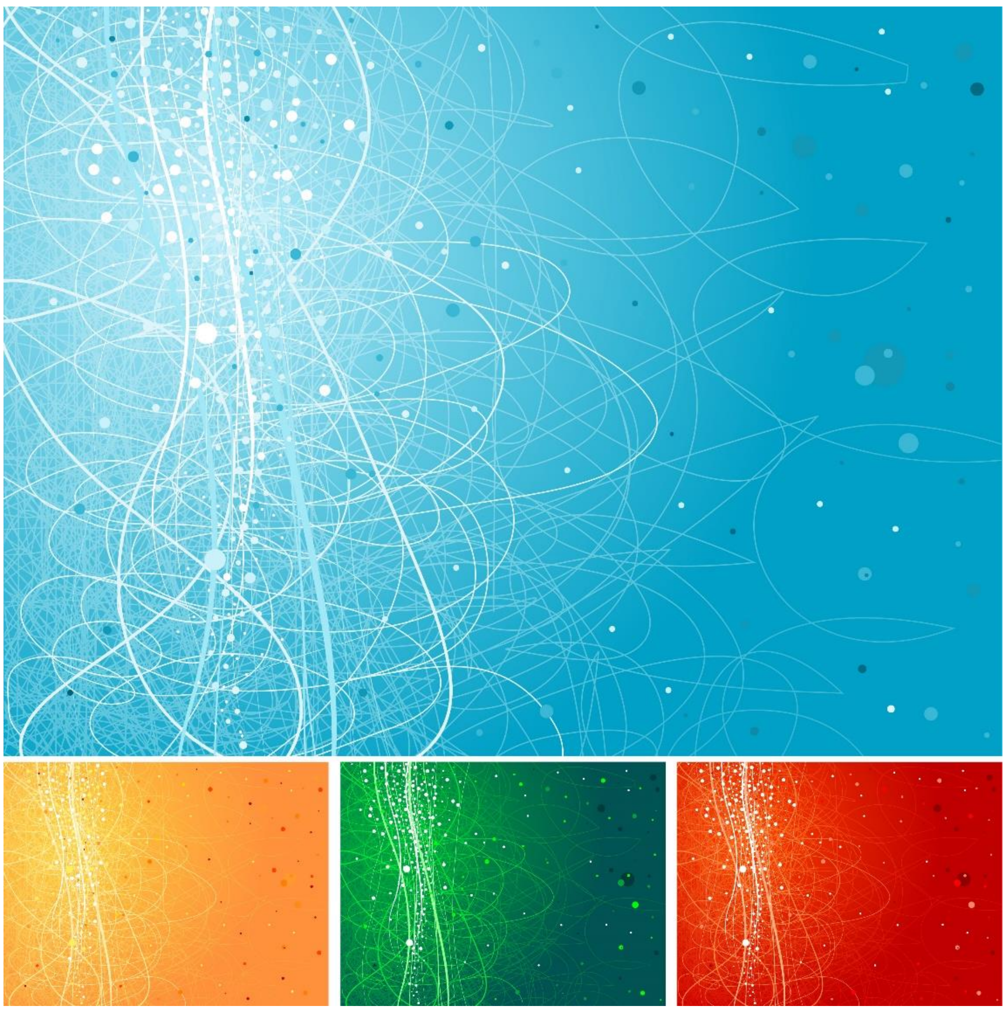
Science-Metrix

Bibliometric study on CNBC's scientific publications 1980–2017

Final analytical report



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Final analytical report

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Submitted to:

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By:

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1 Introduction

The Canadian Neutron Beam Centre (CNBC) is seeking to summarize its research activity over the last several decades, as it winds down operations in 2018. The Canadian community of neutron beam users is working to secure access to alternative facilities for the next decade. In parallel, the Government of Canada has signalled a need for national discussions with stakeholders about investments for the longer term. This study therefore aims to provide timely highlights of the benefits that neutron-scattering research has already offered to this country's scholarly communities and, to a lesser extent, industries.

The current study uses the bibliometric record to capture the outcomes and achievements of the CNBC's teams and networks of collaborators from 1980 to 2017. It contextualizes the CNBC's activities through a comparison to three Canadian and five international benchmark institutions, which provide points of reference to guide the interpretation of bibliometric findings.

A 2014 evaluation of Canadian facilities in the field of nuclear science and technology, produced by KPMG, had previously made use of findings Science-Metrix produced on the CNBC for the 2007 to 2013 period.[1] The current study expands the range of bibliometric indicators and the comparative scope of findings on the CNBC. KPMG's study offers complementary results to track broader outcomes achieved by the CNBC, most notably from the industrial perspective. It also includes findings from international experts' views of the CNBC, as well as case studies of industrial partnerships.

Basic parameters of the study

Science-Metrix retrieved and analyzed the scientific production of the CNBC from 1980 to 2017. Although the Centre operated prior to 1980, covering an earlier period might have led to unreliable findings, given the limitations in coverage and the poor quality of data in bibliographic databases prior to that date.

The following indicators were applied for the analysis:

- Publication output:
    - Number of publications
    - Growth in output
- Scientific impact:
    - Average of relative citations
    - Average of relative impact factors
    - Highly cited publications—publications falling in the top 10% most cited papers
    - Citation distribution index
    - Citation distribution chart
- Collaboration and co-authorship

[1] KPMG. (2014). *A report on the contribution of nuclear science and technology (S&T) to innovation*. Toronto: KPMG Canada. Retrieved from http://cins.ca/docs/Nuclear%20ST%20Innovation.pdf.

- International collaboration
- Intersectoral collaboration

These indicators have been produced on both the full period under study (1980–2017, although some citation indicators can only be produced up to 2015) and longitudinal time series with finer-grained periods. For many indicators, the use of shorter temporal intervals revealed signals that were otherwise obscured over the aggregate period.

Comparable institutions

Science-Metrix selected the eight comparators in close coordination with the CNBC. While the CNBC was the only Canadian facility fully dedicated to neutron-scattering research, three other national institutions are active in the broad field of material sciences and applied physics, sharing a basic context and associated parameters. Canadian institutions share ecosystems of granting agencies and other funders; access to a higher education sector that provides students, staff and collaborators; and a political context that inflects local research programming with changing priorities and demands.

The three Canadian comparators are the Brockhouse Institute for Materials Research (BIMR), Canadian Light Source Inc. (CLS) and TRIUMF. They are all major scientific user facilities, offering access to versatile capabilities for materials research. For example, the BIMR offers electron beams, CLS offers X-rays and TRIUMF offers muon beams. TRIUMF is the only Canadian comparator with some degree of research using neutron beams, offered as a "parasitic operation" on instruments otherwise mainly used for other classes of experiments. With the exception of its muon beam capability, TRIUMF is the only comparator to operate primarily in the domain of nuclear and particle physics, rather than materials science. The two other Canadian comparators do not engage in research using neutron beams at all, but as scientific facilities that combine fundamental research with services for academic and industrial users, they do follow a similar organizational model to that of the CNBC.

Five neutron beam user facilities were selected at the international level. While active in different structural and policy environments, these institutions' facilities, instruments and experimental practices tend to be closer to those of the CNBC than is the case for the Canadian comparators. They include Institut Laue-Langevin (ILL), France; Laboratoire Léon Brillion (LLB), France; Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR), USA; Los Alamos Neutron Science Center (LANSCE), USA; and the National Institute for Standards and Technology (NIST) Center for Neutron Research (NCNR), USA.

Table I provides an overview of basic facts about the CNBC and the eight comparators, to help contextualize the CNBC's scientific performance. It was, however, not feasible to account within the bibliometric indicators themselves for the differences between the centres in terms of numbers of staff members, scientific and technical resources, budget or other such parameters.

Table I Publication output of selected comparable institutions (1980–2017)

Institution	Country	Focus on neutron scattering	Count of users	Count of neutron scattering instruments
Canadian Neutron Beam Centre (CNBC)	Canada	yes	121	6
Brockhouse Institute for Materials Research (BIMR)	Canada	no	~500	N/A
Canadian Light Source Inc. (CLS)	Canada	no	1103	N/A
TRIUMF	Canada	no	367	3
Institut Laue-Langevin (ILL)	France	yes	831	55
Laboratoire Léon Brillouin (LLB)	France	yes	637	23
Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR)	USA	yes	450	11
Los Alamos Neutron Science Center (LANSCE)	USA	yes	249	7
NIST Center for Neutron Research (NCNR)	USA	yes	887	16

Note: Figures have been collated from various sources and have not been produced following standardized definitions and methods. Number of instruments for ILL differs between sources. TRIUMF operates 3 instruments with some neutron beam capacity as part of a much larger suite of instruments. The count of users provided for TRIUMF is for all instruments, across subfields, but only for external visitors. BIMR and CLS counts of users are for all their (non-neutron beam) instruments. Self-reported counts of users are indicative only, as only the data for CNBC, HFIR, LANSCE and NCNR presented have been compiled using a shared methodology, including the number of instruments available to users. LANSCE has a few additional neutron instruments that are not available to users.

Source: Self-reported data from CNBC, HFIR, LANSCE and NCNR, compiled by NCNR; TRIUMF, 2013; Brockhouse Institute for Materials Research, & McMaster University, 2014; Laboratoire Léon Brillouin, 2016; Canadian Light Source Inc., 2017; Institut Laue-Langevin, 2017.[2]

What Table I shows clearly—and what the reader should also keep in mind while interpreting the findings presented below—is that the CNBC is the smallest neutron beam facility in the group. While in operation, it also had more limited resources and equipment at its disposal than CLS and TRIUMF. BIMR may be a closer comparator in terms of infrastructure size, although as a university-based facility, its context of practice is quite distinct. As already noted, BIMR also does not operate any neutron beam instruments.

The next section (§ 2) presents the results of the bibliometric investigation of the CNBC's activities and outcomes. A brief conclusion follows (§ 3), while an appendix provides detailed explanations of the design choices and methodologies applied during the project.

[2] TRIUMF. (2013). *TRIUMF five-year plan 2015-2020*. Vancouver: TRIUMF. Retrieved from https://www.triumf.ca/sites/default/files/TRIUMF-Five-Year-Plan-2015-2020_Oct01_0.pdf; Brockhouse Institute for Materials Research, & McMaster University. (2014). *BIMR annual report 2013*. Hamilton: Brockhouse Institute for Materials Research. Retrieved from http://www.bimr.ca/sites/default/files/bimr_2013_annual_report.pdf; Laboratoire Léon Brillouin. (2016). *Annual report 2016*. Gif-sur-Yvette: Laboratoire Léon Brillouin. Retrieved from http://www-llb.cea.fr/fr-en/RAPPORT-activite-LLB-2016.pdf; Canadian Light Source Inc. (2017). *Annual highlights 2016-2017*. Saskatoon: Canadian Light Source Inc.; Institut Laue-Langevin. (2017). *Annual report 2017*. Grenoble: Institut Laue-Langevin. Retrieved from https://www.ill.eu/fileadmin/user_upload/ILL/1_About_ILL/Documentation/Annual_report/AR-17/ILL_Annual_Report_2017.pdf.

2 Results

The structure of the present section mirrors the list of indicators outlined in § 1 above. The first subsection (§ 2.1) covers publication output, while the second subsection (§ 2.2) addresses the impact of research within the scholarly community, and the final subsection (§ 2.3) treats collaboration, as measured through co-authorship.

2.1 Publication output

2.1.1 Volumes within the sample of institutions

Publication outputs have been characterized for the CNBC and the comparators, both overall and divided into thematic areas. Papers were associated with the centres when they were listed as the institutional affiliation of an author, or when they were acknowledged explicitly in the paper (either in the acknowledgments section or in the abstract). Additionally, lists of associated papers were available for the CNBC and HFIR. The CNBC list contained approximately 1,600 papers, 292 of which were not indexed by the Web of Science (WoS) database (produced by Clarivate Analytics). Many of these were published in engineering conference proceedings, but they also included journals articles and book chapters. These 292 papers were not included in the bibliometric analysis. The CNBC itself considers that it has a stronger focus on engineering than the comparators, and that a greater proportion of its output would be taken up by engineering conference papers than the other institutions included here.

Publication practices and portfolios vary considerably between the nine research institutions examined here, as shown in Table II below. Two institutions stand out in terms of sheer output volumes. ILL was far and away the most active institution studied here, with 12,639 papers. As will be seen in greater detail below in § 2.3, the ILL was also heavily engaged in international collaborations, which may explain part of its output figures. TRIUMF was the other organization with a notably voluminous record of publications over the period of interest, with 5,333 documents, although it should be noted that this number covers TRIUMF researchers' activities in all scientific subfields rather than its neutron-scattering activities specifically.

Table II Publication output of selected comparable institutions (1980–2017)

Institution	Country	Years Covered	Papers	Papers /year	Growth rate 2009–2012: 2013–2016	Trend
Canadian Neutron Beam Centre (CNBC)	Canada	1980–2017	1,307	35.3	0.8	
Brockhouse Institute for Materials Research (BIMR)	Canada	1996–2017	827	39.4	0.8	
Canadian Light Source Inc. (CLS)	Canada	2001–2017	2,024	126.5	2.1	
TRIUMF	Canada	1980–2017	5,333	144.1	1.1	
Institut Laue-Langevin (ILL)	France	1980–2017	12,639	341.6	0.9	
Laboratoire Léon Brillouin (LLB)	France	1980–2017	3,503	94.7	0.9	
Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR)	USA	1982–2017	1,278	36.5	1.6	
Los Alamos Neutron Science Center (LANSCE)	USA	1988–2017	1,648	56.8	0.9	
NIST Center for Neutron Research (NCNR)	USA	1993–2017	2,988	124.5	1.0	

Note: Full counting method used. Publication year 2017 not yet completely indexed in the database. Colour coding varies from red (below the world level) to white (on par with the world level) to green (above the world level).

