Fusion Energy Sciences: Workforce Development Needs

Executive Summary

This report has been prepared in response to the charge from the Acting Director of the Office of Science that the Fusion Energy Sciences Advisory Committee (FESAC) perform an "assessment of workforce development needs in Office of Science research disciplines." A subcommittee of FESAC was formed to address the four specific charge questions: (1) identify disciplines that are not well represented in academic curricula; (2) identify disciplines in high demand, nationally and/or internationally, resulting in difficulties in recruitment and retention at U.S. universities and DOE national labs; (3) of the disciplines identified in the previous two bullets, indicate those for which the DOE national labs may play a role in providing needed workforce development; and (4) provide specific recommendations for programs at the graduate student or postdoc levels that can address discipline-specific workforce development needs.

Community input was sought through a survey and general calls for whitepapers that were broadcast to the mailing lists of the American Physical Society, the U.S. Burning Plasma Organization, and the University Fusion Association, as well as to a list of Principal Investigators of research projects funded by Fusion Energy Sciences (FES). The survey targeted institutions rather than individuals in order to cover the majority of U.S. institutions participating in research funded by FES, including universities, national labs, and industry. Both core disciplines and emerging disciplines, which were selected on the basis of a set of published FESAC and community reports, were listed in the survey for respondents to evaluate with regard to the first three charge questions. The survey covered three broad areas: Magnetic Fusion Energy (MFE) sciences, High-Energy-Density Laboratory Plasma/Inertial Fusion Energy (HEDLP/IFE), and Discovery Plasma Science. In addition, the survey also asked for input regarding growth or decline of each group, department, or institution over the past decade, in order to evaluate the health of our fields in terms of the workforce development needs to achieve the corresponding missions of FES. Individual comments and input were also taken into account during the deliberation process by the subcommittee. Below, concise summaries are given on our findings and recommendations. The details are described in the text of the full report.

<u>Overview of the survey results</u>. The three core areas are reasonably represented in academia, but a possible crisis is developing in MFE due to the declining number of faculty, departments, and institutions. Emerging disciplines in Discovery Plasma Science represent a vibrant component of plasma science research and likely will remain so in the foreseeable future. In contrast, emerging disciplines in fusion engineering sciences (topics requiring integration of fundamental plasma physics and applied technologies) represent the largest potential gaps in workforce development.

<u>Four key findings to identify disciplines not well represented in academic curricula</u>:

- **F1.** *Curricula in MFE core disciplines are reasonably represented in academia, but there is a clearly decreasing trend in the size and number of university research groups, suggesting a possible future crisis. Deliberate efforts by FES are required to reverse this trend.*
- **F2.** *The university research groups involved in HEDLP/IFE research are small in number but apparently stable in size.*
- **F3.** *A relatively large number of universities have strong curricula in Discovery Plasma Science, and they appear to be stable and healthy.*
- **F4.** *Almost all of the emerging disciplines in fusion engineering sciences are poorly represented in academic curricula.*

Two key findings to identify disciplines in high demand:

F5. *The demand in workforce in the core disciplines is strong and is well matched by the strong curricula, with the exception of diagnostics for MFE, which is least represented in curricula even though this expertise is in high demand by university research groups, national labs, and industry (especially the latter two groups).*

F6. *As a whole, the fusion engineering sciences are in high demand, but are poorly represented in the academic curricula.*

One key finding to identify disciplines for which the DOE national laboratories may play a role in providing needed workforce development:

F7. *There is general recognition that national labs can play a role in workforce development for the emerging disciplines, especially in fusion engineering sciences.*

One key finding and four specific recommendations for programs at the graduate student or postdoc levels that can address discipline-specific workforce development needs:

F8. *It is critical to support faculty who develop and deliver curricula of sufficient depth and breadth and who provide research training needed for workforce development.*

Two specific recommendations on curriculum development and classroom education:

R1. *Establish periodic summer schools for graduate students and postdocs on fusion engineering sciences.*

R2. *Establish a consortium among national labs and academic institutions to enhance graduate student training and develop curricula for advanced diagnostics and fusion engineering sciences.*

Two specific recommendations on the workforce development needs in research training, with the latter recommendation having two closely coupled parts: one on programs for universities and the other on programs for national labs:

R3. *Establish a renewed program to encourage graduate students and postdocs to pursue fusion engineering sciences.*

R4a. *Enhance the participation of academic institutions in large FES projects and FES international collaborations – particularly in the areas of advanced diagnostic and materials development. This can help avert the crisis of shrinking research at universities by effectively coupling to local experiments.*

R4b. *Establish a focused program at national labs to support graduate students and postdoctoral researchers in advanced diagnostics and in targeted emerging engineering science areas, including nuclear materials.*

Final Comments.

