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WR0110 CHARACTERISATION OF RESIDUES FROM INDUSTRIAL PROCESSES AND WASTE TREATMENT

ANNEX G – REASSESSMENT OF MONOLITHIC WASTE ACCEPTANCE CRITERIA FOR ENGLAND AND WALES

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REPORT ON

REASSESSMENT OF MONOLITHIC WASTE ACCEPTANCE CRITERIA FOR ENGLAND AND WALES WR0110

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EXECUTIVE SUMMARY

A review of the Monolithic Waste Acceptance Criteria has been completed addressing issues raised during a peer review of the original modelling work undertaken by Golder Associates and following further physical testing of actual cementaceous hazardous waste obtained in Europe.

The peer review of the earlier work highlighted an assumption that the waste would remain saturated and testing has been targeted at determining the porosity of typical monolithic wastes and their moisture contents. The results indicated that a modified approach to assessing diffusive release was warranted and changes to the model were made which has allowed the generation of revised values for the diffusive emissions from monolithic waste that provide the same environmental protection as those developed for Granular Wastes (a requirement on Member States resulting from the decision document published by the European Council. The revised values are approximately 2 times the original values.

Testing of the monoliths revealed that few of the species assessed for waste acceptance criteria are released from the monoliths via a purely diffusive release. This calls into question the validity of treating cement stabilised materials as monolithic waste and strongly suggests that the UK's approach of allowing materials to be crushed and then applying the granular waste acceptance criteria as an alternative test method, is the most appropriate method for these materials.

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1.0 INTRODUCTION

1.1 Terms of Reference

Golder Associates (UK) Limited has been appointed by WRc plc to reassess the derivation of monolithic waste acceptance criteria for England and Wales following a review of the development of the current values by Hans van der Sloot of ECN in The Netherlands and Ole Hjelmar of DHI in Denmark. The contract forms part of a wider research contract awarded to WRc by Defra, related to Waste Characterisation (Defra reference number WR0110).

1.2 Background

The European Council decision document 2003/33/EC sets out landfill waste acceptance criteria (WAC) for granular wastes but left responsibility to Member States for developing limit values for monolithic wastes. The WAC for monolithic wastes were to provide the same degree of environmental protection as for granular wastes. Following a period of consultation, the UK WAC for monolithic wastes ("MonWACs") have been published in the Landfill (England and Wales) (Amendment) Regulations 2005. The UK MonWACs were developed for the Environment Agency by Golder Associates (UK) Limited. Details of the methodology and sensitivity analyses undertaken are reported in Hall *et al.* (2005).

Due to the limitations of time and funds, there was no opportunity for external peer review or performance testing of the MonWACs, prior to publication. However, the development of the criteria now has the benefit of a review by Hans van der Sloot of ECN in The Netherlands and Ole Hjelmar of DHI (Denmark).

The review helpfully highlighted that an assumption in the previous work that the monolithic waste was saturated might overestimate the diffusive flux and thereby result in over cautious acceptance criteria.

1.3 Purpose of this Study

The purpose of this study was to address the assumption that the monolithic waste was fully saturated and to then reassess the criteria. Furthermore, the project offered an opportunity to undertake testing of actual, rather than synthetic, monolithic wastes and to compare the results of the 64 day tank test undertaken on monolithic wastes with testing of the same material using the granular leach test methods.

Mercury porosimetry was also undertaken to assess typical cement based monolithic waste porosity and pore throat size distribution. The results of this testing have helped to justify the change in approach adopted in this modelling exercise.

1.4 Report Structure

Section 2 follows this introduction and presents a summary of the relevant results of testing of four samples of monolithic waste commissioned by WRc plc. The results have led to changes in the modelling that underpinned the criteria and these are described in Section 3. The results of the revised modelling are summarised in Section 4. A comparison of the results of using different test methods is made in Section 5 and Conclusions of this study in Section 6.

2.0 RESULTS OF TESTING OF MONOLITHIC WASTE

Following an agreement on the scope of testing required by Golder, WRc plc has supplied Golder with the results of testing of four samples of monolithic waste. Results of the following testing were provided (with duplicates for mercury porosimetry and moisture content):

- Mercury porosimetry;
- Determination of moisture content;
- Leaching by the two step test method (CEN EN 12457-3); and
- The Dutch tank test (NEN 7375).

Mercury porosimetry testing was specifically requested to allow a reduction in uncertainty in relation to the porosity of cementaceous monolithic wastes. Earlier work had assumed a low porosity with any pores present being infilled with gels.

2.1 Description of the Sampling and Analyses

We understand the four samples were taken from European hazardous waste treatment plants generating monolithic waste.

All samples were stored in a manner aimed at preserving their chemical and structural integrity before being dispatched for testing.

All the testing was carried out by ECN, in The Netherlands

2.2 Results of Testing

The results of the determination of skeletal density and total porosity by mercury porosimetry are summarised in Table 1. Bulk density is calculated from these measurements. The results of determination of moisture content are also presented in Table 1 along with the calculated air porosity. Further details of the porosity distribution with pore throat size and general physical data are contained in Appendix 1 to this report.

Table 1: Summary of Relevant Results of Testing

	Apparent Skeletal Density (g/cm^3)	Porosity (% v/v)	Bulk Density (g/cm^3)	Moisture Content (% v/v)	Air Porosity (% v/v)
WRC-P13N - Run 1	2.2513	26.6686	1.6509	24.2686	2.40
WRC-P13N - Run 2	2.194	25.4216	1.6363	23.8216	1.60
WRC-P15C - Run 1	2.6314	43.1486	1.496	41.3486	1.80
WRC-P15C - Run 2	2.5309	40.7519	1.4995	39.0519	1.70
WRC-P15N1 - Run 1	2.5301	40.1346	1.5146	39.3346	0.80
WRC-P15N1 - Run 2	2.4134	36.6998	1.5277	35.9098	0.79
WRC-P15N2 - Run 1	2.4731	33.8954	1.6348	32.9054	0.99
WRC-P15N2 - Run 2	2.5692	42.3515	1.4811	41.1015	1.25

Results of emissions from tank tests undertaken by ECN are reported in Table 2. Further details are contained in Appendix 2 of this report.

Table 2: Results of Tank Tests for the Samples of Monolithic Waste

Species	P15N1	P15N2	P15C	P13N
	(mg/m^2 at 64 days)	(mg/m^2 at 64 days)	(mg/m^2 at 64 days)	(mg/m^2 at 64 days)
Sb	3.26	4.02	0.81	2.56
As	0.85	0.74	0.4	0.89
Ba	1021	694.6	2506	799.1
Cd	0.021	0.023	0.056	0.029
Cr	3.73	9.68	2.81	22.7
Cu	0.14	0.24	0.07	267.2
Pb	30.2	30.7	74	131.1
Mo	7.11	13.2	14.2	18
Ni	0.12	0.15	0.13	77.1
Zn	10.3	12.7	18.6	24.9
Se	3.17	3.22	3.09	4.16
F	118.4	114.8	137.2	303.1
SO4	1609	7475	2039	32514
Cl	1,607,774	1,661,459	2,798,992	2,456,123

As well as tank tests to measure diffusion from a solid sample, under current UK Regulations, it is permissible to crush the sample and subject it to a granular leach test at L/S 10, comparing the results with the leach criteria for granular materials. It was therefore considered worthwhile undertaking the same testing regime on the hazardous monolithic waste samples so that a comparison of pass/fail criteria could be made (assuming the samples showed a range of pass and fail criteria). The results of the leach tests are shown in Table 3 with additional detail contained in Appendix 3 to this report.

Table 3: Granular Leach Test Results

	P15N1	**P15N1 (duplicate)**	**P15N2**	**P15C**	**P13N**
	mg/kg dry substance at L/S =10	**mg/kg dry substance at L/S =10**	**mg/kg dry substance at L/S =10**	**mg/kg dry substance at L/S =10**	**mg/kg dry substance at L/S =10**
Sb	0.0223	0.0179	0.0082	0.0051	0.0566
As	0.0064	0.00045	0.0004	0.0005	0.0020
Ba	192.3	98.8	39.5	165.9	24.1
Cd	0.0015	0.00051	0.0019	0.0006	0.0153
Cr	0.0861	0.1207	0.1026	0.1011	0.5659
Cu	0.0045	0.0014	0.0019	0.0014	3.3167
Pb	7.0084	4.8198	4.5773	16.0019	10.6966
Mo	0.2015	0.4054	0.5309	0.5793	0.8277
Ni	0.0030	0.0042	0.0038	0.0039	1.7317
Zn	0.3217	0.5489	0.6488	1.1913	1.7939
Se	0.0037	0.0009	0.0128	0.0026	0.0011
F	5.2746	5.4500	6.6979	7.1788	10.9284
SO4	127.0	97.1	208.2	109.3	1649.7

	P15N1	P15N1 (duplicate)	P15N2	P15C	P13N
	mg/kg dry substance at L/S =10	**mg/kg dry substance at L/S =10**	**mg/kg dry substance at L/S =10**	**mg/kg dry substance at L/S =10**	**mg/kg dry substance at L/S =10**
Cl	48,013.8	41,628.6	25,143.4	92,221.2	49,375.6

*L/S10 is a liquid to solid ratio of 10 (l/kg)

When reviewing the results of emissions from tank testing, it is all too easy to look at the cumulative emission to 64 days and take that as the final result, compare it with the criteria and issue a pass/fail based on the result. However, there is a stage of analyses that needs to be completed, investigating the mode of the emission i.e. was the emission recorded during the test solely that of a diffusive release or was it some other mechanism (such as dissolution, surface wash-off etc.). Table 4 below shows how each of the species reacted within the test.

Table 4 – Mode of Emission from Tank Test Results

	P15N1	P15N2	P15C	P13N
Sb	*Dissolution*	Depletion	N/A	*Dissolution*
As	*Dissolution*	*Dissolution*	Depletion	*Dissolution*
Ba	**Diffusion**	Depletion	**Diffusion**	**Diffusion**
Cd	Depletion	Depletion	Depletion	Depletion
Cr	Depletion	Depletion	Depletion	Depletion
Cu	*Dissolution*	*Dissolution*	Depletion	Depletion
Hg	N/A	N/A	N/A	N/A
Pb	Depletion	Depletion	Depletion	*Dissolution*
Mo	Depletion	Depletion	**Diffusion**	Depletion
Ni	*Dissolution*	N/A	N/A	**Diffusion**
Zn	Depletion	Depletion	Depletion	Depletion
Se	*Dissolution*	*Dissolution*	*Dissolution*	*Dissolution*
F	Depletion	Depletion	**Diffusion**	Depletion
SO4	Depletion	Depletion	Depletion	Depletion
Cl	**Diffusion**	**Diffusion**	**Diffusion**	Depletion

It is evident from the table above that very few of the species modelled have an emission that is dominated by diffusion (the mode that the test is designed to record) with a high proportion of emissions showing a mode dominated by dissolution and depletion. As such, it is clear that little of the emission is diffusion controlled. It is therefore questionable whether diffusion testing (via the tank test) is an appropriate test method on which to base monolithic waste acceptance criteria for cementaceous wastes.

A comparable observation was made with the synthetic monolithic waste investigated in 2004 but it was hoped that this was simply a function of the very high quantity of cement to waste in the synthetic samples. That said, it is equally interesting to note that the species shown to be emitted that most closely adhere to a diffusive release mode (chloride and barium) are the same species that show large scale failure to meet the criteria.

3.0 CHANGES TO THE MODEL

A computer model of a monolithic waste deposit was used in 2004 to derive the maximum emission that could be permitted without water quality criteria being exceeded at a number of points of compliance. The results of the testing of the monolithic waste have allowed a number of changes to the model to be made that means it better reflects typical cementaceous monolithic waste.

3.1 Changes to Porosity, Density and Moisture Content of the Waste

The assumed waste porosity has been changed to 0.36 (v/v), which is the average of the eight measurements shown in Table 1.

The average of the eight measurements of bulk density and moisture content (1560 kg/m^3 and 0.35 v/v, respectively) have been used to update the value of these parameters.

3.2 Addition of a Factor to Reflect Tortuosity

There is a difference between the moisture content of deposited monolithic waste and its total porosity. This difference is the air porosity shown in Table 1. The air porosity lengthens the pathway along which diffusion can take place, thus reducing the effective concentration gradient and hence reducing the rate of emission.