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

The remaining organizations were associated with more modest output volumes that ranged from 827 papers at the BIMR (which was established relatively recently, older than only CLS) to 3,503 documents for LLB. The CNBC was situated towards the lower tier in publication output rankings, with a figure of 1,307 publications.

The CNBC's absolute publication output performance, which was comparatively small relative to the other centres, reflects a modest yearly publishing intensity. Here the Centre was positioned at the tail of the comparator group, with an average of 35.3 papers published per year for the period under consideration. By comparison, the staff and guest researchers of the ILL collectively published an average of 341.6 papers annually—more than nine times higher than the figures obtained for the BIMR, the CNBC or HFIR. Distantly following ILL was a cluster of institutions with averages between 125 and 150 papers a year: TRIUMF (at 144.1 papers per year), CLS (at 126.5) and NCNR (at 124.5).

Given the length of the period under consideration, it is also important consider the extent to which the output figures presented here reflect established practices or novel developments. Science-Metrix therefore compared output profiles for each institution between the 2009–2012 and the 2013–2016 periods.[3] The results show that most organizations under consideration, including the CNBC, plateaued in the recent period with respect to their publication output. Two exceptions stand out, however, with the HFIR and especially CLS showing stronger growth; HFIR's output increased by 60%, and that of CLS more than doubled.

These exceptions can also be observed in Figure 1 and Figure 2 below. These figures illustrate publication output dynamics over time, separated into comparisons between the CNBC and other Canadian institutions, and the CNBC and foreign organizations working precisely in the area of neutron scattering. Despite high absolute figures, it can be seen that publication outputs from TRIUMF and ILL have been susceptible to wide swings on a year-by-year basis, explaining why their growth ratios are situated close to the main group of scores obtained (Table I).

At many institutions, findings of a steady state in publication outputs in neutron scattering are in line with the output trends that can be observed in the Science-Metrix subfields of Applied Physics and Materials taken together. Selecting only for institutions from Canada, France and the United States, growth in publication output was only 4% between the 2009 and 2012 timepoints. Taking the 2013 and 2016 timepoints, aggregated output decreased by slightly more than 1% over the period. At the global level, growth rates of 5% and 7% are observed for these periods, driven in large part by the expansion of the Chinese science system.

A final angle to contextualize output figures can be provided by the number of instruments at each institution, with slight differences in numbers from Table I to reflect the equipment available during the period considered. Science-Metrix computed yearly publication output by instrument for the years 2009 to 2013. This period was chosen as one of relative stability in instrument portfolios at the neutron beam research institutions. BIMR, CLS and TRIUMF were excluded from this comparison so that this exercise was conducted between institutions with highly commensurate practices. The rationale supporting the

[3] These two time frames were selected because they are recent, fully indexed in the Web of Science database and include only active years for all institutions.

computation of this metric is that instrument access is a central feature of scientific work in material sciences and applied physics, and that it crucially constrains the space of experimentation and publication possibilities of given institutions and researchers.

Findings presented in the next paragraphs should be considered as exploratory. Normalizations that use instrument characteristics or other features of experimental work (in contrast to discipline- or subfield-level normalizations) do not see widespread usage in the bibliometrics community; it is therefore not possible to draw on previous experience to evaluate their robustness. Additionally, a given neutron beam is not constantly in operation and requires regular downtime. Instrument counts at institutions have not been themselves normalized by annual rates of operation or by neutron flux. Finally, numbers of instruments used are those for 2016 and do not account for potential changes between 2009 and 2013.

Findings for publication outputs by instrument show LANSCE to have been particularly productive, with an average of 17.5 papers published per year and per instrument between 2009 and 2013. ILL's output figure was more modest using this metric, at 9.4 papers per year and per instrument. The CNBC (7.4 papers per year per instrument) was less productive per instrument than the previously mentioned institutions as well as NCNR (11.5) and HFIR (10.6). CNBC was followed by LLB (6.2 papers per year per instrument).

Science-Metrix also calculated average yearly growth in publication outputs per instrument over the five-year period considered. Growth was small for the CNBC (2.3%) and trivially negative for ILL, LLB and NCNR. HFIR and LANSCE exhibited pronounced average yearly growth on this metric, with results of 30% and 12.4% respectively.

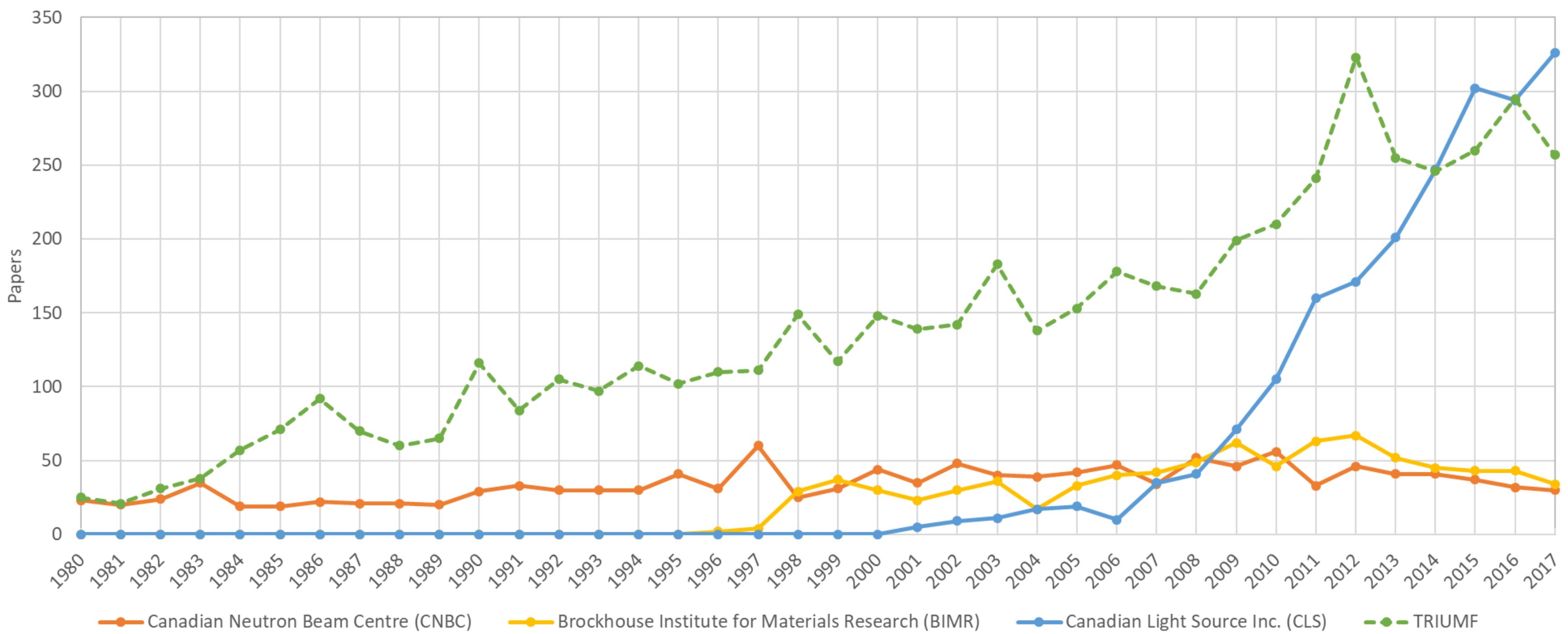

Figure 1 Publication output for the Canadian Neutron Beam Centre (CNBC) and comparable Canadian institutions, 1980–2017

Note: The total number of papers is based on institutional addresses and lists of papers (for CNBC) as data for funding acknowledgements are only widely available as of 2008 and abstract texts are only widely indexed after 1991. The scales of the vertical axes differ for Figure 1 and Figure 2.

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

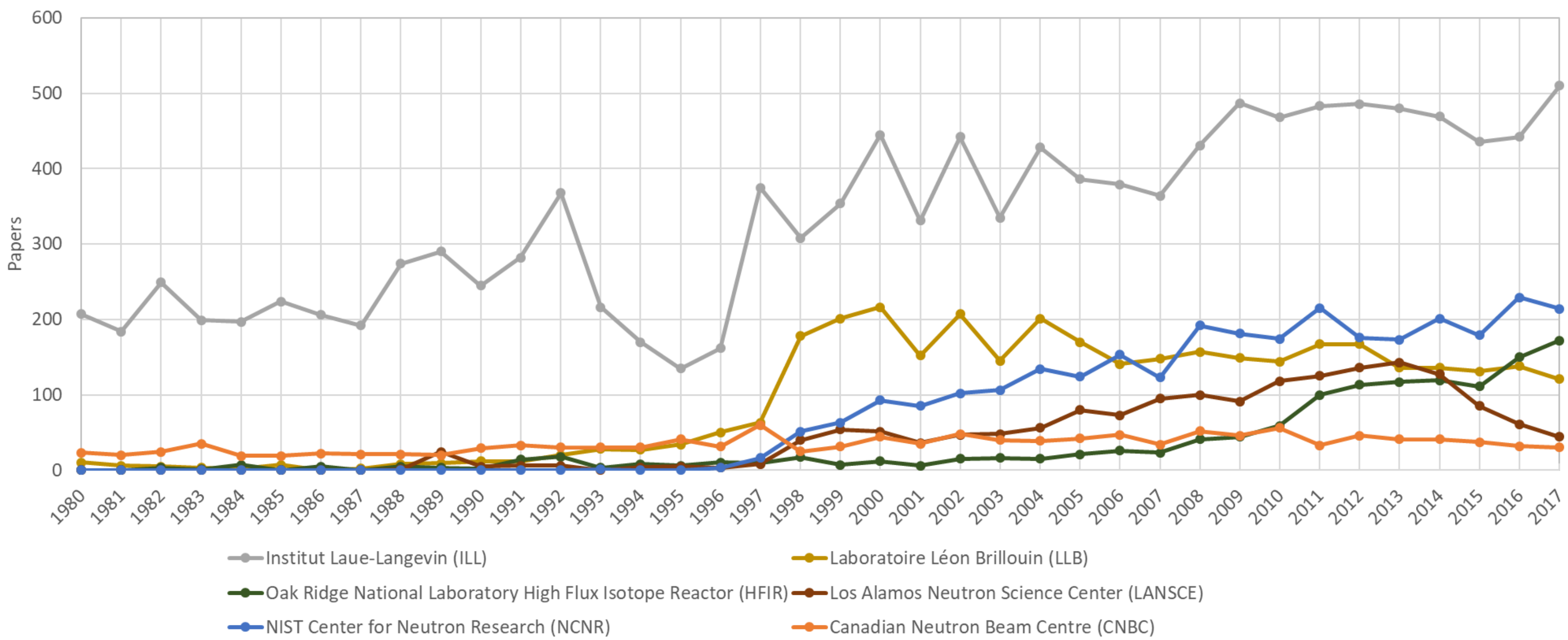

Figure 2 Publication output for the Canadian Neutron Beam Centre (CNBC) and comparable international institutions, 1980–2017

Note: The total number of papers is based on institutional addresses and lists of papers (for CNBC and HFIR) as data for funding acknowledgements are only widely available as of 2008 and abstract texts are only widely indexed after 1991. A much larger number of papers were identified for LANSCE in 1989 relative to the years before and after; to maintain an accurate comparison between institutions, this anomalous data point was removed from the analysis. The scales of the vertical axes differ for Figure 1 and Figure 2.

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

2.1.2 Distribution of output across subfields

While total output volumes are interesting, they are often usefully complemented by a finer-grained analysis that divides them into specific thematic areas. To support such analyses, Science-Metrix created and maintains a three-level taxonomy of research,[4] assigning each journal in the WoS to one of 6 domains, 22 fields and 176 subfields.

Of those 176 subfields, the research produced by the CNBC fell into 30 of them. Of its total of about 1,300 papers, the largest share was found in the subfield of Applied Physics (369 publications; nearly 30% of the CNBC's output), followed by General Physics (210; over 15%), Materials (163; nearly 15%), Chemical Physics (103; about 8%), Inorganic & Nuclear Chemistry (96; over 7%) and Fluids & Plasmas (82; over 6%; CNBC publications in the Fluids & Plasmas category are published in a small number of condensed matter physics journals that Science-Metrix' ontology includes in this subfield). Together, these six categories account for almost 80% of all publications associated with the CNBC. The remaining subsets of publications were associated with speciality projects that make use of CNBC equipment and infrastructure. There were 69 publications (about 5%) that fell into the Science-Metrix domain of the Health Sciences, for example. Other subsets of research papers contributed to the subfields of Geochemistry & Geophysics, Mining & Metallurgy, Mechanical Engineering & Transports, and Polymers, each of which accounted for fewer than 25 papers from the CNBC.[5]

2.1.3 Top CNBC users' output

Output figures at the individual researcher level show that a core list of scientists made regular use of CNBC instruments. Many of these were affiliated with McMaster University and accounted for notable portions of the CNBC publication portfolio; these were John Greedan (67 CNBC publications), Bruce Gaulin (56), Luke Graeme (29), and Maikel Rheinstaedter (22). Other frequent users of CNBC facilities with high publication outputs included Dominic Ryan (McGill; 55); Thad A. Harroun (Brock; 41); J.M. "Sean" Cadogan (at the University of Manitoba at the time of CNBC usage, now at University of New South Wales, Australia; 36 CNBC publications); Chris Wiebe (University of Winnipeg, 26); Comondore "Ravi" Ravindran (Ryerson; 16); and David Mitlin (previously with the University of Alberta, now at Clarkson; 14).

