Update to Fuel Burnups and Power Ratings

NWMO-TR-2019-04   **April 2021**

T. Lampman

Kinectrics

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Authored by:	T. Lampman		
Verified by:	I. Cheng		
Approved by:	S. Kaasalainen		
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Reviewed by:	M. Gobien		
Reviewed by:	M. Ion		
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Revision Summary		
Revision Number	**Date**	**Description of Changes/Improvements**
R000	2020-05	Initial issue
R001	2020-12	Updated to include more bundle power information for Hydro Quebec and tables of summary statistics for bundle powers.
R002	2021-04	Addressed OPG comments

ABSTRACT

Abstract
Maximum burnups and linear element powers for fuel bundles that have been discharged from Ontario Power Generation, Bruce Power, Hydro-Quebec, and New Brunswick Power reactors were extracted from all available digital archives. Data was not readily available in digital format for early Pickering A, Point Lepreau and Gentilly-2 operation and estimates of the distribution of the maximum burnup and linear power ratings were prepared. Estimated bundle power distributions were determined from the linear power rating distributions. The electronic and estimate data was combined and statistically analyzed and plotted as frequency histograms.

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1. INTRODUCTION

Used fuel burnups and maximum power ratings are important parameters for deep geological disposal of spent fuel. They largely determine the inventory of radionuclides present in the fuel as well as the fraction of fission products that are able to migrate to the fuel gap and grain boundaries.

In 2006, an Ontario Power Generation report was issued that summarized the burnups and maximum (bundle) power ratings for CANDU fuel discharged from the Darlington, Pickering A & B, and Bruce A & B reactors during the period from 1970 to 2006 (Wilk & Cantello, 2006). This report was subsequently updated in 2013 (Wilk, 2013) with information for Hydro-Quebec (Gentilly-2) and New Brunswick Power (Point Lepreau) stations. The discharged fuel bundle data for each station's reactors were combined and plotted as frequency histograms of burnup and maximum power rating for the time periods 1970-1979, 1980-1989, 1990-1999, 2000-2010 and 2010-2012, where data was available. Also presented were the maximum, median, 90th, 95th and 99th percentile burnups and maximum power ratings for each station (for each time period), as well as the total number of bundles discharged from each reactor over the entire period (1970-2012).

The purpose of this project is to update the previous report by including more recent data for those reactors (2012-2018). Additionally, for periods where the data is not readily available in electronic format, estimates of this data were constructed and incorporated into the frequency histograms.

2. DATA EXTRACTION

For all Ontario Power Generation (OPG) and Bruce Power (BP) reactors, fuel bundle data were extracted via Unix and FORTRAN scripts from SORO (Wilk, 2005) digital archives on the Kinectrics Unix LAN. Care was taken to assess the effects of inter-unit recycling, whereby bundles discharged from one reactor are inserted into another one, and then discharged from that second reactor. Such bundles appear twice in SORO discharged bundle records, and scans of the records (such as for this report) incorrectly double-count such bundles unless some complex data filtering is applied. Considering the relatively small number of such bundles (see Table 1) in comparison with the total number discharged from a station, the programming effort required to perform the required filtering was considered unwarranted. For example, by far the greatest number of inter-unit recycled bundles occurred for Bruce A, where 1,504 bundles were inter-unit recycled, corresponding to ~0.3% of the Bruce A bundles.

The bundle data provided by Hydro-Québec were contained in several files, each spanning a different period of operating history, with separate files for burnups and bundle serial numbers, bundle powers, and fuelling history. Exit burnups were available for the entire operational period from 1983 to discharge of final bundles after shutdown in September 2013. However, the maximum experienced bundle powers were available only for the reactor operating period from 2900.2 effective full power days (October 1993) to unit shutdown at 8261.0 effective full power days (December 2012). A Python script was prepared to track bundle movements (by serial number) and to extract the exit burnups and discharge dates for all bundles. Where possible, the maximum bundle powers for the discharged bundles was also collected for bundles with a complete power history. Since the burnups had been provided in units of

MWh/bundle, they were converted to MWh/kgU by dividing by the mean mass of uranium per bundle (19.2 kg, as provided by Hydro-Quebec staff).

The data files provided by New Brunswick Power for the Point Lepreau reactor included histories of bundle burnups, bundle powers, refuelling operations and a list of bundle serial numbers correlated to discharge channel/position and date. A Python script was prepared to read the data and extract exit burnups, maximum experienced bundle power and discharge date for all discharged bundles for which a complete history was available. The available digital information for Point Lepreau covers the period from January 1994 to October 2018, with discharged bundles only available to April 2018.

3. ESTIMATION OF HISTORICAL DATA

Fuel bundle data was not readily available in electronic format during the following periods for Pickering A units, Point Lepreau and Gentilly-2:
- Unit Commissioning (starting 1970) to December 1986 for all Pickering A units,
- Unit Commissioning (February 1983) to December 1993 for Point Lepreau, and
- Unit Commissioning (October 1983) to October 1993 for bundle power data at Gentilly-2.

Through discussion with the Nuclear Generating Stations, samples of the archived, non-electronic-format bundle records were collected and examined to determine how to convert these records to electronic format for analysis. Information loss using automated conversion methods was too significant to reconstruct bundle data information of sufficient quality. However, it was possible to reasonably estimate the frequency histograms working with industry experts knowledgeable in Pickering A, Point Lepreau and Gentilly-2 operations and reviewing the available data and operations at each Nuclear Generating Station. It was concluded that there was little value in proceeding with extracting data from non-electronic records as it was found that estimation based on similar data was acceptable.

The process to construct the estimates started with a review of year-to-year variations in the frequency histograms. It was found that the shape, or distribution, of the yearly histograms does not significantly change. This is expected as reactor fuelling practises are consistent. However, occasionally there is a minor change in the distributions. Expert panel reviews were held for each Nuclear Generating Station with industry experts and station staff knowledgeable in the station's operating history to identify the cause of the changes. By reviewing the entire operating history of the Nuclear Generating Station, and correlating changes in the distributions to operating changes, the expert panel reviews established the technical basis to create an estimate of the frequency histograms for the periods for which data was not readily obtainable. These estimates were combined with the known histograms from electronic data to give the combined frequency histograms representing the entire operating period of the Nuclear Generating Stations given in this report.

4. DATA ANALYSIS

All data were analyzed by a Python script that calculated some basic statistical parameters and generated histograms of exit burnup and maximum power rating.

Table 1 shows, for each station, the number of discharged bundles from electronic records that contributed to the statistical analysis. Table 2 shows the maximum, median, 90th percentile, 95th percentile, and 99th percentile burnups and power ratings for the known bundle data grouped by station and decade. Table 3 shows the same information for bundle powers.

Table 4 provides the maximum, median and selected percentiles in the burnup and linear power distributions for all bundles (known plus estimated bundle data) discharged from each station. The aggregated values for all stations combined is given in Table 4 as well. Table 5 shows the same information for bundle powers.

Figures 1-8 and 9-16 show the histograms of exit burnup and maximum linear power rating, respectively. Figures 1 and 9 are for the aggregate of all station data, known and estimated. Note that the histogram bin widths are 10 MWh/kgU for burnups and 0.75 kW/m for bundle powers. The binning convention is to include a value that exceeds the left edge of the bin but is smaller than or equal to the right edge of the bin. The tick marks along the horizontal axis align with bin edges.

It should also be noted that all of the above discharge burnups and bundle power ratings are predicted (simulated) quantities based on various theoretical models and calculational tools. As such, they possess inherent uncertainties. As in previous work, no attempt has been made here to account for these uncertainties.

Table 1: Known Discharged Bundles Summary Data

Reactor	Start Date (yyyymmdd)	End Date (yyyymmdd)	Bundles Discharged	Inter-unit Recycled Bundles
Bruce A Unit 1	19770821	20181231	120,226	1,443
Bruce A Unit 2	19770210	20181230	107,109	0
Bruce A Unit 3	19780507	20181213	163,987	13
Bruce A Unit 4	19790510	20181231	153,434	48
		Total	544,756	1,504
Bruce B Unit 5	19850708	20181231	184,983	4
Bruce B Unit 6	19840913	20181229	184,158	0
Bruce B Unit 7	19860625	20181229	177,724	32
Bruce B Unit 8	19870730	20181231	171,437	36
		Total	718,303	72
		BP Total	**1,263,059**	
Pickering A Unit 1	19880524	20181231	55,385	0
Pickering A Unit 2	19890611	20070528	24,488	0
Pickering A Unit 3	19870106	20081013	30,844	0
Pickering A Unit 4	19870107	20181231	58,938	0
		Total	169,655	0
Pickering B Unit 5	19830814	20181231	107,436	0
Pickering B Unit 6	19840607	20181231	107,414	0
Pickering B Unit 7	19850531	20181231	102,780	0
Pickering B Unit 8	19860805	20181231	95,957	0
		Total	413,587	0
Darlington Unit 1	19910505	20181228	143,139	8
Darlington Unit 2	19901031	20170111	138,825	0
Darlington Unit 3	19930407	20181231	139,618	65
Darlington Unit 4	19930926	20181231	136,995	0
		Total	558,577	73
		OPG Total	**1,141,819**	
Gentilly-2	19831121	20130930	129,928	0
		HQ Total	**129,928**	
Point Lepreau	19940104	20180404	88,528	0
		NBP Total	**88,528**	
		Overall Total	**2,623,334**	

Table 2: Maximum, Median, and Percentiles for Known Bundle Burnups and Linear Power Ratings

