A Survey of the Role of Thermodynamics and Transport Properties IN ChE UNIVERSITY EDUCATION in Europe and the USA

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Thermodynamics and Transport Properties (TTP) is a central subject in the majority of chemical engineering university curricula worldwide, and it is thus of interest to examine how it is taught today in various countries. The content and the organization of the courses implicitly reflect an unexpressed "thermodynamics philosophy." The discussion of different learning styles[1] and their implication on teaching methods has also spurred us to investigate which methods are used for TTP teaching, especially since it is often regarded as a "difficult subject." Our ultimate aim is to improve chemical engineering education for the benefit of the graduates and the industries that will hire them.

A survey on graduate thermodynamics education exclusively in the United States was performed a few years ago by Dube and Visco.[2] As far as we know, no systematic study of the undergraduate TTP education has been undertaken, at least in recent years.

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In the present study, a survey about TTP education in both undergraduate and post-graduate programs in Europe and the United States is presented. Responses received from 136 universities from 20 different European countries and the United States were thoroughly analyzed and the major findings are presented here.

The study differs from the earlier one of Dube and Visco in that:

i. Both Europe and the United States were included in the study and a comparison is performed between Europe and the United States regarding certain educational aspects.

ii. Both undergraduate and graduate education are examined.

iii. The teaching methods were investigated.

A survey regarding education in EU (European Union) countries is especially timely in light of the Bologna process. The Bologna process seeks to establish standards of comparison for curricula that have developed independently in many countries over many years. The unification envisioned by the EU means that career mobility and training must be taken into consideration. Performing this survey at this time provides a snapshot of the thermodynamics curriculum that can serve to advance the Bologna process while simultaneously documenting the status of chemical engineering education in both Europe and the United States.

TABLE 1
Number of universities / colleges per country that were contacted and that responded to the survey*

Country	number of answers (number of inquiries sent)
Austria	1 (2)
Belgium	3 (12)
Bosnia and Herzegovina	1 (1)
Croatia	2 (3)
Denmark	2 (4)
Estonia	1 (1)
Finland	4 (4)
France	6 (24)
Germany	28 (36)
Greece	3 (3)
Hungary	2 (3)
Italy	5 (14)
Netherlands	1 (13)
Norway	1 (6)
Portugal	5 (7)
Russia	2 (14)
Serbia	1 (1)
Slovenia	2 (2)
Sweden	4 (7)
United Kingdom	7 (18)
USA	55 (150)
TOTAL	136 (325)

* *Countries from which no response was received include (the number of institutions contacted is shown in parenthesis): Iceland (1), Ireland (3), FYR Macedonia (1), Moldova (1), Switzerland (1), Poland (3).*

SURVEY METHODOLOGY

The survey was conducted by an international team of chemical engineering professionals from academia and industry using a Web-based surveying system.[3] Invitations were sent out by e-mail to universities and colleges offering an accredited chemical engineering program. The e-mail was normally sent out by one of the co-authors of this paper, in most cases from the same country as the contacted university or from a neighboring country. The corresponding addresses were collected with personal knowledge or based on information from the Web pages of the institutions. In each case, the invitation was sent either to a teacher responsible for TTP teaching or to the head of the chemical engineering program, department, or school. In a few cases, no such information could be found and the invitation was sent to the general e-mail address of the institution. Several reminders were sent out to increase the final response rate; nevertheless significant variation in the frequency of responses per country was observed. A summary of the institutions contacted and the responses received per country is shown in Table 1. Overall, the response rate in Europe was 46% whereas in the USA a lower rate of 36% was recorded. About one-third of the European responses were from Germany whereas from most other countries the response rate was much lower.

RESULTS AND DISCUSSION

TTP Teaching With Other Disciplines

More than 70% of the universities that responded offer a B.Sc. in chemical engineering, 65% offer an M.Sc., and 55% offer a Ph.D. Most universities offer at least two courses of TTP in the chemical engineering curricula.