Millington and Quirk (1961) developed a relationship that can be used to describe the change in apparent diffusion coefficient as follows:

D_{waste}/D_{water} = water content^10/3 / waste porosity^2

The rate of diffusive emission of a contaminant from a monolithic waste is proportional to the square root of its diffusion coefficient (e.g. NEN 7375). The simulated cumulative emission at any time has therefore been amended by multiplying by the square root of the above quotient.

The above quotient has a value of 0.22 for the average values of measured water content and waste porosity. It has been calculated for all eight samples tested and ranges between 0.13 and 0.29.

3.3 Emission to Fissures in Waste

The simulated emission takes place into fissures between the waste blocks. The water in the fissures is assumed to comprise 0.02 (v/v) of the landfill. A sensitivity study has been carried out on this assumed value.

The water in the fissures is assumed to be clean. In other words, concentrations of contaminants in the water do not affect the rate of emission. Whilst in a monolithic landfill, water infiltrating the surface will develop an increasing concentration of contaminants as it moves through the waste the assumption approximates the conditions of the tank test in which water is replenished on eight occasions.

All other aspects of the original conceptual model developed in 2004 were retained in this simulation including the liner degradation assumptions, geometry and pathway properties.

4.0 RESULTS OF REVISED MODELLING

The model has been re-run for both monolithic waste placed in a non-hazardous landfill (i.e. a site with a 1 m thick liner with a permeability of $1x10^{-9}$ m/s) representing the situation where monolithic waste is disposed of to a site accepting non-reactive, stable non-hazardous wastes and a hazardous landfill (i.e. a site with a 5 m thick liner with a permeability of $1x10^{-9}$ m/s).

The results are provided in Table 5 and Table 6.

Table 5: Calculated and Recommended Revised Monolithic Waste Acceptance Criteria for Waste Destined for a Stable Non-Reactive Hazardous Waste in a Non-Hazardous Landfill and Non-Hazardous Waste in the Same Cell

	Existing Non Hazardous Monolithic Waste Acceptance Criteria (mg/m^2 at 64 days)	Existing Dutch Monolithic Waste Acceptance Criteria (mg/m^2 at 64 days)	Revised Monolithic Waste Acceptance Criteria from Model 10_10_07e (mg/m^2 at 64 days)	Multiplier that Relates Simulated Non Hazardous Granular Waste Acceptance Criteria to Those Adopted	Revised Monolithic Waste Acceptance Criteria (mg/m^2 at 64 days)	Recommended Monolithic Waste Acceptance Criteria (mg/m^2 at 64 days)
Sb	0.3	50	0.43	2.1	0.89	1
As	1.3	50	1.97	0.3	0.65	0.7
Ba	45	1,500	48.43	2.0	97	100
Cd	0.2 (0.03)	5	0.06	45.5	2.6	2.5
Cr	5	500	13.31	1.4	19	20
Cu	45	500	5.94	22.0	131	100
Hg	0.1 (0.01)	1	0.0222	200.0	4.4	1
Pb	6	1,000	1.97	10.5	21	20
Mo	7	900	7.40	2.7	20	20
Ni	6	400	3.93	2.1	8.4	10
Zn	30	800	15.89	6.5	103	100
Se	0.4	60	0.86	1.1	0.93	1
F	60	2,500	75.37	1.8	133	130
SO4	10,000	250,000	12,562	1.8	22,827	25,000
Cl	10,000	250,000	12,562	2.0	24,760	25,000

Note that the recommended values have been subjected to a degree of rounding.

Table 6: Calculated and Recommended Revised Hazardous Landfill Monolithic Waste Acceptance Criteria

	Existing Hazardous Monolithic Waste Acceptance Criteria (mg/m^2 at 64 days)	Existing Dutch Monolithic Waste Acceptance Criteria (mg/m^2 at 64 days)	Revised Monolithic Waste Acceptance Criteria from Model 10_10_07f (mg/m^2 at 64 days)	Multiplier that Relates Simulated Hazardous Granular Waste Acceptance Criteria to those Adopted	Revised Monolithic Waste Acceptance Criteria (mg/m^2 at 64 days)	Recommended Monolithic Waste Acceptance Criteria (mg/m^2 at 64 days)
Sb	2.5	50	0.57	9.3	5	5
As	20	50	2.95	12.6	37	40
Ba	150	1,500	60.41	5.1	308	300
Cd	1 (0.04)	5	0.08	69.4	6	6
Cr	25	500	20.34	2.4	49	50
Cu	60	500	8.48	15.8	134	130
Hg	0.4 (0.01)	1	0.0341	69.0	2	2
Pb	20	1,000	2.95	14.2	42	40
Mo	20	900	10.37	3.9	40	40
Ni	15	400	5.91	5.6	33	30
Zn	100	800	23.50	8.6	202	200
Se	5	60	1.14	9.1	10	10
F	200	2,500	79.32	5.7	452	450
SO4	20,000	250,000	13,220	4.4	58,167	50,000
Cl	20,000	250,000	13,220	3.1	40,981	50,000

The sensitivity of the model predictions has been assessed to the assumed water content of the fissures between monolithic blocks. The results of simulating the monolithic waste in a hazardous landfill with the assumed value of water content set at 0.005 (v/v of total landfill) and 0.3 (v/v of total landfill) are presented in Table 7.

Table 7: Results of Assessment of Sensitivity of Predictions to Assumed Water Content of Fissures

	Revised Monolithic Waste Acceptance Criteria from Model 10_10_07f (mg/m^2 at 64 days) Water Content of Fissures = 0.05 v/v Total Landfill	Revised Monolithic Waste Acceptance Criteria from Model 10_10_07g (mg/m^2 at 64 days) Water Content of Fissures = 0.005 v/v Total Landfill	Revised Monolithic Waste Acceptance Criteria from Model 10_10_07h (mg/m^2 at 64 days) Water Content of Fissures = 0.3 v/v Total Landfill
Sb	0.57	0.57	0.51
As	2.95	2.96	2.85
Ba	60.41	60.91	51.46
Cd	0.08	0.08	0.08
Cr	20.34	20.37	19.82
Cu	8.48	8.51	7.92
Hg	0.0341	0.0342	0.0333
Pb	2.95	2.96	2.85
Mo	10.37	10.41	9.56
Ni	5.91	5.92	5.70
Zn	23.50	23.55	22.42
Se	1.14	1.15	1.02
F	79.32	80.49	65.31
SO4	13,220	13,415	10,884
Cl	13,220	13,416	10,884

5.0 COMPARISON OF RESULTS USING DIFFERENT TEST METHODS

The samples of monolithic wastes have been subjected to both tank testing and granular leach testing. Table 8 shows a comparison of the limit values and how each of the samples performed against the different criteria.

None of the samples pass any of the sets of criteria for disposal at a hazardous waste landfill. There is, however, correlation between the determinands that fail the criteria for monolithic testing and those that fail the granular leach test criteria. All samples fail for chloride. All the samples fail the tank test criteria for barium. In addition one sample fails the tank test criteria for copper, lead and nickel and another for lead only.

	Revised Monolithic Waste Acceptance Criteria	**Tank Test Results**					**Granular Test Leaching Results**						**Existing Granular WACs L/S = 10 l/kg**
		P15N1	**P15N2**	**P15C**	**P13N**		**P15N1**	**P15N1 (duplicate)**	**P15N2**	**P15C**	**P13N**		
	(mg/m² at 64 days)	**(mg/m² at 64 days)**	**(mg/m² at 64 days)**	**(mg/m² at 64 days)**	**(mg/m² at 64 days)**		**mg/kg dry substance at L/S =10**	**mg/kg dry substance at L/S =10**	**mg/kg dry substance at L/S =10**	**mg/kg dry substance at L/S =10**	**mg/kg dry substance at L/S =10**		**mg/kg dry substance**
Sb	5	3.26	4.02	0.81	2.56		0.022	0.018	0.0082	0.0051	0.057	Sb	5
As	37	0.85	0.74	0.4	0.89		0.0064	0.00045	0.0004	0.0005	0.002	As	25
Ba	308	**1021**	**694.6**	**2506**	**780**		192	98.8	39.5	166	24.1	Ba	300
Cd	6	0.021	0.023	0.056	0.029		0.0015	0.00051	0.0019	0.0006	0.015	Cd	1
Cr	49	3.73	9.68	2.81	22.7		0.086	0.12	0.10	0.10	0.57	Cr	70
Cu	134	0.14	0.24	0.07	**267**		0.0045	0.0014	0.0019	0.0014	3.3	Cu	100
Hg	2											Hg	2
Pb	42	30.2	30.7	**74**	**131**		7.00	4.82	4.58	16.0	10.7	Pb	50
Mo	40	7.11	13.2	14.2	18		0.20	0.41	0.53	0.58	0.83	Mo	30
Ni	33	0.12	0.15	0.13	**77.1**		0.0030	0.0042	0.0038	0.0039	1.73	Ni	40
Zn	202	10.3	12.7	18.6	24.9		0.32	0.55	0.65	1.19	1.79	Zn	200
Se	10	3.17	3.22	3.09	4.16		0.0037	0.0009	0.013	0.0026	0.0011	Se	7
F	452	118.4	114.8	137.2	303.1		5.27	5.45	6.7	7.18	10.93	F	500
SO4	58,167	1609	7475	2039	32514		127.0	97.1	208	109.3	1649.7	SO_4	50,000
Cl	40,981	**1,607,774**	**1,661,459**	**2,798,992**	**2,456,123**		**48,014**	**41,629**	**25,143**	**92,221**	**49,376**	Cl	25,000

Table 8 – Results of Sample Testing Against Revised Criteria and Existing Granular Limit Values

Note that the values in Red bold exceed the criteria.

Note that the comparison above is based on the calculated revised criteria and not on our recommended criteria that includes a rounding function.

6.0 CONCLUSIONS

This study has addressed the assumption in the derivation of existing MonWACs that the monolithic waste is fully saturated. The simulated rate of emission from the waste has been reduced by a factor that takes account of the effect of tortuosity on the diffusion coefficient. The values of other parameters have been adjusted to reflect the results of testing of samples of cementaceous monolithic waste.

Revised criteria have been developed that in the case of hazardous waste landfills are approximately twice as high as previously developed.

The model results are insensitive to the value of assumed water content of the fissures between monolithic blocks.

The potential variability in criteria could be assessed by re-running the model with different values of the Millington-Quirk factor. Such an exercise might provide an indication of MonWACs that could be suitable for waste stabilised by means other than cement (such as vitrified wastes).

As part of this work we have looked at the behaviour of the waste samples in the tank test. It is apparent that the mechanism for emission in many steps of the tests is not primarily diffusion. Dissolution and contaminant depletion are instead often dominant mechanisms. Further, anecdotal evidence from ECN suggests the samples collected for this study were some of the more resilient samples to the effects of submersion in water they have received. We therefore have doubts that many so called monolithic wastes have a mean unconfined compressive shear strength of at least 1MPa (after 28 days curing). Consideration should be given to demonstrating the strength characteristics of the material under saturated, or near saturated, conditions in any further changes to MonWACs.

Furthermore, there is, on the basis of this small sample, some correlation between the criteria pass/fail results for the samples of waste tested between the derived tank test results and those obtained using the granular leaching test methods. On the basis that none of the cementaceous monolithic samples examined in this study showed emissions dominated by diffusion, reliance on the granular test method (as currently permitted in the UK as an alternative to diffusion testing) and as adopted by the Nordic Council of Ministers (Hjelmar 2006) for hazardous stabilised waste has some significant advantages in terms of testing cost and laboratory turn-around time.

