate channels, such as the Research Networks, Research Partnerships, and Special Collaborative Projects programs.

We argue that the GSC should use the additional 10% in the support of excellence by beginning to address the cost-of-research and infrastructure issues which we have identified as the greatest threat to our international competitiveness in CMP research. Even a full 10% increase could of course not solve the infrastructure problem, particularly as it relates to large facilities, but it could certainly begin to address the largest Research Grant-related problem we have identified - the significant underfunding of even our best materials-related programs relative to what is needed to make them internationally competitive. Together with the adoption of the other recommendations, the increased level of funding would enable the GSC to better address these cost-of-research issues, to decouple dollars awarded from perceived degrees of excellence.

This would enhance our ability to mount programs in materials growth, modification, fabrication and analysis which focus on the important issues of our times, and which can still be competitive on the international stage. In this sense our recommendation ***is*** a programmatic one, not limited to predefined subfields, but rather to improving Canadian capabilities across the broad range of materials growth, modification and fabrication - wherever the excellent researchers are in place to put increased funding to good use.

Response to a 10% Decrease - If we are to be consistent in our recommendations, in the event of a 10% cut to the budget, we must urge the GSC to proceed exactly as the above philosophy would dictate. To do otherwise, to 'share the pain', will only result in a slow descent to a uniform level of irrelevance. By following our other recommendations, the GSC would already have eliminated all dubious grant applications - a 10% cut would therefore inevitably result in a number of excellent researchers and programs going unfunded. This is the real crux of the entire argument surrounding 'selectivity' - in the (we believe unlikely) event that the funding for research continues to decline, would we wish to maintain ~211 grants at a level which guarantees that increasingly more of them will become invisible in terms of international impact, or do we choose to fund a smaller number at a level which gives them a real chance at making significant contributions, and staking out a place in the international arena of science? To us, the choice, while difficult, is clear.

VI.3 Other Issues, Recommendations and Suggestions

Materials Networks - It is both remarkable and worrying that Materials Science, recognized everywhere as a critical enabling technology, is so scantly represented within the Federal Networks of Centres of Excellence programs. In fact, the only networks in Canada which feature any significant CMP presence in Materials Science are the result of the CIAR initiatives described in Section III, rather than any NCE-related program. The reasons for this are complex, but a major factor is related to the difficulty that physicists have also typically had in accessing the university-industry programs of NSERC, and even the Strategic Grants program. This has not resulted solely from a lack of effort on the part of physicists, nor from the absence of a significant role for physicists in modern, high technology industries (as evidenced by strong interactions elsewhere), but to a great extent is a result of the unusual situation in Canada regarding industrial appreciation of and investment in research.

There are reasons to believe that this is improving. We therefore recommend that NSERC recognize Materials Science and Engineering as a strategic enabling technology, in part through the appointment of the Materials Group Chair, and that it be receptive to efforts to establish Research Networks in areas of Advanced Materials under the Research Partnerships programs, or under any new NCE competition. The need for such networks goes well beyond a mere increase in funding, as follows from our analysis showing networking and collaboration as major factors driving the two success stories we have identified in CMP. It is also necessary that the CMP community redouble its efforts to forge meaningful links with industry, and that it form groupings to pursue all available opportunities, such as those represented by the Networks of Centres of Excellence and Research Networks programs.

Equipment Grants - There has been some concern expressed that Equipment Grant requests are not accorded the same level of careful deliberation as are the Research Grants. In particular, new researchers and those making major changes in direction often submit Research and Equipment Grant requests which are tightly coupled, in the sense of the equipment being necessary for the undertaking of the proposed research, yet the two requests may be adjudicated in an uncoupled manner. The CMP GSC has followed a clear and commendable strategy of coupling the equipment and operating requests for new applicants, as demonstrated by the 1995 results, which reveal an equipment grant success rate ($ awarded/$ requested) of 88% for new applicants who obtained a Research Grant in that competition, versus a budget-limited equipment grant success rate of only 28% for continuing researchers. Many other GSCs are not nearly so proactive as GSC28 in this regard, with equipment success rates for new applicants as low as 24% (NSERC analysis of 1995 competition results).

This does not address the second aspect, the adjudication of equipment grant requests tied to new grant proposals from continuing applicants, for which statistics are more difficult to obtain. Perhaps it would make more sense to modify at least part of the Equipment Grants program to a model closer to that practiced in the Strategic Grants, where needed equipment is requested in a coupled Strategic Equipment Grant Request. Funds would still have to be set aside for equipment requests coming in the middle of a grant cycle, in order to replace broken equipment, or to allow changes in research direction.

Support for Research at Smaller Universities - This was one of the specific issues to be addressed by the Review. We use here the phrase 'smaller universities' to cover a variety of situations which have in common an environment where it is perceived to be more difficult to pursue research than at a large, research-intensive university. To begin with, there is no direct link between small universities and excellence - excellent research can exist anywhere, and it should receive suitable support wherever it is located. Clearly, there is excellent research in CMP in some Canadian departments which fall into this category, and it should continue to be well supported. It is similarly true that dubious, low impact research can be found in large institutions, and that it should not be funded. We would not wish that an inability to achieve adequate selectivity on our own should lead, for example, to a system such as has been implemented in the UK, where entire departments are rated as to their suitability for funding. This issue also involves the question of geographic diversity in research, since these departments are often the only facilities where research takes place within their geographic vicinity.

As has been discussed above, the vast majority of responses to the Draft Review accepted that excellence and impact should be prerequisites for a grant no matter where the researcher is located, and we can accept this view with no further discussion. However, a distinction can be drawn between excellence and productivity, which can be adversely affected by a number of circumstances which tend to be found in these departments, such as a dearth (or absence) of graduate students, large teaching loads, and low levels of university infrastructure. Provided that excellence and impact is demonstrably present, the GSC is certainly justified in weighing the local circumstances in judging the research productivity. Indeed, these applications may have additional needs for funds, for travel and communication, for example, which are entirely valid and worthy of consideration. However, we reiterate that the admittedly valuable aspects of having as large a geographic diversity of research activities as possible cannot outweigh the requirement for demonstrated excellence, as mandated by the criteria for the Research Grants program. The peer-reviewed GSC process is in any case not well suited to weighing such non-scientific criteria, and if such geographic diversification is found to be needed, it would be best adjudicated through a separate program with different, but well-defined, criteria (We understand that the MRC does have a special program to assist researchers in these situations to link with industrial partners.).

Team Grants - It has often been noted that Team Research Grants, as opposed to individual ones, are not used nearly as frequently as would seem justified. While there are only a handful of such grants within GSC28, among them are several examples of how this approach can be used with considerable success. Increased selectivity and emphasis on excellence and impact, as proposed above, will likely drive an increase in the number of Team Grant applications. Of course a team proposal which lacks demonstrated (or clearly promised) excellence and impact should have as little chance of funding as an individual application with similar attributes. Still, by forming a team and focusing their efforts on a significant project, and perhaps also working with a wider group of collaborators, a group of researchers who individually lack the resources to meet the threshold for proven or expected impact and excellence may be able to reach a critical mass which makes these goals achievable.

Participation - It is crucial to emphasize the importance of membership and participation in the bodies which represent our interests to government and agencies such as NSERC. The CAP has lately done a superb job in putting forward the agenda of physics (and science and technology in general) to the federal government, in instituting the CAP/NSERC Liaison process, in fighting the closure of large facilities, etc. CAP is in fact the only organization which can represent us in this, and other, ways, and it seems self-evident that it would be beneficial for all CMP grantholders to be members of CAP, and its Division of Condensed Matter Physics, and to participate in their deliberations and operations.

The DCMP has the potential to be a strong representative for CMP in Canada, and can foster communication between its members, help organize wider initiatives such as networks, and participate in lobbying for new Materials Science Facilities. One small example is the mail-forwarding it already provides, which permits e-mail messages to be automatically copied to all members, by simply sending the message to the forwarding site. There is also no reason that the DCMP and CAP should not be involved in discussing and setting priorities within physics, although this is a role which CAP has not embraced in the past. The obvious consequence of an unwillingness to set priorities from within the community is having to live with priorities which are determined externally.

We therefore strongly encourage 100% participation of GSC28 grantholders in CAP and the DCMP. Increased membership immediately enhances CAP's credibility in representing the interests of physicists to the government and society, and improves the rather weak image of physics as a discipline which is not organized enough to know what it wants and where it is going.

VII ISSUES FOR ASSESSMENT

For completeness, we provide here a concise summary of issues, in the form of claims or statements, on which we would wish to have the comments of the Assessors, in addition of course to their detailed analysis of the data and recommendations contained in the previous sections.

Excellence

- The group and individual efforts highlighted here are excellent by international standards.
- These same efforts enjoy appropriately high levels of international impact and visibility.
- Relative to its comparatively modest expenditures, Canada receives an excellent return from CMP, both in terms of the actual quality and impact of the research being done, as well as in the training of highly qualified personnel, having skills valuable to the economy.

Dynamics

-The Canadian CMP effort is representative of international trends in CMP research, and is successful in developing and adequately supporting important new areas, and in de-emphasizing mature fields where the scientific and/or economic justification has diminished.

Funding

-CMP research in Canada is funded at an inadequate level in comparison with other industrialized economies, particularly when one takes into account the wide range of Materials Science research which is supported under the CMP umbrella in Canada, and the lack of alternate funding sources.

- The present Research Grants Program does not fund even the best Canadian experimental programs at an internationally competitive level.

-The allocation of available Research Grant funding is skewed to the detriment of CMP, as compared to funding patterns elsewhere.

-The absence of any large facilities dedicated to Materials Science, as seen in the ‘parasitic’ mode of operation of neutron scattering and MuSR research in Canada, and the absence of a synchrotron source, is unusual for an economy of the size and sophistication of Canada’s. This is indicative of the historically low emphasis placed on research in Materials Science in Canada, which needs rethinking.

-The increasing difficulty of obtaining infrastructure support even for existing facilities, let alone new ones, results in lost opportunities and underutilization, and will inevitably hamper Canada’s ability to pursue forefront, internationally competitive research in Materials Science .

NSERC

-The existing NSERC Research Grants Program has served Canada well, and the continuity of funding for excellent researchers, together with the relatively streamlined application procedures, are positive aspects worth retaining.

- Still, by its very nature this scheme tends to result in a relatively static, or at best incremental funding scenario, and is not particularly well suited to the redirection of shrinking (or growing) resources.

Selectivity

- It is clear that the CMP GSC has increasingly supported excellence, but that it has not succeeded in providing competitive levels of research funding for many forefront experimental efforts.
- In considering the entirety of the research efforts supported by the CMP GSC, it is also clear that excellence and impact on an international level have not been the sole criteria for funding, and that some degree of increased selectivity is both possible and desirable.