Station	Decade	Burnup (MWh/kgU)					Linear Power Rating (kW/m)				
		Median	Percentile			Max	Median	Percentile			Max
			90th	95th	99th			90th	95th	99th	
Bruce A	1970's	133	231	248	279	355	35.3	47.1	49.1	51.7	55.8
	1980's	203	259	270	296	706	44.8	53.3	54.8	57.2	63.7
	1990's	192	264	274	297	657	38.5	50.6	52.7	55.0	58.9
	2000's	206	275	284	304	384	43.2	52.1	53.0	54.3	56.7
	2010's	210	272	279	294	425	44.0	51.4	52.2	53.5	56.3
Bruce B	1980's	179	215	229	268	492	42.5	46.6	47.6	49.0	51.6
	1990's	190	216	224	251	407	40.2	45.3	46.3	47.8	51.6
	2000's	190	218	226	244	435	40.0	42.7	43.5	44.7	47.9
	2010's	188	218	225	240	452	41.5	44.1	44.6	45.4	48.0
Pickering A	1980's	192	231	244	286	518	39.9	48.2	50.1	53.6	60.9
	1990's	202	265	285	318	521	45.2	52.9	54.2	56.0	62.2
	2000's	198	266	279	295	438	44.9	52.1	53.4	54.8	57.8
	2010's	210	277	288	303	415	46.0	52.4	53.5	54.9	56.6
Pickering B	1980's	188	218	228	249	479	45.0	51.1	52.5	54.9	60.6
	1990's	193	225	236	259	595	45.5	51.0	52.2	54.4	59.7
	2000's	190	225	235	253	548	44.9	49.5	50.5	52.0	55.7
	2010's	196	230	239	256	466	45.0	49.8	50.8	52.4	56.2
Darlington	1990's	195	230	241	262	320	42.9	46.7	47.6	49.0	52.2
	2000's	205	240	250	268	390	44.5	48.2	49.0	50.1	52.4
	2010's	201	239	249	269	349	44.9	48.6	49.3	50.3	52.6
Gentilly-2	1980's	175	215	229	250	291					
	1990's	177	213	227	245	346	43.0	50.1	51.6	53.4	55.7
	2000's	171	208	224	241	321	41.1	49.4	50.8	53.0	55.5
	2010's	162	197	214	234	268	37.3	46.7	48.2	50.5	52.7
Point Lepreau	1990's	170	211	228	248	321	42.3	49.1	50.4	51.9	53.9
	2000's	169	210	227	248	321	38.3	46.6	47.9	50.0	53.8
	2010's	161	200	219	246	313	40.2	48.9	50.3	52.1	54.6

Table 3: Maximum, Median, and Percentiles for Known Bundle Powers

Station	Decade	Bundle Power (kW)				
		Median	Percentile			Max
			90th	95th	99th	
Bruce A	1970's	554	739	771	811	876
	1980's	703	836	861	898	1000
	1990's	604	793	828	864	924
	2000's	678	818	831	852	889
	2010's	692	808	821	840	883
Bruce B	1980's	668	732	746	769	810
	1990's	633	711	727	750	811
	2000's	633	677	688	707	764
	2010's	652	694	702	716	767
Pickering A	1980's	486	587	610	653	741
	1990's	551	644	660	682	758
	2000's	546	635	650	668	703
	2010's	560	639	652	668	690
Pickering B	1980's	548	622	639	668	738
	1990's	554	621	636	662	726
	2000's	547	603	615	633	678
	2010's	548	606	618	638	684
Darlington	1990's	675	735	749	772	835
	2000's	704	765	778	800	843
	2010's	717	776	788	806	843
Gentilly-2	1980's					
	1990's	675	786	810	839	875
	2000's	645	775	798	832	871
	2010's	585	732	756	793	827
Point Lepreau	1990's	664	771	790	815	846
	2000's	602	731	753	785	844
	2010's	631	767	789	818	857

Table 4: Maximum, Median and Percentiles for the Bundle Burnup and Linear Power Ratings in the Total Dataset (Known Data plus Estimated Data)

Station	Burnup (MWh/kgU)					Linear Power Rating (kW/m)				
	Median	Percentile			Max	Median	Percentile			Max
		90th	95th	99th			90th	95th	99th	
Bruce A	198	266	276	296	706	42.2	51.9	53.3	56.0	63.7
Bruce B	188	217	225	248	492	40.6	44.5	45.6	47.6	51.6
Pickering A	206	273	286	305	521	45.3	52.3	53.6	55.3	62.2
Pickering B	192	226	236	255	595	45.1	50.3	51.4	53.6	60.6
Darlington	201	238	248	267	390	44.2	48.1	48.9	50.1	52.6
Gentilly-2	173	211	225	244	346	41.2	49.5	51.1	53.3	56.2
Point Lepreau	166	207	224	246	330	40.0	48.3	49.7	51.8	54.8
Aggregated	**193**	**243**	**261**	**288**	**706**	**42.6**	**49.7**	**51.5**	**54.3**	**63.7**

Table 5: Maximum, Median and Percentiles for the Bundle Powers in the Total Dataset (Known Data plus Estimated Data)