7.0 REFERENCES

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APPENDICES

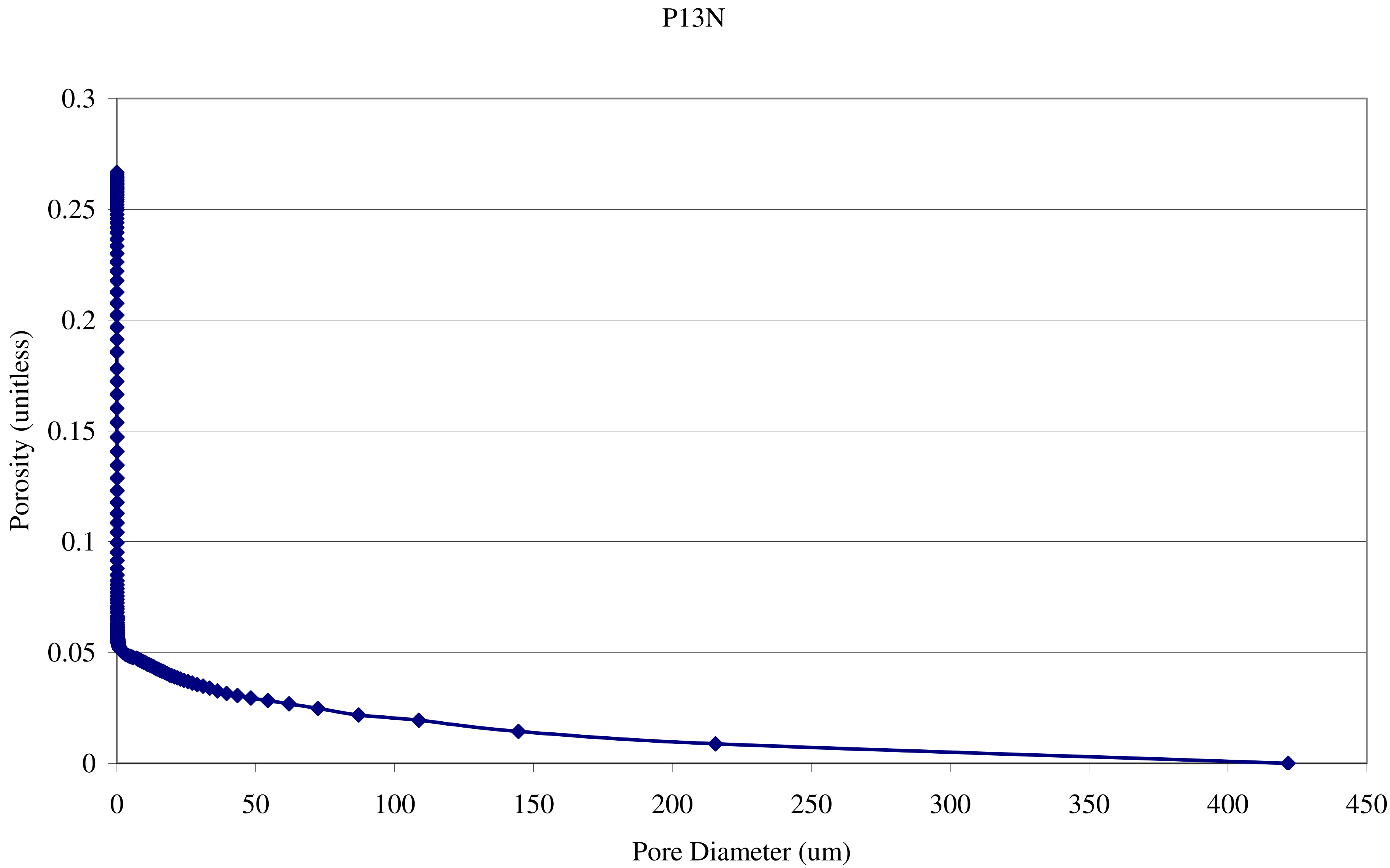
APPENDIX 1

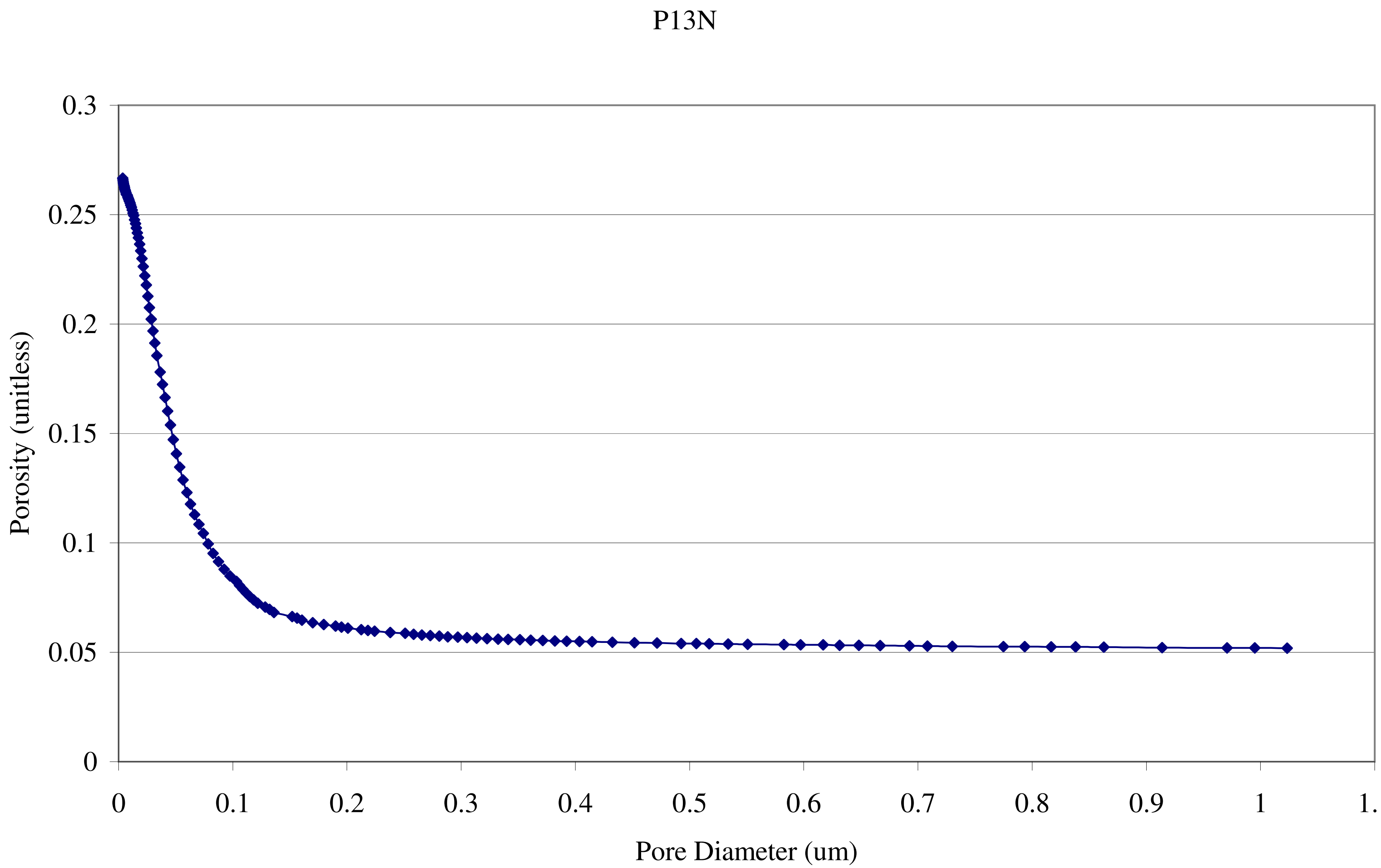
DATA RELATING TO MERCURY POROSIMETRY RESULTS AND PORE SIZE DISTRIBUTIONS

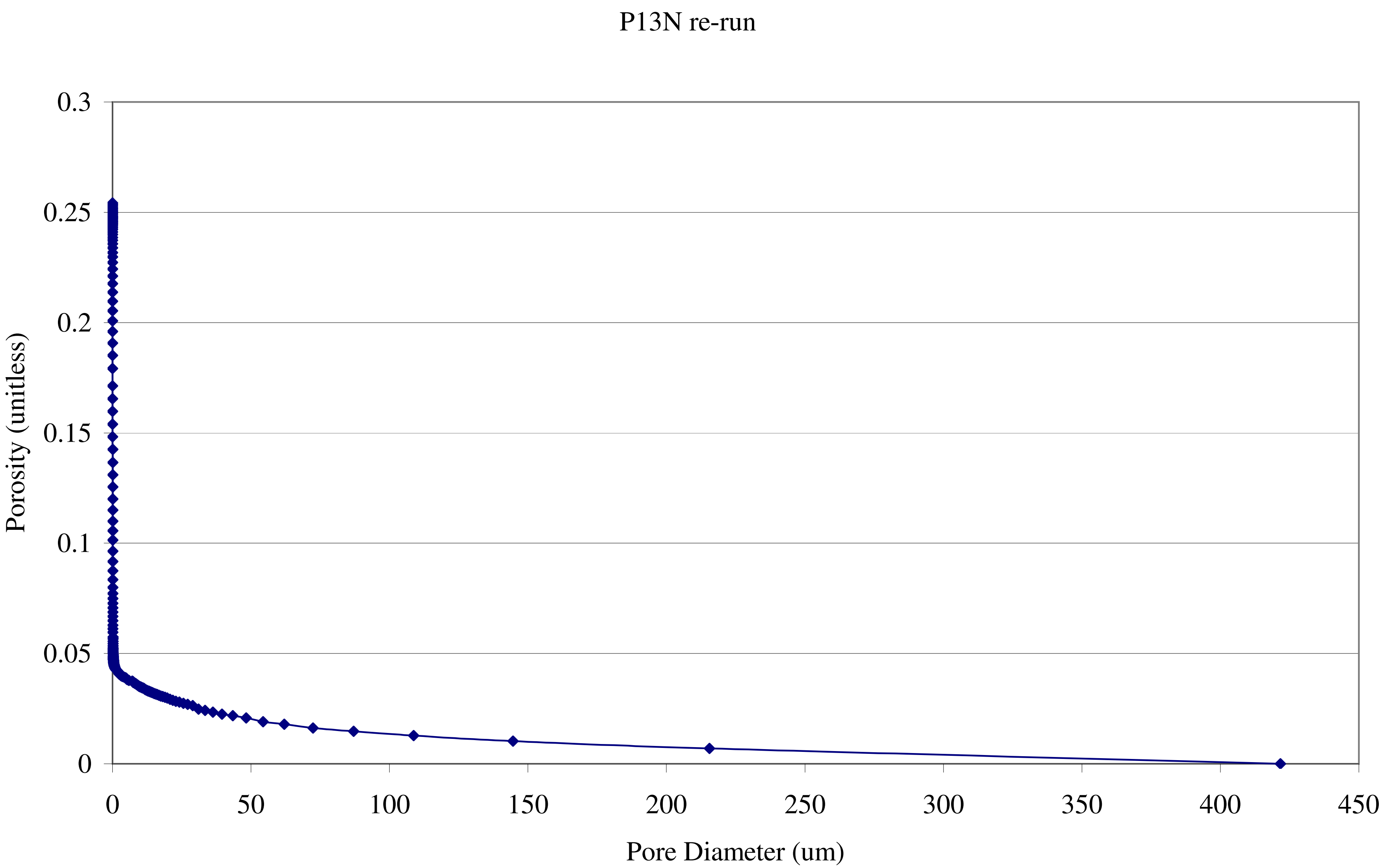
Results of Porosimetry Testing and Other Physical Results

Monolithic Test Summaries								
Porosimetry Ref	Sample ID	Sample Weight	Skeletal Density	Porosity	Bulk Density	Moisture content at Field Capacity	Air porosity	Tank Test Bulk Density
		g	g/ml	%	g/ml	% v/v	%v/v	g/L
MAS552	P13N - Run 1	1.1582	2.2513	26.6686	1.6509	24.2686	2.4	1691.6
MAS552 re-run	P13N - Run 2	1.1783	2.194	25.4216	1.6363	23.8216	1.6	
MAS553	P15C - Run 1	0.5766	2.6314	43.1486	1.496	41.3486	1.8	1548.5
MAS553 re-run	P15C - Run 2	0.6927	2.5309	40.7519	1.4995	39.0519	1.7	
MAS554	P15N1 - Run 1	0.6215	2.5301	40.1346	1.5146	39.3346	0.8	1674.4
MAS554 re-run	P15N1 - Run 2	0.7218	2.4134	36.6998	1.5277	35.9098	0.79	
MAS555	P15N2 - Run 1	0.5946	2.4731	33.8954	1.6348	32.9054	0.99	1634.2
MAS555 re-run	P15N2 - Run 2	0.5972	2.5692	42.3515	1.4811	41.1015	1.25	