Interdisciplinarity

- The Canadian CMP community and GSC28 has a strong record of recognizing and supporting excellence in areas of truly interdisciplinary research, and is correct in identifying the future of CMP research as being significantly tied to the timely inclusion of new areas of interest, where the tools and approaches of physics can make significant contributions.

APPENDIX 1

Summary of the Questionnaire Results

The following summary is organized in the same order as the original questionnaire. Except for the very first item, all of the information below contains data only on those who responded to the questionnaire. Detailed responses are not given where these are already dealt with in the main document.

Subfields - The questionnaire began with a check list of subfields, and the respondents were requested to check **all** which were appropriate. Since only about one half of the GSC28 grantholders responded, this information has been supplemented by placing each of the nonresponding grantholders into the most appropriate **single** subfield, which accounts for the numbers in brackets. For grouping these nonresponding researchers we **did not** use the Materials Science subfield, as this would have been too broad.

Subfield	No. Experiment	No. Theory
Materials Science	37	10
Surface science	14 (8)	7 (10)
Biophysics	11 (2)	7 (1)
Soft Materials	10 (5)	10 (2)
Pattern Formation	6	2
Magnetic	26 (11)	9 (2)
Electronic	24 (10)	7 (7)
Phase Transitions	24 (5)	13 (5)
Semiconductors	18 (10)	4 (1)
Photonic Materials	7	2
Neutron diffraction	11 (3)	1
X-ray and Synchrotron	10 (3)	
Materials Growth	13 (5)	
Materials Modification	9 (1)	
Materials Characterization	28 (9)	
Computational Materials Science	2	11 (6)
Superconductivity (normal)	6 (2)	1 (1)
Superconductivity (high T_c)	13 (8)	6 (2)
Mesoscopic	6 (3)	3 (5)
Highly Correlated Electron	9 (2)	6 (3)

Funding - The average Research Grant funding of the experimental respondents was $33,100 and of the theorists $33,800, or somewhat above the average levels in GSC28.

36% of experimentalists and 25% of theorists had other sources of NSERC funding (excluding equipment grants).

Just over half of both the experimentalists and theorists had funding sources other than NSERC.

Productivity - In total numbers of published papers, and papers over the previous five years, there was little difference between experiment and theory. There was a difference between grants over/under $30K (roughly the average grant) of about a factor of 1.4 for total papers and 1.6 for recent papers.

Awards etc. - In the categories of awards, honors and invited papers, there was again little difference between theorists and experimentalists and a larger difference (greater than a factor of two) between those over/under $30K.

Collaborative Projects - Over 90% of the respondents reported some involvement in collaborative projects, with little difference between theory and experiment, or between funding levels. Many examples of cross-GSC initiatives were reported.

University Infrastructure - This was almost unanimously seen as an essential support for the research effort, and at the same time as something which was under constant pressure, and eroding to a dangerous extent.

Central facilities - 55% of experimentalists and 30% of theorists reported a reliance on or need for central facilities, with synchrotron and neutron scattering facilities being the most common, followed by centralized computing resources, and materials growth and fabrication facilities.

Computing - 22% of experimentalists and 75% of theorists indicated that the availability of large-scale computing facilities would be beneficial. A number of theorists stated that it was increasingly difficult for them to remain competitive with colleagues elsewhere who had access to computing resources which were far superior to those currently available for academic research in Canada.

Doubled/Halved Grant - The response to the questions on the impact of doubling or halving the respondents Research Grant focused mostly on manpower issues, with a doubled grant resulting in more PDF's, grad students, etc., and therefore higher productivity. Some also described new initiatives which could be pursued with increased funding. Most thought that they would be subcritical with a 50% cut, and questioned whether they could go on, but a minority thought that they could proceed as before but with much lower productivity.

Strengths - As noted in Section III, there was consistent recognition of biomembranes (together with soft matter in general), and high T_c as Canadian areas of strength in CMP. Cosmology and the Sudbury Neutrino Observatory (SNO) were also mentioned by a number of respondents. Quite a few responses also singled out the NSERC Research Grants themselves as a strength, especially their continuity, and the focus on past performance rather than a particular project, together with the relatively painless application procedure.

Weaknesses - In CMP, isolation and lack of critical mass were frequently referred to as causes of weakness. Areas which were referred to as weak, in terms of not being as intensively pursued as they should be, were nanofabrication, porous media, and materials growth.

Focus - Almost 60% of both experimentalists and theorists thought that there should be areas of focus for Canadian research in CMP. Suggestions tended to be rather broad, with some examples coming from areas which were seen to have been underdeveloped in the past, such as nanomaterials and nanofabrication, while others sought to build on areas of perceived strength, such as soft materials or biomaterials. There was a fairly consistent dissenting opinion that it was better not to micromanage research, and to instead stick to funding excellent **individuals**, and let the areas sort themselves out.

Selectivity - 36% felt that the GSC should in future become more selective, while 60% felt it should stay about the same, and only 4% thought it should be less selective (all 3 votes for lower selectivity coming from experimentalists). Of those below $30K the numbers were 18%, 76% and 6%, respectively, while for those over $30K they were 52%, 45% and 3%. It is interesting that among those opposing increased selectivity, some felt that past increases in selectivity had hurt the more applied research efforts, while others had exactly the opposite opinion. The need to support the best efforts at internationally competitive levels was often given as a reason for increased selectivity.

Geographical - When asked whether special considerations should be given to geographical issues such as regional representation (of grants, not of committee members), the overall vote was 41% for and 59% against, with a strong divergence between those over/under $30K, with 57%/34% in voting yes. Opinions ranged from "yes, it's the Canadian way" to many stressing that excellence should be the **only** criterion for funding. Those in support of special geographic considerations most often stressed the need to keep research alive at institutions which had over time generated many of the excellent undergrads and grad students who had gone on to excel elsewhere in the system.

Smaller universities - On the issue of whether any special considerations should apply to grant applications from smaller universities, 51% thought yes vs. 43% no, with 6% of equivocal responses. Of the four subgroupings, only the experimentalists had a small preponderance of no votes. Those supporting special considerations for smaller universities emphasized the importance of exposing students everywhere to the excitement of research, and the positive effect this had on the overall research effort. Others suggested that a new source of funding, with a different set of priorities, may have to be found in order to support research in smaller universities. The range of detailed responses reflected the ambiguity of the question - 'special considerations' were taken to mean anything from lower standards on the excellence of the research, through lower expectations on productivity, to special considerations regarding the need for extra travel funding.

Minimum Grant - On the question of whether there should be a minimum grant level, 71% said yes, 24% no, and 5% were equivocal. Of those supporting the concept, suggested minimum useful grants ranged from a low of $10,000 for theorists up to $40,000 for experimentalists. There was a surprisingly strong sentiment that grants under $10,000 accomplished essentially nothing. Those against the idea argued that any amount, no matter how small, could have a positive impact under the right circumstances.

Maximum Grant - Here the response was 37% for and 49% against setting a maximum grant level, with 14% of equivocal responses. Those against this concept thought that such questions were best dealt with by the GSC. One of the arguments used in support of a maximum grant level was that highly supported researchers should be able to find additional funding elsewhere.

Startups - There was a very uniform response, with 71% feeling that startup grant levels had been about right, and 27% voting for an increase in future. There was virtually no input suggesting a decrease in startup support. Several observed that while the support for actual startups (first awards) was quite good, the real problem was how slowly even outstanding researchers could ramp up their support to (relatively) appropriate levels **after** the startup.

Equipment Grants - There were indications of problems with the adjudication of equipment grants, with 20% thinking they were handled well vs. 69% saying there were problems, and 11% major problems.

Geographical Considerations for Research Partnerships - Most respondents thought that NSERC should not, or could not, compensate for the unequal geographic distribution of potential partners (industries) which can pose an impediment to participation in the Research Partnerships Programs, without reducing the quality and justification of the program. The partnerships must first make sense for both partners - they cannot be artificially stimulated. Others questioned whether geographical separation was really relevant in the modern age. There was a general sentiment that **all** of CMP could benefit by a better brokering of problems and capabilities between university and industry.

Should NSERC take a direct role in promoting the following? (yes %) -

risk taking -	70%	(most thought that the present Research Grants already performed this function)
spin offs -	44%	(many misgivings about NSERC losing its focus on **research**)
communication -	73%	(recognized as important; many hoped for an NSERC organizing role)
interdisciplinary research -	53%	(doubts expressed as to whether real, worthwhile interdisciplinary collaborations can be artificially created or accelerated)

Major Initiative - 68% thought that the health of CMP research in Canada could be enhanced by a major initiative, often based on a large, multidisciplinary facility, such as the Canadian Light Source.

Applied Research - Most thought that there were no major problems in CMP in recognizing and supporting excellence anywhere along the fundamental-applied continuum, but a small minority of opinions thought that one or the other side was getting short shrift at present. There was some concern that NSERC might go too far in supporting actual product development, as opposed to research. Many were troubled that while there was only one source of support (Research Grants) for fundamental research (which support applied research as well), there were many additional programs available only to applied researchers. Beyond this, there was the worry that by requiring Canadian industrial support, the definition of 'applied' tended to have too short a time frame, with no means of encouraging longer term, more fundamental studies in areas of clear strategic importance for the future.

Vision for the Future - The most common response was a further recognition of the importance of Materials Science and interdisciplinary research.

Teaching - There was almost uniform agreement that active participation in research improved the quality of undergraduate teaching.

Graduate Student Involvement in Industrial Projects - Most of the responses openly admitted to being based on opinion, rather than experience. The majority felt that direct involvement of graduate students with industrial projects could be very positive, if properly supervised, but a minority felt that there was simply too much of a mismatch in objectives and time scales for this to work.

Training - The data collected on manpower training issues is summarized in the following table, where the first two rows are averages per investigator over the past five years, and the last five rows over the past six years:

	Exper.	Theory	< $30K	> $30K
Number of MSc graduates	2.5	1.7	1.7	2.8
Number of PhD graduates	1.6	1.4	1.2	1.9
Permanently employed in related industrial position	1.6	1.5	1.1	2.1
Permanently employed in related academic position	0.6	0.8	0.3	1.1
Permanently employed in unrelated position	0.2	0.2	0.2	0.2
Continuing education (includes PDF's and RA's)	1.9	3.3	1.8	2.7
Whereabouts unknown	0.3	0.1	0.1	0.4

Questions from the CMP supplement (fewer responses than for the questionnaire)

GSC structure - On the question of whether the reorganization of the GSC structure along the lines of a group of GSCs dealing with Materials Science and Engineering made sense for CMP researchers, 25% thought it was a very good idea, 50% thought it was a good idea, 5% were neutral and 20% thought it would be a negative move. Experimentalists were on average more comfortable with this idea than were theorists, who worried about whether they would be seen to 'fit in' to such a grouping, particularly since the influence of physicists on the new GSCs would be diluted. There was also concern that over time the importance of fundamental materials research would diminish with respect to engineering and development work.