For some partners, CNBC-based research accounted for as much as a third or more of their total publications; these were Thad A. Harroun (Brock University), Maikel Rheinstaedter (McMaster), Comondore Ravindran (Ryerson University), Jeremy P. Carlo (previously at McMaster and now at Villanova University, Philadelphia), Jianjun Pan (South Florida University), Soo Yeol Lee (previously at the University of British Columbia, now at Chungnam National University, South Korea), and Drew Marquardt (University of Windsor).

The CNBC also attracted highly prolific researchers with personal publication records of 150 papers or more: the aforementioned John Greedan, Bruce Gaulin and Luke Graeme (each from McMaster; 285,

[4] http://science-metrix.com/classification

[5] Full details for this thematic analysis are provided in the companion databook.

194, and 283 papers, respectively); Dominic H. Ryan (McGill; 258); J.M. Cadogan (now at University of New South Wales; 217); Y.J. Uemura (Columbia; 278); and Haidong Zhou (University of Tennessee, Knoxville; 192).

Finally, in terms of temporal distribution of CNBC-associated publications from these top users, most of them appear to have maintained rather constant involvement with the Centre, rather than having engaged in ad hoc or sporadic projects. In other words, CNBC publications from these authors were distributed quite evenly year over year in the full period under consideration, including in recent years, rather than appearing in occasional bursts of activity that might be associated with short-term projects.

2.2 Citation impact

While scholarly impacts of scientific research are complex processes, measuring citations made to scientific publications by other scholarly papers is the best approach currently available to capture those phenomena. Several indicators of citation impact are applied here. The average of relative citations (ARC) shows how often an institution's or researcher's papers are cited, normalized for subfield and year of publication. The indicator is normalized to 1.0, which represents the world level; a score of 1.2 would mean that the papers are cited 20% more than the world level, whereas a score of 0.8 would mean that the papers are cited 20% less than the world level.

Citation distributions are very skewed, however, with the most-cited documents receiving the vast majority of total citation attention. Accordingly, averages based on low numbers of papers may be very affected by a relatively small number of very cited papers. While the average remains an important intuitive tool, it is complemented here by two further indicators. The first assesses contributions to the 10% most highly cited papers worldwide ($HCP_{10\%}$), as a share of an institution's or researcher's total portfolio. At the world level, 10% of papers fall into this top decile of HCP (by definition), and placing more than 10% of one's publication output in this elite set means that one is contributing more than expected to the most influential research worldwide.

The second indicator used to complement the ARC is the citation distribution index (CDI). Whereas the $HCP_{10\%}$ examines contributions to the most impactful decile, the CDI considers contributions to each decile, and then integrates these contributions into a single score. While it is difficult to offer an intuitive interpretation of one score's meaning, it is worth noting that the CDI is very robust even in cases of smaller sample sizes and highly skewed distributions; it is thus highly valuable for ranking. It is also a valuable numerical aid for experts in interpreting the accompanying citation distribution charts (CDCs). The CDI score ranges from -50 (theoretical minimum, seldom seen in practice) to -25 (a very low score that one might actually observe) to 0 (the world level) to 25 (a very high score that one might actually observe) to 50 (theoretical maximum, seldom seen in practice).

Finally, while the ARC, $HCP_{10\%}$ and CDI all offer views of paper-level impact, the average of relative impact factors (ARIF) shows the average visibility or influence within the scholarly community of the journals in which an institution or researcher publishes. Like the ARC, the ARIF is normalized by subfield and year. The indicator is normalized to 1.0, which represents the world level; a score of 1.2 would mean that the papers appear in journals that are 20% more influential than the world level, whereas a score of 0.8 would mean that the papers appear in journals that are 20% less influential than the world level.

2.2.1 Overview of citation impact

Table III and Table IV provide summary findings on citation metrics for the CNBC and the eight comparators, for the periods 1980–2017 and 2000–2017. The second table provides slightly different results, given that data sets on citations are incomplete for many organizations before 2000. After an initial overview, the current section presents longitudinal trends for the $HCP_{10\%}$ and ARIF indicators. The section ends with a consideration of citation profiles by subfields of activity.

The citation profiles presented in Table III differ markedly from the findings analyzed above for publication output. Centres that were associated with high publication volumes were found to have publications of less impact than other institutions from the comparators sample. This was clearly the case for ILL and LLB, which occupied top and middle positions in output but bottom positions in citation impact. These two institutions obtained $HCP_{10\%}$ scores of 11.7% and 10.5% respectively, while their CDI scores were 8 and 6. Taken together, these two indicators show that these two institutions contributed slightly more than their expected share of papers to the most cited worldwide, but that overall their performance is only slightly higher than the global trend. TRIUMF and CLS also showed marked differences in output and citation profiles, and found themselves in the middle of the pack for citation impact after recording high publication output volumes.

A group of institutions appear to be associated with smaller output volumes but higher quality publications. This group included BIMR, HFIR and the CNBC. With a score of 15.9%, the CNBC was in the top half of the comparator sample for $HCP_{10\%}$. For the CDI, the Centre was positioned right in the middle of the sample in terms of absolute ranking (with a score of 11), although the CNBC was part of a cluster of four organizations with very close scores; this group of comparators to which the CNBC belonged was distinctly ahead of the cluster of organizations that followed, whose CDIs stood between 6 and 9.

There was one exception to the trends sketched above. The NCNR came in third in publication output volume, and came first by a wide margin for all citation indicators (including an $HCP_{10\%}$ score of 22.6% and a CDI of 17).

Findings from a more recent period—2000 to 2017, presented in Table IV—tended to be quite comparable to those obtained for the full study period. The CNBC gained a rank on the $HCP_{10\%}$ metric in the more recent period, but otherwise its relative position remained the same for other impact indicators. Rankings for all comparators remained generally unchanged between periods for the ARIF, and for the ARC of internationally co-authored papers.

Table III Citation impact of selected comparable institutions (1980–2017)

Institution	ARC	ARC int'l	ARIF	CDI	CDC	$HCP_{10\%}$
Canadian Neutron Beam Centre (CNBC)	1.31	1.51	1.33	11		15.9%
Brockhouse Institute for Materials Research (BIMR)	1.52	1.59	1.38	13		18.2%
Canadian Light Source Inc. (CLS)	1.50	1.82	1.36	9		15.3%
TRIUMF	1.48	1.76	1.24	12		14.6%
Institut Laue-Langevin (ILL)	1.15	1.11	1.23	8		11.7%
Laboratoire Léon Brillouin (LLB)	1.06	0.99	1.21	6		10.5%
Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR)	1.48	1.73	1.24	12		17.2%
Los Alamos Neutron Science Center (LANSCE)	1.32	1.31	1.24	9		14.6%
NIST Center for Neutron Research (NCNR)	1.94	2.02	1.44	17		22.6%

Note: Colour coding for impact indicators varies from red (below the world level) to white (on par with the world level) to green (above the world level). "ARC int'l" is the ARC score for papers that involved a collaborator from at least one other country.
Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

Table IV Citation impact of selected comparable institutions (2000–2017)

Institution	ARC	ARC int'l	ARIF	CDI	CDC	$HCP_{10\%}$
Canadian Neutron Beam Centre (CNBC)	1.39	1.58	1.35	11		17.3%
Brockhouse Institute for Materials Research (BIMR)	1.48	1.61	1.38	13		17.1%
Canadian Light Source Inc. (CLS)	1.50	1.82	1.36	9		15.3%
TRIUMF	1.73	1.95	1.28	13		16.9%
Institut Laue-Langevin (ILL)	1.03	1.04	1.26	6		10.2%
Laboratoire Léon Brillouin (LLB)	1.06	1.01	1.24	6		10.3%
Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR)	1.57	1.79	1.27	13		18.6%
Los Alamos Neutron Science Center (LANSCE)	1.30	1.25	1.24	9		14.5%
NIST Center for Neutron Research (NCNR)	1.95	2.05	1.45	17		22.7%

Note: Colour coding for impact indicators varies from red (below the world level) to white (on par with the world level) to green (above the world level). "ARC int'l" is the ARC score for papers that involved a collaborator from at least one other country.
Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

When shifting from a focus on the whole study period to these more recent years, some reshuffling took place within subsets of organizations, notably on the ARC and CDI indicators. One cluster was made up of the BIMR, CLS, HFIR and TRIUMF, towards the top positions; the second cluster included LANSCE, ILL and LLB towards the lower rankings. There was some minor jockeying of positions within the groups on various indicators, but no institution jumped from one group to the other when shifting focus from the whole period to the more recent one.

2.2.2 Longitudinal analyses

Table V below presents longitudinal data for the $HCP_{10\%}$ scores. These scores are especially interesting as they capture those papers that achieve long-lasting uptake within the broader community and contribute to an institute's recognition. These data show that the CNBC's citation impact performance went through swings in the 1990s and early 2000s before stabilizing in the two most recent periods. Capacity for producing high-impact papers appears to have slowly decreased over time at ILL and LLB. TRIUMF, in contrast, saw a sharp increase in its portion of $HCP_{10\%}$ papers in the recent period, after 25 years of steady figures between 10% and 12% within the $HCP_{10\%}$.

A longitudinal look at ARIF scores (Table VI) shows that the CNBC posted the top performances within the group of comparators for most periods examined. Only the most recent period, covering papers published between 2010 and 2015, found the Centre slipping in ranking. This slip in ranking resulted from a slight decrease in ARIF at the CNBC, along with sharp gains by almost all other centres. NCNR and the BIMR remained strong performers on this indicator throughout the period. TRIUMF showed wide swings from one period to another (in contrast to its relatively stable $HCP_{10\%}$ scores, which increased sharply in recent years). HFIR, which had strong if uneven $HCP_{10\%}$ scores, shows rather modest ARIF scores in contrast, especially in the 1992–1997 and 1998–2003 periods.

Appendix A presents additional longitudinal graphs on citation impact metrics, including the ARC, the ARIF, the CDI and the $HCP_{10\%}$. These figures were obtained by using three-year moving windows instead of multi-year intervals, therefore offering slightly different perspectives on impact for ARIF and $HCP_{10\%}$ then those reported above. Taken together, these graphs show peak performances by CNBC on citation impact around the year 2000, and citation impacts that are constantly slightly to distinctly above average.

Table V Longitudinal analysis of the $HCP_{10\%}$ of selected comparable institutions (1980–2015)

Institution	1980-2017	1980-1985	1986-1991	1992-1997	1998-2003	2004-2009	2010-2015
Canadian Neutron Beam Centre (CNBC)	15.9%	11.8%	21.0%	10.0%	19.9%	15.7%	17.0%
Brockhouse Institute for Materials Research (BIMR)	18.2%	N/A	N/A	N/C	20.5%	17.8%	16.3%
Canadian Light Source Inc. (CLS)	15.3%	N/A	N/A	N/A	N/C	14.2%	15.7%
TRIUMF	14.6%	10.4%	10.3%	10.1%	10.7%	12.2%	22.3%
Institut Laue-Langevin (ILL)	11.7%	15.1%	13.8%	12.3%	12.1%	8.9%	10.8%
Laboratoire Léon Brillouin (LLB)	10.5%	21.2%	18.6%	7.9%	10.8%	10.8%	9.7%
Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR)	17.2%	N/A	N/C	11.1%	4.1%	11.7%	21.5%
Los Alamos Neutron Science Center (LANSCE)	14.4%	N/A	N/C	N/C	15.3%	12.5%	15.8%
NIST Center for Neutron Research (NCNR)	22.6%	N/A	N/A	N/C	23.3%	22.1%	22.9%

Note: $HCP_{10\%}$ scores are not presented for periods where fewer than 30 papers with a relative citation score were identified (indicated as "N/C"). "N/A" refers to cases where no papers were identified. Colour coding varies from red (below the world level) to white (on par with the world level) to green (above the world level).

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

Table VI Longitudinal analysis of the ARIF indicator score of selected comparable institutions (1980–2015)

Institution	1980-2017	1986-1991	1992-1997	1998-2003	2004-2009	2010-2015	2016-2017
Canadian Neutron Beam Centre (CNBC)	1.33	1.33	1.23	1.45	1.40	1.33	1.02
Brockhouse Institute for Materials Research (BIMR)	1.38	N/A	N/C	1.25	1.33	1.52	1.28
Canadian Light Source Inc. (CLS)	1.36	N/A	N/A	N/C	1.06	1.36	1.44
TRIUMF	1.24	1.10	1.05	1.37	1.11	1.39	1.24
Institut Laue-Langevin (ILL)	1.23	1.28	1.06	1.18	1.18	1.34	1.32
Laboratoire Léon Brillouin (LLB)	1.21	1.32	1.00	1.13	1.28	1.27	1.27
Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR)	1.24	N/C	0.82	0.89	1.17	1.33	1.28
Los Alamos Neutron Science Center (LANSCE)	1.24	N/C	N/C	1.18	1.26	1.28	1.07
NIST Center for Neutron Research (NCNR)	1.44	N/A	N/C	1.41	1.42	1.47	1.48

Note: Relative journal impact factors are only available from the year 1985 onwards, and therefore scores have been omitted for the 1980–1985 period. ARIF scores are not presented for periods where fewer than 30 papers with a relative impact factor score were identified (indicated as "N/C"). "N/A" refers to cases where no papers were identified. Colour coding varies from red (below the world level) to white (on par with the world level) to green (above the world level).