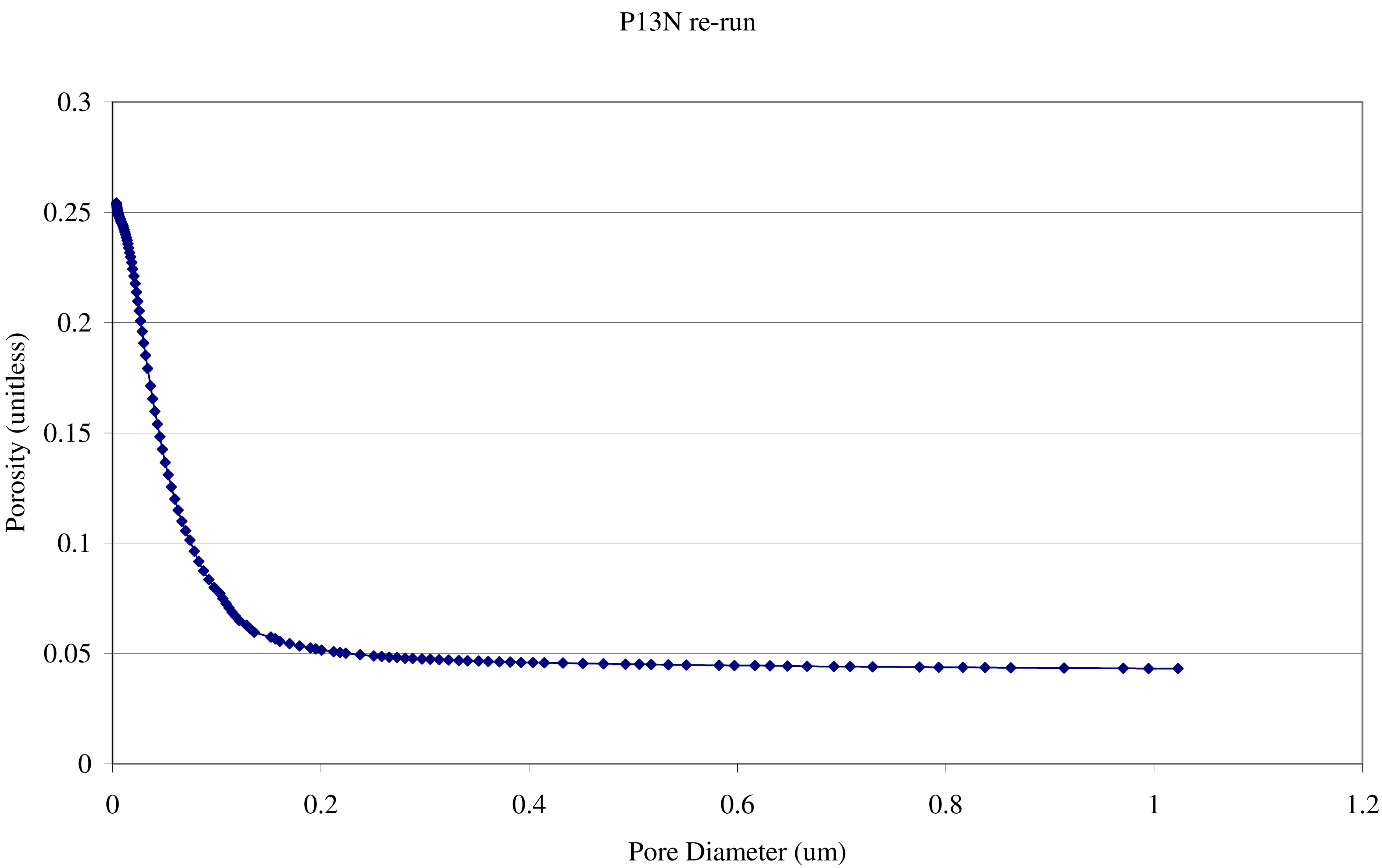
Pairs of Graphs of each of the test runs (one showing pore sizes from 0 to 450 μm and one showing the range 0 to 1 μm) follow.

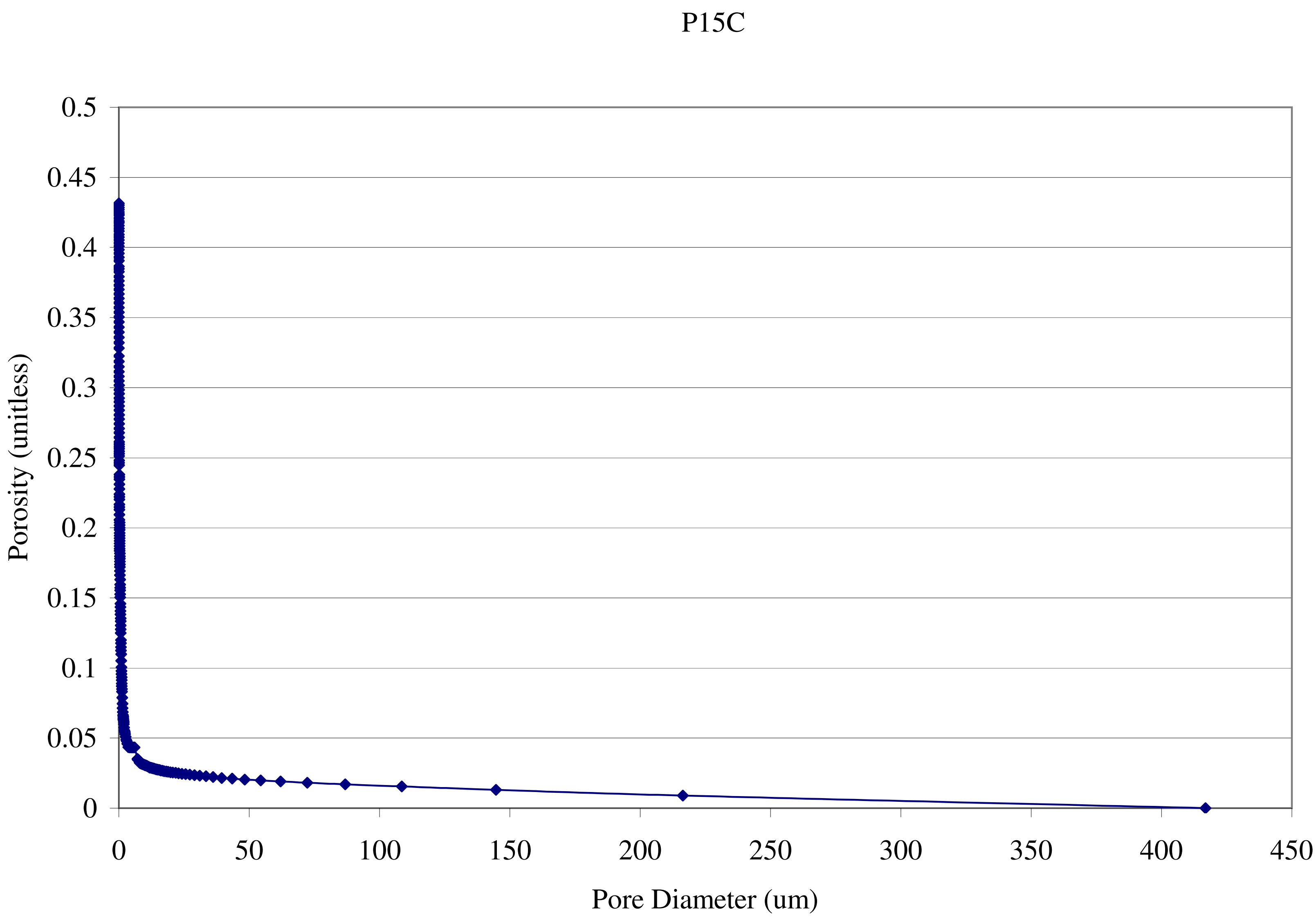

P13N
Porosity (unitless)
0.3
0.25
0.2
0.15
0.1
0.05
0
0
50
100
150
200
250
300
350
400
450
Pore Diameter (um)

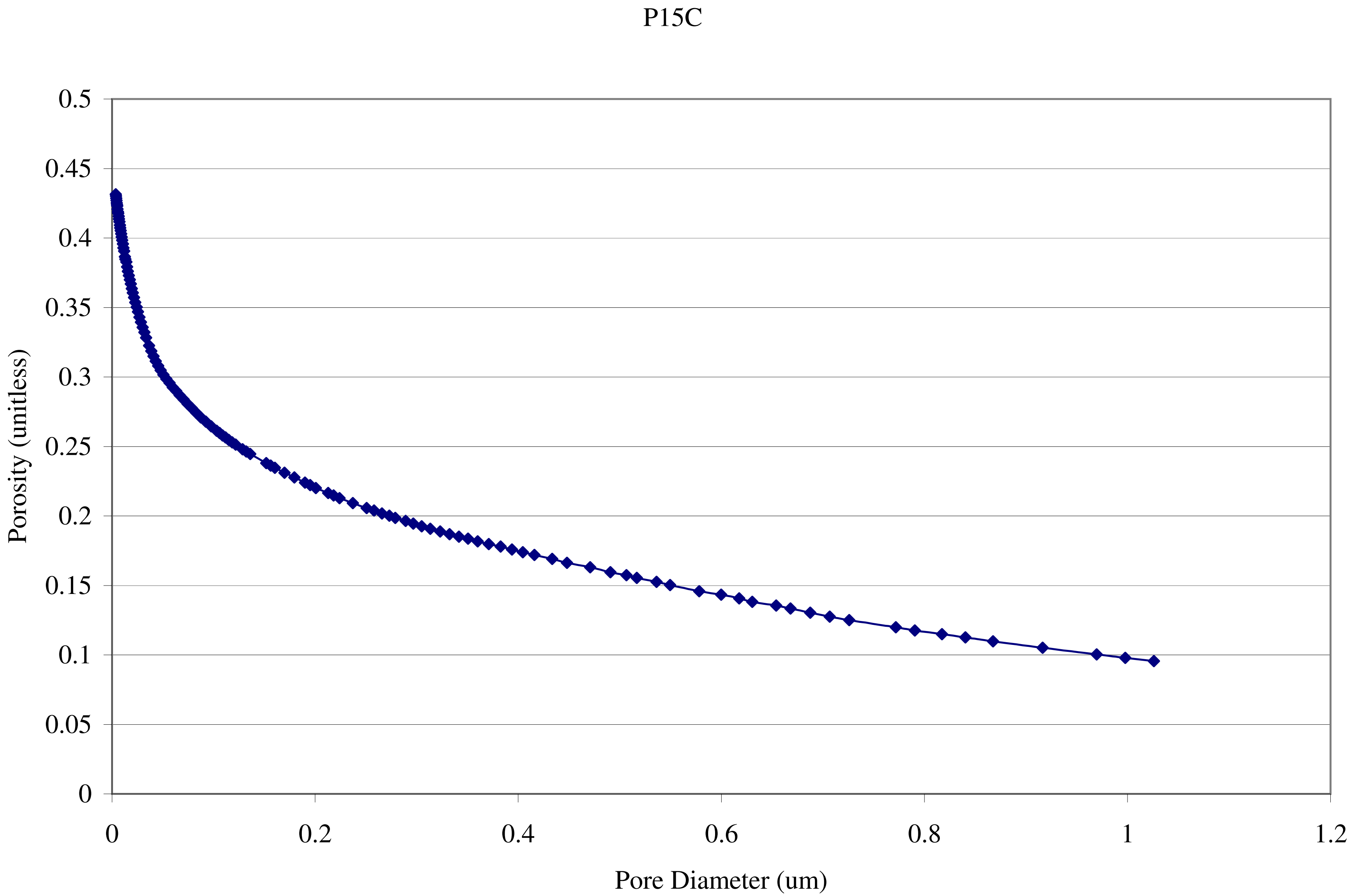

P13N
Porosity (unitless)
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
Pore Diameter (um)