About half of the courses are taught to chemical engineers exclusively whereas the rest are taught together with other disciplines of engineering, mainly mechanical and/or process engineering. The first course is often studied together with other disciplines of engineering, especially in Europe: In 39% of the cases (10% in the United States), this second discipline is mechanical engineering, in 29% of the cases (2% in the United States) it is process engineering, and in 19% of the cases (0% in the United States) is energy engineering. Other programs with joint TTP teaching include chemistry/applied chemistry (14% in Europe and 4% in the United States), materials science (11% in Europe and 6% in the United States) and bio engineering (10% in Europe and 9% in the United States). In some cases one thermodynamics course is studied together with several other disciplines.

The second TTP course is studied together with other programs to a much lesser extent: In 27% of the cases in Europe (6% in the United States) it is studied together with mechanical engineering, in 28% of the cases in Europe (0% in the United States) with process engineering and in 22% of the cases in Europe (3% in the United States) with energy engineering. These results indicate that in many instances the first TTP course has to be kept at a general level (and does not specialize in chemical thermodynamics) to accommodate the various fields of study of the students.

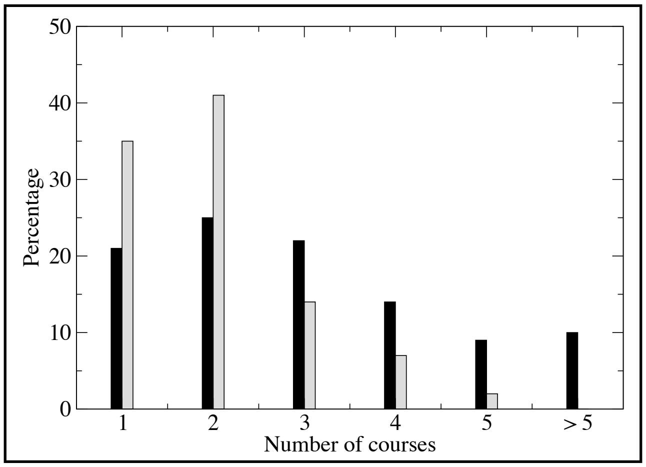

***Figure 1.** Number of TTP courses reported by the various universities. (Black bars: Europe. Gray bars: USA.)*

TTP Teaching in Terms of Quantity

The extent of TTP that is taught has been analyzed both with respect to the number of courses and their size. The number of courses reported from each university is given in Figure 1 where it can be seen that the majority of European universities report more than two courses each whereas the majority of U.S. universities reports at most two courses. Hence, most of the following discussion is based on the first two courses reported from each university.

An issue that caused much confusion among the respondents was the definition of the size of a course since no unambiguous measure of the length and the workload per course exists. We have chosen to use the workload measured by the amount of full-time study weeks per course, *i.e.*, the intention is that if a course was expected to be studied as the only course during a given period, the value given should be the number of weeks that course was expected to fill the student's time. If the student in a given program was expected to follow more than one course at the same time, the week should be split between the courses according to the generated work load. An example: If two courses are given in parallel during 10 weeks and both of them are expected to generate the same workload, each of them is regarded to as being of five weeks' length. To simplify the calculation for European universities, we introduced a transformation based on the European Credit Transfer System (ECTS) introduced with the Bologna process in Europe: 1.5 ECTS units correspond approximately to one week of work since one year usually contains about 40 study weeks corresponding to 60 ECTS units. Judging from the reactions of the respondents, however, such a course-size measure is not yet familiar in many countries, and thus some care has to be exercised when interpreting the results.