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

2.2.3 Citation profiles by subfield

The CNBC subfields of activity and publication have not all contributed equally to the Centre's citation impact figures. There are three subfields that appear to be the primary drivers of the CNBC's impact scores: Applied Physics, Materials and Biophysics. The CNBC had a very high proportion (24.3%) of its Biophysics papers in the top 10% most highly cited papers for the subfield. Its output in the subfield also had strong CDI (14) and very strong ARC (1.8) scores. The group of papers in the Applied Physics subfield pulled CNBC scores upwards for the $HCP_{10\%}$ (19.8% of papers), the CDI (13) and the ARC (1.5). The papers in the Materials subfield also pulled the Centre's scores upward, especially for the CDI (at 18). A high CDI score—considering that it measures overall contributions across all impact deciles—suggests that Materials research teams using the CNBC reached a very high degree of consistency in research quality, whereas in other subfields the teams at the CNBC might not have been as consistent in their overall quality, even if they succeeded in producing a roughly equal share of their papers among those that are the most highly cited.

Publications within the tail end of subfields accounting for fewer than 30 papers each lagged behind the average citation impact scores at the CNBC, especially on the $HCP_{10\%}$ indicator (10.0% of papers in those subfields, rather than the 15.9% aggregated figure for all subfields for the 1980 to 2017 period). There were two other subfields for which citation data were robust and where findings indicated weaker performances. One was Nuclear & Particle Physics, where all citation indicators were well under the Centre's aggregated figures. Papers associated with these citation figures, were published for the most part before 2000. The other was Fluids & Plasmas, where ARC (1.4) and ARIF (1.9) scores were high but CDI (11) and $HCP_{10\%}$ (10.5%) scores were slightly below the CNBC's aggregated findings. Research results from this area were published in journals with high impact factors on average, but the papers themselves did not systematically achieve commensurate uptake from colleagues in the research community.

2.2.4 Note on top users' citation profiles

A final component of the impact assessment of the CNBC might have been provided by analyzing performances on this dimension by its top external users. However, only five of these top users had 30 or more papers related to their work with the CNBC; Science-Metrix strongly cautions against the use of impact indicators that are computed on the basis of fewer than 30 data points, and therefore will not present a researcher-level analysis here.

However, if it is absolutely necessary for the CNBC to report on researcher-level data, Science-Metrix strongly recommends using their full publication portfolio (across all years, and not only limited to their CNBC-affiliated papers), to ensure the largest possible underlying data set. Findings should be interpreted with caution, used in conjunction with other lines of evidence (including non-bibliometric evidence), and used to inform rather than to replace expert judgement. Furthermore, impact indicators based on fewer than 10 data points should not be used in any cases whatsoever; for this reason, Science-Metrix does not provide them in the companion databook.[6]

2.3 Collaborations and co-authorship

International and intersectoral collaborations are valued because they often lead to more impactful research, whether in purely scientific terms or when assessing the broader societal uptake of scientific projects.[7] In the present study, collaboration is measured through co-authorship of research articles, looking specifically at institutions' shares of publications that are produced in these collaborations.

Table VII below presents summary findings on both international and intersectoral co-authorship for the CNBC and the eight comparators. International collaboration is defined as the share of papers with at least one co-author affiliated with an institution from outside the country in which the institution in question is located. Intersectoral collaborations were calculated on the basis of the addresses appearing on a paper associated with a given institution. Collaborations with a "parent" institution (e.g., NIST for the NCNR) were excluded from a given institution's collaborations. This was only possible where we were able to successfully identify an address for a given institution. In cases where an address was not available, all intersectoral collaborations were included. Academic co-publications include at least one co-author affiliated with a university. Private co-publication is defined as including a co-author from a firm or other for-profit organization in the private sector. The "public" category includes governmental agencies and non-university, government-financed research centres. The "other" category includes research hospitals, public–private research consortia or multilateral research centres, including many EU-financed institutions.

Table VII Collaboration patterns of selected comparable institutions (1980–2017)

Institution	Papers	International collaboration	Intersectoral collaboration			
			Academic	Private	Public	Other
Canadian Neutron Beam Centre (CNBC)	1,307	51.8%	75.5%	4.1%	31.6%	6.0%
Brockhouse Institute for Materials Research (BIMR)	827	48.7%	59.4%	3.5%	31.9%	13.3%
Canadian Light Source Inc. (CLS)	2,024	55.3%	94.5%	5.0%	34.2%	5.1%
TRIUMF	5,333	74.6%	83.1%	4.0%	57.5%	31.6%
Institut Laue-Langevin (ILL)	12,639	73.0%	66.9%	1.9%	56.3%	8.6%
Laboratoire Léon Brillouin (LLB)	3,503	60.6%	61.0%	0.9%	43.5%	5.9%
Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR)	1,278	42.8%	74.6%	4.5%	48.7%	3.2%
Los Alamos Neutron Science Center (LANSCE)	1,672	45.4%	72.0%	5.7%	49.3%	5.3%
NIST Center for Neutron Research (NCNR)	2,988	52.0%	88.7%	7.4%	50.8%	2.5%

Note: Colour coding varies from white (below the world level) to green (above the world level).
Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

2.3.1 International collaborations

Examining international collaborations first, TRIUMF and ILL took the top rankings on the share of papers written by authors from at least two countries. It is well known that ILL hosts a very high number

[6] Impact indicators based on fewer than 30 data points are flagged in the companion databook. For more details on the responsible use of metrics, consult the Leiden Manifesto: http://www.leidenmanifesto.org/.

[7] Struck, D. B., Roberge, G., & Campbell, D. (2017). The influence of open access, gender and co-authorship on citation scores. Presented at the Science, Technology & Innovation (STI) Indicators 2017, Paris, France. Retrieved from https://sti2017.paris/wp-content/uploads/2017/11/oa-db-struck-et-al.pdf.

of foreign guest scientists every year, and therefore this figure is not surprising. TRIUMF also entrusts research group leadership to many academics abroad, which is evidently leading to a greater share of its publications being international co-authorships.

The CNBC was positioned within a cluster of institutions with rates of international collaboration falling between 48% and 52%. US facilities tended to fall within the lower half of the rankings, a consequence perhaps of the size of the national community of researchers and increased possibility for intranational collaborations that this size brings. This finding is consistent with broader patterns for US research, observed regularly across most if not all thematic areas.

In Table VII, one can also observe that the centres with higher rates of international collaboration seem to be those with higher publication output volumes. Many of the highly collaborative centres fell within the lower positions of the impact analysis (see § 2.2). This is an unexpected finding, given that international co-publications are known within the bibliometric community to tendentially receive more citations than papers that involve only domestic partners (or no co-authorship at all).

A longitudinal analysis of international collaboration showed a general increase in international co-publication rates from the 1980s onwards, a finding that is consistent with broader global patterns in this thematic area as well as in most others. Additionally, the longitudinal analysis showed some jockeying within the rankings among the comparator institutions. In particular, Table VIII reveals a noteworthy acceleration in the international collaboration rate of the CNBC starting in the 1998–2003 period. Between 1980 and 1997, 22% to 37% of the Centre's publications were published with a co-author abroad, but starting in 1998, these rates were often as high as 65%–70%. Compared to the ordering obtained over the full 1980–2017 period, the CNBC moved up three ranks in international collaboration in the two most recent periods (2010–2015 and 2016–2017).

Comparators' trajectories were otherwise steadily increasing or stable from 1998 to 2017. TRIUMF and ILL remained the comparators with the highest rates of international co-publication in recent years and have indeed consolidated their strengths in this area, respectively attaining international collaboration rates of 90% and 88% in 2016–2017. US institutions, on the other hand, continued to post comparatively lower shares of international co-publications, even in the most recent period studied.

Table VIII Longitudinal analysis of international collaboration of selected comparable institutions (1980–2017)

Institution	1980-2017	1980-1985	1986-1991	1992-1997	1998-2003	2004-2009	2010-2015	2016-2017
Canadian Neutron Beam Centre (CNBC)	51.8%	22.1%	32.2%	36.5%	65.5%	56.9%	71.3%	69.4%
Brockhouse Institute for Materials Research (BIMR)	48.7%	N/A	N/A	0%	49.7%	41.6%	52.2%	58.4%
Canadian Light Source Inc. (CLS)	55.3%	N/A	N/A	N/A	56.0%	45.1%	54.1%	60.6%
TRIUMF	74.6%	32.1%	46.4%	59.3%	79.0%	77.8%	86.4%	90.4%
Institut Laue-Langevin (ILL)	73.0%	36.0%	48.4%	59.0%	82.6%	85.1%	86.0%	88.4%
Laboratoire Léon Brillouin (LLB)	60.6%	18.2%	41.9%	49.5%	63.4%	64.0%	57.5%	64.9%
Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR)	42.8%	0%	0%	13.0%	58.9%	41.2%	42.8%	50.3%
Los Alamos Neutron Science Center (LANSCE)	45.4%	N/A	11.1%	46.2%	40.9%	41.6%	48.8%	53.3%
NIST Center for Neutron Research (NCNR)	52.0%	N/A	N/A	45.0%	45.6%	51.0%	54.7%	54.6%

Note: "N/A" refers to cases where no papers were identified. Colour coding varies from white (below the world level) to green (above the world level).

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

Examining the top 24 individual users of CNBC facilities provides additional insight into international collaboration practices at the CNBC.[8] Of these top users, 12 are now affiliated with Canadian universities, 9 are affiliated with US universities, and one each are affiliated with either an Australian, Slovakian or South Korean institution (having moved in some cases from a previous position at a Canadian university).

Examining top institutional partners abroad,[9] CNBC-affiliated scientists co-published 189 papers with US Department of Energy (DOE) researchers; 95 with US Oak Ridge National Laboratory researchers;[10] 60 with US National Institute of Standards and Technology (NIST) scientists; and 55 with UK Science and Technology Facilities Council (STFC) colleagues. The NIST and STFC findings may indicate partnerships with NCNR and with the ISIS neutron beam facilities, respectively. In other words, these results seem to suggest a high degree of collaboration within the neutron beam community on projects combining work from different facilities. The CNBC was the clear Canadian entry point into this community of collaborators.

DOE was a frequent collaborator for all institutions included in the sample. Frequent partners for other institutions in the sample included the University of Chicago (a partner for five of the comparators, with a range of 77 to 1,381 co-publications) and the German Helmholtz network of laboratories dedicated to infrastructure-intensive science (a frequent partner for four of the comparators, with co-publications counts ranging from 55 to 1,365 articles).

2.3.2 Intersectoral collaborations

Turning now to intersectoral collaborations (also presented in Table VII), CNBC researchers appear to have oriented their collaborations mainly towards universities and other academic centres. More than 75% of publications by CNBC-affiliated researchers also included a university-affiliated researcher among the authors list. On this indicator, the CNBC found itself within a middle tier among the comparators, one that also included LANSCE and HFIR. Almost all papers linked to CLS involved some academic collaboration (95%). TRIUMF and NCNR publication portfolios were also to large extents academic co-publications (83% and 89%, respectively).

In terms of the share of papers published with a co-author in the private sector, the CNBC positioned itself right in the middle of the pack on this indicator, with 4% of its papers written in such a collaboration. The NCNR obtains the highest score here with over 7% of its article records made up of co-publications with private organizations. Looking at the lower end, one finds the two French organizations, with rates of just under 2% for ILL and under 1% for LLB. It should be noted as a potential caveat of this indicator that not all partnerships between firms and research centres lead to WoS-indexed peer-reviewed publications. Co-authorship is but one measure of collaboration, and in the case of collaboration with private sector entities, if those collaborations do not lead to published papers (or if there is a difference

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8 These figures are not presented here. Please refer to the databook.

9 These figures are not presented here. Please refer to the databook.

10 It was not possible for Science-Metrix to verify whether these were HFIR researchers specifically.

in practice regarding inclusion within the authors list), then the indicator applied here will be telling only a partial story.

Looking at collaboration with researchers affiliated with government agencies or public research centres, the CNBC was the comparator with the lowest share of its articles co-published with such researchers; over the 1980–2017 period, 31.6% of its papers were co-published with the public sector. The Centre is joined by two other Canadian organizations at the bottom end of the ranking: the BIMR (31.9%) and CLS (34.2%). Such findings might suggest that conditions specific to the Canadian context could be hindering these collaborations; however, such a hypothesis is challenged by the fact that TRIUMF placed in the top position among the comparators for public sector collaboration (having written 57.5% of its papers in co-publication with public organizations).

Some institutions did not fit neatly into the sectoral taxonomy laid out above; placed in the "other" category, these institutions included research hospitals, public–private research consortia or multilateral research centres (including many EU institutions such as ILL, CERN or the European Molecular Biology Laboratory). Many of the institutions coded as "other" are found in Europe or in the United States. Given the heterogeneity within this category, it is more difficult to draw meaningful conclusions here. Nonetheless, it is noted that TRIUMF published the highest share of papers in collaboration with "other" sector organizations (31.6% of its papers). The BIMR made the other noteworthy showing, with 13.3% of papers co-authored with this category. The CNBC held the fourth position on this metric. Closing the ranking were the US comparators.

It should be noted that figures for shares of intersectoral collaboration are not mutually exclusive. For example, a CNBC paper co-authored between CNBC staff scientists, a university-based scientist, a firm-based scientist and a National Research Council Canada-based scientist will count in the shares of academic, private and public papers.

It is worthwhile to take more fine-grained longitudinal perspectives on intersectoral collaborations with academic and private organizations. Aggregate findings on these dimensions somewhat mask interesting dynamics in recent periods. Table IX shows sharp increases, across all institutions, in the rates of papers counting as co-publications written with academic collaborators. The CNBC, which shows the fourth highest share of papers written as academic co-publications, came in first on this score in the 2004–2009 period and third in the 2010–2015 and 2016–2017 periods.

In terms of papers written in co-publication with private sector authors, the CNBC also had much higher shares in the recent period than in the full 1980–2017 period, as shown in Table X. For the years 2016 and 2017, the CNBC had a share of 11.3% of papers written as private sector co-publications. This score is the highest recorded across institutes and periods, although it remains, of course, provisional. The CNBC's 2010–2015 share of 5.9% was also the highest seen in this period. Rates of private sector co-publications for all institutions generally show wide swings from one period to the next, making the isolation of any long-term trend difficult.