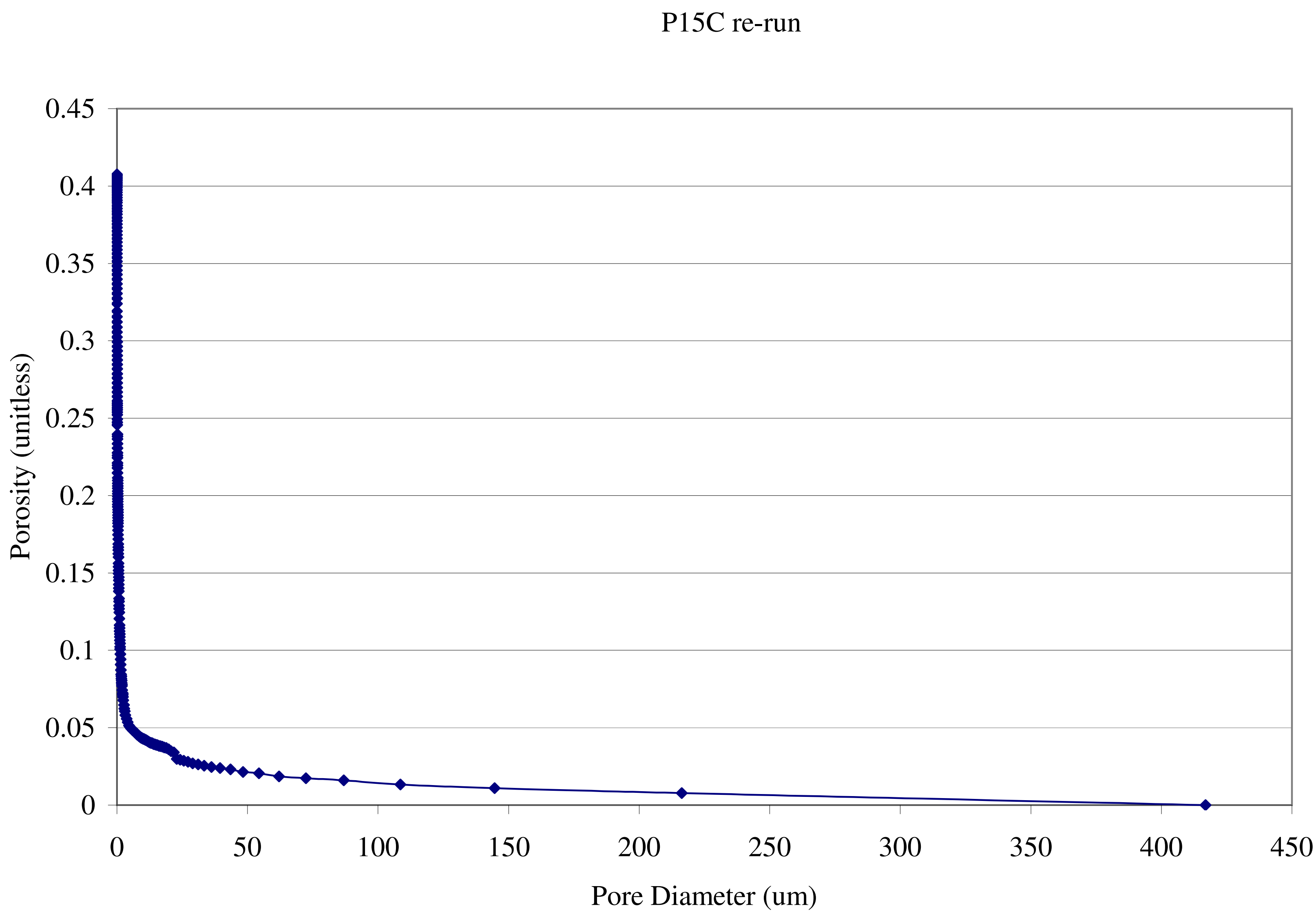


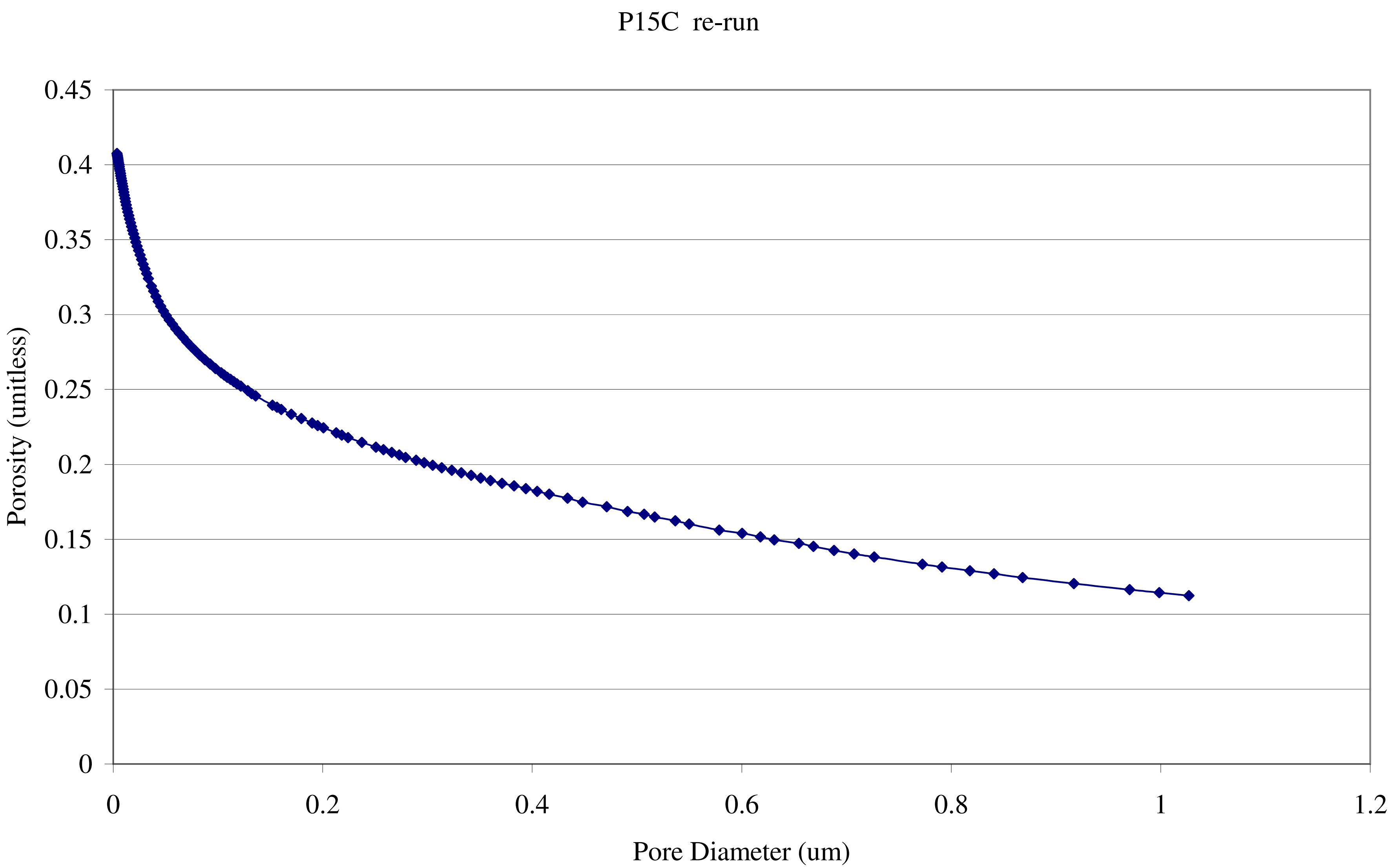
P13N re-run
Porosity (unitless)
0.3
0.25
0.2
0.15
0.1
0.05
0
0
50
100
150
200
250
300
350
400
450
Pore Diameter (um)


P13N re-run
Porosity (unitless)
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
1.2
Pore Diameter (um)

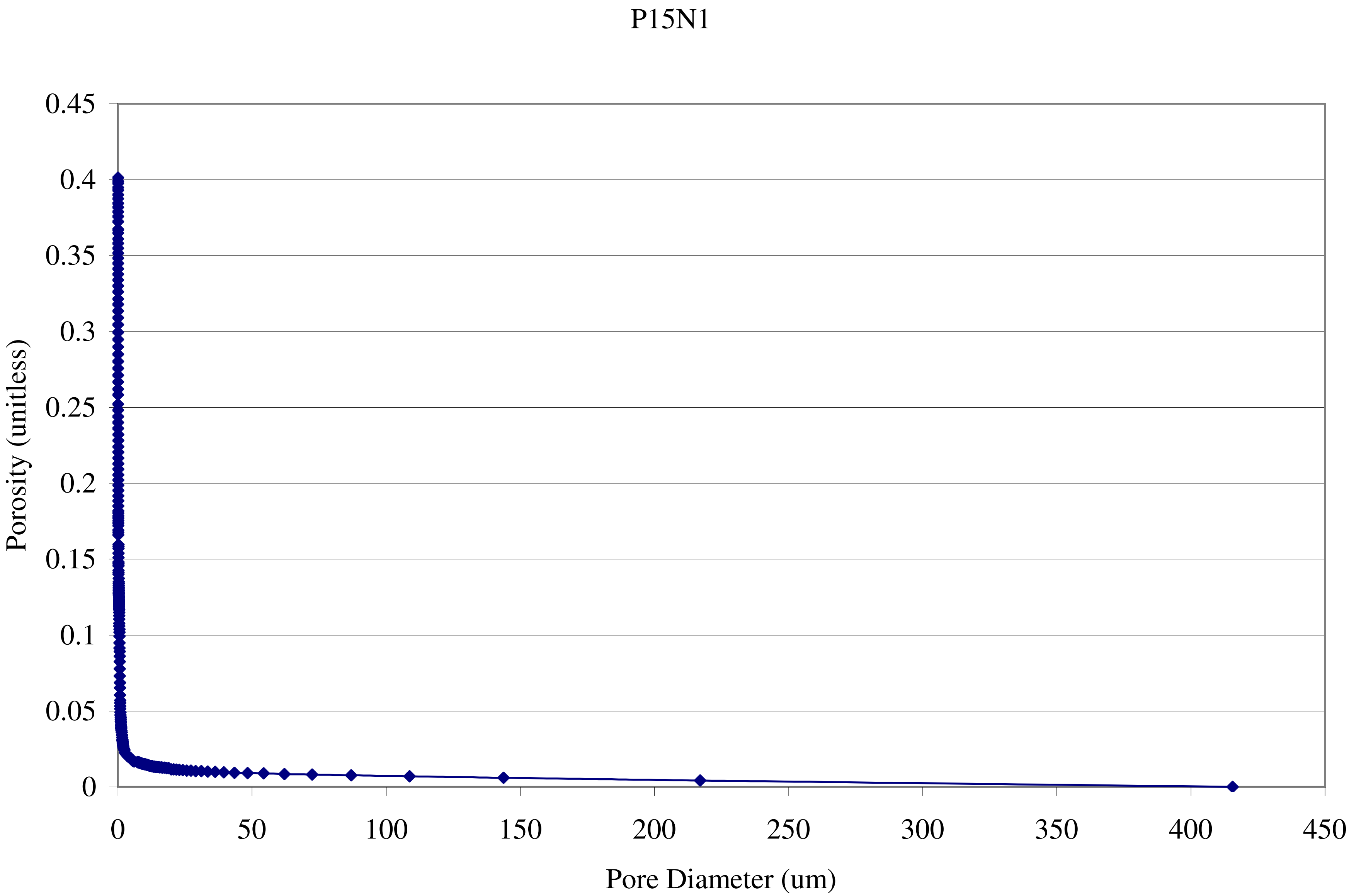

P15C
Porosity (unitless)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
50
100
150
200
250
300
350
400
450
Pore Diameter (um)