As input from this subcommittee to the ongoing FESAC Strategic Planning Subcommittee, we emphasize the following three points regarding workforce development:

a. *The importance of a complete educational pipeline from pre-college to employment opportunities, beyond graduate students and postdocs.*

b. *The importance of strong coupling between academia, national labs, and industry, covering the diversity of professional opportunities crucial for the health of our field.*

c. *The importance of establishing and supporting faculty in the emerging disciplines for stability and future growth in achieving missions by FES over a long period of the time.*

1 Introduction:

Fusion Energy Sciences (FES), along with the five other program offices within the Office of Science of the U.S. Department of Energy, was charged with performing an "assessment of workforce development needs in Office of Science research disciplines" (see Appendix A). This assessment had four specific charge questions:

- Identify disciplines that are not well represented in academic curricula;
- Identify disciplines in high demand, nationally and/or internationally, resulting in difficulties in recruitment and retention at U.S. universities and DOE national labs;
- Of the disciplines identified in the previous two bullets, indicate those for which the DOE national labs may play a role in providing needed workforce development; and
- Provide specific recommendations for programs at the graduate student or postdoc levels that can address discipline-specific workforce development needs.

A Fusion Energy Sciences Advisory Committee (FESAC) subcommittee was formed to perform this assessment. Its chair was appointed (see Appendix B), and its members were appointed (see Appendix C). This subcommittee first created a survey document to solicit input from the community. A copy of this survey, along the cover letter sent together with the survey, is provided in Appendix D. The survey asked respondents to rate the importance (with regard to the above four charge questions) of several disciplines that were identified in the recommendations of past FESAC, NRC, and community planning reports.[1] These disciplines included experimental, theoretical/computational, and diagnostic research in magnetic fusion energy (MFE), high energy density laboratory plasma/inertial fusion energy (HEDLP/IFE) science, and discovery plasma science, as well as more specific areas ranging from plasma-material interactions to plasma medicine. The survey respondents also suggested additional emerging disciplines as listed in Appendix E.

Input was requested from university departments, national laboratories, and private industry. This last category is important to FES since DIII-D, the largest fusion experiment in the U.S., is based at the General Atomics Corporation and since several other private companies play an important role in the career plans of the FES workforce. In some respects, the DIII-D laboratory plays a role similar to that of a national lab.

The subcommittee also solicited comments and white papers from the community and combined them with the results of the survey to identify the relevant disciplines within the FES purview. After receiving a broad range of community input, the subcommittee then performed an assessment of the data. From this it has derived its responses to the charge.

2 Overview of the Survey Results

Before performing a complete assessment of the disciplines, we provide a broad, high-level summary that will be used to guide the detailed responses to the four charge questions. We have identified three major results from the survey.

[1] FESAC: Fusion Workforce Planning report (2004); National Research Council Report "Plasma Science: Advancing Knowledge in the National Interest" (2007); FESAC: Priorities, Gaps and Opportunities Report (2007); Low Temperature Plasma Science report (2008); FESAC: Advancing the Science of High Energy Density Laboratory Plasma report (2009); Workshop on Opportunities in Plasma Astrophysics report (2010).

1. In the broadest sense, the three core areas of MFE, HEDLP/IFE, and discovery plasma science are, *at present*, reasonably represented in academia. But the survey identified very important concerns, suggesting a possible future crisis in MFE: namely, a declining number of faculty, an overall shrinking of the number of universities that have viable research programs in plasma science, and a general concern about support for university-based fusion research.

2. The emerging disciplines that were identified as broadly falling in the discovery plasma science area (e.g., multi-phase plasmas, plasmas in extreme conditions, micro-plasmas) scored reasonably well in terms of academic disciplines, but not so well in terms of demand from national labs and corporate labs. These areas are likely to remain in high demand in universities both for now and in the near future, because universities generally take the lead in curiosity-driven research. Thus, it could be concluded that – within the constraints noted in item 1, above – discovery plasma science will likely remain an important part of the university portfolio.