Station	Bundle Power (kW)				
	Median	Percentile			Max
		90th	95th	99th	
Bruce A	663	815	837	879	1000
Bruce B	641	700	716	746	811
Pickering A	552	637	652	673	758
Pickering B	549	612	626	653	738
Darlington	699	765	779	801	843
Gentilly-2	647	778	802	837	883
Point Lepreau	633	763	786	819	859
Aggregated	**620**	**753**	**785**	**837**	**1000**
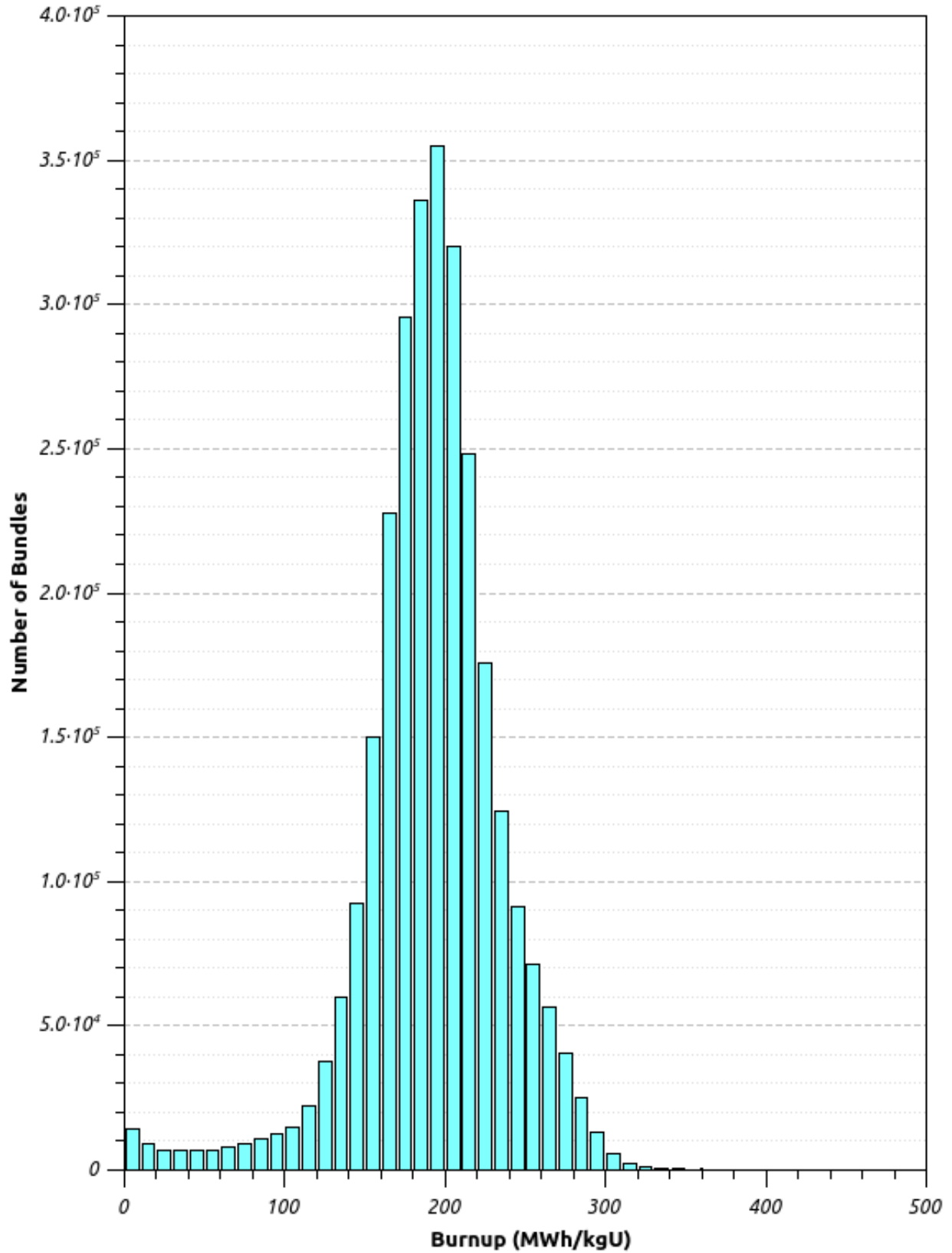
Figure 1: Bundle Discharge Burnups for All Stations
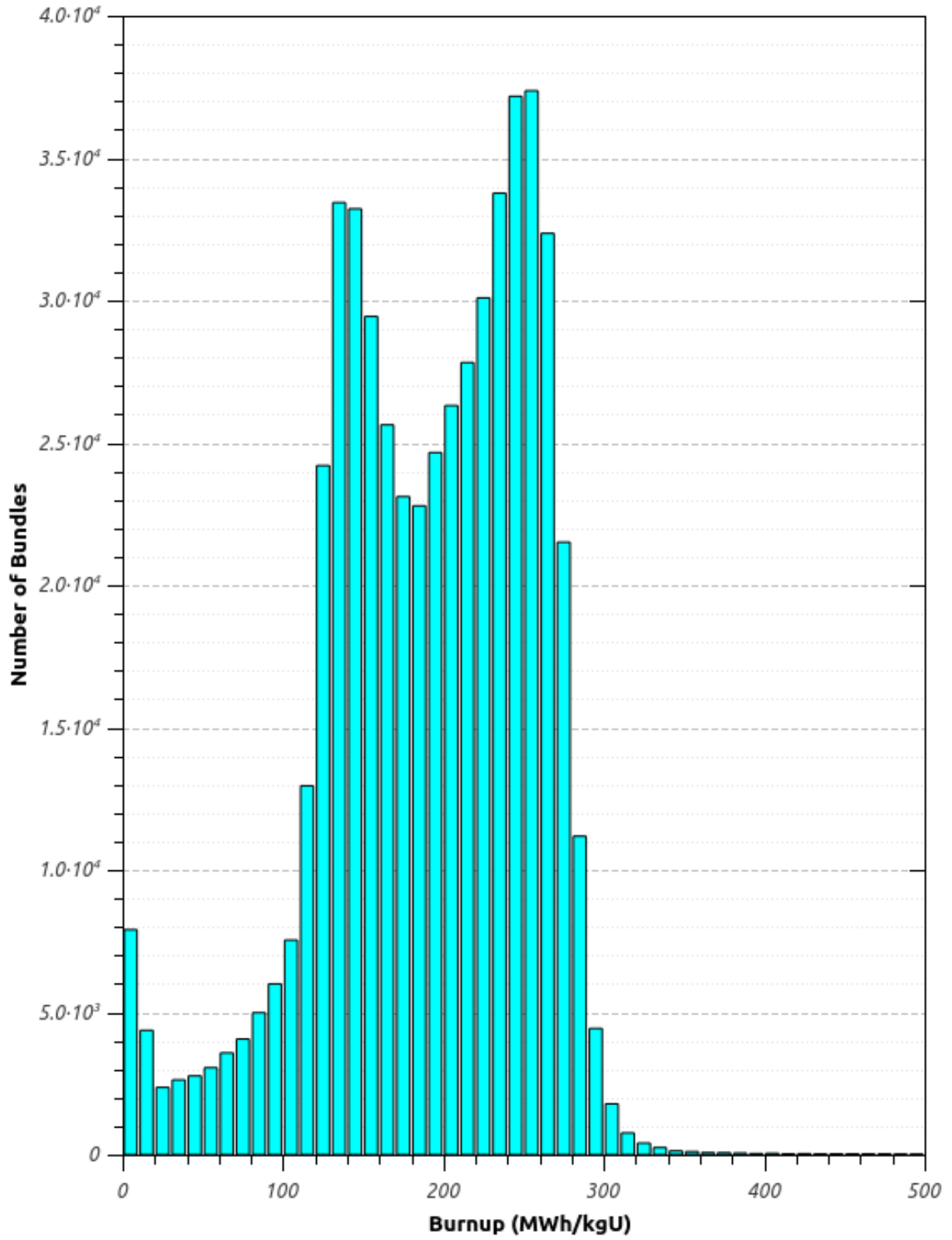
Figure 2: Bruce A Bundle Discharge Burnups
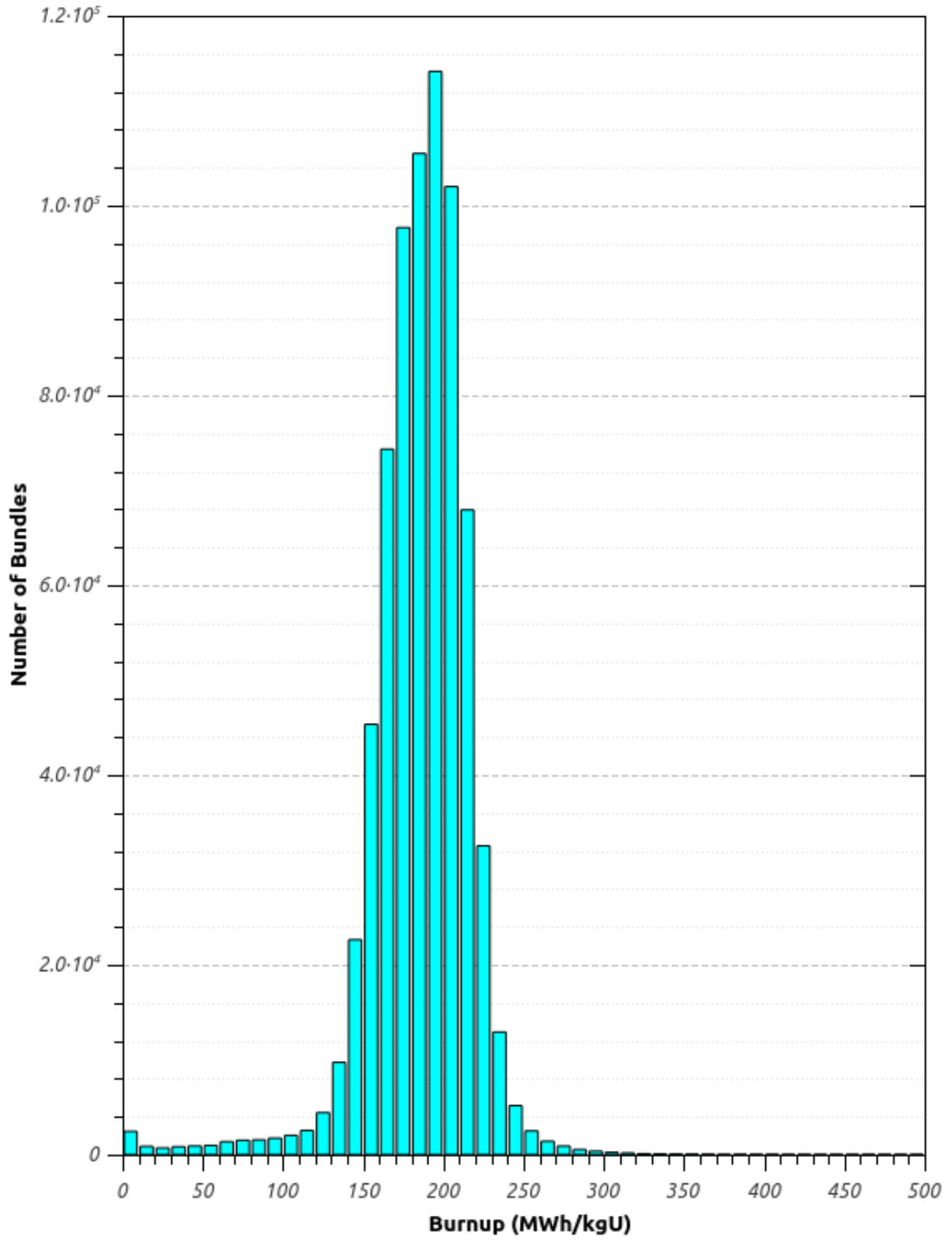
Figure 3: Bruce B Bundle Discharge Burnups