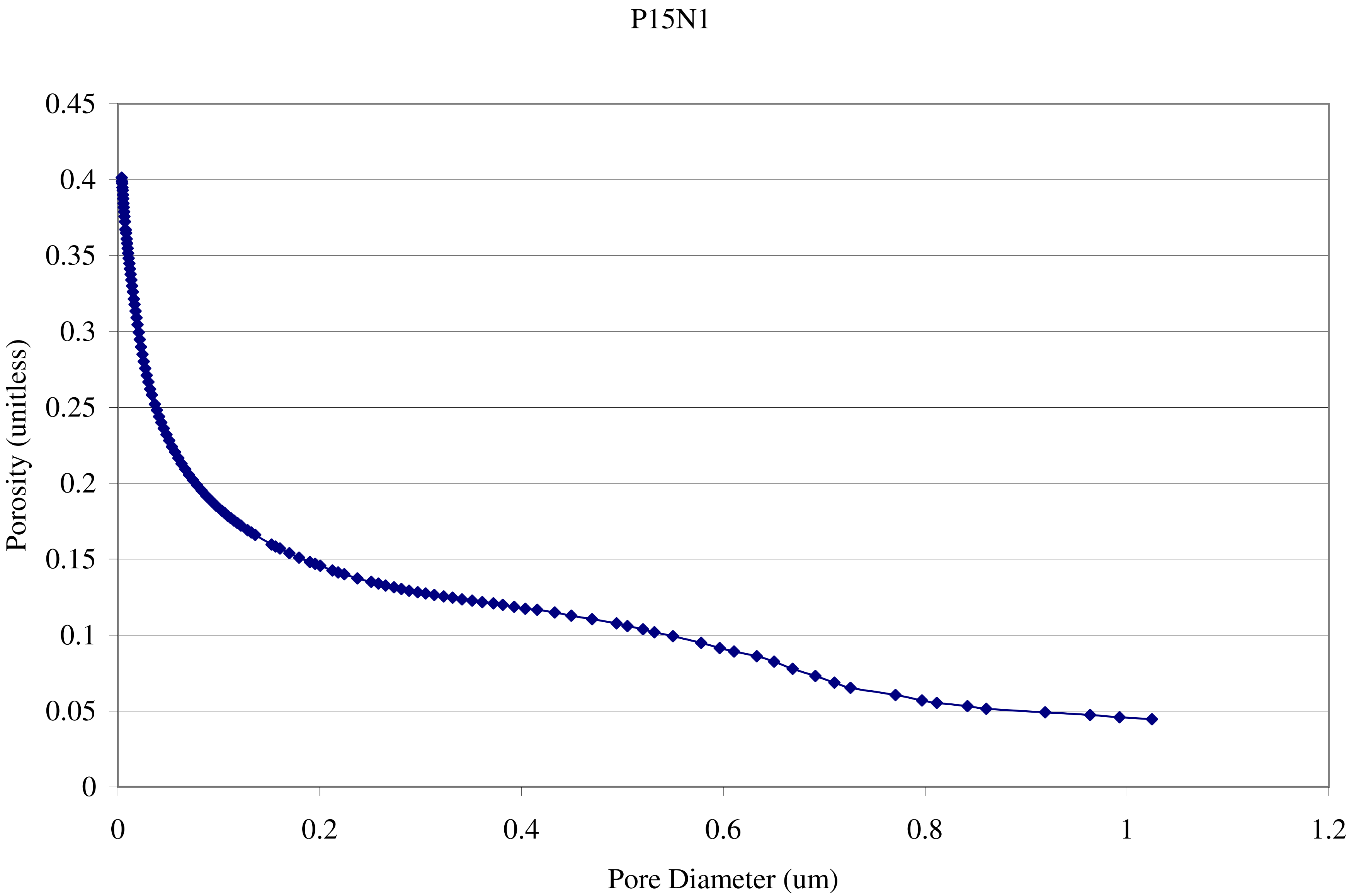

P15C
Porosity (unitless)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
1.2
Pore Diameter (um)


P15C re-run
Porosity (unitless)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
50
100
150
200
250
300
350
400
450
Pore Diameter (um)

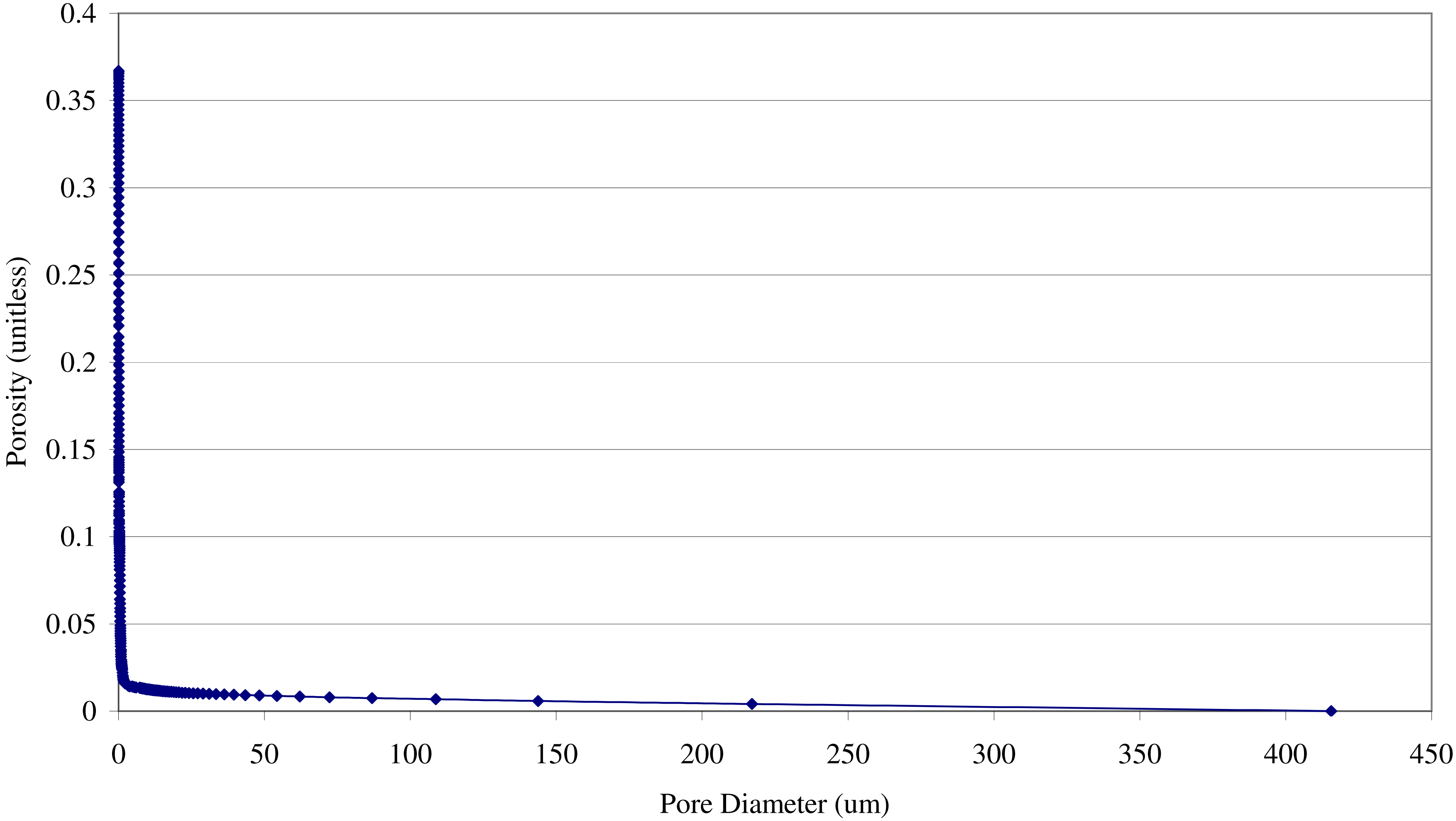


P15C re-run
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Porosity (unitless)
0
0.2
0.4
0.6
0.8
1
1.2
Pore Diameter (um)

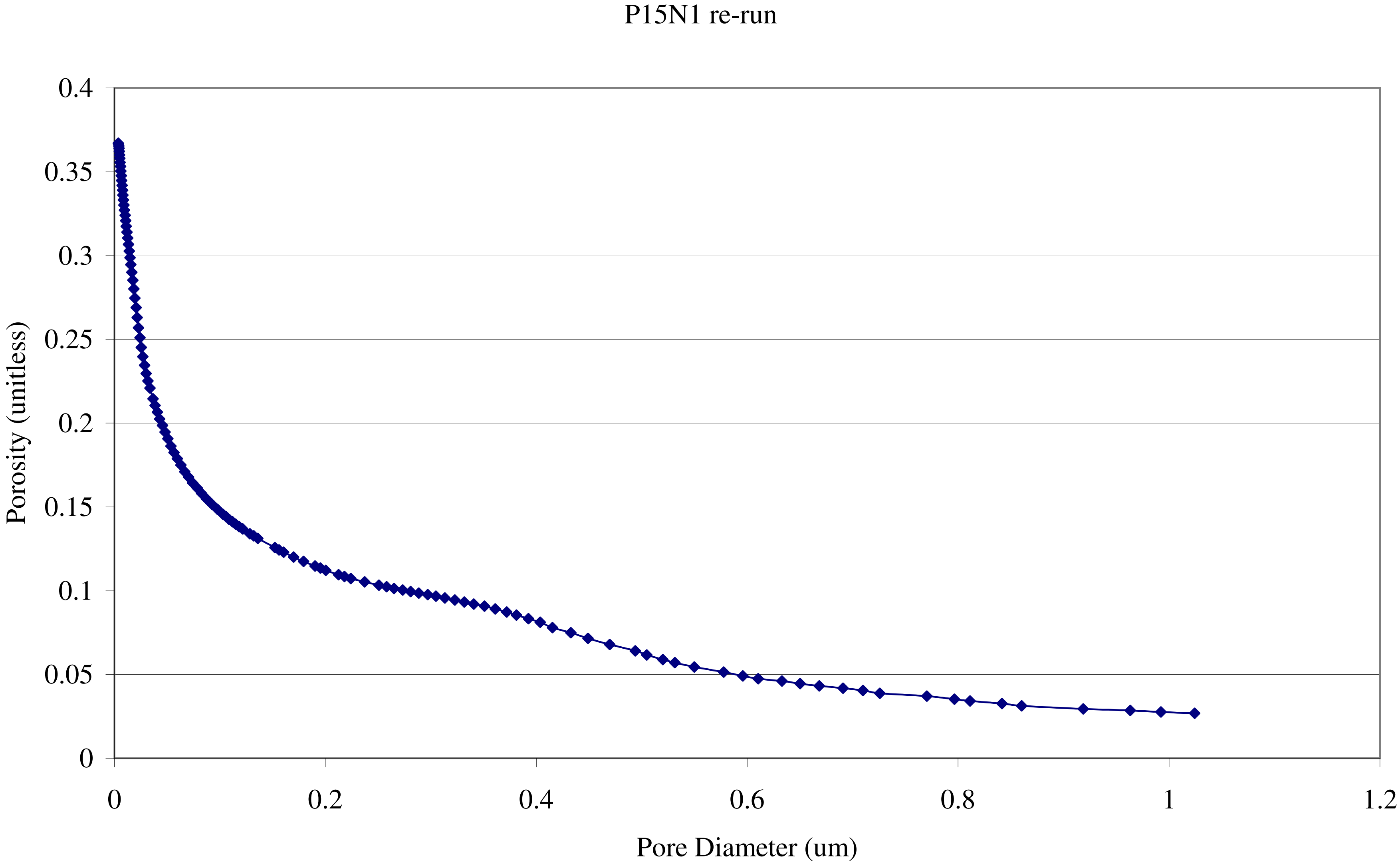

P15N1
Porosity (unitless)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
50
100
150
200
250
300
350
400
450
Pore Diameter (um)


P15N1
Porosity (unitless)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
1.2
Pore Diameter (um)