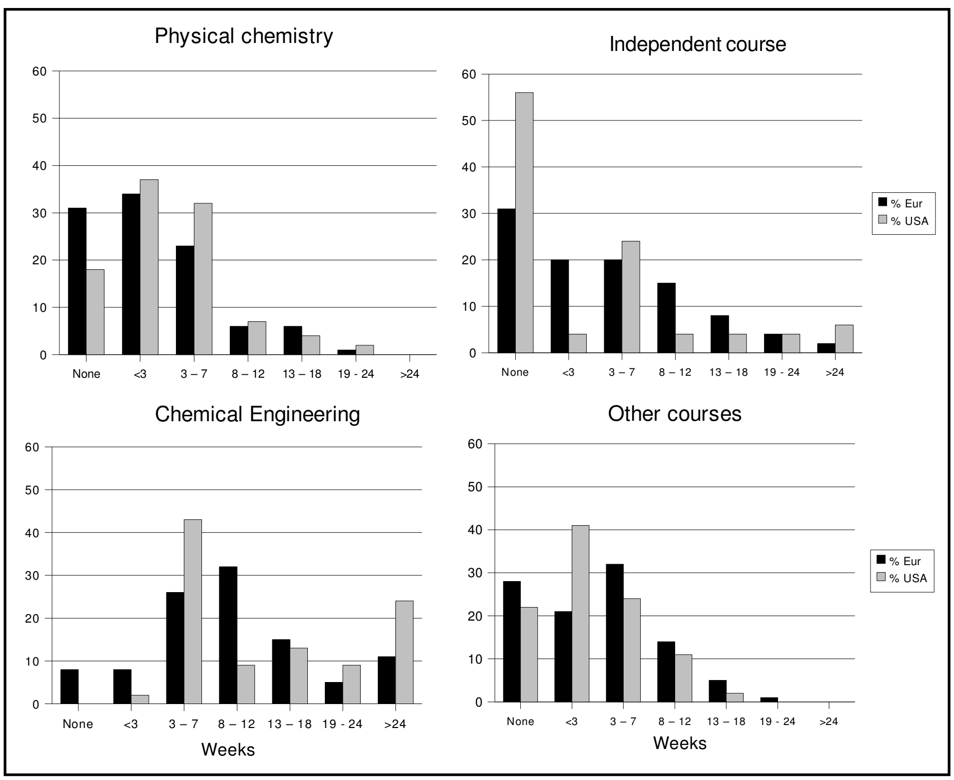

***Figure 2.** The extent of TTP (as full-time study weeks) taught as part of different course(s). Frequently thermodynamics is taught as a part of many different courses, like physical chemistry and applied chemical engineering courses, and the amount of thermodynamics in those courses is shown here. Sometimes, however, a pure thermodynamics course is given and those courses are presented as "Independent course" in this paper. (In this context "Chemical Engineering" does not include physics, physical chemistry, and similar fundamental courses but only the amount of TTP in the applied chemical engineering courses.)*

Both in Europe and the United States, just over 40% of the courses spend at most seven weeks on thermodynamics. In Europe the courses are generally less than 19 weeks whereas in the United States, one-fifth of the respondents spend more than one semester on TTP. As seen from Figure 2, for the chemical en-

TABLE 2 Contents of thermodynamics Course 1 (percentage of total number of responses)

Topic	Central		Treated in some detail		Mentioned		Not part of course	
	Europe	USA	Europe	USA	Europe	USA	Europe	USA
1st law	90	91	8	7	0	2	2	0
2nd law	88	80	10	11	1	2	1	7
Entropy	80	74	14	13	4	6	3	7
Molecular/Statistical interpretation of entropy	9	9	24	15	35	48	32	28
Free energy and quality of energy	44	43	22	26	22	19	11	13
3rd law and absolute entropy	26	33	21	18	35	35	18	33
Thermodynamic cycles	55	50	28	37	8	7	10	6
Heat expansion of solids and liquids	14	18	34	30	33	35	20	17
Equations of state	45	56	36	32	10	11	9	2
Phase equilibria	39	48	26	15	16	9	19	28
Vapor Liquid Equilibria	30	46	21	18	21	4	28	32
Liquid Liquid Equilibria	15	22	18	19	15	19	52	41
Heat transfer	9	7	19	11	20	39	52	43
Thermochemistry	21	9	16	20	6	30	56	41
Statistical thermodynamics	5	2	4	6	26	30	65	63
Molecular simulation	1	0	1	7	14	15	84	78
Kinetic theory of gases	8	0	15	9	32	22	45	68
Non-equilibrium thermodynamics	3	2	12	2	12	9	78	87
Thermodynamics for biological systems	4	0	3	6	16	37	78	58

TABLE 3 Contents of thermodynamics Course 2 (percentage of responses for course 2)