Table IX Longitudinal analysis of intersectoral collaboration with academic organizations of selected comparable institutions (1980–2017)

Institution	1980-2017	1980-1985	1986-1991	1992-1997	1998-2003	2004-2009	2010-2015	2016-2017
Canadian Neutron Beam Centre (CNBC)	75.5%	47.1%	52.7%	59.0%	83.0%	88.5%	94.9%	91.9%
Brockhouse Institute for Materials Research (BIMR)	59.4%	N/A	N/A	16.7%	49.7%	52.3%	70.9%	61.0%
Canadian Light Source Inc. (CLS)	94.5%	N/A	N/A	N/A	88.0%	87.0%	95.1%	95.8%
TRIUMF	83.1%	44.4%	57.1%	65.7%	86.0%	88.2%	95.2%	95.8%
Institut Laue-Langevin (ILL)	66.9%	31.7%	38.8%	47.1%	74.0%	78.1%	85.4%	87.3%
Laboratoire Léon Brillouin (LLB)	61.0%	15.2%	41.9%	49.1%	60.0%	60.8%	64.8%	72.2%
Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR)	74.6%	N/A	3.4%	22.2%	50.7%	70.6%	83.5%	82.6%
Los Alamos Neutron Science Center (LANSCE)	72.0%	N/A	16.7%	57.7%	64.5%	72.1%	77.2%	77.1%
NIST Center for Neutron Research (NCNR)	88.7%	N/A	N/A	65.0%	83.6%	86.2%	92.3%	91.4%

Note: "N/A" refers to cases where no papers were identified. Colour coding varies from white (below the world level) to green (above the world level).
Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

Table X Longitudinal analysis of intersectoral collaboration with private organizations of selected comparable institutions (1980–2017)

Institution	1980-2017	1980-1985	1986-1991	1992-1997	1998-2003	2004-2009	2010-2015	2016-2017
Canadian Neutron Beam Centre (CNBC)	4.1%	0.7%	3.4%	2.7%	6.3%	2.3%	5.9%	11.3%
Brockhouse Institute for Materials Research (BIMR)	3.5%	N/A	N/A	N/A	7.0%	3.3%	1.9%	2.6%
Canadian Light Source Inc. (CLS)	5.0%	N/A	N/A	N/A	8.0%	2.1%	5.1%	5.8%
TRIUMF	4.0%	0.8%	2.7%	1.4%	2.5%	8.1%	4.2%	3.6%
Institut Laue-Langevin (ILL)	1.9%	1.0%	3.2%	3.0%	1.5%	1.1%	2.0%	1.6%
Laboratoire Léon Brillouin (LLB)	0.9%	N/A	N/A	4.5%	0.8%	0.7%	0.7%	N/A
Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR)	4.5%	N/A	3.4%	11.1%	5.5%	0.6%	5.0%	4.7%
Los Alamos Neutron Science Center (LANSCE)	5.7%	N/A	N/A	3.8%	5.4%	6.3%	5.7%	6.7%
NIST Center for Neutron Research (NCNR)	7.4%	N/A	N/A	N/A	10.4%	7.8%	5.5%	8.4%

Note: "N/A" refers to cases where no papers were identified. Colour coding varies from white (below the world level) to green (above the world level).
Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

As for intersectoral collaborations put in place with the top external users, most are currently affiliated with universities (22 out of 24). The remaining two users are with the Oak Ridge National Laboratory.

The CNBC's top 10 most frequent collaborating institutions included six universities (with a sum of 579 co-publications) and the previously mentioned four public organizations (399 total co-publications): the US DOE, the Oak Ridge National Laboratory, the US NIST and the UK STFC. The top academic partners were McMaster University (230 co-publications) and McGill University (84).

Examining findings for comparators, one can see CLS' co-publications with its top 10 most frequent collaborators were highly concentrated, with the largest share co-published with the University of Saskatchewan (642 publications from a total of 1,749 for its group of frequent collaborators). ILL also published a large subsection of its co-publications with the French CNRS, although the CNRS is really a network of institutions rather than a single institution. No private organizations (either for-profit or not-for-profit) placed among the top 10 most frequent collaborators, for the CNBC or any of the comparators featured in this study. Only one institution that falls in the "other" category placed among the most frequent collaborators: the European Synchrotron Radiation Facility, which collaborated with ILL and LLB.

3 Conclusion

The range of findings presented in the previous sections show the material sciences and applied physics ecosystem to be composed of widely differing institutions, each with distinct bibliometric profiles. ILL is the archetypal big science centre for the neutron-scattering community, with high numbers of users, collaborations and networks, and high numbers of publications. It is by far the largest facility included in this study, with substantial resources and capacities at its disposal. Despite the large volumes of publications such resources and capacities allow, ILL papers tended to achieve only average to low impact scores during the study period. The NCNR is another central player in the specialty, and the only institution examined to have displayed consistently high performances across most indicators.

The CNBC was the smallest facility examined as part of this study. Given these starting conditions, the CNBC made clear contributions to the scientific and industrial subfields where it was active.

The CNBC's absolute publication output was small, taken in the context of the interorganizational comparison. ILL published, on average, almost 10 times as many papers per year as the CNBC. While most of its output was concentrated in the expected core research areas of Applied Physics, General Physics and Materials research, significant publication subsets were also retrieved in subfields as varied as Polymers or Geochemistry and Geophysics.

CNBC publications appear to have been of consistently average to high quality, as measured with citation-based indicators. CNBC papers were published in reputable journals, and the institution achieved either top-tier or top-half ARIF scores within the sample (publishing in journals 35% more cited than the world average for the 1980–2017 period). The CNBC also fluctuated between the 3rd and 4th ranks for the $HCP_{10\%}$ indicator, which captures some of the most significant and remarkable publications in a given field. CNBC publications fell within this category of highly cited papers 50% more than the world average for the 1980–2017 period. The CNBC was situated in the middle rankings for the other citation indicators. CNBC performances on citation indicators were exceeded by the NCNR, which consistently scored distinctly above all other institutions in the sample. Close competitors of the CNBC on these indicators were BIMR, CLS and HFIR.

Citation performances examined by subfields show the CNBC to have had especially strong outcomes in Applied Physics and Materials, but also, and perhaps more surprisingly, in Biophysics. In the latter field, 24.3% of CNBC publications achieved $HCP_{10\%}$ levels of citation. The shares of papers achieving such a status were almost two times above world average in the Applied Physics (19.8%) and Materials (19.2%) subfields.

The CNBC sharply accentuated its engagement in international collaborations over the last 20 years of the study period, a trend that is masked in the aggregate 1980–2017 figures. It tended towards deep collaborations characterized by at least 10 joint publications. CNBC scientists maintained networks, exchanges and joint projects with major international institutions in the neutron beam field. The list of frequent partners includes US DOE research teams (189 co-publications), US Oak Ridge National Laboratory teams (95 joint publications), US NIST centres (60 co-publications) and UK STFC research centres (55 co-publications).

Finally, the CNBC showed sustained intersectoral collaborations with the private sector, especially in the Canadian context. The three US comparators exceeded all other institutions in rates of co-publications with the private sector, while the CNBC ranked ahead of TRIUMF and the BIMR on this indicator, and was surpassed by CLS. The CNBC had, however, shown the highest shares of private co-publications in the sample for the 2010–2015 and 2016–2017 periods.

Turning now a more historical and longitudinal perspective, the early period covered in this report, from 1980 to 1998, was shaped by the generally high performances in both output and quality of the two French laboratories, and, to a lesser, degree, TRIUMF. ILL and TRIUMF also already displayed distinctively higher rates of international co-publications at this earlier stage, ahead by at least 10 percentage points above the remaining institutions.

The CNBC's output performances in this early period were steady and remained at the same level until 2017. Citation performances were subject to rather drastic swings, with $HCP_{10\%}$ scores fluctuating between 10% and 21%.

The CNBC appears to have experienced a major turning point during the 1998–2003 period. Rates of international co-publications increased by 30 percentage points, ARIF scores reach their peak and publications from that period were in the top 10% most cited papers group twice as often as the world average ($HCP_{10\%}$ of 19.9%). Publications from the BIMR and NCNR also started being registered over this period, showing high levels of research impact right from the start.

The CNBC continued to consolidate its international collaborations in recent periods, with international co-publication rates in steady increase. Various citation scores had decreased somewhat from their peaks but remained much higher than in the earliest periods. In comparison, HFIR and CLS, while in a sort of steady state between 2000 and 2010 in terms of output and quality, displayed surges on both dimensions in the recent period.

The CNBC's longitudinal trajectory contrasts with that of most other comparators included in the sample. HFIR and CLS were defined by their aforementioned surges in the recent period. ILL and LLB had large publication outputs but with a decreasing scientific impact over the years. TRIUMF was the other comparator with large publication outputs, but this institution went from modest citations for the first 30 years to high figures in the last period considered. NCNR displayed enviable scores throughout. The BIMR achieved high citation scores right from the time of first availability of data and consolidated or improved those performances as time went on.

In summary, the CNBC's performance between 1980 and 2017 can be described as a steady output of papers of a high quality that incrementally improved over time.

Appendix A – Longitudinal citation impact graphics

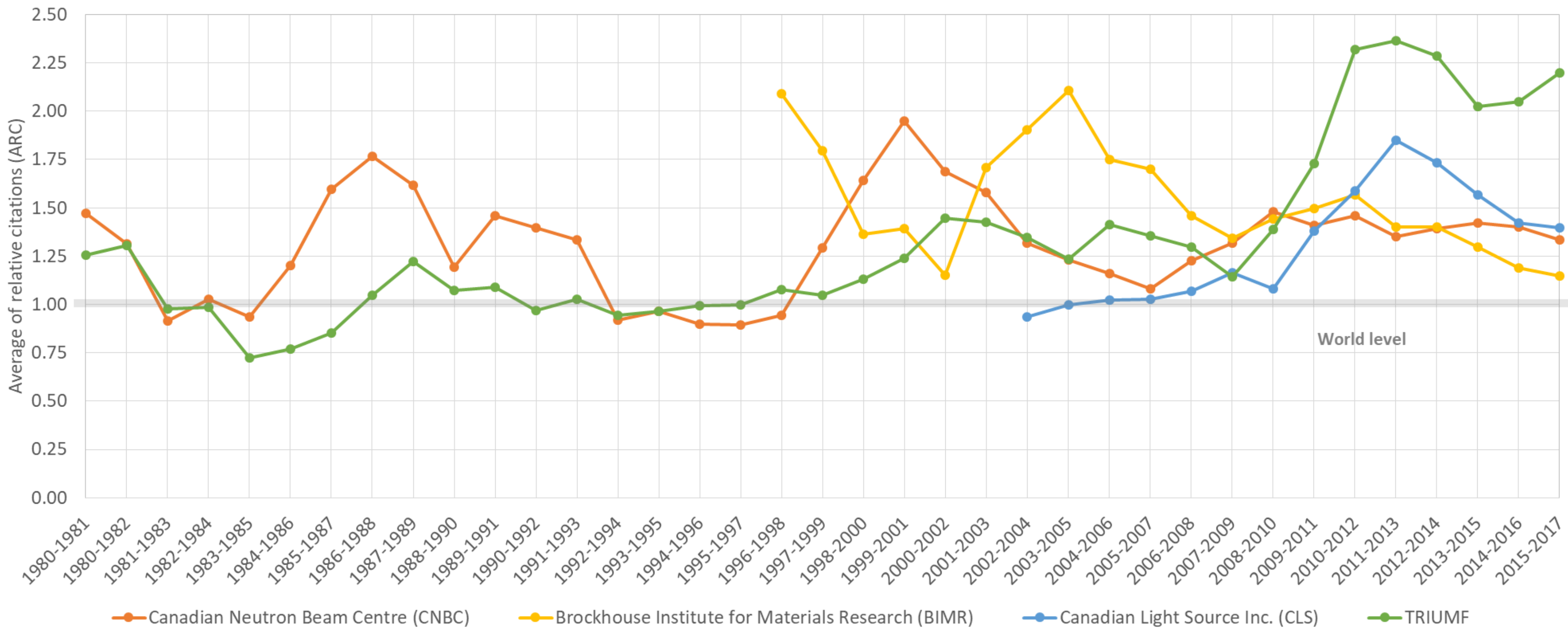

Figure 3 Average of relative citations (ARC) for the Canadian Neutron Beam Centre (CNBC) and comparable Canadian institutions, using a three-year moving window, 1980–2017

Note: ARC scores are not included for periods where fewer than 30 papers with a relative citation score were identified. The 1980–1981 period only covers 2 years. Scores are not calculated beyond 2015; therefore, the 2015–2017 period only contains impact scores for the year 2015.