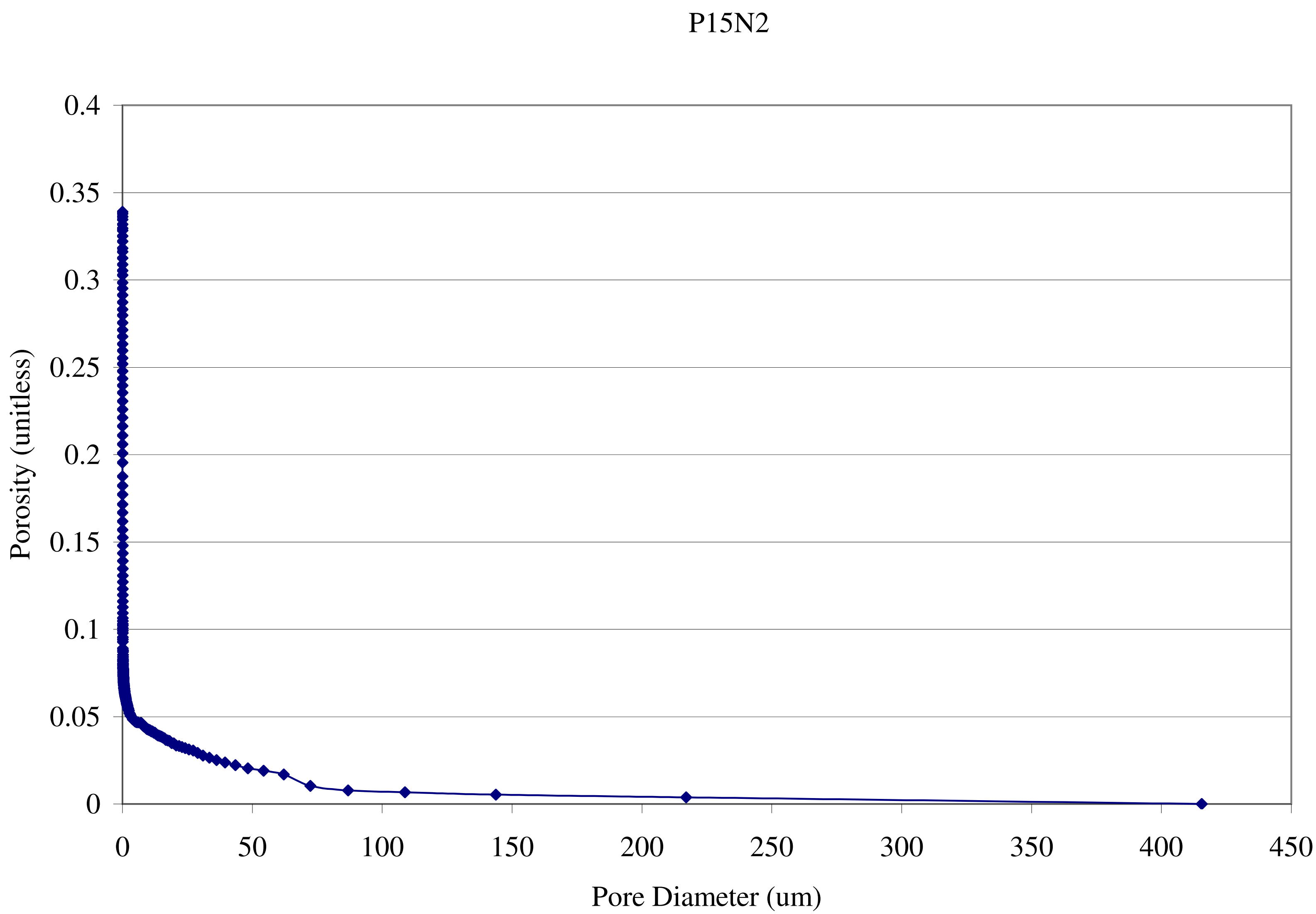
P15N1 re-run

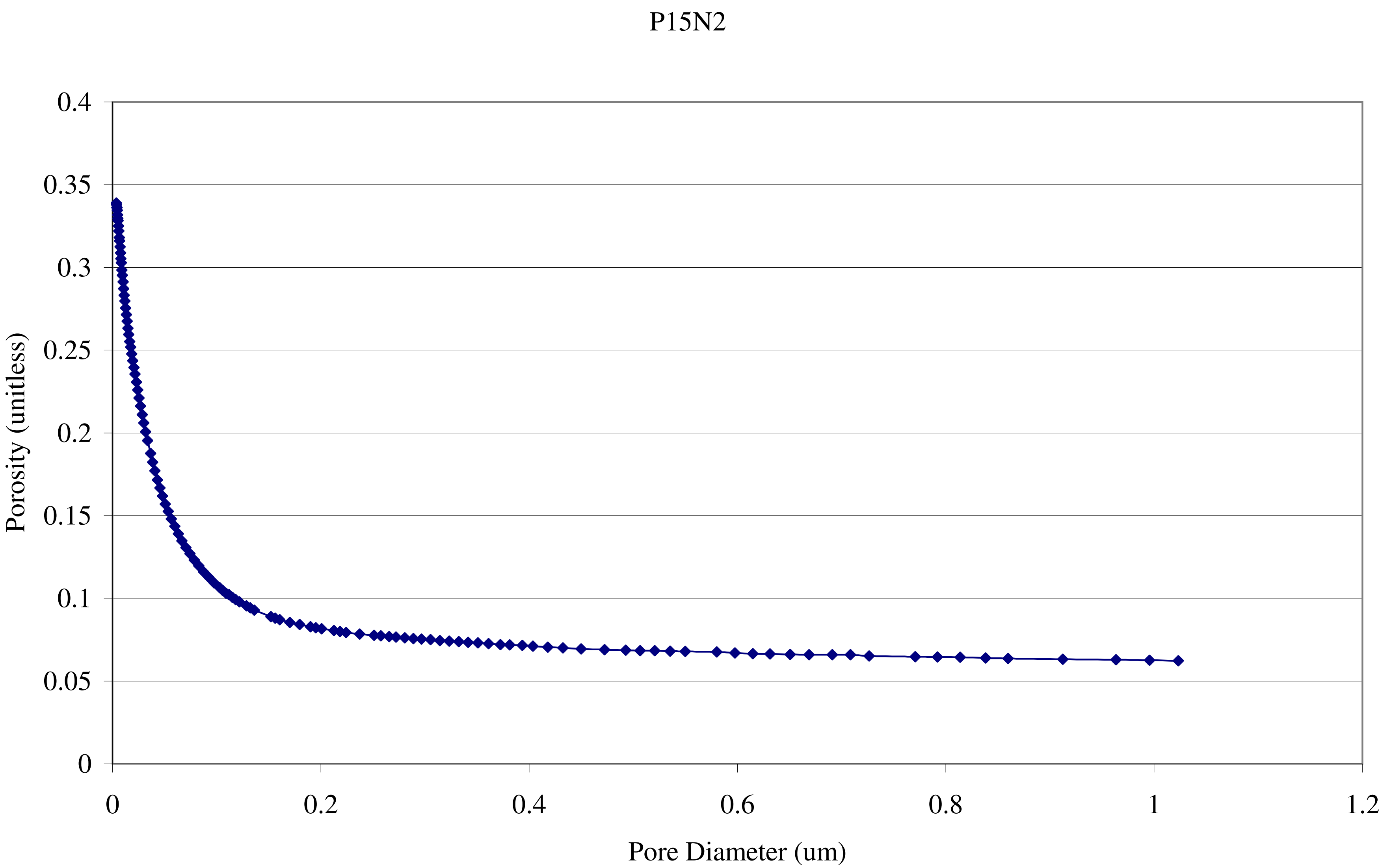


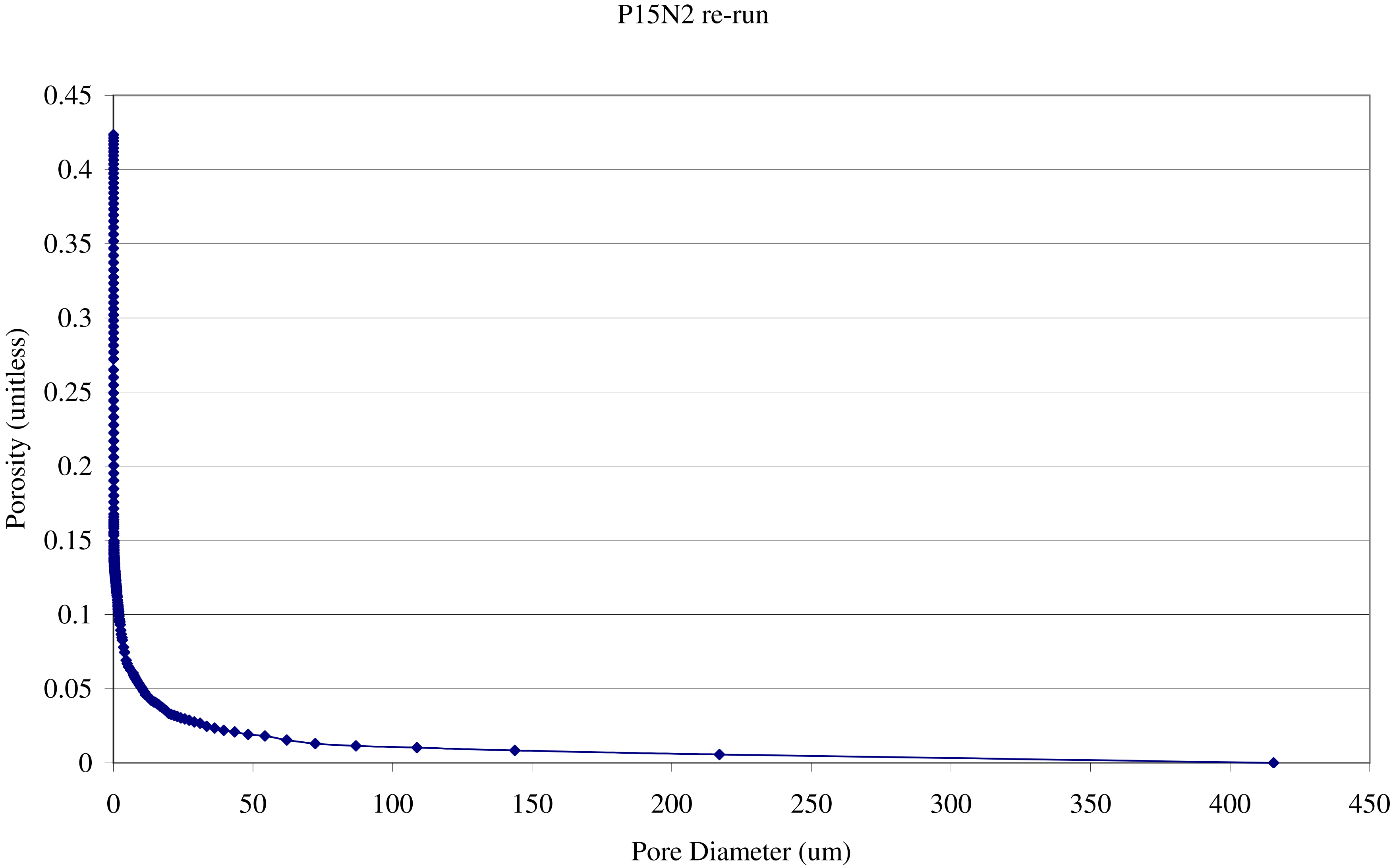
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Porosity (unitless)
0
50
100
150
200
250
300
350
400
450
Pore Diameter (um)