10% increase - In the event of a 10% increase (from Reallocation), 7% thought it should go to the highest funded researchers, 31% thought it should be applied across the board, 14% thought it should go to the smaller grants, 31% to startups and newer researchers, and 17% to new initiatives.

10% decrease - In the event of a 10% decrease in overall funding for GSC28, 23% each opted for taking the money either from the highest funded researchers or from an across-the-board cut, while 4% thought it should come from the startup budget, and 50% thought that it should come from applying higher selectivity to any 'marginal' cases.

GSC memory - 72% thought that the memory of the GSC, or the time period over which it evaluates past performance, was about right, while 24% thought that it was too long (mostly from the >$30K group), and 4% thought that it was too short.

Grant spread vs. impact - 44% felt that the spread in granting level was roughly appropriate, given the spread in impact of the supported programs, with the rest divided almost equally between the funding spread being either exaggerated or too small

Appendix 2

NSERC Funding for CMP Research

(a) GSC28 Research Grants

Researcher		University	Project Title	Year n of m	Amount ($/yr)
AFFLECK	IK	UBC	Physics of strongly correlated electrons	3-4	75000
ALTOUNIAN	Z	McGill	Metastable structures	1-5	28000
AMM	DT	Queen's	Organic and inorganic thin films: fabrication and characterization	3-3	24000
ANDERSON	A	Waterloo	Studies of intermolecular forces by spectroscopic techniques	1-4	23000
ARMSTRONG	RL	NB	Magnetic resonance in condensed matter systems	3-3	58000
ARROTT	AS	SFU	Phenomenology of ferromagnetism	2-2	57700
AUBIN	M	Sherbrooke	Supraconducteurs haute température et semiconducteurs	4-4	24000
AZIZ	RA	Waterloo	Properties of substances at low temperatures	2-4	7700
BEAMISH	JR	Alberta	Phase transitions in porous media	3-4	34500
BECHHOEFER	JL	SFU	Equilibrium and nonequilibrium studies of interfaces in soft-condensed matter	3-4	35000
BEERENS	J	Sherbrooke	Magnéto-optique et magnétotransport dans des matériaux et structures à dimensionalité réduite	3-4	20000
BENNETT	JC	Acadia	Transmission electron microscopic investigation of modulated crystal structure in charge-density wave compounds and laser-processed nickel aluminum bronze alloys	1-4	13000
BERGERSEN	B	UBC	Applications of statistical physics	2-2	21200
BERLINSKY	AJ	McMaster	High temperature superconductivity and frustrated antiferromagnetism	4-4	40000
BETTS	DD	Dalhousie	Theoretical studies of quantum spin systems and highly correlated electron systems at zero temperature	2-4	9600
BLACKBURN	JA	Wilfrid Laurier	Superconducting weak links / chaos / instrumentation	4-4	22500
BLACKFORD	BL	Dalhousie	Scanning tunneling microscopy and scanning force microscopy	4-4	13000
BLOOM	M	UBC	Nuclear magnetic resonance studies with applications to membranes	4-4	84000
BOAL	DH	SFU	Mechanical properties of biomembranes	4-4	33500
BOLOGNESI	CR	SFU	InAs - based heterostructures and quantum wells for ultrafast electronic devices	2-4	26000
BONN	DA	UBC	Microwave studies of superconductors	2-4	34000
BOSE	SK	Brock	"Electronic structure related studies of quasicrystals, disordered alloys, metallic glasses, and liquid metals"	2-4	15400
BOSE team with GOYETTE	TK J	Trois-Rivières	Etudes diélectriques des mélanges de gas non-polaires et des liquides binaires critiques	3-3	18000

BOURBONNAIS	C	Sherbrooke	Propriétés électroniques et structurales des conducteurs de basse dimensionalité	1-5	35000
BREBNER	JL	Montréal	Electronic states in semiconductor heterostructures and in silica	4-4	30221
BREWER	JH	UBC/ TRIUMF	Muon spin rotation/relaxation/resonance in solids	4-4	75000
BRODIE	DE	Waterloo	Crystalline and amorphous semiconducting films	1-2	15000
CAILLE	A	Sherbrooke	Phases modulées de la matière condensée	4-4	33000
CARBOTTE	JP	McMaster	Studies in superconductivity	2-4	57700
CARLONE	C	Sherbrooke	Les défauts ponctuels dans l'arséniure de gallium	3-4	18000
CAROLAN	JF	UBC	Physical properties of anisotropic materials especially superconductors	3-3	11000
CARON	LG	Sherbrooke	Propriétés électroniques des solides	4-4	25000
CHARBONNEAU	S	Ottawa	Optical characterization of self-assembled quantum dots	1-4	10000
CHEEKE	D	Concordia	Physics of acoustic devices	2-4	36600
CHEN	ZY	Waterloo	Statistical mechanics of polymers	1-4	27000
CLAYMAN	BP	SFU	Infrared properties of condensed matter	2-4	14400
COCHRAN	JF	SFU	Magnetic excitations in ferromagnetic metals	1-3	25000
COCHRANE	RW	Montréal	"Structural, electrical and magnetic properties of thin films and multilayers"	3-4	38000
CODE	RF	Toronto	Low signal F nmr studies of condensed matter	1-2	14000
COLBOW	K	SFU	Hydrogen storage and selective hydrogen gas sensors from layerstructure materials	3-4	18000
COLLINS	MF	McMaster	Scattering of neutrons from condensed matter	1-4	43000
CORBETT	JM	Waterloo	Electron microscopy and diffraction of crystalline materials	1-4	18000
COTTAM	MG	UWO	Theory of surface excitations in solids	3-4	32000
CROZIER	ED	SFU	Spectroscopy and structural determinations of ordered and disordered systems	3-4	37000
CURRIE	JF	École Poly.	"Thin film electronic, photonic, and mechanical device, design, fabrication, and physical characterization"	4-4	30623
CURZON	AE	SFU	Studies in the science of materials using electron microscopes and energy dispersive x-ray analysers	2-2	9600
DAHN	DC	PEI	Scanning probe microscopy: techniques for biological applications	1-4	12000
DAHN	JR	SFU	Physics and chemistry of materials for energy storage	3-4	44000
DANNEFAER team with KERR	S DP	Winnipeg	Positron studies of defects in semiconductors	3-3	40000
DATARS	WR	McMaster	Cyclotron resonance in solids	1-4	56000
DAVIES	JA	McMaster	"Ion beam analysis, channeling and radiation effects"	1-5	30000
DAVISON	SG	Waterloo	Quantum theory of solid surfaces	4-5	25000
DEBELL	K	Trent	Properties of thin metal films	1-4	17000
DEBRUYN	JR	Memorial	Patterns and complex dynamics in nonequilibrium systems	2-4	35600
DENES	GY	Concordia	Fluoride ion conductors and other materials	2-4	12500
DESAI	RC	Toronto	Statistical physics of condensed matter	2-5	44300

DESGRENIERS	S	Ottawa	Structural and lattice dynamics experimental studies of very dense solids	3-4	20000
DIORIO	M	Ottawa	Beyond single-particle conduction in simple microstructures	1-4	10000
DIXON	AE	Waterloo	Confocal scanning laser imaging: development of instrumentation and applications	2-2	26000
DONG	RY	Brandon	Nuclear magnetic resonance of liquid crystals	3-4	32000
DUNLAP	RA	Dalhousie	"Magnetic, electrical and structural properties of metals and ceramics"	3-3	24000
DUTCHER	JR	Guelph	Elastic and magnetic properties of thin films and surfaces	3-4	30000
EGELSTAFF	PA	Guelph	Structure and dynamics of amorphous and fluid materials	1-4	25000
EGERTON	RF	Alberta	"Synthesis, electron microscopy and electrical characterization of thin films"	3-4	32000
ELDRIDGE	JE	UBC	"Infrared studies of a variety of superconductors in a magnetic field, along with infrared and Raman studies of quantum-well structures and organic conductors"	1-4	32000
FAWCETT	E	Toronto	Magnetic properties of itinerant antiferromagnetic systems	1-3	11000
FLETCHER	R	Queen's	Transport properties of various 3D and reduced dimensionality systems	1-5	35000
FORTIN	E	Ottawa	Research in semiconductor physics	3-5	36000
FRANCK	JP	Alberta	Investigation of basic properties and mechanisms of high temperature superconductors	1-4	36000
FREEMAN	MR	Alberta	Picosecond dynamics of magnetic systems	2-4	45000
FRINDT	RF	SFU	Formation and properties of novel layered structures	3-4	40000
GALLAGHER	MC	Lakehead	Scanning tunneling microscopy and surface physics of metal oxides	1-1	12000
GAULIN	BD	McMaster	Neutron and x-ray scattering studies of materials and their phase transitions	2-4	38500
GELDART	DJ	Dalhousie	"Density functional theory, critical phenomena and disordered systems"	1-4	30000
GLEESON	JT	Calgary	Non-equilibrium dynamics in complex fluids	3-3	24000
GOODING	RJ	Queen's	"Theory of (i) moderately doped high Tc superconductors, and (ii) complex elastic systems"	2-5	36600
GOODMAN	FO	Waterloo	Theory of surface interactions	1-4	8000
GORTEL	ZW	Alberta	Dynamical processes at surfaces and properties of two dimensional systems	1-4	25000
GRANT	M	McGill	Formation of structure and patterns in nonequilibrium systems	1-4	65000
GRIFFIN	A	Toronto	"Dynamics of Cooper pair fluctuations in the cuprates, and atomic Bose gases near the superfluid transition"	2-4	30800
GRUTTER	PH	McGill	Scanning probe microscopy	3-3	30000
GUO	H	McGill	Theoretical investigation of device and material related physics	3-3	30000
HALLETT	RF	Guelph	Light and neutron scattering from vesicle systems	4-4	27000