3. Finally, many of the emerging disciplines that fall broadly into the area of fusion engineering science are those that show the largest potential gap between academia and the workforce needs of the field. Here, "fusion engineering science" refers to those disciplines that require the integration of fundamental plasma science developments and associated technology advancements such as, plasma diagnostics, magnets, plasma-material interactions, tritium, safety, control, power, etc. As will be explained in our response to the charges, it is challenging to take each individual area and create a one-to-one mapping to a need, but the overall trend is rather clear from the data.

3 Finding in Response to the Four Charge Questions

3.1 *Charge 1: Identify disciplines that are not well represented in academic curricula.*

In this section we assess the current status and trends of academic preparation at U.S. universities in disciplines relevant to the FES mission and to FES-supported research activities. The subcommittee relied on a number of sources, most importantly the community survey. Question 1 of this survey asked:

"How well are disciplines represented in YOUR academic curricula, if your institution is an academic institution?"

The survey first asked about three broad areas: MFE plasma sciences, HEDLP/IFE, and Discovery plasma sciences. The last is a broad category including the areas of basic, low temperature, and space/astrophysical plasmas, which are important for FES stewardship of plasma science but less directly related to the fusion energy science mission. Each area was subdivided into theory, experiment, and diagnostics, and respondents were asked to rate the representation in their academic curricula on a scale of 1 to 5, with 5 the highest rating. Respondents were next asked about coverage of several sub-disciplines that we felt may be of particular near-term importance. The areas in these 'emerging' sub-disciplines were derived from recent DOE-FES reports, including the 2007 Greenwald report and the 2009 ReNeW report. We point out that one of the sub-disciplines, "Plasma-material interactions/Divertor," is regarded as an emerging area in the context of the recent focus and prioritization in the area of fusion materials, but is also recognized as a significant component of MFE research.

We summarize here our findings related to this question of the charge, following the same divisions into broad areas, followed by emerging disciplines.

3.1.1 Magnetic Fusion Energy Sciences

This topic is the most central to the current mission of FES, representing a majority of the research currently supported. Education in this area is thus particularly critical to meeting the FES mission and workforce needs. While there are a number of institutions and academic departments with strong programs in this area, we found cause for concern in the trends reported and the comments received.

A total of fourteen universities reported offering strong curricula in MFE sciences (as indicated by a rating of 4 or 5 in at least one sub-topic). These include (alphabetically) Auburn University, University of California, Irvine (UC-Irvine), University of California, Los Angeles (UCLA), University of California, San Diego (UCSD), Columbia University, Georgia Institute of Technology, University of Illinois at Urbana-Champaign (UIUC), University of Maryland at College Park, Massachusetts Institute of Technology (MIT), Princeton University, The University of Texas at Austin (UT Austin), University of Washington, West Virginia University, and University of Wisconsin at Madison (UW-Madison). Four of these institutions, including some of the largest fusion groups, are represented by multiple academic departments, and/or a research center as well as a university department. This provides opportunities for students to take courses offered by multiple departments or participate in research projects at local facilities. Most of these universities have strong programs in Theory, Experiment, and Diagnostics, suggesting a well-balanced and integrated research group. In fact, some respondents indicated they consider diagnostics an integral part of an experimental effort. A few groups reported strong curricula only in Theory, with Experiment less well represented, while only two were stronger in Experiment. We thus consider MFE research as a whole in the following discussion.

Fusion is included in a variety of academic departments. Of those with strong curricula, there are nine Physics and/or Astrophysics Departments, three Departments of Nuclear Engineering, two Applied/Engineering Physics, two Mechanical Engineering, one Electrical Engineering and one Department of Aeronautics and Astronautics. We found the number of Physics and Nuclear Engineering departments with strong programs surprisingly small, given the importance of these subjects for MFE and considering the number of such departments in the US. While the number of university MFE programs in the US is still reasonably large, the reported trends and comments in the survey are cause for concern. Notably, ***nine survey respondents reported that their programs have been shrinking in the last decade, while only two are growing***. Six departmental programs are stable. We also noted that several university departments that we believe in past years had significant MFE programs, based on their research and student training, no longer report strong fusion curricula. The departments in decline span the range of academic departments. Most have had experimental facilities that either have been terminated or are proposed for termination by FES in recent years (for example, the Maryland Centrifugal Experiment at the University of Maryland, the Electric Tokamak at the University of California Los Angeles, Alcator C-Mod and the Levitated Dipole Experiment (joint with Columbia University) at the Massachusetts Institute of Technology, and the Translation, Confinement, Sustainment-Upgrade experiment at the University of Washington). Some departments which currently have modest fusion programs are reportedly planning to discontinue them, e.g., MIT's Department of Electrical Engineering and a smaller university that reports, "Our institution plans to dismantle any plasma physics related research in the future." In many cases this is clearly linked to funding: "With recent funding changes, we now have only a single theorist in any kind of fusion. Our one experimentalist is really only half in fusion."