Topic	Central		Treated in some detail		Mentioned		Not part of the course	
	Europe	USA	Europe	USA	Europe	USA	Europe	USA
1st law	33	43	17	17	27	20	23	20
2nd law	36	46	14	20	25	17	25	17
Entropy	28	49	22	23	23	14	27	14
Molecular/Statistical interpretation of entropy	11	11	16	26	34	34	39	29
Free energy and quality of energy	36	34	19	37	22	14	23	14
3rd law and absolute entropy	19	11	25	23	22	29	34	37
Thermodynamic cycles	34	6	5	17	13	34	48	43
Heat expansion of solids and liquids	11	11	27	17	19	43	44	29
Equations of state	56	51	16	40	8	6	20	3
Phase equilibria	59	78	11	11	13	9	17	3
Vapor Liquid Equilibria	52	78	14	11	8	6	27	6
Liquid Liquid Equilibria	42	54	12	17	8	20	38	9
Heat transfer	22	6	12	17	14	20	52	56
Thermochemistry	36	29	17	31	6	23	41	17
Statistical thermodynamics	8	14	9	14	16	40	67	31
Molecular simulation	3	3	3	9	17	46	77	43
Kinetic theory of gases	8	3	8	14	23	26	61	57
Non-equilibrium thermodynamics	3	0	9	9	11	14	77	77
Thermodynamics for biological systems	3	3	8	17	6	31	83	49

TABLE 4 **Contents of thermodynamics Course 3 (percent of responses for course 3)**

Topic	Central		Treated in some detail		Mentioned		Not part of the course	
	Europe	USA	Europe	USA	Europe	USA	Europe	USA
1st law	33	36	21	43	23	14	23	7
2nd law	30	21	14	21	23	21	33	36
Entropy	28	50	28	29	12	14	40	7
Molecular/Statistical interpretation of entropy	5	43	12	21	21	21	63	14
Free energy and quality of energy	26	36	21	29	7	21	47	14
3rd law and absolute entropy	12	21	12	14	23	29	54	36
Thermodynamic cycles	16	14	9	21	21	43	54	21
Heat expansion of solids and liquids	7	7	19	21	14	29	61	43
Equations of state	49	21	19	7	12	57	21	14
Phase equilibria	51	64	14	29	9	0	26	7
Vapor Liquid Equilibria	33	57	7	29	9	0	51	14
Liquid Liquid Equilibra	44	36	9	21	7	29	40	14
Heat transfer	35	7	7	21	12	7	47	64
Thermochemistry	9	14	12	57	26	7	54	21
Statistical thermodynamics	9	21	5	21	9	21	77	36
Molecular simulation	7	7	7	7	12	36	74	50
Kinetic theory of gases	12	0	14	29	16	21	58	50
Non-equilibrium thermodynamics	9	0	9	0	12	29	70	71
Thermodynamics for biological systems	2	0	2	14	16	14	79	71

gineering courses, two sets of course lengths were observed, corresponding either to at least a full semester of full-time studies or to less than half a semester. Most students meet thermodynamics in physical chemistry and chemical engineering courses. In Europe, but not in the United States, a pure thermodynamics course is also included in most programs.

Contents of TTP Courses

A list of selected items was made and the respondents were asked to fill in how central that was in each course, given four alternatives: "Not part of the course," "Mentioned," "Treated in some detail," and "Central." The results for courses 1-3 are given in Tables 2-4.

In the first course, the first and second laws of thermodynamics as well as entropy are central in both regions. It should be noted that in 7% of the U.S. universities entropy is not discussed. Normally the statistical interpretation of entropy is mentioned as well as the third law and absolute entropy, but not in significant depth. One reason for this can be that in many cases a TTP course has to cover the educational needs for other disciplines as well. The second course frequently concentrates more on phase equilibria. In the main, both of these courses consist of classical thermodynamics whereas the molecular interpretation often is touched upon. Statistical thermodynamics and molecular simulation as well as thermodynamics for biological systems are not core topics in any of the two courses either in United States or in Europe, although they are more frequently mentioned in the United States. Equally, non-equilibrium thermodynamics is not part of any of the two first courses in any of the regions. An interesting detail is that about half of the two main courses in the United States at least mention thermodynamics of biological systems.