HAMEL LA	Montréal	Formation du signal dans les détecteurs semiconducteurs	2-2	11500
HARDY WN	UBC	High temperature superconductors	2-4	101000
HARRIS R	McGill	Numerical and analytical studies in condensed matter physics	1-4	21000
HARRISON JP	Queen's	Quantum fluids and flux dynamics in high Tc superconductors	3-4	52000
HAWTON MH	Lakehead	Photon-matter interactions/physics of adsorbed water	1-4	13000
HEINRICH BV	SFU	Molecular beam epitaxy of 3d transition metals	2-4	57700
HIRD B	Ottawa	Surface structure investigations by medium energy ion scattering. Multicharged ion production in surface scattering	3-4	19000
HUNTLEY DJ	SFU	Luminescence dating	4-4	41000
IRWIN JC	SFU	Raman scattering studies of high temperature superconductors and related materials	2-4	35600
JACKMAN TE	McMaster	Processing of semiconductor of reduced dimensions	2-4	9600
JACOBS AE	Toronto	Theory of ferroelastics; theory of the Hubbard model	4-4	23000
JAN N team with HUNTER DL	St. Francis Xavier	Critical complexity	2-4	30800
JANDL S	Sherbrooke	Propriétés optiques des oxydes ferroélectriques et supraconducteurs	3-4	30000
JEFFREY KR	Guelph	"Studies of molecular conformation, structure and dynamics in soft condensed matter: biomembranes, polymers and glasses"	1-4	28000
JERICHO MH	Dalhousie	"Scanning tunneling and atomic force microscopy, phase transitions"	4-4	44000
JOHN S	Toronto	Novel properties of disordered and quantum many-body systems	2-4	46200
JOOS B	Ottawa	Structural properties of adsorbed films and interfaces	4-4	24000
JUNG JA	Alberta	Josephson junction network in high temperature superconductors	3-3	25000
KALLIN C	McMaster	Strongly correlated electron systems	4-4	41000
KEELER WJ	Lakehead	Optical spectroscopy of semiconductor heterostructures and heterogeneous materials	3-4	14500
KIEFL RF	UBC/ TRIUMF	Application of Muon spin rotation to condensed matter	2-4	72200
KIEFTE H team with CLOUTER MJ	Memorial	Light scattering studies of phase transitions and simple molecular systems	5-5	92000
KIRCZENOW G	SFU	Theory of electrons in small systems	1-4	49000
KOS JF	Regina	Electron transport in metals at low temperatures	3-3	5000
KREUZER HJ	Dalhousie	Surface and interface dynamics	3-4	37000
LAMARCHE G	Ottawa	Properties of magnetic materials	1-4	6000
LAU LW	UWO	Ion scattering studies of surface reactions with low energy (1-100ev) ions	2-4	30800
LEBLANC MA	Ottawa	"Classical and high T, superconductors, AC losses, flux cutting and vortex motion phenomena"	1-4	28000

LEE	MJ	Toronto	Electronic states of metals and metal-vacuum interfaces	1-4	27000
LENNARD	WN	UWO	Interaction of charged particles with condensed media/surfaces	1-5	30000
LEONELLI	R	Montréal	"Résonances excitoniques dans les hétérostructures du type (In, Ga) (As, P)"	3-3	25000
LEPINE	Y	Montréal	"Propriétés électroniques des matériaux polaires: défauts, interfaces et polarons"	4-4	17000
LEWIS	LJ	Montréal	"Propriétés statiques et dynamiques de systèmes de symétrie réduite: surfaces, interfaces, défauts et matériaux désordonnés"	1-4	31000
LOOKMAN	T	UWO	"Dynamics of polymers, interfaces and multi-component fluids using lattice gas methods"	3-3	20000
LOSS	D	SFU	Theory of mesoscopic systems	1-4	31000
MARSIGLIO	FJ	McMaster	Electron-electron and electron-phonon interactions in strongly correlated systems	1-4	10000
MARTINU	L	École Poly.	Optical and mechanical properties of plasma deposited multilayer structures	3-3	26000
MASCHER	P	McMaster	Defect characteristics of electronic and electrophotonic materials	1-4	24500
MASON	TE	Toronto	Magnetic properties of highly correlated electron systems	1-4	50000
MASUT	RA	École Poly.	Properties and fabrication of quantum-confined semiconductor structures	3-3	35000
MCGREER	KA	Manitoba	Disordered superconducting thin films	1-4	28000
MCLEAN	AB	Queen's	Photoemission studies of semiconductor surfaces and interfaces	1-4	41000
MEUNIER	M	École Poly.	Dépôt de couches minces stimulés par photons ultraviolets	2-4	28900
MISRA	SK	Concordia	Epr and endor investigations of paramagnetic ions in single crystals and amorphous materials	4-4	23000
MITCHELL	IV	UWO	Fast ion solid interactions in single crystals	3-4	40000
MITROVIC	B	Brock	"Localization and superconductivity, transport properties of strongly correlated systems"	4-4	21000
MOHAMED	MA	UNBC	Magnetic flux motion and related phenomena in the high Tc superconductors	3-3	10000
MORRIS	D	Sherbrooke	Photoluminescence résolue en temps à l'échelle femtoseconde dans des nanostructures III-V	3-3	25000
MORRIS	SW	Toronto	Pattern formation in nonequilibrium systems	1-3	25000
MORRISH	AH	Manitoba	New magnetic materials	2-4	38500
MORROW	MR	Memorial	Lipid bilayer phase behavior and organization at ambient and high pressure	2-4	27900
NAGI	AD	Waterloo	1) Study of Hubbard and t-j models; 2) Normal-state properties of high-temperature superconductors	3-3	20000
ORD	GN	UWO	Quantum propagators and critical interfaces	3-3	5000
PAGE	JH	Manitoba	Propagation and localization of acoustic waves in strongly disordered media	2-2	28900
PARANJAPE	VV	Lakehead	Research in solid state physics	1-4	8000
PARSONS	RR	UBC	Optical multilayer coatings	3-3	18000

PATHRIA RK	Waterloo	(I)Phase transitions in finite systems; (II) Optimization of thermodynamic processes	1-4	10000
PEEMOELLER H	Waterloo	Nuclear magnetic resonance studies of disordered systems	3-4	20000
PERZ JM	Toronto	Electronic properties of conducting solids	3-3	16000
PIERCY P	Ottawa	Surface structure and dynamics	3-3	25000
PINK DA	St. Francis	"Theoretical studies of model and biomembranes, gels, and related systems"	6-6	41900
PINTAR MM	Waterloo	Nuclear spin relaxation in condensed matter	3-4	48000
PLISCHKE M	SFU	"Theory of fluctuating interfaces, membranes and inhomogeneous liquids"	4-4	36000
POIRIER M	Sherbrooke	Matériaux exotiques à dimensionalité réduite: propriétés hyperfréquences et élastiques	3-4	32000
POOLE PH	UWO	Computer simulations of complex fluids and amorphous materials	1-4	20000
PRESTON JS	McMaster	"Growth, characterization and application of high temperature superconducting films"	1-4	40000
PRINCE RH	York	Thin film production using pulsed laser deposition (pld)	1-4	22000
RANCOURT DG	Ottawa	"Mossbauer spectroscopy methodology, synthetic and meteoritic Fe-Ni alloys, and crystal chemistry and 2D magnetism in layer silicates"	2-4	28900
RAZAVI FS	Brock	"Pressure dependence of magnetic properties and specific heat measurements of single crystals of UPd2Si2, UNi2Si2 and UNi2Ge2"	3-4	25000
ROORDA S	Montréal	Materials modification by MeV ion implantation	2-4	33700
ROSHKO RM	Manitoba	SQUID studies of ultra-slow dynamics and quantum tunneling in glassy magnetic materials	3-3	22000
ROTH AP	Ottawa	Growth and characterization of semiconductor quantum wires and dots	2-4	9600
RYAN DH	McGill	Mossbauer studies of magnetic order in the presence of competing interactions	2-4	28900
SACHRAJDA AS	Sherbrooke	Fluctuations in mesoscopic systems	2-4	8000
SAYER M	Queen's	Functional coatings and bacteriocidal surfaces	3-4	41000
SEARS WM	Lakehead	The electrical properties of the surface-gas interface of wide band gap semiconductors	3-3	11000
SENECHAL D	Sherbrooke	Magnétisme quantique et électrons fortement corrélés	1-4	20000
SHAM TK	UWO	"Electronic structure of bimetallic, semiconductor and metal silicide materials and synchrotron radiation"	2-4	43300
SHEGELSKI MR	UNBC	Theory of the low energy electron point source microscope	1-3	10000
SHUKLA RC	Brock	"Thermodynamic, transport and anharmonic properties of solids"	2-4	9600
SIMPSON PJ	UWO	Variable energy positron studies of thin films, surfaces and interfaces	3-3	10000
SINGH M	UWO	Quantum transport and optical properties of low dimensional semiconductors and high temperature superconductors	2-4	25000
SINGH MA	Queen's	Experimental study of non-equilibrium dynamics in polymer materials	1-3	26000

SIPE	JE	Toronto	Theoretical physics of quantum and nonlinear optics	1-5	44000
SLAVIN	AJ	Trent	"Growth modes of ultrathin metal films, and oxidation of these films"	3-5	29000
SONG	AK	Ottawa	Theory of atomic processes induced by electronic excitation in insulating materials	1-4	20000
SOUTHERN	BW	Manitoba	Theoretical studies in condensed matter physics 1) disordered systems 2) excitations in quantum spin systems	4-4	33000
STADNIK	ZM	Ottawa	Electronic structure and magnetism of quasicrystals and their approximants	3-4	25000
STAMP	PC	UBC	Quantum coherence in superconductors and magnets	3-3	30000
ST. ARNAUD	JM	Trois-Rivières	Détermination de la densité d'un gaz à partir de la mesure de la constante diélectrique	3-3	9000
STATT	BW	Toronto	NMR of high temperature superconductors	3-4	26000
STEINITZ	MO	St. Francis	Experimental studies in solid state physics	1-5	22000
STERNIN	E	Brock	Magnetic resonance and relaxation study of structure and motion in model membranes and non-bilayer phases of lipids	2-3	24100
STEVENS	JR	Guelph	The study of molecular relaxations and ionic conduction in polymer-salt electrolytes with industrial applications	2-4	30800
STOTT	MJ	Queen's	Theoretical studies of the electronic structure and energetics of condensed matter	4-4	27000
STROINK	G	Dalhousie	Magnetic and electronic properties of alloys: imaging current distributions	4-4	23000
STROMOLSEN	JO	McGill	Metastable and disordered alloys: properties and applications	3-5	60000
SULLIVAN	DE	Guelph	Statistical mechanics of complex liquids	3-4	30500
SULSTON	KW	PEI	Theory of ion atom interactions with solid surfaces	2-4	10600
SUTTON	DM	McGill	X-ray diffraction studies of materials	3-4	43000
TAILLEFER	L	McGill	Unconventional superconductivity in heavy fermion and high T_c compounds	2-4	57700
TAYLOR	DR	Queen's	Structural phase transitions: random field effects and domain properties	4-4	24000
THEWALT	MLW	SFU	Optical studies of semiconductors and other condensed matter systems	2-4	75000
TIEDJE	T	UBC	"Semiconductor surfaces, interfaces and devices"	1-4	82000
TIMUSK	T	McMaster	Infrared properties of exotic conductors	2-4	75000
TINDALL	DA	Dalhousie	Neutron scattering and thermal expansion in the rare earths	1-4	9000
TONG	BY	UWO	Silicon thin films and optical band gap materials	3-4	22000
TORRIE	BH	Waterloo	"Raman, infrared and neutron scattering studies of the structures and lattice dynamics of molecular crystals"	3-4	15000
TREMBLAY	AS	Sherbrooke	Supraconductivité à haute température et électrons fortement corélés	3-5	60000
TURRELL	BG	UBC	Superheated superconducting granule detector and studies and magnetic materials	3-4	24000
VAIL	JM	Manitoba	Theory and simulation of point defects in crystalline materials	1-5	17000
VANDRIEL	HM	Toronto	Coherent control and nonlinear optics in solids	1-5	77000