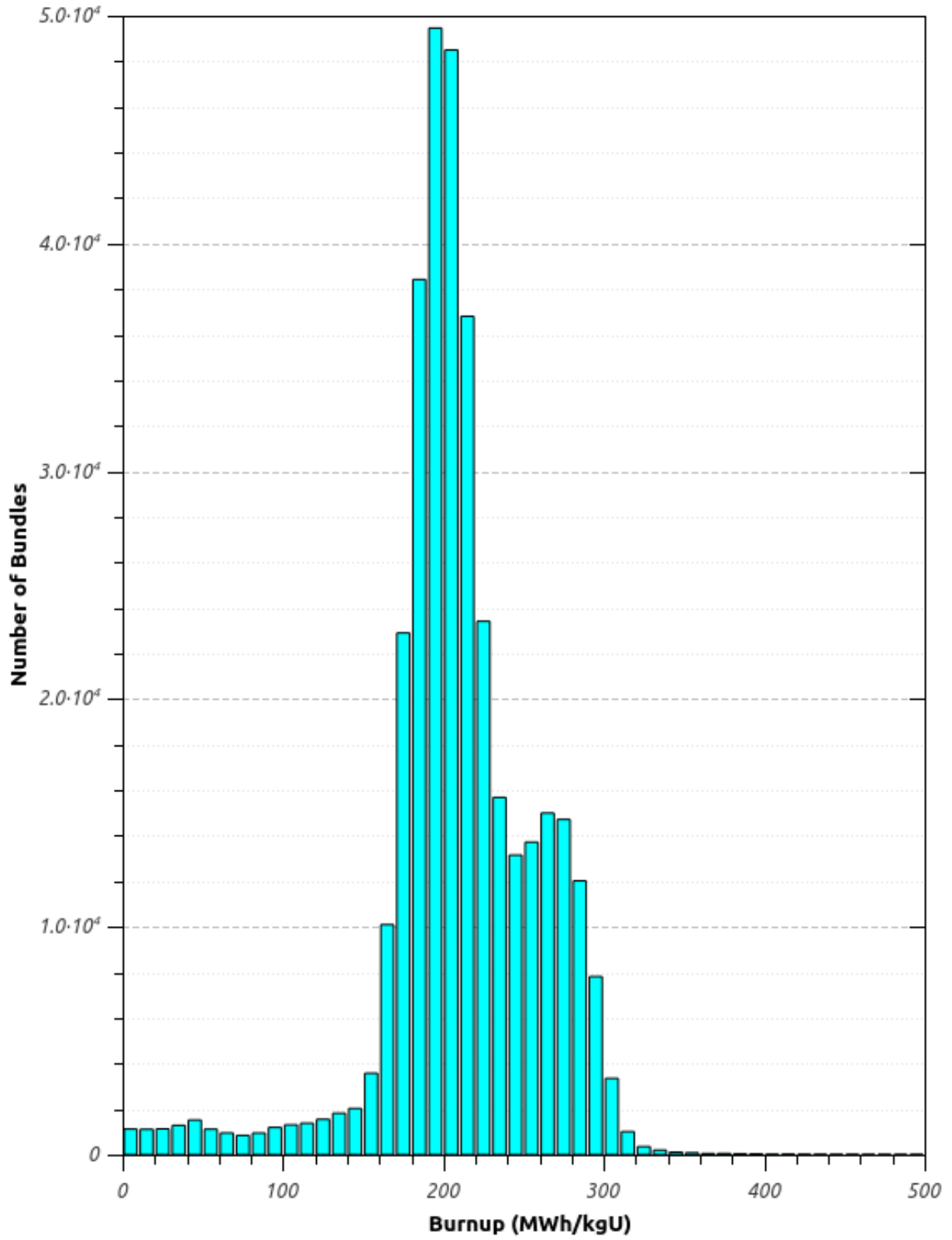
Figure 4: Pickering A Bundle Discharge Burnups
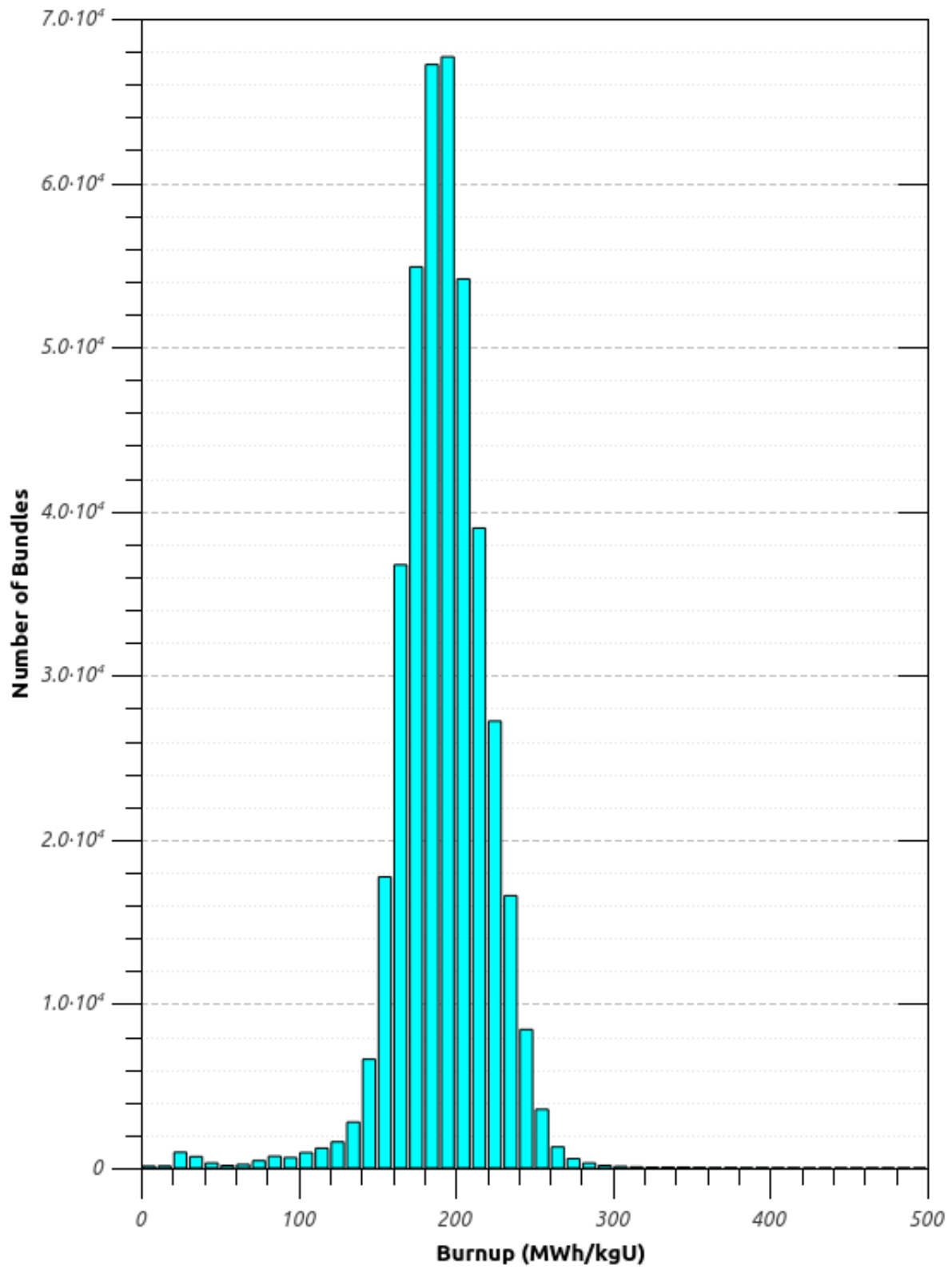
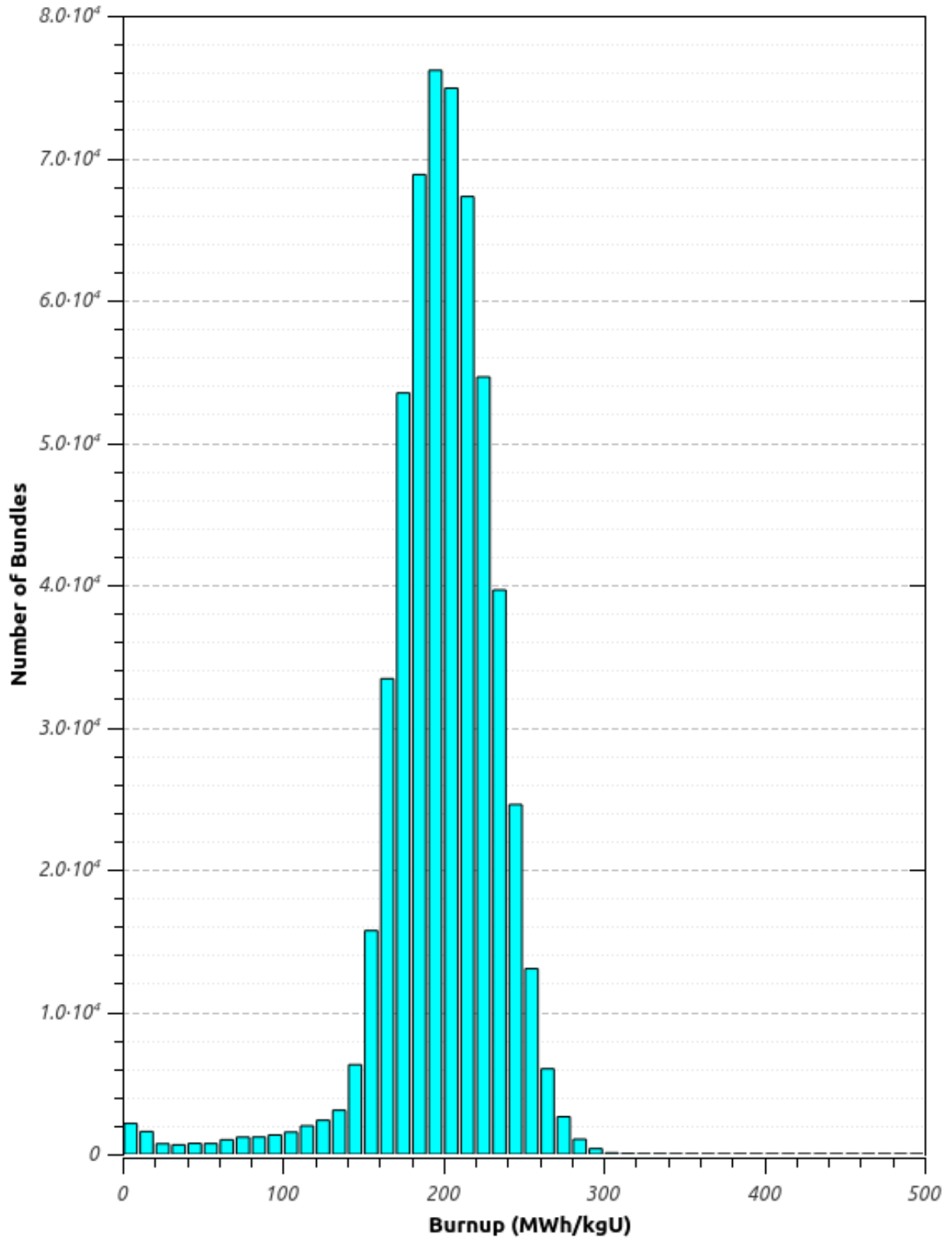**Figure 5: Pickering B Bundle Discharge Burnups**
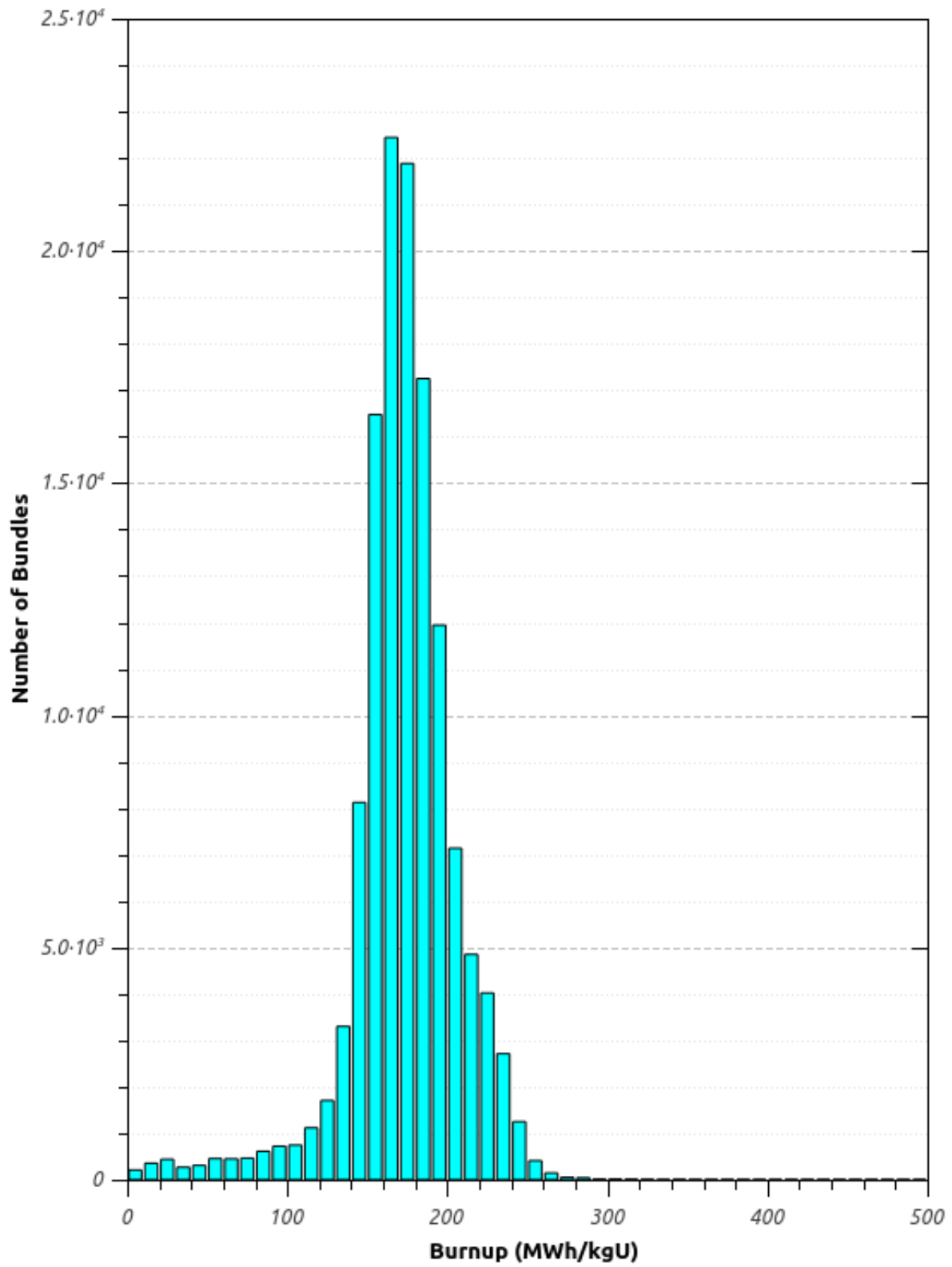
Figure 6: Darlington Bundle Discharge Burnups