A third TTP course is taught at about half of the European universities but only at one-fifth of the universities in the United States. This course is mainly spent on phase equilibria (but also on entropy in the United States). Statistical Thermodynamics also forms a part of the majority of the third course in the United States and in 42% of the courses it is central or treated in some detail. In Europe, however, there is no mention of statistical thermodynamics or molecular simulation in most courses. Further details are provided in Table 4. These results partly reflect the fact that many of the first thermodynamics courses are taught to general engineering students whereas the latter courses normally are taught to chemical engineering students and hence are more specialized. Another observation is that atomistic perspectives are encountered earlier in the United States than in Europe, where classical thermodynamics normally is the central theme in all the first three courses.

TABLE 5 **The most popular textbooks for Course 1 and 2 (percentage of each course). Books by the same author or team of authors have not been separated since the exact version is often unclear from the answers. Books listed are those that were used by at least 4% in at least one of the continents. This limitation together with the large number of courses where locally produced material (about 10%) and books published only in the national languages leads to the numbers not summing up to 100%.**

Author(s)	Course 1		Course 2	
	Europe	USA	Europe	USA
Atkins & de Paula[5, 7, 8] *	18		23	3
Baehr, *et al.*[9]	8		8	
Cengel[10, 11]	4	2		
Elliott & Lira[12]		14		
Felder & Rosseau[13]		11		
Gmehling, Kolbe[14]			6	
Koretsky[15]		7		6
Prausnitz, *et al.*[16]			6	4
Sandler[6]		13		14
Smith, van Ness, & Abbott[4]	11	39	8	43

* Including translations into German and Greek. One instance of Reference 8 was reported for course 1 and at least one instance of Reference 7 was reported for course 2. The rest is mainly Reference 5, but References 5 and 7 were not always discerned by the respondents.

Textbooks Used in TTP Courses

Another issue that reflects the approach to thermodynamics is the choice of textbooks. The most popular (*i.e.*, used by at least 4% of the courses in one of the continents) textbooks in the first two courses are listed in Table 5. Clearly, there is a difference in the choice of course books between the two continents although a few popular books are common, as for example *Chemical Engineering Thermodynamics* by Smith *et al.*[4]—clearly the most popular TTP book in the United States. The book was first published about 60 years ago but it has been thoroughly revised several times to date. The same applies to the most popular book in Europe, which is the physical chemistry book by Atkins and co-authors first published more than 30 years ago.[5] The fact that it is a physical chemistry book can be seen as an indication of the emphasis put on TTP courses in many European universities, or of the background of the corresponding teacher. The popularity of the book by Sandler[6] may possibly be coupled to the study of biochemical and biological systems.

A striking fact is that many respondents (about 10%) mention a compendium written for the course as main literature. This is especially frequent in Europe. It is an indication of the published textbooks not being appropriate for the course and could be due to non-overlapping contents between the available textbooks and the course, lack of textbooks in the national language, or the professor regarding available textbooks to be non-pedagogical or too comprehensive (or perhaps just too expensive).

Structure of TTP Courses

An interesting issue is what methods are used in thermodynamics teaching and whether there are any differences between the continents (cf. Reference 1 for a discussion of teaching methods). Therefore we asked questions about the use of different teaching methods in the thermodynamics courses in the two continents. The answers for the first two courses mentioned by each respondent are summarized in Tables 6 and 7.

The teaching of the first two courses appears to be traditional in both continents. Courses are centered around lectures and exercise classes with little or no laboratory work whereas home assignments are given in the vast majority of the courses. The teaching methods for Course 1 and 2 are similar except for the case of Problem-Based Learning (PBL) in the United States, cf. below. An interesting observation is the fact that for the first course, no work outside class coupled to the lectures and exercise classes is expected in about half of the universities in the United States. Instead, students tend to have home assignments. It can also be noted that a rather large amount of time is used in class for home assignments (actually this must be going through the task and discussing the outcome afterwards). In Europe, students appear to be expected to study by themselves without special assignments as indicated by the amount of time the students are expected to spend "outside" class on lectures and exercise classes.