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

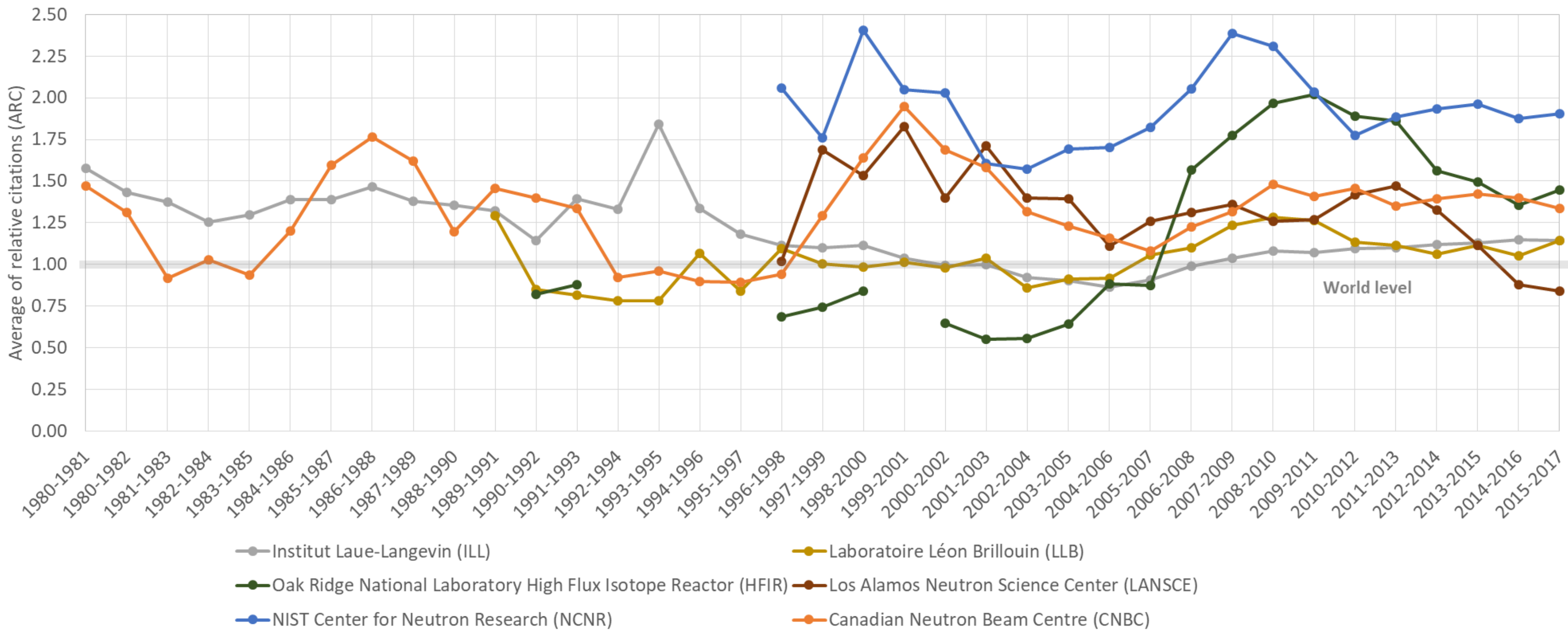

Figure 4 Average of relative citations (ARC) for the Canadian Neutron Beam Centre (CNBC) and comparable international institutions, using a three-year moving window, 1980–2017

Note: ARC scores are not included for periods where fewer than 30 papers with a relative citation score were identified. The 1980–1981 period only covers 2 years. Scores are not calculated beyond 2015; therefore, the 2015–2017 period only contains impact scores for the year 2015. A much larger number of papers were identified for LANSCE in 1989 relative to the years before and after; to maintain an accurate comparison between institutions, this anomalous data point was removed from the analysis.

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

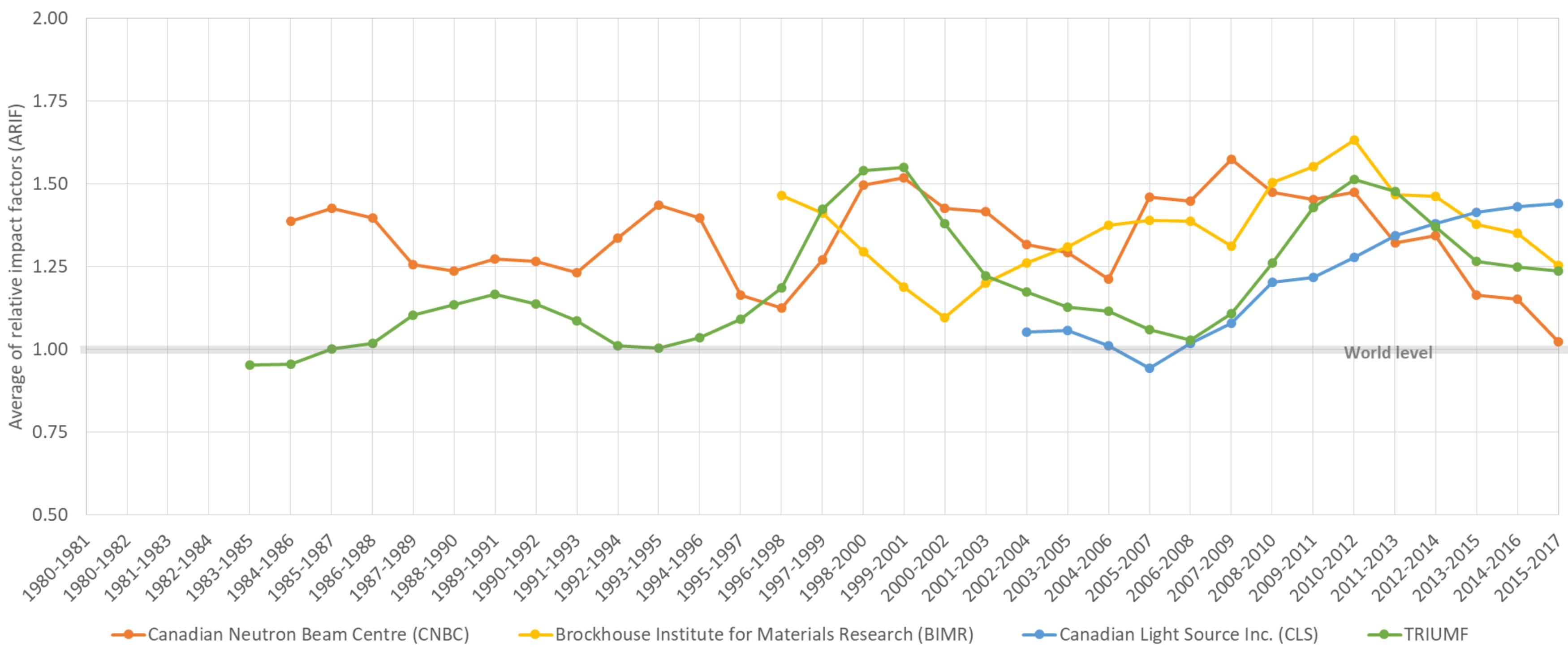

Figure 5 Average of relative impact factors (ARIF) for the Canadian Neutron Beam Centre (CNBC) and comparable Canadian institutions, using a three-year moving window, 1980–2017

Note: ARIF scores are not included for periods where fewer than 30 papers with a relative citation score were identified. Five years of citation data are required to generate relative impact factor scores; as a result, ARIF scores are not available prior to 1985. The 1983–1985 period only contains scores for 1985, and the 1984–1986 period only contains scores for 1985 and 1986. The 2016–2017 period only covers 2 years.

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

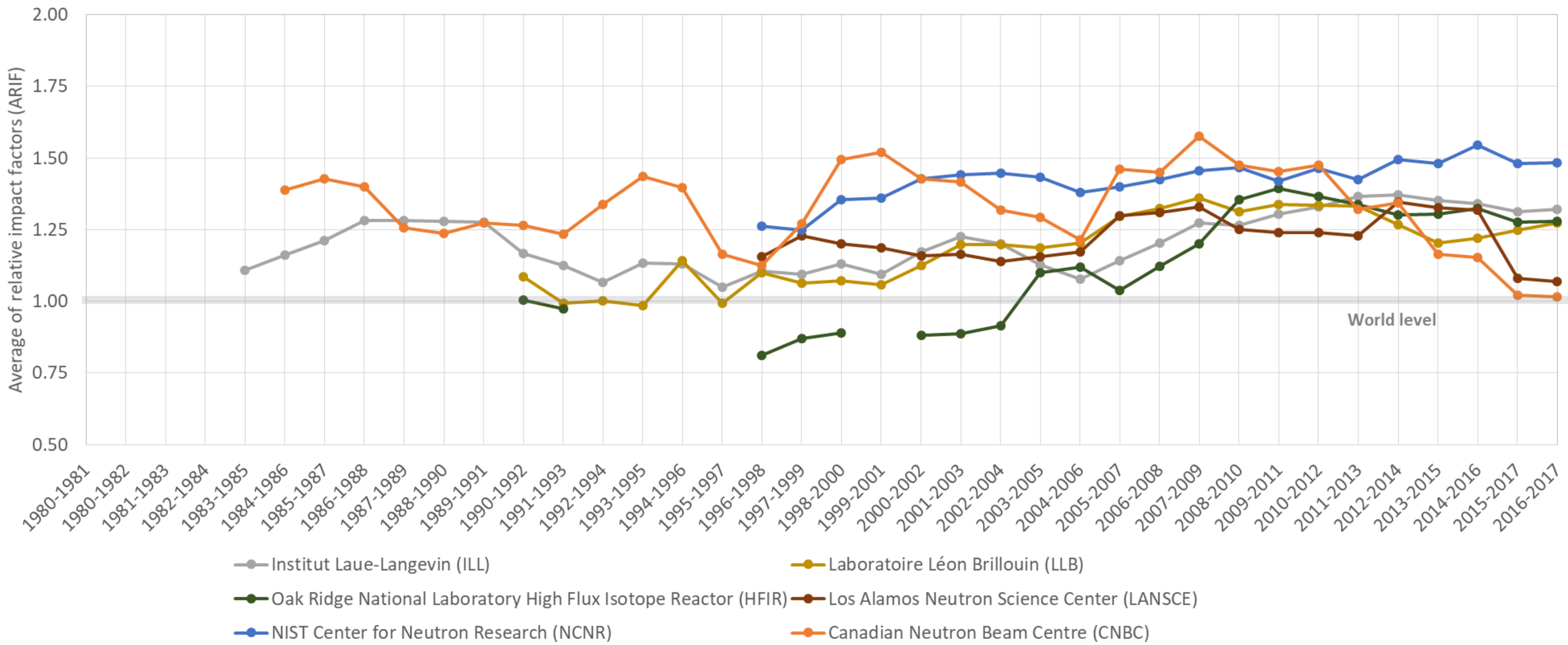

Figure 6 Average of relative impact factors (ARIF) for the Canadian Neutron Beam Centre (CNBC) and comparable international institutions, using a three-year moving window, 1980–2017

Note: ARIF scores are not included for periods where fewer than 30 papers with a relative citation score were identified. Five years of citation data are required to generate relative impact factor scores; as a result, ARIF scores are not available prior to 1985. The 1983–1985 period only contains scores for 1985, and the 1984–1986 period only contains scores for 1985 and 1986. The 2016–2017 period only covers 2 years. A much larger number of papers were identified for LANSCE in 1989 relative to the years before and after; to maintain an accurate comparison between institutions, this anomalous data point was removed from the analysis.

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

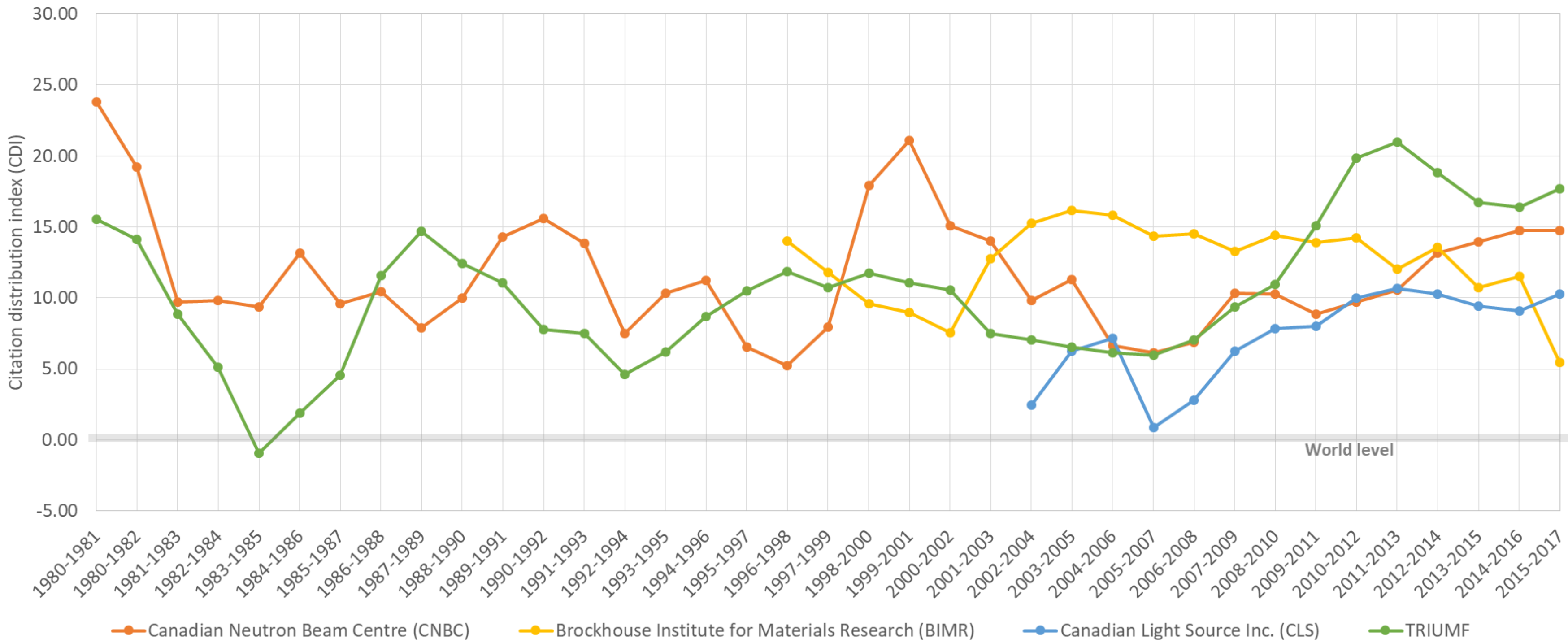

Figure 7 Citation distribution index (CDI) for the Canadian Neutron Beam Centre (CNBC) and comparable Canadian institutions, using a three-year moving window, 1980–2017

Note: CDI scores are not included for periods where fewer than 30 papers with a relative citation score were identified. The 1980–1981 period only covers 2 years. Scores are not calculated beyond 2015; therefore, the 2015–2017 period only contains impact scores for the year 2015.