Comments from university respondents nearly universally indicate concern about the present state and future prospects of academic fusion research. One respondent noted that the size of grants has been generally declining, while another, which currently focuses on Discovery Plasma Science, stated: "With a small and uncertain DOE program, it is not possible for us to hire someone in MFE or ICF". Declining and highly variable funding is also affecting recruitment of graduate students to the field. "Students are aware of the uncertainty in the program and this hurts our ability to recruit students - to physics in general." While recognizing some role for national laboratories in education, many note that this can be problematic and that it requires strong involvement by faculty members. "Departments will not admit students who are interested in going off to a national lab to work with someone who has no connection to/collaboration with a faculty member in our department."

With regard to the impact of funding changes, we note that in order to accept a new graduate student, a department must be assured of research support for a 3-5 year period. Granting tenure to a new faculty member implies a commitment for decades, which will only be made if departments expect stable or growing support. Thus even short-term cuts, such as occurred in FY 2013, have long-term impacts on the academic pipeline. For example, the proposed termination of C-Mod has resulted in a decrease from typically 30 students to fewer than ten, most of whom will graduate in the coming year. Even though C-Mod funding has been temporarily restored, very few new students will be accepted.

Key Finding 1: There are currently a number of academic departments with strong curricula in Magnetic Fusion Energy, and there do not appear to be imminent shortages of qualified workforce in the US program particularly in the plasma physics discipline. However, the clear trend toward decreasing the number of universities and the size of their programs in the fusion program is cause for concern. Deliberate action by FES to stabilize the educational pipeline and reverse this trend is required.

3.1.2 High Energy Density Laboratory Plasma Sciences and Inertial Fusion Energy

HEDLP Sciences and IFE are well represented, although in a smaller number of institutions, with only eight universities reporting a score of 4 or 5 in these areas. Five of these also have strong MFE programs, while three focus primarily in the HEDLP/IFE area: Florida State University, University of Michigan, and University of Rochester. Michigan and Rochester have particularly strong, multi-departmental programs in HEDLP/IFE. All three institutions report stable or growing size. This is an encouraging sign for the health of this discipline. The five programs that also have strong MFE curricula are shrinking; however, since the survey did not ask separately about trends in each area, it is not clear whether it is the HDELP/IFE or the MFE program that is being reduced. The academic departments with strong curricula in HEDLP again span a range of disciplines: two Nuclear Engineering, one Scientific Computing, and two Mechanical Engineering departments. Notably and somewhat surprisingly, only four Physics Departments report strong programs in HEDLP. As with MFE, most institutions with HEDLP plasma programs include Theory, Experiment, and Diagnostics, though relative ratings vary. While the relatively smaller number of programs in HEDLP vs. MFE may be reasonable, given the smaller size of the FES-supported research effort, the small number of institutions involved, and particularly the small number of physics departments represented, this makes workforce development in this field sensitive to changes at any of these universities.

Key Finding 2: The university research groups involved in High Energy Density Laboratory Plasma and Inertial Fusion Energy research are small in number but apparently stable in size. Given the small number, in particular of physics departments, it will be important for FES to maintain stable support and to seek to expand participation in academic research in this discipline.