In the first course, there is a significant component of PBL in more than half of the universities in the United States whereas it is used in only one-third of the European universities. An interesting observation is that PBL is more prevalent in the first course whereas one may have expected it to be used more in later courses when the students would be expected to have a greater potential to assimilate such a teaching method.

TABLE 6 **Time (in hours/course) used for different forms of teaching in Course 1 in Europe (Values for the USA are given in parenthesis)**

Percentage of answers; "(outside)" means "expected student work outside class," PBL = Problem-Based Learning, cf. [1]

Type	0 h	1-20 h	21-40 h	41-60 h	>60 h
Lectures (in class)	-(-)	16 (11)	48 (54)	25 (30)	11 (6)
Lectures (outside)	16 (43)	39 (33)	28 (11)	11 (7)	5 (6)
Exercise classes	8 (11)	44 (59)	40 (22)	6 (7)	2 (-)
Exercise class (outside)	20 (48)	36 (35)	32 (13)	9 (2)	1 (2)
PBL etc. (in class)	70 (26)	25 (56)	5 (13)	- (4)	- (2)
PBL etc. (outside)	66 (44)	29 (32)	4 (15)	1 (7)	- (2)
Home assignment (in class)	41 (20)	4 (37)	8 (28)	6 (9)	1 (6)
Home assignment (outside)	34 (11)	35 (28)	16 (20)	1 (20)	3 (20)
Laboratory classes	66 (83)	25 (15)	4 (-)	3 (2)	2 (-)
Lab classes (outside)	78 (83)	18 (13)	3 (4)	1 (-)	1 (-)

TABLE 7 **Time (in hours/course) used for different forms of teaching in Course 2 in Europe (Values for the USA are given in parenthesis)**

Percentage of answers for Course 2 in Europe and the USA, respectively, cf. Table 6

Type	0 h	1-20 h	21-40 h	41-60 h	>60 h
Lectures (in class)	3 (-)	19 (16)	46 (48)	22 (25)	10 (11)
Lectures (outside)	18 (16)	35 (39)	25 (28)	3 (11)	5 (5)
Exercise classes	10 (8)	38 (44)	38 (40)	10 (6)	5 (2)
Exercise classes (outside)	24 (20)	32 (36)	27 (32)	13 (9)	5 (1)
PBL etc (in class)	67 (70)	27 (25)	- (5)	5 (-)	2 (-)
PBL etc (outside)	73 (66)	22 (29)	5 (4)	- (1)	- (-)
Home assignments (in class)	48 (41)	40 (44)	8 (8)	3 (6)	2 (1)
Home assignments (outside)	38 (34)	32 (35)	18 (16)	2 (1)	11 (3)
Laboratory classes	73 (66)	16 (25)	6 (4)	2 (3)	5 (2)
Lab classes (outside)	81(78)	16 (18)	3 (3)	- (1)	- (1)

CONCLUSIONS

Classical thermodynamics is (and will probably continue to be) a core discipline for chemical engineers and it is reflected in the invariability of the relevant university courses for several decades now. Also, the fact that there have been no profound changes in classical thermodynamics during the past decades is reflected in this invariability. The most popular textbook had its first edition 60 years ago and most other textbooks follow the same outline. More "modern" atomistic or molecular viewpoints are normally found in the courses in the late stage of studies (if present at all) where they often are combined with statistical thermodynamics. In the USA atomistic/molecular descriptions or explanations seem to be somewhat more popular than in Europe. The high fraction of the first thermodynamics course that is studied with other disciplines of engineering in Europe probably limits the use of an atomistic approach. Even though the results for teaching methods are quite similar for the United States and Europe, a notable difference is the higher amount of problem-based learning and home assignments in the United States.