VASILOPOULOS	P	Concordia	"Coulomb correlations, (non) local effects, and ballistic transport in low-dimensional systems"	2-4	26900
VENUS	DE	McMaster	Spin-polarized electron spectroscopy of magnetic and non-magnetic surfaces	3-3	30000
VOVAN team with BADER GIROUARD	T G FE	Moncton	Propriétés optiques et électriques des matériaux et couches minces	3-5	30000
WALKER	MB	Toronto	Theory of phase transitions in solids	4-5	48000
WALTON	D	McMaster	Relaxation in disordered systems	1-2	20000
WATKINS	SP	SFU	Growth and characterization of compound semiconductors	2-4	25000
WHITEHEAD	JP	Memorial	"Layered structures in superconductivity, magnetism and biophysics"	3-4	16000
WHITMORE	MD	Memorial	Theory of mesophase behavior in macromolecular blends	3-4	22000
WILLIAMS	G	Manitoba	Magnetoresistance in disordered conductors; orbital effects and giant anomalies	3-4	39000
WILLIAMS	PJ	Acadia	Thin film studies with a scanning tunneling microscope	3-3	10000
WINTLE	HJ	Queen's	Carrier transport effects in insulators	4-4	18500
WORTIS	M	SFU	"Statistical physics of interfaces, membranes, and other condensed matter systems"	6-6	50000
YELON	A	École Poly.	Studies of thin film surfaces and interfaces	3-4	30000
YOUNG	JF	UBC	Optical spectroscopy of nanostructures	4-5	44000
ZAREMBA	E	Queen's	"Theory of mesoscopic systems, surface physics and electronic excitations in solids"	3-4	30000
ZINKE-ALLMANG	MT	UWO	Kinetic processes and self-similar behavior at semiconductor interfaces	3-3	32000
ZUCKERMANN	MJ	McGill	Theoretical studies of structured fluids and polymer systems: numerical simulation in statistical physics	1-4	46000

(b) Women's Faculty Award (WFA) Grants Associated with CMP Research

COUGHLIN	KM	Montréal	Understanding and Modeling Transitional Flows	1-1	22,600
FRISKEN	BJ	SFU	Structure and Dynamics of Soft Condensed Matter	2-4	28,900
LAGOWSKI	JB	Memorial	Molecular Modeling and Dynamic Simulation of Polymers	2-4	26,000
NICOL	EJ	Guelph	Theoretical Investigations of Non Equilibrium and Inhomogeneous Superconductors	3-3	30,000
REEDYK	M	Brock	Very Far Infrared Properties of Exotic Low Tc Materials	3-3	29,000

(c) Major Facilities Access Grants Supporting CMP Research

Principal Investigator	Institution	No. CMP Invest./ Total No. Invest.	Title	Funding ($/yr)
Bancroft GM	Western	4/22	Canadian Synchrotron Radiation Facility	230,000
Berlinsky AJ	McMaster	10/20	Brockhouse Institute for Materials Research	100,000
Brebner JL	U. de Montréal	9/17	Laboratories de Recherche des Couches Minces	157,000
Brewer JH	UBC	3/6	MuSR User Facility	135,000
Collins MF	McMaster	5/9	Neutron Scattering Facilities at Chalk River	55,000
Lesperance A	École Poly.	4/46	Centre de Caractérisation Microscopique des Matériaux	60,000
Mitchell IV	Western	3/6	Accelerator Facility for Materials Science	100,000
Tiedje T	UBC	14/31	Pacific Centre for Advanced Materials and Microstructures	95,000

(d) Strategic Grants Supporting CMP Research

Principal Investigator	Institution	Title	Funding ($/yr)
Beerens J	Sherbrooke	Fabrication de dispositifs photonique par étapes répétées d'implantation ionique à faible énergie et recuit thermique rapide	88,000
Bolognesi CR	SFU	GaAsSb/InP Heterojunction Bipolar Transistors with High Breakdown Voltage for Telecommunications	84,600
Bonn DA	UBC	Superconducting Materials for Microwave Applications	109,000
Maciejko R	École Poly.	Ultrafast Technologies for Photonic Devices	121,000
Martinu L	École Poly.	Plasma Processing for Optoelectronic Materials	98,940
Mascher P	McMaster	Fabrication of Thin Film Optical Coatings for Optoelectronic Applications	81,000
Masut R	École Poly.	Conventional and Selective Area LP MOVPE Growth of InGaAsP /InAsP/InP Reduced….	133,914
Meunier M	École Poly.	Pulsed Laser Deposition of Superionic and Mixed Conducting Perovskite ceramic Oxide Thin Films	111,690
Roorda S	U. Montréal	Advanced Implantation Techniques for Silicon Semiconductor Device Processing	85,700
Watkins SP	SFU	Use of Alternate Precursors for Fabrication of QW Lasers	86,000
Yelon A	École Poly.	A New Magnetic Field Sensor	96,000

(e) Collaborative Project Grants Supporting CMP Research

Principal Investigator	Institution	Title	Funding ($/yr)
Bloom M	UBC	The Physical Properties of Skin	72,000
Franck JP	U. Alberta	Investigation of the Site-Selective Isotope Effect in High T_c Superconductors	49,481
Freeman MR	U. Alberta	Integrated Microprobes for Ultrafast Scanning Probe Microscopy	68,500
Gaulin BD	McMaster	Geometrically Frustrated Magnetic Materials	75,000
Grant M	McGill	Study of Adhesion in Dynamic Situations	71,000
Grutter PH	McGill	Scanning Near-Field Optical Microscopy	120,000
Hardy WN	UBC	Growth and Spectroscopic Characterization of the Next Generation of High Temperature Superconductors	123,100
Jericho MH	Dalhousie	Determination of Protein-Lipid and Protein-Protein Interaction Forces in Aqueous Media	92,500
Mitchell IV	Western	Compositional Disordering of Quantum Wells in Semiconductors	90,000
Zinke-Allmang	Western	Novel Technique for Formation of sub-lithographic Crystallites	72,015

(f) Collaborative Special Project Grants Supporting CMP Research

Principal Investigator	Institution	Title	Funding ($/yr)
Crozier ED	SFU	Synchrotron Radiation Studies with the Pacific Northwest Consortium	215,000
Sutton DM	McGill	Proposal for Partial Funding of the IBM-MIT-McGill Collaborative Access Team at the Advanced Photon Source	282,000

(g) Collaborative Research and development Grants with Principal Investigators in CMP

Principal Investigator	Institution	Collaborator	Title	Funding ($/yr)
Aubin M	Sherbrooke	Hydro-Québec	Pertes c.a. dans les rubans de supraconducteurs à haute température critique	32,364
Currie JF	École Poly.	Mitel	Study of refractive metal reactive sputtering	65,500
Currie JF	École Poly.		Solid-phase epitaxy - GaAs: materials and devices	44,080
Geldart DJW	Dalhousie	Envir. Canada	Remote sensing by LIDAR of atmospheric aerosols and cloud parameters	5,000
Sayer M	Queen's	Gennum Nortel OCMR	Analog and digital ferroelectric memories and devices	35,955

(h) Industrially Oriented Research Grants with Principal Investigators in CMP

Principal Investigator	Institution	Collaborator	Title	Funding ($/yr)
Dahn JR	Dalhousie	Moli Energy	Materials for advanced batteries	50,000
Stevens JR	Guelph	British Gas BF Goodrich	Development of polymer electrolyte membranes	40,478

Appendix 3

Awards, Honors, and Distinctions of Current GSC28 Grantholders

Awards which are internal to universities have not been listed. This Table is not claimed to be exhaustive - it is a best effort attempt using questionnaire responses and other readily available information.

Researcher		University	names of awards, honors and distinctions
AFFLECK	IK	UBC	Fellow of the Royal Society of Canada (FRSC) CAP Herzberg Medal NRC Steacie Prize Rutherford Medal of the Royal Society of Canada CAP/CRM Medal for Theoretical and Mathematical Physics Sloan Fellowship Alexander von Humboldt Senior Scientist Award
ARMSTRONG	RL	NB	CAP Herzberg Medal
ARROTT	AS	SFU	FRSC APS Fellow CAP Medal for Achievement in Physics BC Science Council Gold Medal
AZIZ	RA	Waterloo	APS Fellow
BECHHOEFER	JL	SFU	Sloan Fellowship
BERLINSKY	AJ	McMaster	APS Fellow Sloan Fellowship Rutherford Medal of the Royal Society of Canada
BETTS	DD	Dalhousie	FRSC
BLOOM	M	UBC	FRSC APS Fellow Killam Fellow Killam Canada Prize Sloan Fellowship NRC Steacie Prize Guggenheim Fellowship Alexander von Humboldt Senior Scientist Award CAP Medal of Achievement
BONN	DA	UBC	Sloan Fellowship CAP Herzberg Medal
CAILLÉ	A	Sherbrooke	FRSC Prix Léon-Lortie
CARBOTTE	JP	McMaster	FRSC NRC Steacie Prize NSERC Steacie Fellowship CAP Gold Medal for Achievement in Physics CAP Herzberg Medal
COCHRAN	JF	SFU	Sloan Fellowship
DAHN	JR	SFU (now at Dalhousie)	CAP Herzberg Medal NSERC Industrial Research Chair BC Science Council Gold Medal

DATARS	WR	McMaster	FRSC APS Fellow NSERC Steacie Fellowship Sloan Fellowship
EGELSTAFF	PA	Guelph	CAP Medal of Achievement FRSC
FAWCETT	E	Toronto	APS Fellow
GAULIN	BD	McMaster	Sloan Fellowship
HARDY	WN	UBC	Sloan Fellowship CAP Herzberg Medal FRSC NRC Steacie Prize Killam Fellowship BC Science Council Gold Medal CAP Medal of Achievement
HEINRICH	BV	SFU	APS Fellow
JOHN	S	Toronto	Herzberg Medal NRC Steacie Prize
KALLIN	C	McMaster	NSERC Steacie Fellowship APS Fellow Guggenheim Fellowship Sloan Fellowship
KIEFL	RF	UBC	CAP Herzberg Medal
KIRCZENOW	G	SFU	APS Fellow BC Science Council Gold Medal
KREUZER	HJ	Dalhousie	FRSC Alexander von Humboldt Research Award Fellow of the Max-Planck Society
LEBLANC	MA	Ottawa	APS Fellow
MASON	TE	Toronto	Sloan Fellowship
MORRISH	AH	Manitoba	CAP Medal for Achievement in Physics FRSC
PATHRIA	RK	Waterloo	APS Fellow
SAYER	M	Queen's	FRSC
STEVENS	JR	Guelph	APS Fellow
STOTT	MJ	Queen's	Rutherford Medal of the Royal Society of Canada
TAILLEFER	L	McGill	Sloan Fellowship
THEWALT	MLW	SFU	Sloan Fellowship Rutherford Medal of the Royal Society of Canada FRSC APS Fellow BC Science Council Gold Medal NSERC Industrial Research Chair
TIEDJE	T	UBC	APS Fellow CAP Herzberg Medal NSERC Steacie Fellowship BC Science Council Gold Medal
TIMUSK	T	McMaster	APS Fellow FRSC Sloan Fellowship
TREMBLAY	AS	Sherbrooke	NSERC Steacie Fellowship Killam Fellowship CAP Herzberg Medal