3.1.3 Discovery Plasma Science

A comparatively large number of nineteen universities report strong curricula in the plasma science disciplines collectively considered as "discovery science," that is, those not directly supportive of the MFE and IFE missions. Several of these groups also have strong programs in MFE and, less frequently, in HEDLP/IFE. Universities that primarily focus on discovery plasma science include the University of California at Berkeley (UC-Berkeley), California Institute of Technology (Caltech), University of Chicago, Florida Institute of Technology, Rice University, and Swarthmore College. Most of these groups are relatively small compared to those focusing on fusion research. They appear to be healthy, with three growing, two shrinking, and the others stable. Proportions are similarly balanced in those departments, which also offer strong MFE or HEDLP/IFE curricula; in these cases we cannot be sure which sectors or research are changing.

In a notable contrast to the MFE and IFE research areas, a majority of the discovery plasma science groups, at least fifteen, are located within Physics or Astrophysics Departments. Only about two departments each are Nuclear Engineering, Computing Science, Electrical, or other engineering. The concentration in Physics is reasonable, given the nature of this field. This subfield of plasma science appears to fit more readily in Physics departments. In the words of one respondent (who apparently would like also to be doing more fusion related research) "As a university physics department it is not possible for us to hire faculty for something other than discovery-based work." Several respondents mentioned a strong interest on the part of students in plasma science, in some cases hampered by limited experimental facilities on campus.

A wide variety of sub-disciplines are included in the discovery plasma science category. Some universities focus primarily on space plasma physics or astrophysics, some on low temperature plasmas, and at least one on "primarily antimatter". We note that, since our survey was primarily based on those groups who have received some past support from FES, there are likely other groups whose support has been from sources such as NSF or NASA. Both university and industry respondents stressed "the importance of low temperature plasma science in emerging and established industries and technologies". We agree and recognize the importance of this education for broad workforce development.

Key Finding 3: A relatively large number of universities have strong curricula in Discovery Plasma Science. The majority of research is, appropriately, in Physics Departments. These efforts appear to be stable and healthy. While the Discovery Plasma Science represent ~10% of the FES budget, almost 50% of the students and postdocs supported by FES pursue research in this area. Therefore, although we do not perceive a gap in these sub-disciplines, we strongly encourage their continuing support because these students represent a significant fraction of the potential future workforce on diverse topics connecting to broad scientific areas.

3.1.4 Emerging Disciplines

Table 1 lists the emerging disciplines that were part of the survey and summarizes the responses from university programs to the question: "*How well are disciplines represented in YOUR academic curricula, if your institution is an academic institution?*" **Only 25% of the university respondents (e.g., 10 out of 40 university respondents) had total scores of 20 or more in these emerging disciplines.** We note that having such a large fraction of university programs that do not have emerging areas in fusion engineering science (e.g., plasma-material interaction/divertor, magnets, safety and design) is an important gap that must be addressed proactively. We provide specific recommendations in response to Charge 4 to address this gap.

To capture the overall responses of these institutions to Question 1 of the survey, a map is presented in Fig. 1 of the emerging disciplines with all institutions that had total scores greater than 20 points. Programs overall with more than 25 points in emerging disciplines included Caltech, University of Michigan, MIT, University of Rochester, UCLA, UIUC, and Virginia Polytechnic Institute and State University. Programs overall with more than 20 points in emerging disciplines included University of Texas at Austin, West Virginia University, and University of Wisconsin at Madison.

From the responses, we find that of those university programs that responded positively to Question 1 (about 25% of respondents), the area most represented in academic curricula included the area of plasma-material interactions and divertor, with a total of 10 academic programs reporting high (4 or 5) scores. The next most well respected emerging areas included RF engineering, plasmas in extreme conditions, and high-power/pulsed-power technologies. We note that although these programs responded positively in these emerging areas, a strong correlation exists between research being conducted in a particular university program and the advanced topics (such as those listed in emerging areas) being taught in the classroom. Therefore, one notes, for example, that the response in the Plasma-Material-Interface/divertor area is also consistent with the response from academic programs that there is high demand in this area. This is consistent with a move by large fusion university research programs to place more emphasis on materials studies, both within their fusion research programs and also as introductory topics within coursework, reflecting the need for training in this area.

The area of plasmas under extreme conditions had six institutions give a score 4 or 5 and, interestingly, was either now or anticipated in the future (from answers to the second survey question) to be of high demand by twelve institutions. There is no indication of whether curricula are currently being designed to meet this need. Moreover fifteen institutions had the opinion that labs could contribute strongly in meeting this demand.