The results presented here may reflect the needs for thermodynamics from an industrial perspective. In this respect, there is an ongoing investigation within the Working Party of Thermodynamics and Transport Properties of the European Federation of Chemical Engineering

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APPENDIX: RESPONDING UNIVERSITIES

Austria
Graz University of Technology/Technische Universität Graz

Belgium
University College Ghent
Katholieke Hogeschool Kempen
Université Libre de Bruxelles

Bosnia and Herzegovina
University of Tuzla

Croatia
University of J.J. Strossmayer of Osijek
University of Zagreb

Denmark
Technical University of Denmark
University of Southern Denmark

Estonia
Tallinn University of Technology

Finland
Helsinki University of Technology
Lappeenranta University of Technology (LUT)
University of Oulu
Åbo Akademi University

France
Ecole nationale supérieure de chimie de Paris (ENSCP)
Universite de Paris Sud
Université Claude Bernard Lyon 1
Ecole Polytechnique de l'Université de Grenoble 1 – Polytech'Grenoble
Ecole Nationale Supérieure des Industries Chimiques - Institut National Polytechnique de Lorraine (ENSIC – INPL)

Germany
Universität Duisburg-Essen
Clausthal University of Technology
Universität Kassel
Brandenburgische Technische Universität Cottbus
(Brandenburg State University at Cottbus)
University of Kaiserslautern
Dortmund University of Technology
Georg-Simon-Ohm Hochschule Nürnberg
Universität Stuttgart
Universitaet Karlsruhe
University of Erlangen-Nuremberg
Universität Bremen
Technische Universität Dresden
(Dresden University of Technology)
Universität Bayreuth
Cologne University of Applied Sciences / Fachhochschule Köln
Hamburg University of Applied Sciences
Technical University Berlin
Fachhochschule Flensburg
(Flensburg University of Applied Sciences)
Hochschule Merseburg (FH)
Technische Universität Carolo-Wilhelmina zu Braunschweig
RWTH Aachen University
Technische Universität Hamburg-Harburg
(Hamburg University of Technology)
Hochschule Niederrhein
University of Applied Sciences
University of Siegen
Helmut-Schmidt Universität der Bundeswehr Hamburg
(Helmut-Schmidt University of the Federal Armed Forces Hamburg)
Leibniz Universität Hannover
Technische Universitaet Darmstadt
Universität Kassel
Otto-von-Guericke-Universität Magdeburg
Ruhr-University Bochum

Greece
Aristotle University of Thessaloniki
University of Patras
National Technical University of Athens

Hungary
University of Debrecen (2)

Italy
University of Pisa
University of Trieste
Università di Cagliari
Università di Palermo

Netherlands
Delft University of Technology (TU Delft)

Norway
Bergen University College

Portugal
Universidade de Aveiro
University of Minho
Instituto Superior Técnico, Universidade Técnica de Lisboa
Universidade de Coimbra
University of Porto

Russia
St.Petersburg State University
Lomonosov Moscow State University

Serbia
University of Belgrade

Slovenia
University of Maribor
University of Ljubljana

Sweden
Mälardalens högskola/Mälardalen University
Royal Institute of Technology, KTH
Karlstads universitet/Karlstad University
Högskolan i Borås/University of Borås

United Kingdom
Imperial College London (2)
University of Manchester
Newcastle University
University of Birmingham
University College London
London South Bank University

United States of America
University of Akron
University of Colorado
Virginia Commonwealth University
Mississippi State University
University of Virginia
University at Buffalo, The State University of New York
University of California Santa Barbara
University of South Alabama
University of Toledo
Case Western Reserve University
South Dakota School of Mines and Technology
Purdue University
Brigham Young University
Villanova University
New Mexico State University
South Dakota School of Mines and Technology
Clarkson University
Iowa State University
University of Rhode Island
Northwestern University
University of Maine
Auburn University
The Ohio State University
UC Davis
Wayne State University
Bucknell University
University of Louisville
University of Maryland, Baltimore County
Polytechnic University
University of Notre Dame
Yale University
University of South Carolina
University of Missouri
Texas Tech University
Stanford University
University of Pittsburgh
University of Kansas
University of Minnesota
Michigan State University
California Institute of Technology
U of Arizona
University of Utah
Rowan University
Cleveland State University
Rice University
Tennessee Technological University
Kansas State University
California State University, Long Beach
Johns Hopkins University
University of Nevada, Reno
Rose-Hulman Institute of Technology
Tuskegee University
West Virginia University
Louisiana Technical University
Vanderbilt University ❐