VANDRIEL	HM	Toronto	Guggenheim Fellowship Killam Fellowship Alexander von Humboldt Senior Scientist Award
WALKER	MB	Toronto	CAP Herzberg Medal
WALTON	D	McMaster	APS Fellow
WINTLE	HJ	Queen's	IEEE Fellow
WORTIS	M	SFU	APS Fellow Sloan Fellow SFU Shrum Chair
YOUNG	JF	UBC	CAP Herzberg Medal
ZUCKERMANN	M	McGill	FRSC

APPENDIX 4

Industrial Interactions of CMP NSERC Grantholders

Information on industrial interactions of researchers funded by GSC 28 in departments across Canada was gathered during the period when the draft of the Review was made available for feedback. This was triggered when a number of Canadian physicists, and one of the assessors, asked why such information was not included in the draft. While the CAP is planning to prepare a comprehensive report on employment and economic impact issues by June, it would clearly be to the advantage of Condensed Matter Physics if some of this material were available to our assessors, together with the Review. Accordingly, a letter was sent to selected grantholders at 22 universities, asking each of them to coordinate submissions from their departments detailing such industrial interactions. The results of this effort are tabulated below, ordered alphabetically by university.

We emphasize that this list is not claimed to be complete, nor has it been filtered according to any criteria setting a minimum level for the perceived significance of the interactions. Nonuniformities in style and presentation are the result of the limited time available for the collection of this data, which we hope will be a useful, if incomplete, addition to the present document.

Acadia

Craig Bennett and the Defence Research Establishment Atlantic

Project Title: Characterization of Laser Clad and Laser Surface Melted Nickel Aluminum Bronze With Transmission Electron Microscopy.

Nickel aluminum bronze (NAB) alloys are widely used in marine applications due to their excellent seawater corrosion resistance and good mechanical properties. In this study, the microstructural development of NAB alloys produced by a novel laser melting technique is being investigated using TEM. The overall goal is to develop and patent new alloys which show enhanced mechanical properties leading to an extension of the service life of components such as propellers, valves, etc.

Alberta

R.F. Egerton, J. Beamish and Amptech Corporation (Calgary) and UAEM (University of Alberta) Contract ($8000) to explore new materials for EM shielding of plastic enclosures. Literature search and analysis is completed; we are now awaiting response from the company to our recommendations for experimental development.

R.F. Egerton and Alberta Microelectronics Centre (AMC). The NIOX thin-film test specimen for analytical electron microscopes was developed in collaboration with AMC, based on published research in the Department of Physics. Specimens are now being produced at AMC, tested in the Department of Physics and marketed by AMC via electron-microscope distributors (Soquelec, Pelco International, SPI, Alan Agar Ltd., Plano GmbH). Specimens retail for about $120 and come with 8-page documentation; about 100 have been supplied to the distributors.

M.R. Freeman is interacting with US magnetic recording companies interested fast (subnanosecond regime) device response for high rate data storage. Over the past two years limited postdoctoral, graduate student, and operating support (approximately $40,000 in total) has been received through arrangements with Hewlett-Packard, IBM, and Quantum.

Brock

Fereidoon Razavi is on the board of a small instruments company, TETCON Int'l (Oakville, ON). They are working on an international order for a vacuum pump station, worth $35,000, of which Brock is going to get $2,500 for assembly and calibration of some items.

Maureen Reedyk has just bought one of the very first polarizing interferometers built by ScienceTech, of (London, ON). The company provided some price breaks and other services in exchange for the "beta-testing" and promoting the device. Approximate value: $3,000-$4,000.

Concordia

We have one of the new NSERC/NRC/Industry partnership grants, of which David Cheeke is the PI. It is entitled "Industrial gas sensing using silicon micro hot-plates". The NRC partner is Institute for Chemical Process and Environmental Technology, Ottawa and the industrial partner is Armstrong Monitoring Corporation, Ottawa. The funding is 50/50 NSERC and NRC for a total of $100,000 per year for four years, with an additional company cash contribution effectively $20000 per year (by a rather complicated arrangement). The idea is that together with our colleagues in electrical engineering here (Dr. Les Landsberger) we will make the micro hot plates and the sensing device, NRC will make the oxygen sensing perovskite films and Armstrong will carry out industrial tests and look for applications in the environmental area.

Dalhousie

Industrial interactions of Jeff Dahn:

3M Co. and 3M Canada Co.
NSERC IRC, $400,000/yr, $200,000 cash per year from 3M Canada
Materials for advanced batteries,

Comalco Ltd. Australia
Direct Company Funding, $30,000/yr
Studies of sodium uptake in microporous carbons and its impact on electrodes for Aluminum Smelting

FMC Corp, North Carolina
Direct Company Funding, approximately $20,000 USD/yr.
Testing of cathode materials for Li-ion batteries

Applied Sciences Co, Michigan
Direct Company Funding, approx $25,000 USD/yr.
Testing of anode materials for Li-ion batteries

École Polytechnique

Meunier et al., "Laser Cleaning for Microelectronics", approx. 90,000$/year, with Martine Simard-Normandin, Nortel.

Meunier et al., "Pulsed Laser Deposition of Superionic Thin Films", approx. 110,000$/year, with Michael Paleologou, Paprican and François Morin, IREQ.

Yelon et al., "Sodium Ion Membrane for Industrial Process Caustic Recovery", with Michael Paleologou, Paprican.

REMO MASUT: contract with Nortel. "Study of III-V Mach-Zehnder Modulator Reliability under Optical Stressing"; the contract contributes part of a salary of a student, working at Nortel.

LUDVIK MARTINU: Collaborations with Optical Coating Laboratory Inc. (Santa Rosa, CA.), Flex Products Inc. (Santa Rosa, CA), Denton Vacuum Inc. (Moorestown, NJ) and Noranda, (Ville St-Laurent, Quebec). Subjects: fabrication of optical and protective films and coatings, plasma processing of materials and materials optical and mechanical testing. Support obtained via contracts and unrestricted grants, about 80 k$/year.

JOHN CURRIE: NSERC CRD project with Mitel and Varian Associates on reactive magnetron sputtering of refractory metals, $65,000/yr. NSERC Strategic Grant with Paprican, Domtar on thin film selective membranes, $99,750/yr. NSERC Strategic Grant with Nortel, "Highly-Strained InAsP/InP Heterostructures for Optoelectronic Applications", $121,000. NSERC Strategic Grant with Dettson Industries and Paprican, "Electrically - Integrable Solid State Thin Film Nox Detectors", $158,000/yr. FCAR, Efficacité énergétique, with Hydro-Quebec, Natural Gas Research Institute, $60,000/yr. NSERC university-industry cooperative research initiative with Noranda, "Selenium Radiaographic Detectors", $60,000/yr.

Guelph

Ross Hallett performs particle size analysis by laser light scattering on about 6-10 samples per year of microfluidized milk suspensions from Ault Foods Limited of London, Ontario. The per sample charge is $75, so annually this works out to about $550. From time to time he does similar runs for Labatt's Canada, Owens-Corning Canada, but none yet this year. The service provided uses dynamic light scattering combined with discrete Laplace Inversion techniques to obtain complete particle size distributions. Intensity weighted size distributions can be obtained for almost any particulate suspension. However, we can also obtain number distributions for solid spherical particles, (such as latex paint), hollow sphere systems (such as vesicles and liposomes used in drug delivery) and coated sphere systems.

Lakehead

Marc Dignam, with MPB Technologies Inc. (Dorval, Quebec). Funding is contract paid by the company. The research involves the modeling of optical fiber amplifiers and propagation in transmission fibers for long-haul fiber-optic communications links. The aim is to identify existing and potential problems in long-haul communications links which are under development and to develop solutions to these problems.

Marc Dignam with AFC Technologies Inc., Hull Quebec. No financial arrangement entered into as yet. The research involves detailed modelling of erbium-doped fiber amplifiers for communications systems.

Manitoba

Dr. K. A. McGreer works with TRLabs, Alberta Microelectronic Centre, SDL and EXFO. These companies share funding from a project grant funded by WEPA (Western Economic Partnership Agreement). Dr. McGreer is conducting research on spectrometers for telecommunications applications. TRLabs has provided equipment funding and operating expenses for this research. The spectrometers are fabricated with integrated optics technology on silicon substrates. The devices are to be used to monitor the optical signals transmitted on an optical fiber when wavelength division multiplexing is being used.

J.H. Page has had extensive interactions with scientists at Exxon Research and Engineering Company (Annandale, NJ). While Exxon has not funded Page's research program directly, this research has been supported by a Collaborative Research Grant from NATO and by a University Research Grant from Imperial Oil Limited. This research has involved fundamental studies of classical wave propagation in strongly scattering media using ultrasonics, and the development of novel acoustic techniques for probing disordered materials. (The two key scientists in this collaboration, Dave Weitz and Ping Sheng, have recently left Exxon, but Page is still interacting with a third scientist, Eric Herboltzheimer, who is still at Exxon and who is interested in related problems.) Prior to the work mentioned above with Exxon, Page's research into the ultrasonic characterization of the mechanical properties of silica aerogels was supported by a contract from Sandia National Laboratories (1989-92).

Dr. A. H. Morrish worked with the IBM Research Division, Almaden Research Centre (San Jose, California) on a joint study on the Fe-N system which involved confidential data, publication, etc. IBM supplied some Fe-N films that were studied with Mossbauer spectroscopy. The agreement expired June 30, 1995, but unpublished data remains to be submitted. An agreement was reached between Showa Denko K.K. (Yokohama, Japan) to train Isayuki Horio on measurements of magnetic recording materials. Showa Denko K.K. paid Horio's salary and provided a research grant of $12,000, commencing late 1990. The research collaboration continued after Mr. Horio returned to Japan in late 1991, providing valuable samples such as gamma ferric oxide samples made with the isotope 56Fe and surface coated with the isotope 57Fe. Dr. Morrish is currently involved, indirectly, with some Japanese companies via collaborations with Prof. K. Haneda. Samples of interesting industrial materials and exchange data, eg. magnetic inks and some catalysts, are received.

Dr. G. Williams has an informal arrangement with the International Nickel Co. (INCO), through which they donate free, high purity Ni, for sample preparation, from time to time.