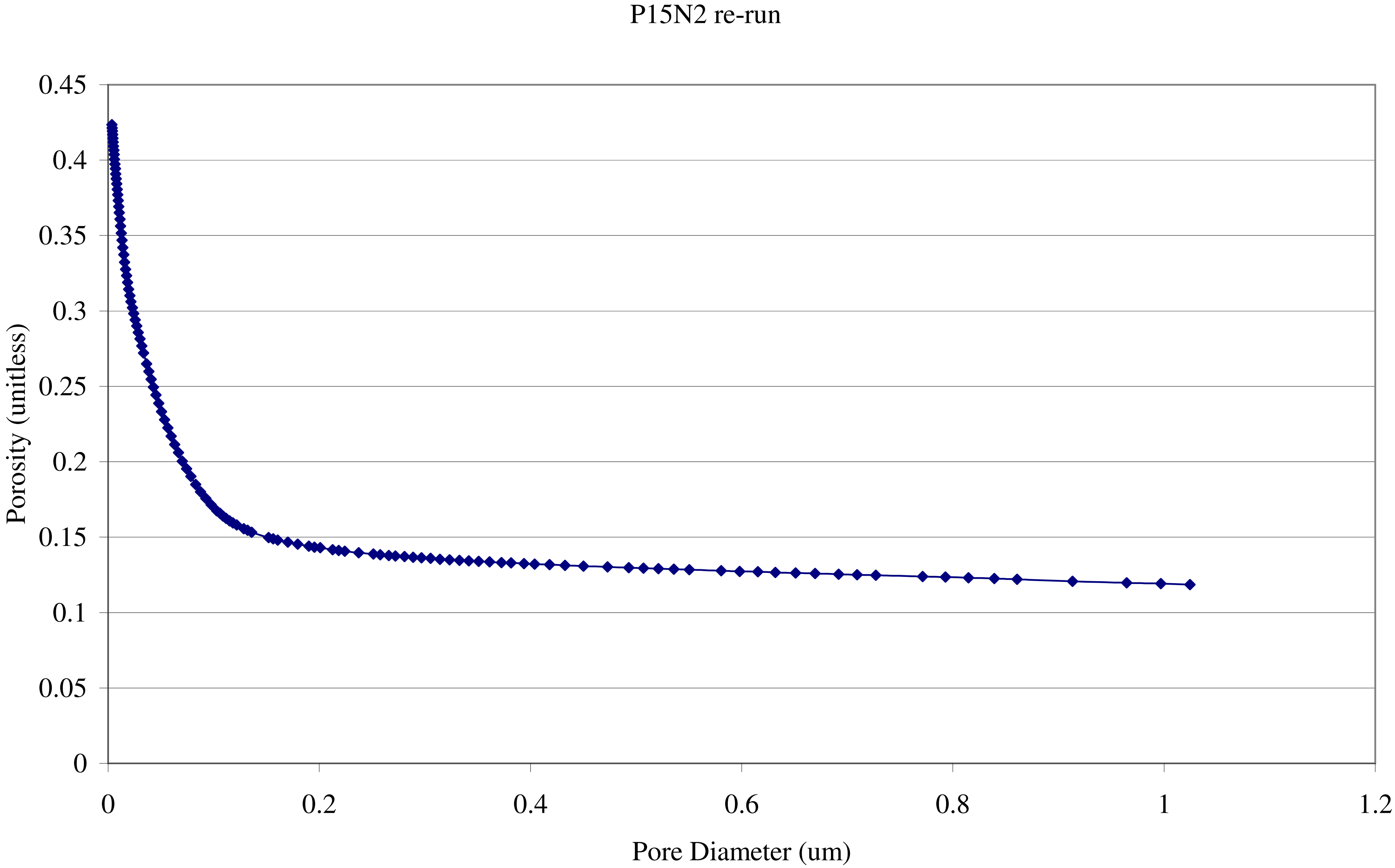
P15N1 re-run
Porosity (unitless)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
1.2
Pore Diameter (um)


P15N2
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Porosity (unitless)
0
50
100
150
200
250
300
350
400
450
Pore Diameter (um)


P15N2
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Porosity (unitless)
0
0.2
0.4
0.6
0.8
1
1.2
Pore Diameter (um)



P15N2 re-run
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Porosity (unitless)
0
50
100
150
200
250
300
350
400
450
Pore Diameter (um)


P15N2 re-run
Porosity (unitless)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
1.2
Pore Diameter (um)

APPENDIX 2

TANK TEST RESULTS

Laboratory ECN
(Availability measured by this lab)

Sample:			Time (days)	As mg/m2	Ba mg/m2	Cd mg/m2	Cr mg/m2	Cu mg/m2	Mo mg/m2	Ni mg/m2	Pb mg/m2	Sb mg/m2	Se mg/m2	Zn mg/m2	Cl mg/m2	SO4 mg/m2	F mg/m2
P15N1	calculated	e64-calc	Frac.1-8	0.46	1100	0.021	3.54	0.14	7.65	0.12	34.0	3.57	3.28	12.0	1779750	1891	136.2
	calculated	e64-calc	Frac.2-7	0.45	1205	0.019	3.99	0.16	8.65	0.12	41.4	3.85	4.15	13.4	1874452	2014	147.5
	calculated	e64-calc	Frac.1-3	0.19	1178	0.031	2.70	0.34	7.76	0.23	41.5	5.41	4.29	16.7	2028081	3515	190.6
	calculated	e64-calc	Frac.3-6	0.33	1282	0.026	4.47	0.21	9.68	0.12	47.6	3.97	4.32	15.1	2036037	2389	155.7
	calculated	e64-calc	Frac.5-8	0.75	997.0	0.014	4.04	0.075	6.97	0.062	25.0	2.29	2.14	8.54	1512359	985.8	93.4
	Measured:	**e***	**64**	**0.85**	**1021**	**0.021**	**3.73**	**0.14**	**7.11**	**0.12**	**30.2**	**3.26**	**3.17**	**10.3**	**1607774**	**1609**	**118.4**
P15N2	calculated	e64-calc	Frac.1-8	0.75	764.4	0.025	10.1	0.26	14.1	0.18	34.0	4.42	3.36	14.7	1856012	7974	133.3
	calculated	e64-calc	Frac.2-7	0.77	852.6	0.024	13.1	0.25	17.0	0.19	42.0	4.49	3.81	17.0	2035677	10217	142.0
	calculated	e64-calc	Frac.1-3	0.85	866.3	0.049	10.9	0.44	14.7	0.28	41.2	5.46	6.93	20.3	2164911	12482	190.8
	calculated	e64-calc	Frac.3-6	0.81	900.4	0.023	17.3	0.33	19.8	0.22	46.3	5.30	4.89	19.5	2280794	14591	150.2
	calculated	e64-calc	Frac.5-8	0.68	648.5	0.014	8.38	0.17	12.6	0.11	26.5	3.22	1.97	10.3	1538503	4753	92.2
	Measured:	**e***	**64**	**0.74**	**694.6**	**0.023**	**9.68**	**0.24**	**13.2**	**0.15**	**30.7**	**4.02**	**3.22**	**12.7**	**1661459**	**7475**	**114.8**
P15C	calculated	e64-calc	Frac.1-8	0.40	2379	0.037	3.10	0.068	15.1	0.15	84.3	0.95	3.18	21.8	3148792	2392	158.9
	calculated	e64-calc	Frac.2-7	0.54	2568	0.030	3.62	0.083	16.0	0.16	103.6	0.97	3.85	24.8	3349490	2659	167.8
	calculated	e64-calc	Frac.1-3	0.36	1943	0.14	3.24	0.13	15.5	0.29	124.5	1.49	4.42	33.8	3828501	3931	248.2
	calculated	e64-calc	Frac.3-6	0.55	2708	0.027	4.20	0.073	16.9	0.17	124.1	1.21	3.66	27.8	3577360	3053	169.0
	calculated	e64-calc	Frac.5-8	0.34	2647	0.014	2.57	0.037	13.9	0.10	53.5	0.59	1.97	13.9	2553416	1364	101.1
	Measured:	**e***	**64**	**0.40**	**2506**	**0.056**	**2.81**	**0.070**	**14.2**	**0.13**	**74.0**	**0.81**	**3.09**	**18.6**	**2798992**	**2039**	**137.2**
P13N	calculated	e64-calc	Frac.1-8	0.76	768.8	0.029	25.5	216.6	20.8	74.5	127.3	2.10	4.14	27.9	2722048	27295	355.9
	calculated	e64-calc	Frac.2-7	0.71	759.5	0.027	28.8	221.0	23.0	76.7	132.5	1.63	5.03	27.8	2827903	29661	399.4
	calculated	e64-calc	Frac.1-3	1.22	762.8	0.064	56.4	168.4	41.7	75.1	269.0	2.26	11.0	63.5	6579316	119284	560.2
	calculated	e64-calc	Frac.3-6	0.48	726.2	0.031	30.4	207.6	23.6	72.8	117.8	1.78	6.90	31.6	2889849	33522	437.4
	calculated	e64-calc	Frac.5-8	0.68	790.4	0.014	13.2	278.2	11.7	77.2	61.1	1.84	1.60	12.6	1337517	7940	230.0
	Measured:	**e***	**64**	**0.89**	**799.1**	**0.029**	**22.7**	**267.2**	**18.0**	**77.1**	**131.1**	**2.56**	**4.16**	**24.9**	**2456123**	**32514**	**303.1**

APPENDIX 3

GRANULAR TEST RESULTS

Results of BS EN 12457-3 leaching of crushed cores of stabilised hazardous waste

Sample Code	L/S ratio	pH	As mg/kg	Ba mg/kg	Cd mg/kg	Cr mg/kg	Cu mg/kg	Hg mg/kg	Mo mg/kg	Ni mg/kg	Pb mg/kg	Sb mg/kg	Se mg/kg	Zn mg/kg	Cl mg/kg	F mg/kg	SO_4 mg/kg
Stabilized_waste_P13N	**2**	11.95	0.0030	1.44	0.0278	0.609	3.12	0.00052	0.72	1.86	2.17	0.0911	0.00051	1.49	50154	1.15	2306
	2-10	12.30	0.0020	24.1	0.0153	0.566	3.32	0.00024	0.83	1.73	10.7	0.0566	0.00107	1.79	49376	10.9	1650
Stabilized_waste_P15C	**2**	12.53	0.0002	51.6	0.0001	0.055	0.0003	0.00004	0.27	0.0002	14.3	0.0018	0.00036	0.332	76210	0.71	103
	2-10	12.53	0.0005	166	0.0006	0.101	0.0014	0.00024	0.58	0.0039	16.0	0.0051	0.00261	1.19	92221	7.18	109
Stabilized_waste_P15N1	**2**	12.54	0.0001	17.7	0.0001	0.092	0.0003	0.00004	0.26	0.0008	0.88	0.0035	0.00018	0.102	39088	0.555	82.7
	2-10	12.51	0.0004	98.8	0.0005	0.121	0.0014	0.00024	0.41	0.0042	4.82	0.0179	0.00090	0.549	41629	5.45	97.1
Stabilized_waste_P15N2	**2**	12.87	0.0005	1.03	0.0001	0.365	0.0018	0.00005	1.38	0.0008	1.25	0.0043	0.00103	0.230	44349	1.09	1655
	2-10	12.50	0.0004	39.5	0.0019	0.103	0.0019	0.00024	0.53	0.0038	4.58	0.0082	0.01281	0.649	25143	6.70	208

Comparison with landfill WAC for hazardous and stable, non-reactive hazardous granular wastes

Sample Code	L/S ratio	pH	As	Ba	Cd	Cr	Cu	Hg	Mo	Ni	Pb	Sb	Se	Zn	Cl	F	SO_4
haz WAC L/S10	**mg/kg**		**25**	**300**	**1.0**	**70**	**100**	**2.00**	**30**	**40**	**50**	**5.0**	**7.0**	**200**	**25000**	**500**	**50000**
SNRhaz haz L/S10	**mg/kg**		**2**	**100**	**0.1**	**10**	**50**	**0.2**	**10**	**10**	**10**	**0.7**	**0.5**	**50**	**15000**	**150**	**20000**
Stabilized_waste_P13N	**Haz**	n/a	**0.00**	**0.08**	**0.02**	**0.01**	**0.03**	**0.00**	**0.03**	**0.04**	**0.21**	**0.01**	**0.00**	**0.01**	**1.98**	**0.02**	**0.03**
	SNRHaz	n/a	0.00	0.24	0.15	0.06	0.07	0.00	0.08	0.17	1.07	0.08	0.00	0.04	3.29	0.07	0.08
Stabilized_waste_P15C	**Haz**	n/a	**0.00**	**0.55**	**0.00**	**0.00**	**0.00**	**0.00**	**0.02**	**0.00**	**0.32**	**0.00**	**0.00**	**0.01**	**3.69**	**0.01**	**0.00**
	SNRHaz	n/a	0.00	1.66	0.01	0.01	0.00	0.00	0.06	0.00	1.60	0.01	0.01	0.02	6.15	0.05	0.01
Stabilized_waste_P15N1	**Haz**	n/a	**0.00**	**0.33**	**0.00**	**0.00**	**0.00**	**0.00**	**0.01**	**0.00**	**0.10**	**0.00**	**0.00**	**0.00**	**1.67**	**0.01**	**0.00**
	SNRHaz	n/a	0.00	0.99	0.01	0.01	0.00	0.00	0.04	0.00	0.48	0.03	0.00	0.01	2.78	0.04	0.00
Stabilized_waste_P15N2	**Haz**	n/a	**0.00**	**0.13**	**0.00**	**0.00**	**0.00**	**0.00**	**0.02**	**0.00**	**0.09**	**0.00**	**0.00**	**0.00**	**1.01**	**0.01**	**0.00**
	SNRHaz	n/a	0.00	0.39	0.02	0.01	0.00	0.00	0.05	0.00	0.46	0.01	0.03	0.01	1.68	0.04	0.01