The areas of: **magnets, tritium handling, system, safety and design** were identified as least represented in academic curricula. Over twelve institutions indicated that national laboratories could contribute strongly in meeting this gap, given that these areas were also considered of high demand by respondents.

Key Finding 4: The results of the survey suggest an overarching conclusion that there is a gap in almost all of the emerging disciplines that fall broadly in the area of fusion engineering sciences. It is important to note that the connection between funded research programs within an academic department and its academic curriculum is critical, as recruitment of faculty in academia demands strong publication and funding successes. The academic curriculum typically mirrors research in the department, given that investigators are connecting concepts from their research to the classroom. The emerging disciplines are highly specialized topics. In order for their representation in academic curricula to exist, fusion engineering science must be funded and, in particular, strong support for junior faculty is needed as they establish their careers in these fields.

Table 1. List of emerging areas and the average score by universities responding to survey (total = 48 responses from ~ 40 universities) to the question: "*How well are disciplines represented in YOUR academic curricula, if your institution is an academic institution?*" In addition, the number of institutions responding with scores of 4 or 5 is also listed.

Emerging Area	Average Score	Strong Program (# of institutions scoring 4 or 5)
Plasma material interaction / Divertor	2.33	10
Magnets	1.33	0
Blankets/Structures	1.65	4
Control	1.61	5
RF Engineering	1.74	6
Tritium handling	1.11	0
System, safety and design	1.49	1
High power / pulse power electrical engineering	1.95	6
Multi-phase plasmas (plasmas in solids, liquids, etc.)	1.72	5
Plasmas in extreme conditions (relativistic, radiation/pair-dominated, strongly magnetized, etc.)	2.40	6
Micro-plasma and plasma medicine	1.69	4

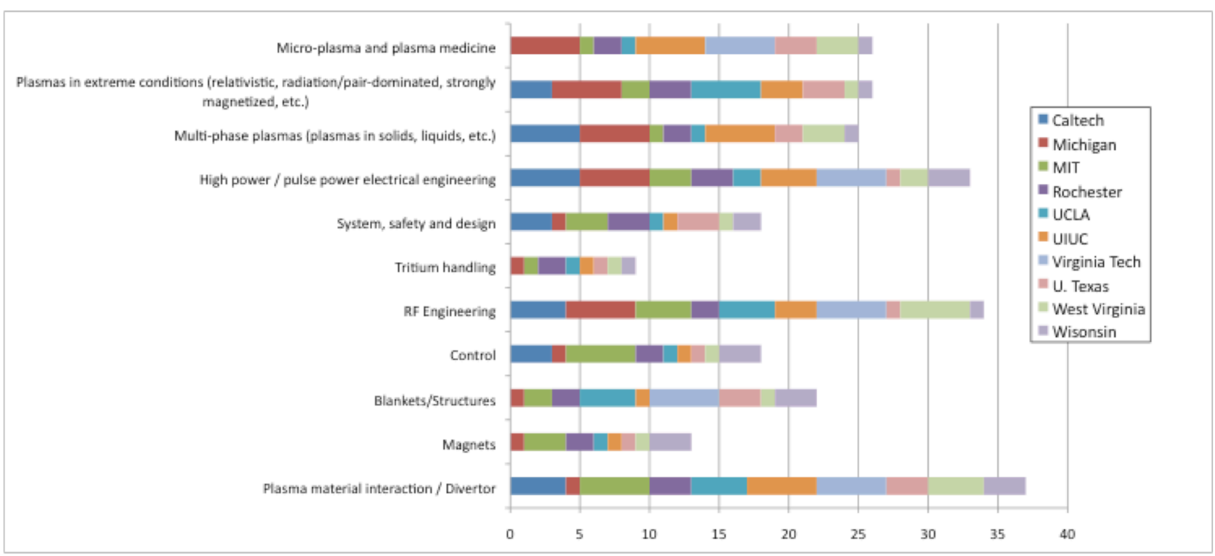

Fig.1. Map of universities responding with total scores of greater than 20 to the survey question: "*How well are disciplines represented in YOUR academic curricula, if your institution is an academic institution?*" in the context of emerging areas. Color code regions are scaled to the x-axis.