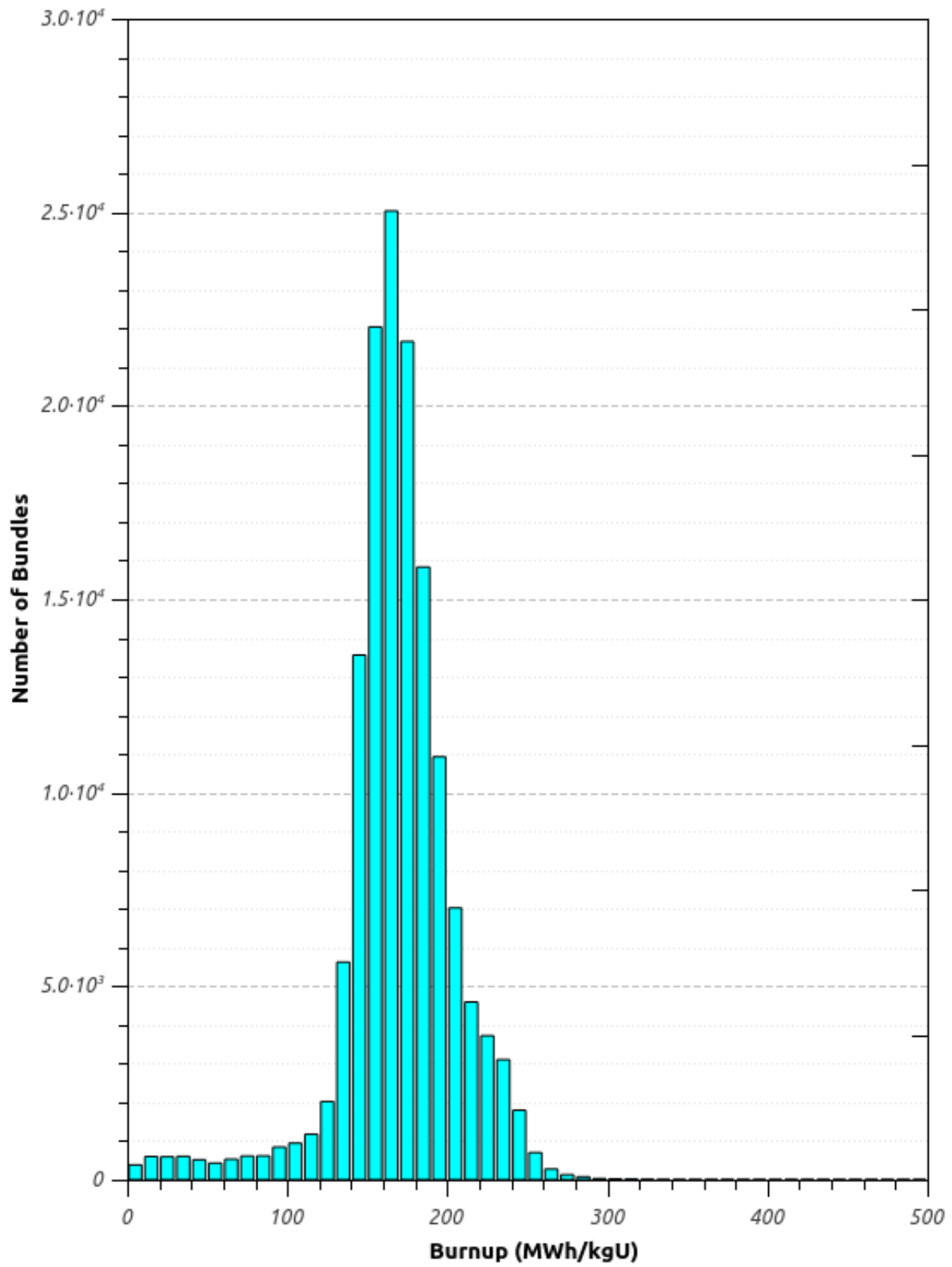
Figure 7: Gentilly-2 Bundle Discharge Burnups
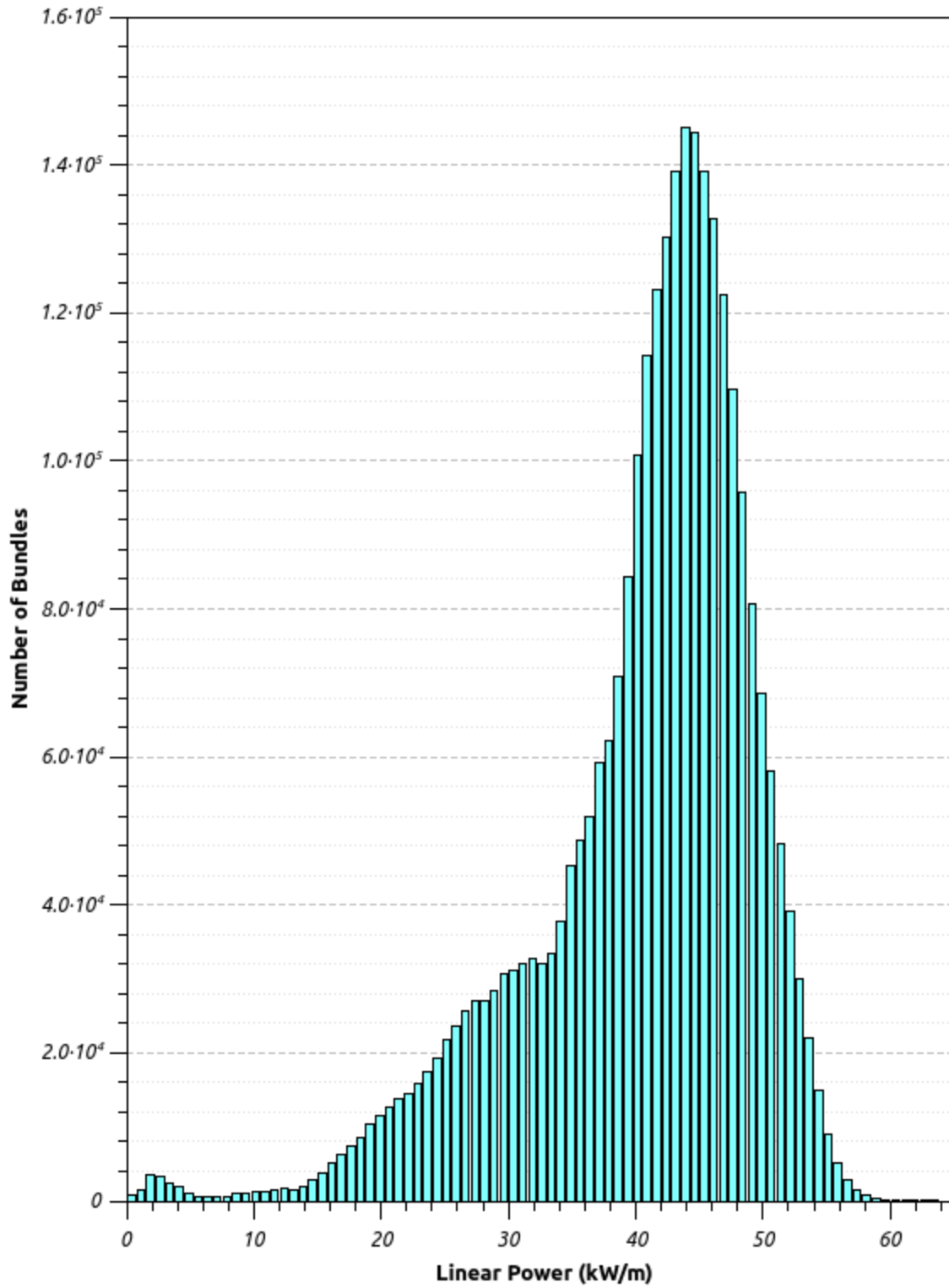
Figure 8: Point Lepreau Bundle Discharge Burnups
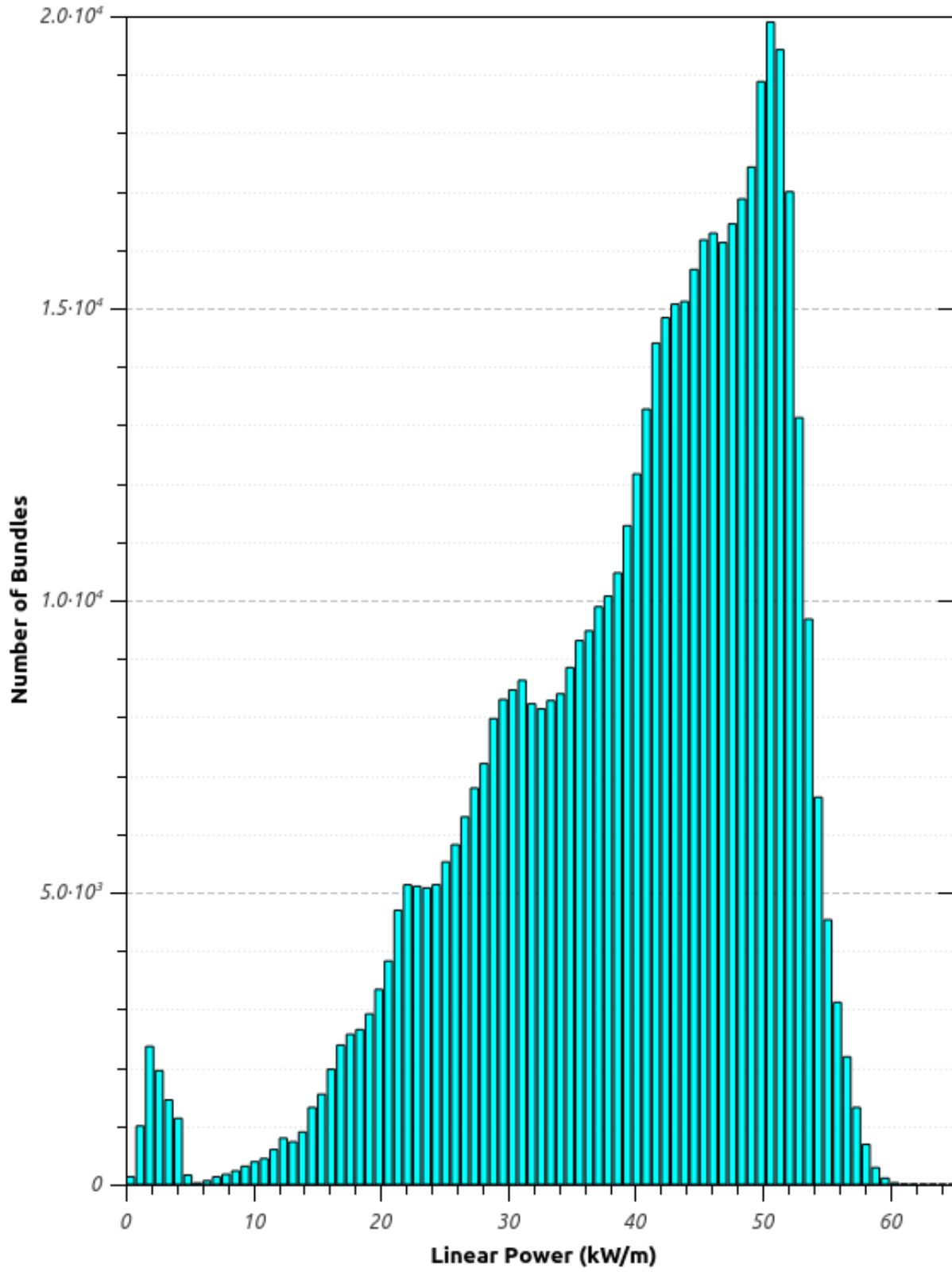
Figure 9: All Station Maximum Bundle Linear Power Ratings