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

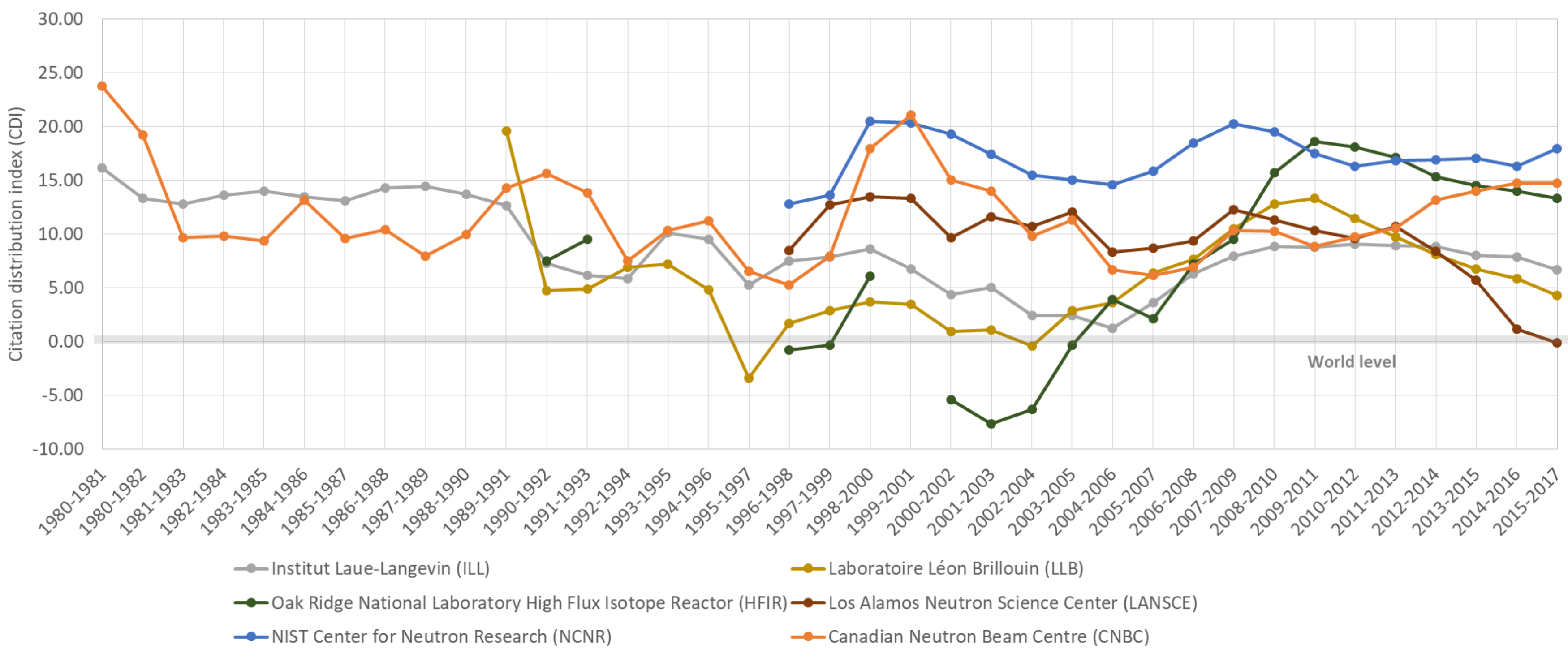

Figure 8 Citation distribution index (CDI) for the Canadian Neutron Beam Centre (CNBC) and comparable international institutions, using a three-year moving window, 1980–2017

Note: CDI scores are not included for periods where fewer than 30 papers with a relative citation score were identified. The 1980–1981 period only covers 2 years. Scores are not calculated beyond 2015; therefore, the 2015–2017 period only contains impact scores for the year 2015. A much larger number of papers were identified for LANSCE in 1989 relative to the years before and after; to maintain an accurate comparison between institutions, this anomalous data point was removed from the analysis.

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

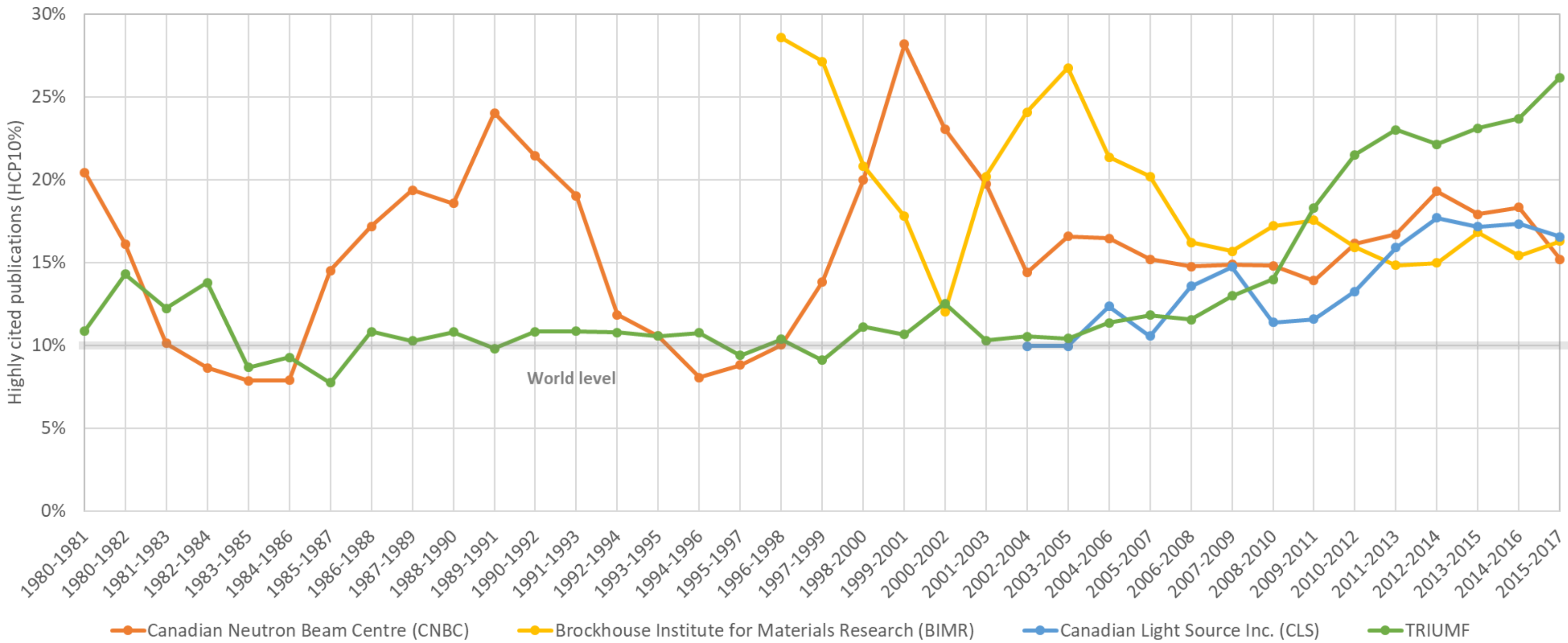

Figure 9 Highly cited publications ($HCP_{10\%}$) for the Canadian Neutron Beam Centre (CNBC) and comparable Canadian institutions, using a three-year moving window, 1980–2017

Note: $HCP_{10\%}$ scores are not included for periods where fewer than 30 papers with a relative citation score were identified. The 1980–1981 period only covers 2 years. Scores are not calculated beyond 2015; therefore, the 2015–2017 period only contains impact scores for the year 2015.

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

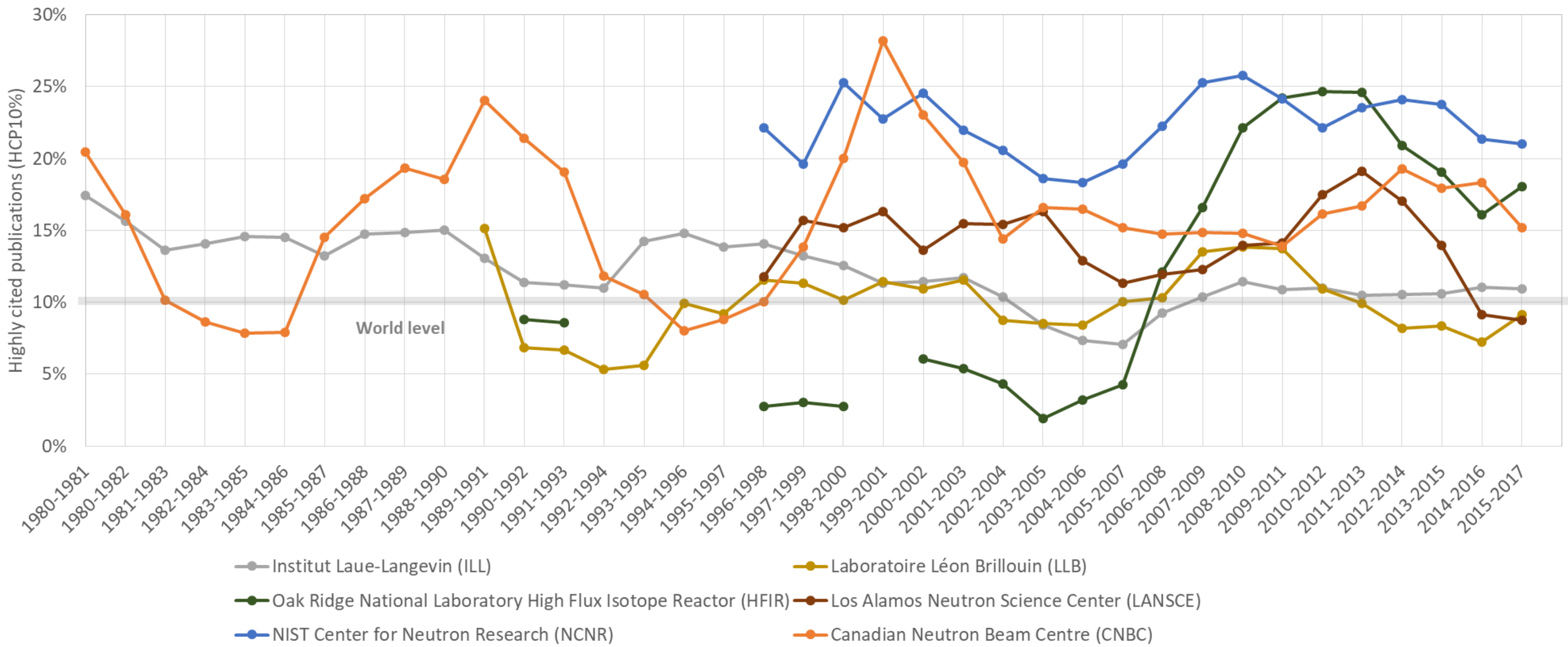

Figure 10 Highly cited publications ($HCP_{10\%}$) for the Canadian Neutron Beam Centre (CNBC) and comparable international institutions, using a three-year moving window, 1980–2017

Note: $HCP_{10\%}$ scores are not included for periods where fewer than 30 papers with a relative citation score were identified. The 1980–1981 period only covers 2 years. Scores are not calculated beyond 2015; therefore, the 2015–2017 period only contains impact scores for the year 2015. A much larger number of papers were identified for LANSCE in 1989 relative to the years before and after; to maintain an accurate comparison between institutions, this anomalous data point was removed from the analysis.

Source: Prepared by Science-Metrix using the Web of Science database (Clarivate Analytics)

Appendix B – Methods

Database selection

Web of Science: The Web of Science (WoS), produced by Clarivate Analytics, offers comprehensive coverage of the most cited scientific literature in the Natural Sciences and Engineering and Health Sciences through its Science Citation Index Expanded (SCI Expanded) database. It also covers the portion of scientific literature in the Social Sciences and Humanities that is published in peer-reviewed journals, through its Social Sciences Citation Index (SSCI) and Arts & Humanities Citation Index (AHCI) databases. Together, these three databases cover about 14,500 journals spanning over 150 sub-disciplines.

The WoS indexes the addresses of all authors on scientific publications, which enabled this study to identify all publications with at least one contributing author from the CNBC or one of the comparators. The WoS also includes the cited references for each document it contains (e.g., articles, reviews), enabling the analysis of scientific impact based on citation counts and journal impact factors.

In producing bibliometric data, only documents that were peer reviewed prior to being accepted for publication were retained. The peer-review process ensures that the research is of good quality and constitutes an original contribution to scientific knowledge. Moreover, the study is based on a selection of document types that include references to and are cited by other academic documents. These document types are mainly research articles and reviews, collectively referred to in this report as *papers* or *publications*.

All papers published over the 1980–2017 period were considered in producing this study's analyses. This period was chosen for two technical reasons, in addition to the adequacy of longitudinal portraits at this point in the CNBC's history. Although the Centre operated prior to 1980, covering an earlier period might have led to unreliable findings, given the limitations in coverage and the poor quality of data in bibliographic databases prior to that date. Secondly, papers published after 2015 will not have had time to accumulate citations over a sufficiently long period to enable a robust comparison of scientific impact. Indeed, a minimal citation window of publication year plus two is generally required. Some citation analyses could therefore only be performed for the period extending to 2015. Finally, articles published in 2017 were not yet fully covered in the WoS at the time of writing this report, with new data sets provided by journal publishers still being added to the database. Nonetheless, the database was complete enough to enable robust evaluation of publication activity from this year as well.