McGill

John Strom-Olsen has had the following industial contracts as a result of work (financed by NSERC operating grants) on the fundamental properties of nanoscale materials. He would stress that none of this would have happened without seed money provided by the NSERC operating grants and further funding by strategic grants. A further result of the NSERC operating grant seed money was the establishment of his Hydrogen Chair by Quebec, which is funded at 100,000/year for 5 years. Between 1988 - 1997 he has or had the following collaborations, with a total volume of transactions of about $ 2 - 3 million:

Pitney Bowes Inc	magnetic fibers
Cerametrix	ceramic fibers
M4 technologies	superhard magnets
Hydro Quebec	hydrogen storage
Gesellschaft fuer Metallurgie	rechargable electrode catalysts

A joint venture has been initiated between Pitney Bowes Inc., Safeguard and MXT Inc. to commercialize a new theft protection device based on melt extraction of thin fibers. This venture contributes a value of about $ 2.5 Million.

Peter Grutter has received seed money provided by Texaco to investigate (in collaboration with L. Piche, NRC) the role of additives in lubricants by ultrasound spectroscopy and AFM. Value: $15,000 for 1 year.
He also has a collaboration with Hydro Quebec on Varistor materials (investigating nanoscale transport properties by AFM techniques). No money changes hands, but his group gets access to the excellent infrastructure at nearby Hydro Quebec (R. Schulz's lab).

McMaster

John Preston:

- -COM DEV - Provincial Centre of Excellence, core research grant, focused on materials science and physics of high temperature superconductors relevant to device applications
- -COM DEV - Provincial Centre of Excellence, collaborative grant, development of large area laser ablation deposition chamber for high temperature superconducting films
- -Crystar and COM DEV - Strategic grants, New substrates for superconducting thin films (with John Greedan and Tom Timusk).

Peter Mascher:

- -EG&G Optoelectronics, NSERC Strategic (with H.K. Haugen, P.E. Jessop, and H.E. Ruda (U of T)): Fabrication of Thin Film Optical Coatings for Optoelectronic Applications
- -EG&G Optoelectronics, OCMR Research Contract (with H.E. Ruda (U of T)): Facet Treatment for Improved Reliability of GaAs based Lasers
- -Exactatherm Ltd., OCMR Collaborative Research Project: Optical Monitoring of Plasma Assisted Coating Processes
- -American Sensors Inc., OCMR Collaborative Research Project (with A.H. Kitai): Low Power Metal Oxide Semiconductor Sensors for the Detection of Hazardous Gases

Bruce Gaulin:

- -Ontario Hydro - Contract - "X-ray determination of the microstructure of metals."
- -General Mills - Contract - proprietary research.
- -IBM San Jose - Collaborative research - "X-ray and neutron scattering of magnetic multilayers".
- -Lucent Technology/ Bell Labs - Collaborative research - "X-ray and neutron scattering from superconductors".

Tom Timusk:

- -COM DEV - NSERC Strategic grant - see John Preston (above)
- -COM DEV - OCMR grant - see John Preston (above)
- -Sciencetech - Consulting - Design of spectrometers.
- -Lucent Tech./Bell Labs - Collaborative research - "Optical properties of quasicrystals".

Montreal

Louis-André Hamel:

- -Development of CZT detectors for gamma and X-rays with Noranda, $60,000 in 1996, $25,000 in 1997.
- -Construction of gamma camera with Noranda, $17,000 in 1996.

Sjoerd Roorda:

- -Mitel Bromont, contact person Claude Jean, Strategic Grant on gettering and ion implantation in Si, $75K per year or so paid by NSERC, some in kind contribution from Mitel.
- -Atlantic Nuclear Services: Contact person Ken Oxorn, value: about 10 k$ per year
- -ACS Guidant (Medical systems and supplies) contact person Ty Hu, Ion implantation of 32-P, Sjoerd Roorda with Guy Leclerc and Raymond Carrier (HND) value: about 75 k$ per year.

John Brebner:

- -Communications Research Centre, Implantation of Ge-doped silica, $13,000 in 1997
- -Showa Wire and Cable, Japan, Implantation of silica, $5,000 in 1997

Ottawa

Denis Rancourt:

- -National Water Research Institute, Environment Canada. Regular contract work (about 10-15 k$/year) involving quantitative mineralogical characterization of aquatic sediments and slags.
- -CANMET, Steel Group. Exploring joint contracts for industrial clients. Just starting, but have already undertaken preliminary research involving Mossbauer spectroscopy.

-MOSMOD Mossbauer analysis software. Sold on non-profit basis to over 40 laboratories worldwide.
-CANMET, Energy and Mining Divisions. Past contracts involving Mossbauer characterization of coal and coal reactions ($40 000 in 1994), and of tailings and their reaction products ($10 000 in 1990).

Gary Slater:

-Perkin-Elmer, Applied Biosystems Division
a) DNA purification (1996). Approx. $96,000. Development of a new device to purify genomic DNA.
b) Nucleic Acids purification (1997), approx. $100,000. Development of a new device to purify and separate…
c) DNA separation (1996-9), approx. $122,000/yr. Development of a new technology to sequence DNA.

In each case, the contract is shared between Gary W. Slater (Dept. of Physics) and Guy Drouin (Dept. of Biology).

Emery Fortin: Supervision of a grad student at Nortel.

Queen's

M.Sayer:
-Millenium Biologix, Ontario Centre for Materials Research Collaborative Research Program, Bioactive surfaces and ceramics for medical implants and coatings; the principal product derived from work initially carried out at Queen's.
-Datec Coating Corporation, NSERC Technical Partnerships Program, Ontario Centre for Materials Research Collaborative Research Program, direct contract with company; novel ceramic coatings; the principal product derived from work carried out at Queen's
. -SSI Inc. (Wisconsin. USA), direct Contract with company, development of integrated piezoelectric coatings for automotive applications
-Ortech International, direct Contract with company; sol gel oxide coatings for aerospace applications
-National Research Council, Institute of Aerospace Studies, direct Contract with company; fabrication of micromachined transducers for air-spaced ultrasonic transducers
-National Research Council, Industrial Materials Institute, NSERC Strategic Grant; Development of high temperature ultrasonic transducers
-Laser Machining Centre, Gennum Corporation; Sunnybrook Health Sciences Centre, Ontario Centre for Materials Research/Manufacturing Research Council of Ontario Collaborative Grant, development of high frequency ultrasonic arrays for biomedical imaging Techniques for laser processing of ceramics and semiconductors
-Angstrom Engineering, Ontario Centre for Materials Research Grant, sputtered molybendum disilicide coatings
-A proposal has been submitted to NSERC for a Consortium on Industrial Coatings, linking three universities and six companies, entitled, "Characterization methods for adhesion, wear and corrosion of hard coatings."

Simon Fraser

1. Collaboration with EG&G Optoelectronics
S.P. Watkins, C.R. Bolognesi
NSERC Strategic Grant STR192894, 3 year
"Use of alternate precursors for fabrication of quantum well lasers"
$86,000/annum starting from Nov 1996.
Description: Grow quantum well 908nm AlGaAs/InGaAs lasers at SFU, fabricate them at SFU and EG&G in order to investigate the performance of alkyl group V organometallic precursors for growth. Investigate non-aluminum based materials for similar laser structures.

2. Collaboration with Epichem Inc., UK
S.P. Watkins, Characterization of phosphorous sources by growth of InP epitaxial layers, user Fees of $2k in 1996, In kind contribution of source compounds: $10k in 1996

3. Collaboration with NORTEL:
C.R. Bolognesi, S.P. Watkins, NSERC Strategic grant, “GaAsSb/InP HBTs with high breakdown voltages for the telecommunications industry", $84,600/yr.

4. Collaboration with Crystar Research
C.R. Bolognesi, S.P Watkins, NSERC CRD, "Fabrication of ultra high speed low noise InGaAs HEMTs on GaInAs Ternary Substrates", $56K/yr

5. Thewalt: Industrial Research Chair, funded by the following companies in the amount shown.

-Crystar, $10k/yr., PL characterization of ternary substrates, X-ray diffraction (Watkins' group)
-EG&G Optoelectronics, $10k/annum, PL characterization of III-V material, X-ray diffraction (Watkins group)
-BOMEM, $10k/annum, development of new Fourier transform spectroscopic techniques

6. CTF SYSTEMS (B, Heinrich, A.E. Curzon, J.C Irwin).
(a) Surface Physics Laboratory (SPL, B. Heinrich, A.E. Curzon) and CTF Systems (A. Fife, S. Govorkov) cooperates in the following programs:
(i) Micromagnetic studies of flux penetration in High Tc superconducting films, SQUID junctions and superconducting transformers using magneto-optical technique. SFU provides magneto-optical apparatus, and CTF provides samples.
(ii) Development of magnetic sensors based on spin polarized tunneling in magnetic (metal/metal oxide/magnetic metal) structures. CTF Systems provides their expertise in the growth of metallic oxides, and SFU carries out the fabrication of magnetic sensors using MBE and will perform complete magnetic and spin tunneling studies. The above work is supported by NSERC; in part by MFA grant for the Pacific Center for Advanced Materials and Microstructures (PCAMM) (T. Tiedje, B. Heinrich, S. Watkins, K. Mitchel, 1996-1999); and in part by the operating grant of BH. The CTF Systems in kind contribution is $12,000.

(b) J.C. Irwin (CTF collaboration is represented by A.A. Fife).
They have initiated a project that involves the development of a Raman microprobe system which is to be used to characterize thin films of high Tc materials and study working devices such as junctions, flux transformers and SQUIDS on a microscopic basis. For devices fabricated from Yttrium Barium Copper Oxide the Raman data can be used to determine degree of epitaxy, oxygen content, critical temperature and critical current on a local scale. The films and devices and their macroscopic characterization will be provided by CTF Systems. This project involves a graduate student (Kevin Hewitt) and is supported by CTF, NSERC (Operating grant of JFI) and B.C. Science Council GREAT Scholarship for HK.

7. SERVICE WORK (Surface Physics Laboratory (SPL, B. Heinrich, A.E. Curzon):
(a) Blue Star Battery System Corp., North Vancouver, BC. Blue Star Battery System Corp. is a manufacturer of high rate lithium batteries. The Scanning Electron Microscope and Energy Dispersive X-ray analysis system (A.E. Curzon) has played an important role in the identification of battery corrosion products.
(b) Rend Technology, North Vancouver, BC. The SEM and energy dispersive x-ray analyser (A.E. Curzon) has been used to characterize composite materials for Rend Technology which has a general interest in materials research. The materials are for use in energy storage (hydrogen storage and batteries). An example is NbS_2-La.
(c) Moli Energy, Maple Ridge, BC. Moli Energy makes lithium based batteries. This work involved characterization of cans for batteries.
(d) Ballard Power Systems, Burnaby, BC. Ballard makes fuel cells and are in the news for the recent infusion of funds from Daimler Benz. The work dealt with electrode catalysts.
(e) Pulp and Paper Research Institute, Vancouver. Auger analysis (B. Heinrich) of ZnSe windows for the measurements of NaOH concentrations in paper products.
(f) KENMETAL, Macro Division, Port Coquitlam. Auger analysis (B. Heinrich) of imbedded diamonds in Co matrix for grinding wheels.
The service work was supported by SPL service charges ($650/hour) and by the SPL NSERC Infrastructure and SPL NSERC MFA grants.