Figure 10: Bruce A Maximum Bundle Linear Power Ratings
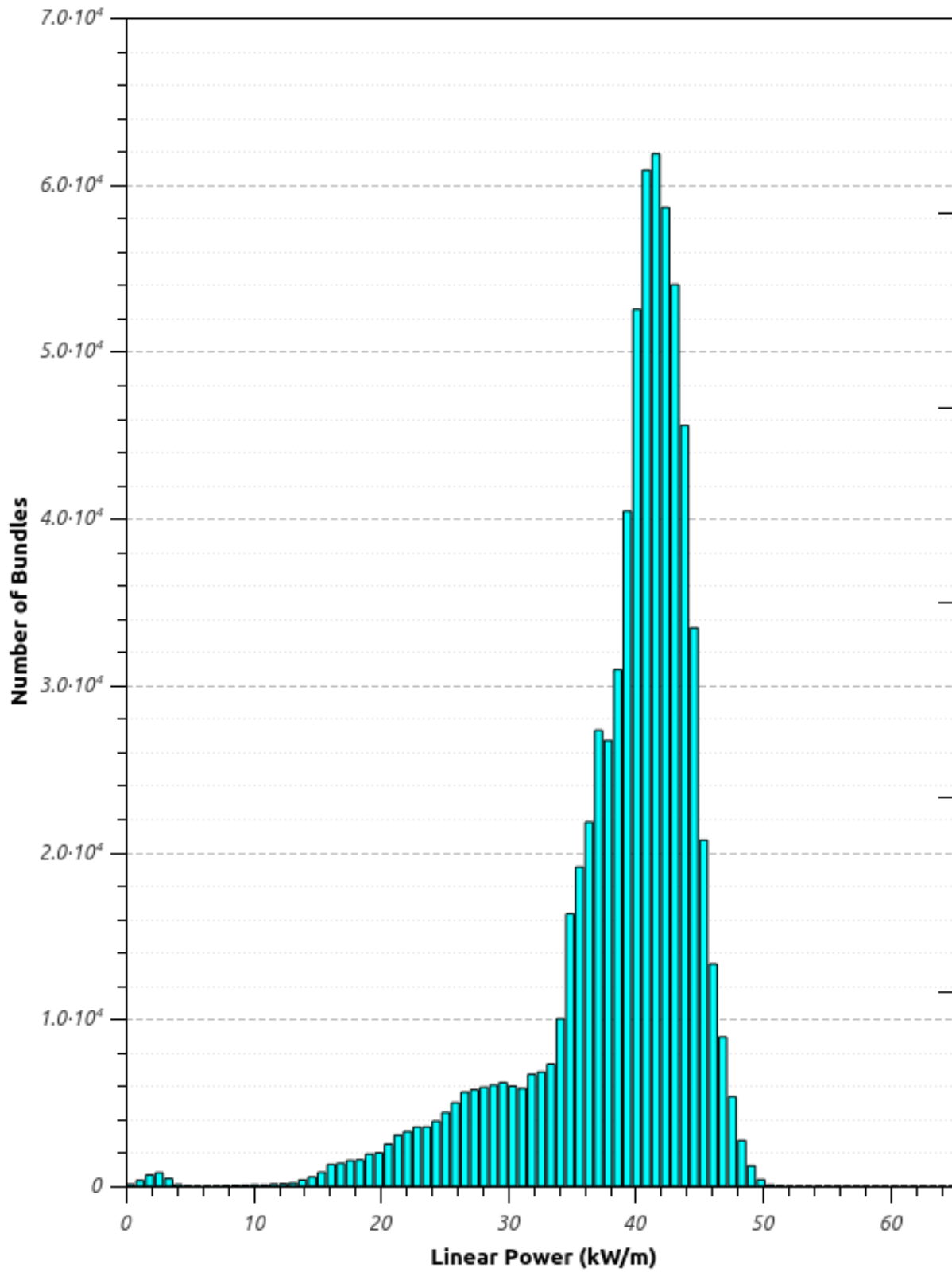
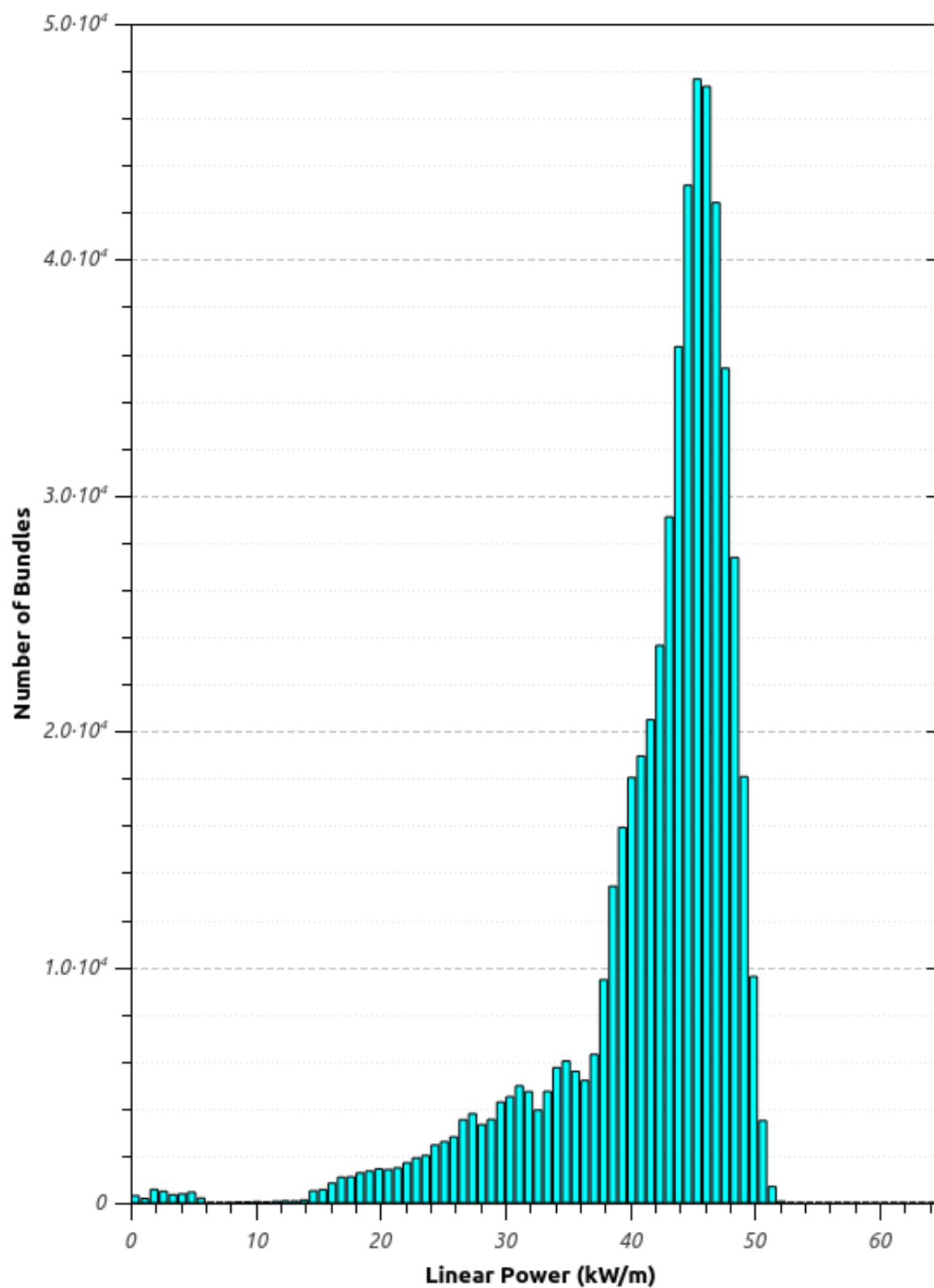**Figure 11: Bruce B Maximum Bundle Linear Power Ratings**
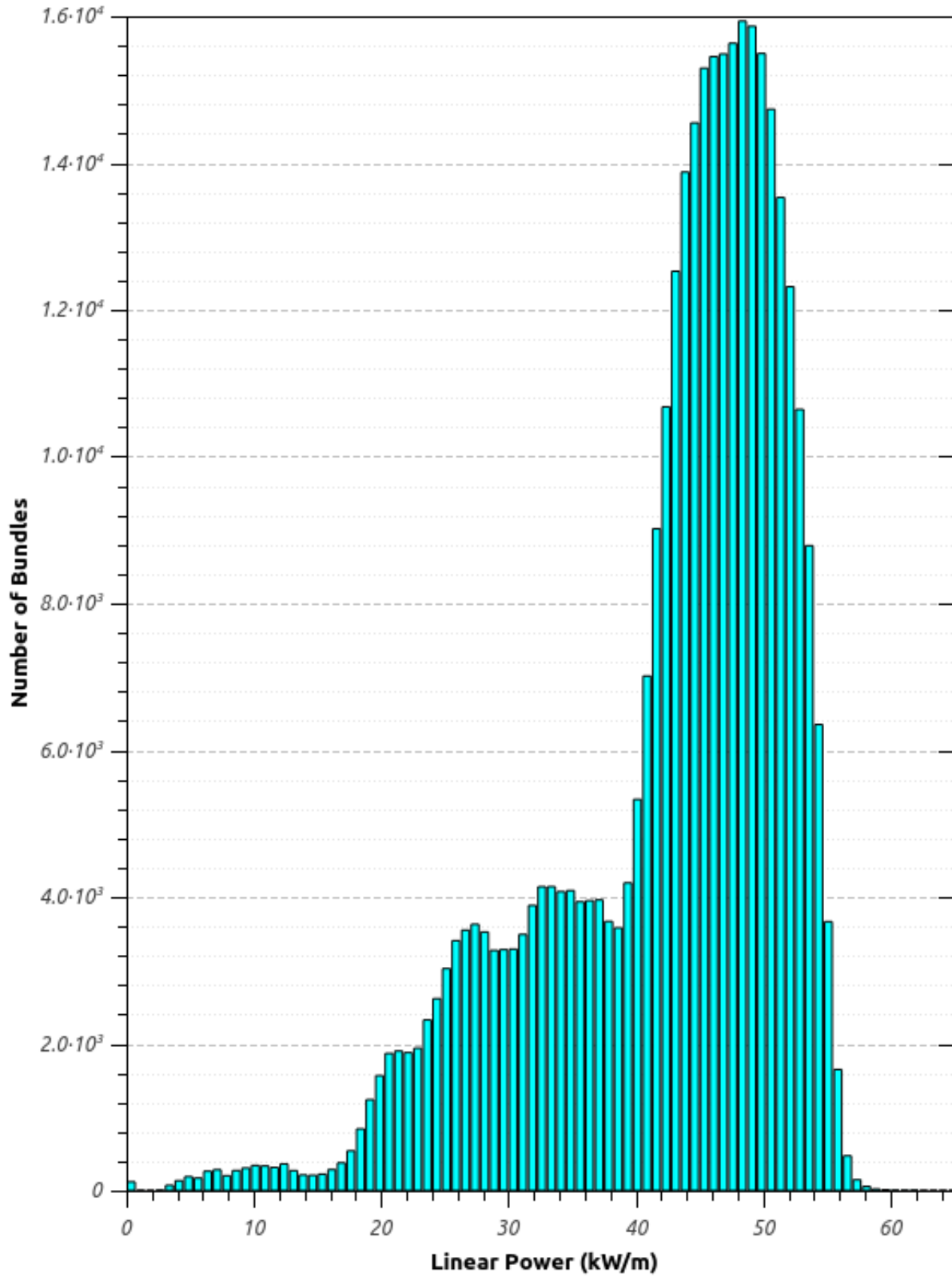
Figure 12: Pickering A Maximum Bundle Linear Power Ratings
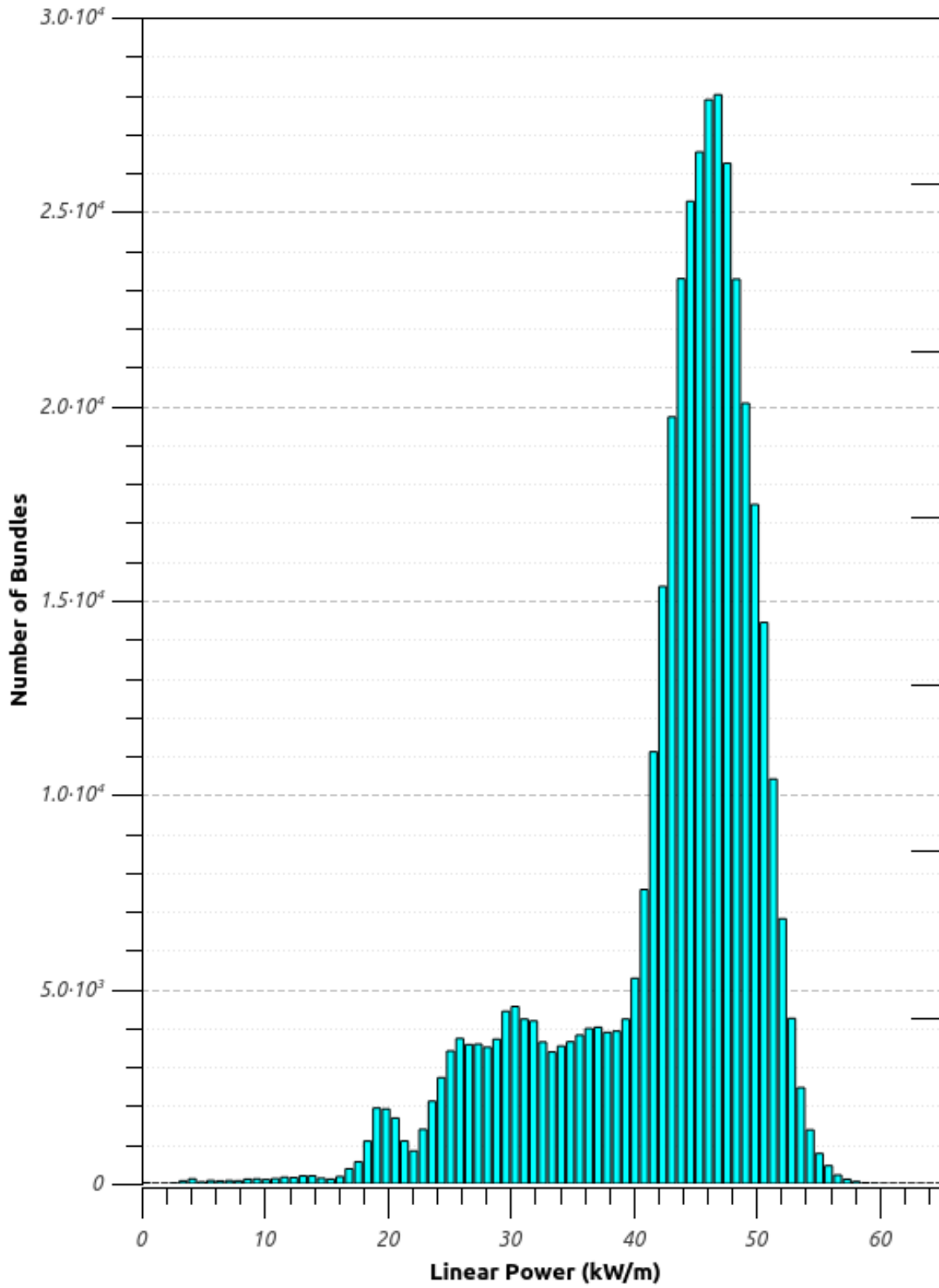
Figure 13: Pickering B Maximum Bundle Linear Power Ratings
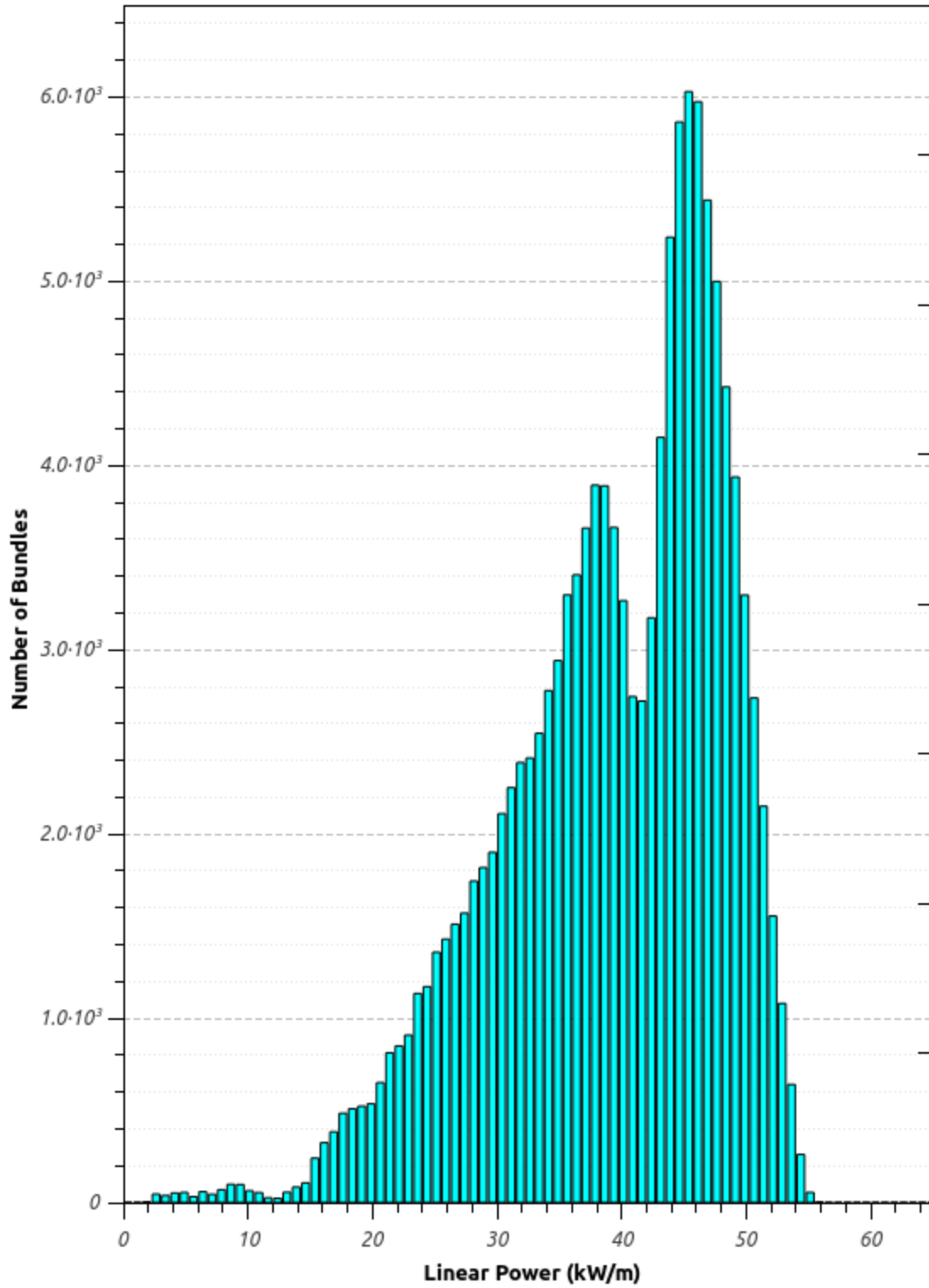
Figure 14: Darlington Maximum Bundle Linear Power Ratings