Data set retrieval and processing

Science-Metrix made use of lists of CNBC researchers and publications provided by the Centre to create a first data set retrieving the corresponding publication in the WoS. When performing searches, Science-Metrix used all possible variants of the CNBC's names over the years, going back to 1980. This included the Neutron and Solid State Branch and the Neutron and Condensed Matter Science Branch of AECL, the Neutron Program for Materials Research (NPMR) of NRC, as well as the Canadian Neutron Beam Centre and the Neutron Scattering Branch of the Canadian Nuclear Laboratories. Similar methods were also applied for the eight comparators.

Publication identification and retrieval was operationalized using two distinct methods. First, institutional addresses alone were used to search for the institutions of interest. In the second method, the core set of publications obtained was enriched with mentions retrieved from the abstracts and funding acknowledgments sections of papers as well. The second method led to larger sets of papers: only 13 more for the CNBC but more than 600 for ILL. However, that enrichment was not applied evenly across the study period because the WoS offers highly incomplete coverage of scientific publications' abstracts before 1991 and of their acknowledgements sections before 2008.

The list of frequent users was established on an initial ranking of individual publication outputs. One limitation regarding this operation was that matching author addresses was a good deal more difficult for those researchers who published most of their output before 2008. In a second step, long-term CNBC researchers were removed from the list, with the exception of a few scientists (Carlo, Marquardt and Rheinstaedter) who were directly employed by the Centre for a period before continuing their research careers elsewhere.

Bibliometric indicators

Number of scientific publications

This indicator shows the number of peer-reviewed scientific publications (i.e., articles, reviews and conference proceedings papers; all aggregated) for a given entity, calculated using the full counting method. Each paper gets a full count of 1 in the total for the given entity (e.g., observatory) even if other entities contributed to the paper.

Relative citation rate

Counting citations can be used as a proxy for measuring contributions to subsequent knowledge generation; however, because citation practices vary between the disciplines and sub-disciplines of science, simple counting would create unwanted biases in the results. To correct these potential distortions, individual publications are evaluated relative to the average citation rate for publications in the same subfield and published in the same year. This measure is known as the relative citation (RC) rate.

For all the indicators relying on the RC scores of papers, a certain amount of time must be allowed for the published work to have an impact on subsequent research and for articles to be cited. Accordingly, impact measures (ARC, CDC, CDI and HCP) for the present study could be computed using articles published in 2015 or earlier. Papers published in 2016 or later have not had sufficient time for citations to accrue.

Average of relative citations

The average of relative citations (ARC) is the average of the relative citation scores of all the articles published by a given entity. The ARC is normalized to 1, meaning that an ARC above 1 indicates that the entity's articles have higher-than-average impact, an ARC below one means that the entity's articles have lower-than-average impact, and an ARC near 1 means that the publications have near-average impact.

Because RC scores are known to be skewed in their distribution—with a small number of papers receiving a large share of the total citations—the ARC offers a useful snapshot of overall performance but can hide important underlying nuance. For this reason, Science-Metrix complements the ARC with additional impact indicators that communicate the underlying distribution of scores (such as the CDC, CDI and HCP, see below), but which on their own might lack the simplicity and intuitiveness of the ARC, which remains a valuable component of this suite.

Average of relative impact factors

The impact factor (IF) of each journal in a given year is measured by counting the total number of citations received in that year by the papers that appeared in that journal in the previous five years. The IF is then obtained by dividing the total number of received citations by the number of articles that appeared in that journal in the previous five years. To account for the differences in citation practices across disciplines, the IF for a journal in a given year is adjusted relative to the average IF of other journals in the same subfield and year (each journal contributes to the average proportionally to the number of papers it published in the given year). Every published paper is given the IF score of the journal in which it is published. The average of relative impact factors (ARIF) of a given entity is simply an average of the IF scores of its articles, relativized to the disciplines in which they are published.

The ARIF is normalized to 1, meaning that an entity with an ARIF above 1 publishes in higher-than-average-impact journals, an ARIF below 1 means that the entity publishes in lower-than-average-impact journals, and an ARIF near 1 means that the entity publishes in near-average-impact journals.

Citation distribution charts & citation distribution index

The citation distribution chart (CDC) is a tool that facilitates a simple but nuanced visual inspection of an entity's research impact relative to worldwide performance. To prepare these charts, Science-Metrix divides all publications in a given research area into 10 groups of equal size, or *deciles*,[11] based on their relative citation (RC) scores. The 1st decile contains the 10% of publications with the lowest RC scores; the 10th decile contains the 10% of publications with the highest RC scores.

For a given research entity, it is expected that the RC scores of its publications will follow the global distribution, with an equal number of publications falling in each of the deciles. The CDC for a given entity compares that entity's scientific impact to the global level by showing how its performance compares to the world level in each of the deciles.

As shown in Figure 11, the CDC shows 10 colour-coded bars for a hypothetical entity; each bar represents the relative presence of this entity's papers in each corresponding decile. The world level, in contrast, is represented by the central horizontal line, with no bars, as it represents the uniform distribution of all the publications across the 10 deciles. Thus, the bar's colour shows whether the specific entity has more or fewer publications in that decile than expected (i.e., the horizontal line). Green bars denote production

[11] Two adjustments are made in order to ensure high-quality results, and these pertain to (a) cases where a number of publications are tied in their scores and (b) cases where the total number of publications is not divisible by 10. For the first case, (a), papers tied at the margin of two deciles will be grouped together and then divided proportionately to ensure that each decile contains the right number of papers. In the case of the total number of papers not being divisible by 10, (b), papers will be fractioned to ensure that the deciles are always of exactly equal size.

exceeding expectation in that decile, red denotes production below expectation in that decile, and the length of the bar shows how far above/below expectation the entity is in that decile. Consequently, the longer the red bar, the fewer publications are found in that decile relative to expectation. Conversely, the longer the green bar, the more publications are found in that decile, again relative to expectation. When a decile has no bar associated with it, the entity's performance is exactly in line with the expectation based on global performance. Accordingly, a CDC with no visible bars shows that the entity in question has 10% of its papers in the 1st global decile, 10% of its papers in the 2nd global decile, and so on, which, as previously noted, corresponds to the world distribution of papers based on their RC scores.

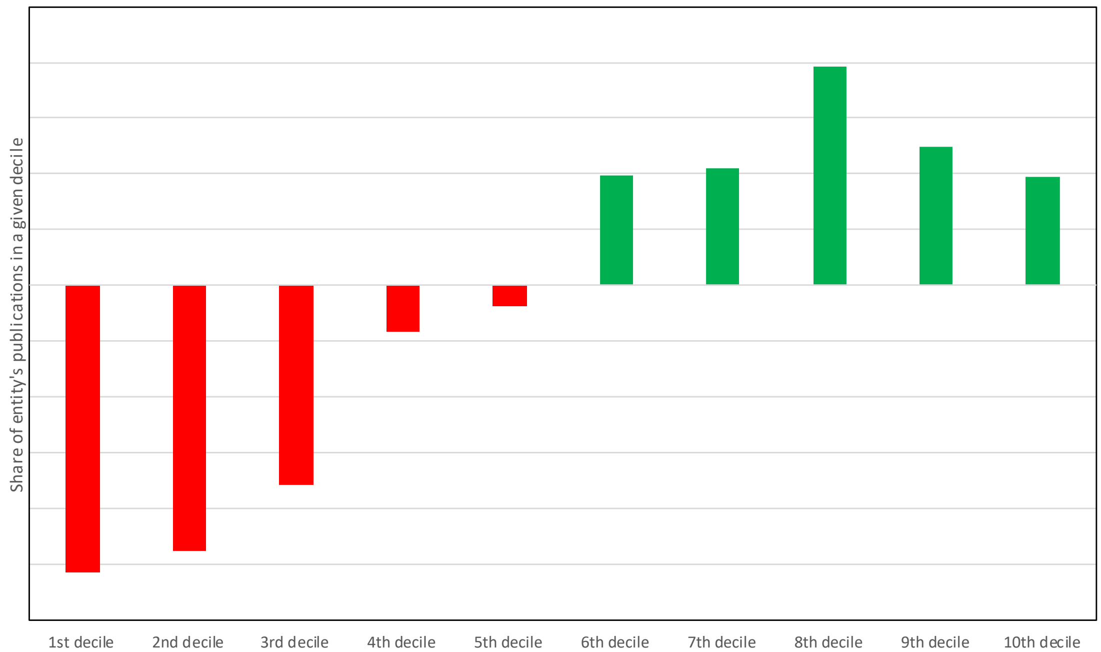

Figure 11 Sample citation distribution chart
Source: Prepared by Science-Metrix

Ideally, one would hope to be over-represented in the highest deciles, where the most impactful publications are found; similarly, one would hope to be under-represented in the lowest deciles, where the least impactful publications are found. Thus, strong research performance is shown by long red bars on the left of the CDC and long green bars on the right of the graph. In contrast, weaker research performance is depicted by long green bars on the left side (indicating more publications than expected in the less impactful deciles) and long red bars on the right side (indicating fewer publications than expected in the more impactful deciles). Figure 12 presents distributions related to best-case and worst-case scenarios.

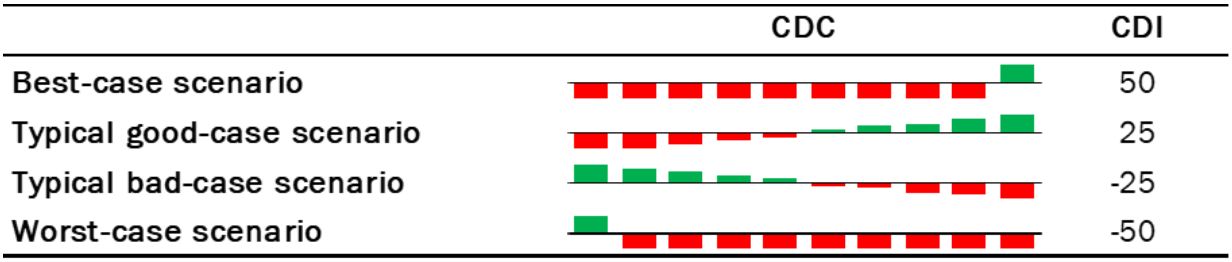

Figure 12 Various scenarios of citation distribution charts and their citation distribution index

Source: Prepared by Science-Metrix

The content of the CDC can also be summarized numerically using the citation distribution index (CDI). For each decile, the performance of a given research organization is compared to the global average, and this ratio is then multiplied by the weight corresponding to that decile (negative weight for deciles 1 through 5, positive for 6 through 10). Once a score has been produced in this fashion for each decile, they are summed to calculate the CDI for the research organization. Thus, having a higher-than-expected number of publications in the 1st decile (i.e., the lowest-impact decile) will reduce the CDI more than having a higher-than-expected number of publications in the 2nd decile. The CDI ranges from -50 (worst-case scenario) to 50 (best-case scenario) with 0 representing parity with the world level. Compared to mean-based normalized citation metrics, the combined use of the CDC and CDI makes it possible to provide reliable citation metrics even when dealing with entities that have produced few publications (from 10 to a couple of hundred).[12]

Highly cited publications

The 10% most cited publications in the database are identified using the relative citation (RC) scores of publications, as presented above for the CDC and CDI. Then, the fraction of an entity's papers falling among these highly cited publications (HCP) can be computed; this gives the $HCP_{10\%}$ score of that entity. A score above 10% indicates performance above expectation, while a score below 10% indicates the opposite. This indicator is often used as a proxy to examine research "excellence" because of the high concentration of citations (close to 45%) in this elite group of publications.[13]

International collaboration rate

An international co-publication is defined as a publication that was co-authored by individuals from at least two countries. The international collaboration rate of an entity is simply a measure of how many of its articles are co-published with international partners as a proportion of the given entity's total output. The international collaboration rate is obtained by dividing the number of international co-publications

[12] Campbell, D., Tippett, C., Côté, G., Roberge, G., & Archambault, É. (2016). An approach for the condensed presentation of intuitive citation impact metrics which remain reliable with very few publications. In I. Rafols, J. Molas-Gallart, E. Castro-Martínez, & R. Woolley (Eds.), *Proceedings of the 21st International Conference on Science and Technology Indicators*, pp. 1229–1240. Valencia, Spain. doi:10.4995/STI2016.2016.4543.

[13] Bornmann, L., Leydesdorff, L., & Wang, J. (2013). Which percentile-based approach should be preferred for calculating normalized citation impact values? An empirical comparison of five approaches including a newly developed citation-rank approach (P100). *Journal of Informetrics*, *7*(4), 933–944.

of an entity by its total number of co-publications (both national and international). Full counting is used to compute this indicator.

Intersectoral collaboration rate

This indicator shows the proportion of an entity's papers that are published in collaboration (i.e., co-published) between economic sectors. For this study, Science-Metrix considered academic, governmental, private and other (e.g., international organizations) sectors. About 90% of addresses were assigned to one of the sectors. Collaborations between an institution and its "parent" organization (e.g., HFIR and Oak Ridge National Laboratory) were excluded from the institution's rate of collaboration with the sector of the broader organization. This was only possible where we were able to successfully identify an address as being associated with a given centre. For example, in some cases papers identified as belonging to the HFIR were only signed with addresses at Oak Ridge, not the centre specifically. This would then count as a collaboration with a public institution, whereas if the author mentioned HFIR in the address, it would not count as a public collaboration.