8. REND TECHNOLOGIES (R. F. Frindt). Recently Rend Technologies negotiated a license with SFU for access to three of our patents on novel materials we have developed. The potential application is for hydrogen gas storage or hydrogen based batteries. Last year Dr. Frindt obtained $20,000 from the SFU Prototype Development Fund to support the collaboration with Rend Technologies.

9. ELECTROLYSER CORP. (K. Colbow), development of sensor systems for hydrogen gas involving semiconductor films. Dr. Colbow is involved in the development of thin film sensors whose electrical conductivity is sensitive to hydrogen gas. The program is supported by NSERC, operating grant of KC.

Sherbrooke

J. Beerens and J. Beauvais, with Nortel, Strategic Grant, fabrication of photonic devices using a method based on repeated steps of low-energy ion implantation (<400 keV) and rapid thermal annealing.

Marcel Aubin with Hydro-Quebec, NSERC University-Industry Partnership Program $30,000, Hydro-Quebec $75,000 over 3 years. Several contracts with Hydro-Quebec (J. Cave scientific contact) have been completed over the last few years for the improvement of High Temperature Superconductor (HTS) materials in view of applications. In the most recent arrangement (funding described above) AC losses in HTS are studied.

St. Francis Xavier

D. A. PINK and Nova Scotia Agricultural College and their Business Partners. Computer simulation is being used to model grazing ruminants in various environments. This work is of interest to the Feed industry and has proven feasible because of Pink's work on modelling protein diffusion as part of his NSERC-supported research program on biomembranes.

D. A. Pink and the Atlantic Canada Opportunities Agency (ACOA). Pink directs the Food Research Laboratory (StFXU), set up by him ten years ago to work with industry. It has a contract for $249,459 with ACOA to develop spectroscopic techniques to characterize seafood. This work is relevant to (a) species identification, (b) frozen seafood and (c) analysis of protein, water and fat content. The work arose through Pink's research on the IR spectra of membrane proteins as part of his NSERC-supported research on biomembranes.

M. O. STEINITZ: discussions with Nova Scotia Research Foundation Corporation re: the possible commercialization of a capacitance dilatometer for use at high temperatures. This device was developed as part of Steinitz's NSERC-supported research on materials. It is of interest to the steel industry and the ceramics industry for the determination of phase transition temperatures and volume changes at temperatures well in excess of 500K.

Toronto

R. Desai: Interaction with industry is limited to having written some joint papers with two theorists - Jaan Noolandi and An-Chang Shi at the Xerox Research Center of Canada in Mississauga. All these are in the equilibrium and stability aspects of industrially important block copolymer systems, and three component polymer blends. No financial support.

Thom Mason: Part of an OCMR project to study residual strains in engineering materials using neutron diffraction in collaboration with DeHavilland Inc. in Downsview and Rockwell International Suspension Systems Co. in Milton. The companies are providing in-kind support in the form of samples, characterization etc., valued at several thousand dollars. Also works on high temperature superconductors in collaboration with researchers from Bell Labs, Lucent Technologies (NJ) and NEC Research (NJ). This is a joint project with industrial contributions, primarily in the form of sample growth and characterization, as well as hardware, significantly in excess of $100 K/yr.

Sajeev John: (i) Development of an Optical Oil Quality Sensor with Caravelle Foods/ McDonalds Canada supported at a rate of $60,000 per year (half coming from Ontario Laser and Lightwave Research Centre) ,
(ii) Applications of Laser Paint with 3M Canada (London, Ontario). This is currently an informal collaboration which may lead to funding from 3M. (iii) Tunable Photonic Crystals from Interpenetrating Electroactive Networks: Design,

Synthesis and Devices with Allied Signal Corporation, New Jersey. We have applied for funding to develop photonic band gap materials containing electroactive polymers. This will lead to a number of optoelectronic devices.

Bryan Statt: Negotiation phase of a contract with INCO exploration division. The topic is to investigate the application of NMR to exploration geophysics. Scale:$100k.

Henry van Driel: Ongoing interaction with Hughes-Elcan of (Midland, Ontario) to develop diode-pumped solid state lasers for use in laser ranging and material diagnostics. Last year they provided $40k of cash funding with an additional $40k of cash funding coming from the Ontario laser and Lightwave Research centre. In 1997-98, the funding level will be comparable.

John Sipe: Involved in doing consultation and numerical simulations for a number of small optical firms in Ontario (confidential): approximately $25k of funding for personnel and computer support. In addition, in 1995-96 received about $30k of support from IMAX corporation (Mississauga) to help optimize screen designs. This was matched by the Ontario Laser and Lightwave Research Centre.

University of British Columbia

Doug Bonn, Walter Hardy and Jim Carolan carry out development work on microwave devices based on high temperature superconductors. This work is sponsored by COMDEV, and is part of an NSERC Strategic grant of $110,000 p.a. This involves the development of appropriate materials, and performing a number of microwave measurements as a service to the company. This group recently received a $12,000 contract from Superconductor Technologies Inc. (STI) in California for microwave characterization measurements.
Walter Hardy acts as a consultant for different organizations. One contract, from B.C. Hydro and the Canadian Electrical Association, is for demonstrating the feasibility of using microwave radiometric techniques to detect hot spots inside porcelain and polymer clad devices. Another contract, from Forest Renewal B.C., is for the development of a hand held device to detect unseen forest fires (e.g. underground fires).

Tom Tiedje and Jeff Young collaborate on a semiconductor optoelectronics research project sponsored by the Canadian Cable Labs Fund. This support has been in place for five years now (originally involving Tom Tiedje and N. Jaeger from Electrical Engineering), based on biannual reviews. It is currently supported at $60,000/yr., and matching funds of $45,000/yr. are obtained from NSERC, through the Industrially Oriented Research Program. This research is aimed at improving the price and performance of optoelectronic components used in the fibre optic network of Rogers Cable. Work on this project, and Roger's support also helped secure an NSERC Strategic Research grant for developing molecular beam regrowth technology on textured substrates. John Eldridge was a co-investigator on this grant.

Tom Tiedje's group has licensed their optically-based temperature monitoring system to a US firm, Thermionics North West. This system was invented at UBC and commercialized by a UBC Ph.D. in Physics working at Thermionics in collaboration with the University of Washington, with US government funding.

Andrew Brown, an Engineering Physics graduate from UBC, has established a B.C. company named Quartz Imaging Corp., that makes electron microscope image acquisition systems that are marketed internationally by Nissei Sangyo. The imaging system is an outgrowth of work done on scanning tunneling microscopes in Tom Tiedje's laboratory.

Brian Turrell's group is developing a novel cryogenic particle detector array based on superconducting spheres. They have received ~ $85,000 ('94-'96) from a US company, BioTraces, in support of this research.

Jeff Young and Tom Tiedje are also involved in Er fibre optics research supported by Augat Photon of Burnaby B.C. The principal investigator on this work is Mike Jackson in the Electrical Engineering department, and the company's contribution is ~ $54,000, of a total grant worth $215,000.

Bob Parsons' research in thin films coatings has led to two spin-off companies, Techware Systems Corp. (Now Brooks Automation), and Corona Vacuum Coaters Inc. These two companies have a combined revenue of about $2 M/yr.

Worldwide. They follow in the tradition of other UBC Physics spin-off companies such as Vortek and MoliEnergy. Corona currently supports research and development of "smart" control systems for industrial-scale physical vapour deposition equipment.

University of Western Ontario

P.J. Simpson has projects with EG & G Optoelectronics (development of positron beam techniques for quality control applications) and with Gennum Corp (positron techniques as an aid to process development), both funded by OCMR, although Gennum paid for some measurements and the connection is currently rather inactive. He also has a new active tie with Toyota working on insulating films (this again uses positrons as an aid to process development) funded by Toyota. He has done some work with Dolf Landheer of NRC which ties into BNR's programs, developing thin silicon oxynitrides.

W.N. Lennard:

- -NSERC CR&D with:
  - Seagate Technology (Calif. USA)
  - Cametoid Inc.
  - Chessen Group Inc.
  - Research relating to thin film technology (hard disks, protective coatings, etc.).
- -NSERC IOR with:
  - COG (Candu Owners Group), which translates into
  - AECL and Ontario Hydro
  - Research relating to hydrogen interactions with pressure tube materials relevant to the Canadian nuclear industry.
- -Contracts with CANMET (Ottawa) relating to precious metals assays for the mining industry as a whole; preparation of standards via ion implantation.
- -Contracts with Nortel relating to ion implantation of Group IV and Group III-V semiconductors (quantum well intermixing); also an NSERC Collaborative Project for the same type of research; NRCC (Ottawa) is also involved in this research.

Waterloo

A company has been set up, called Biomedical Photometrics Inc., to commercialize the confocal scanning laser MACROscope developed in the Physics lab. The three people involved are Ted Dixon (CMP grantholder), Melanie Campbell (also a physicist, working in Optometry on confocal scanning laser ophthalmoscopy), and Brian Wilson (another physicist, Head of Medical Physics, Princess Margaret Hospital, and Associate Director of the Ontario Laser and Lightwave Research Center). Application areas of the MACROscope are biological/biomedical, semiconductor device and materials testing, forensic sciences, quality control, etc. For more info see our home page at www.confocal.com. There is continuing research at UW on applications and development of confocal imaging.

Ted Dixon and Dwayne Miller of OLLRC are presently working to develop a new femtosecond laser for two-photon imaging, supported by the Company, which is building a confocal MACROscope for the Resource Centre of OLLRC.

Mik Pintar is involved in the condensed matter study of 3 phase dynamics, supported by a consortium of oil companies joined in the Porous Media Research Institute including AMOCO, Canada Petroleum Co. Ltd., Chevron Canada Resources Ltd., Imperial Oil Resources Ltd., Husky Oil Operations Ltd., Unocal Corporation, ARCO Exploration and Production Technology, and Mobil Oil Inc.

M. Dusseault   (Geological Engineering)
M. Geilikman   (Geophysics)
H. Peemoeller (Condensed Matter Physics)
M.M. Pintar   (Condensed Matter Physics)

A group of condensed matter physicists led by a geological scientist M. Dusseault is studying oil recovery from depleted oil reservoirs. These reservoirs still contain as much as 60% of the initial oil in oil ganglia embedded in the intergranular space of the sand reservoir. To make this oil flow a gas phase is introduced. In its presence the ganglia spread into thin fluid film which can be extracted with horizontal well technology. In the research project water and oil film gravity drainage is monitored and analyzed with non-invasive 2-D NMR.