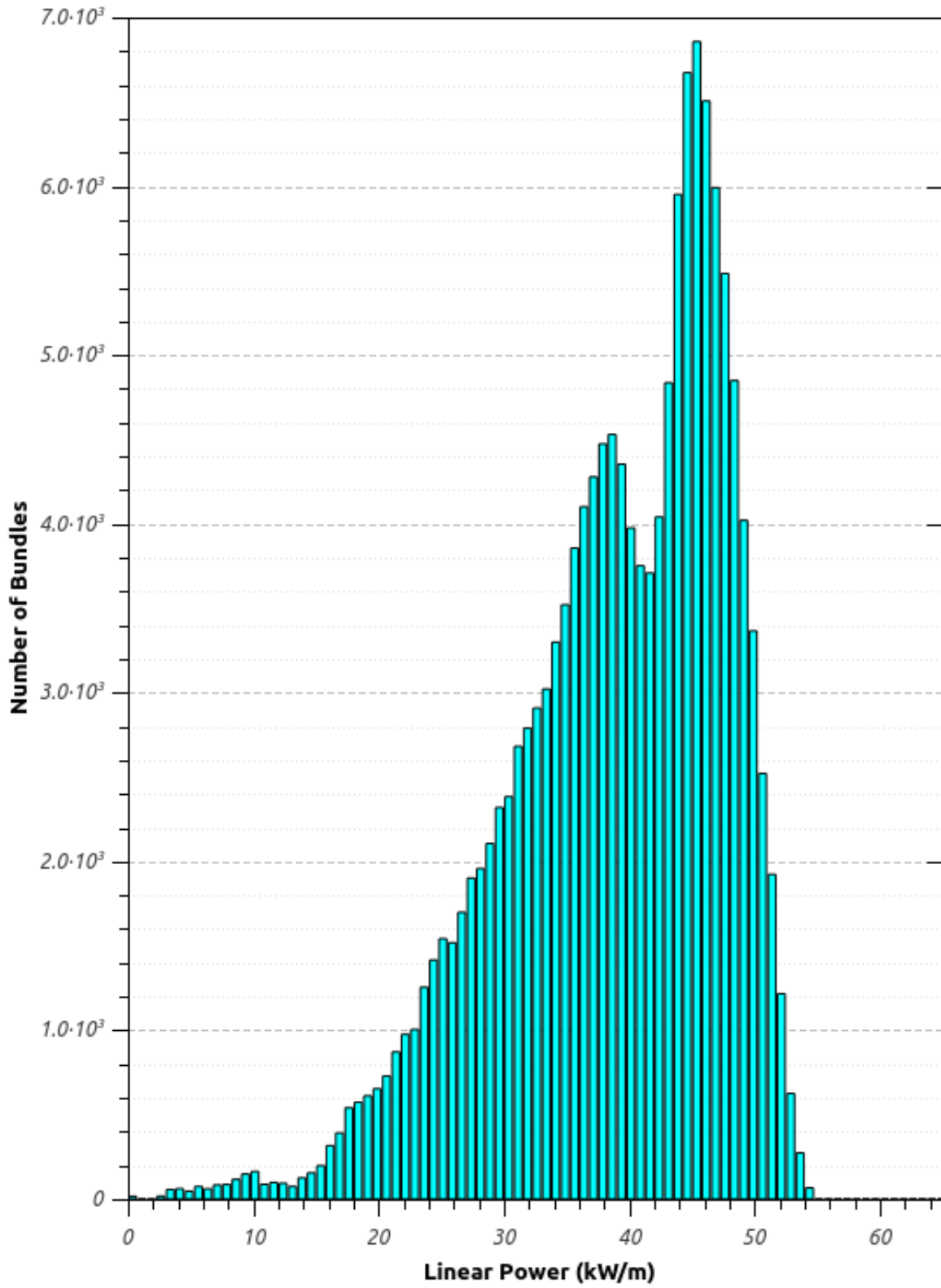**Figure 15: Gentilly-2 Maximum Bundle Linear Power Ratings**

Figure 16: Point Lepreau Maximum Bundle Linear Power Ratings

5. CONCLUSIONS

Burnups and maximum experienced linear powers for fuel bundles that had been discharged from Ontario Power Generation, Bruce Power, Hydro-Quebec, and New Brunswick Power reactors were extracted from all available digital archives. For each station, the data were statistically analyzed and plotted as frequency histograms.

The total number of discharged fuel bundles that were used in this statistical analysis is approximately 2.7 million bundles consisting of both the known and estimated bundle discharges. Each utility's contribution to this total was as follows: 44.1% from Bruce Power, 46.2% from Ontario Power Generation, 4.5% from Hydro-Quebec, and 5.1% from New Brunswick Power.

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