3.2 *Charge 2: Identify disciplines in high demand, nationally and/or internationally, resulting in difficulties in recruitment and retention at U.S. universities and at the DOE national laboratories.*

For identifying disciplines in which significant emphasis in workforce training is needed to address gaps in current and future Office of Science needs, one approach is to identify important disciplines in which workforce demand is high or anticipated to be high. To obtain data concerning demand, we posed this question on the survey:

"Which disciplines are in high demand now or anticipated in the future, in YOUR institution/ department /group?"

The results of the returned surveys were compiled so as to separately keep track of responses from three different main groups: universities, national labs, and corporations. (In this discussion, we actually discuss universities and national labs separately and then combine national labs and corporations into a third group, since we anticipate that this third group is the primary "customer" of the university curricula.) It was anticipated that there are some differences in the needs identified by the different groups, and this was confirmed by the analysis of the survey responses. Analysis of the surveys also showed that there are important differences of emphasis within these groups. That is, within a specific group, two different institutions might have very different rankings for needs, presumably reflecting their respective specializations and interests. For instance, some institutions have strong specializations in fusion activities, whereas some other institutions specialize primarily in non-fusion plasma science.

Given that the demands vary widely in the responses to the survey, we feel that the best methodology to identify disciplines with important high demands is to sum the number of high responses within each group (university, national lab, and corporation), where responses of 4 or 5 are interpreted as meaning a strong demand. These responses are shown in Table 2 for the scientific disciplines of theory, experiment, and diagnostics, which are called the "core" disciplines for purposes of this discussion. Column 1 lists these disciplines, sub-divided into the areas of MFE, HEDLP/IFE, and Discovery sciences; the column titled "Q2 Strong Demand Univ" lists the number of strong responses (called demand) from universities; the third column lists the strong demand from national laboratories; and the final column lists the strong demand from national laboratories and corporations. Another measure of demand is the number of comments that were made to point out the importance of a specific discipline. In the core sciences, there were two such comments for low temperature plasmas for industrial applications, which have been allocated to experiment - discovery science, and one response for diagnostics - MFE.

The meaning of the "strong demand" responses is best interpreted by comparison with the academic strength in each of the disciplines. Column 2, labeled "Q1 Strong Curricula", shows data discussed in Section 3.1 and lists the total number of responses from the universities that were rated 4 or 5, indicating strong curricula in that area. A comparison of the second and third columns shows that the number of responses for strong curricula is generally quite close to the number of responses for strong demand from the universities. This observation is interpreted as an indication that the curricula and demand in the universities are roughly in balance—that is, for those core disciplines where the universities have a strong demand, they also have strong curricula.

A metric that is used to help identify important disciplines not well represented in academic curricula has been obtained by dividing the strong demand for a specific group by the number of responses for strong curricula. Due to the fact that there are different numbers of institutions reporting within the three categories of university, national labs, and national labs plus corporations, this metric cannot be compared in an absolute way between the groups. While the demand numbers for labs may seem low, we note that there are relatively few national labs involved in fusion, but each has quite a large workforce and is very important to the national program. However, within a group, the disciplines with the highest numbers would be interpreted as the most needy ones. These data are shown in Table 2 for the core disciplines as columns labeled “Demand/Curricula” where there are columns for universities, labs, and labs plus corporations. For each of these groups, the highest numbers are highlighted with pink backgrounds in the table.

One point to note is that the lowest demand from the labs and corporations is for the three disciplines of the discovery sciences. In contrast, for the universities, these three areas show some of the highest metrics, i.e., needs for workforce development. These data provide strong evidence that the discovery sciences, as defined here, are generally more strongly pursued in the universities than in the other groups. An important caveat to this point is that respondents indicated that there is need for workforce training in low temperature physics for industrial applications. These comments and other data indicate that there is certainly a strong desire for more workforce development in all disciplines. However, the data indicate that the curricula in the core disciplines are strong. In the context of the charge, we cannot make a strong case that there are important gaps in most of the core disciplines that need to be addressed, particularly in comparison to the fusion engineering sciences, which will be discussed next. As an exception, we note that Diagnostics for MFE has the lowest score for strength in the curricula while being the one discipline identified as having high need in all three groups (university research groups, labs, and labs plus corporations). Indeed, for the labs plus corporations group, the need metric of 0.88 is nearly twice that of any other discipline.

Key Finding 5: Overall, the demand in workforce in the core disciplines is strong across the board and is well matched by the strong curricula in these disciplines. Among all the core disciplines, Diagnostics for MFE is identified as least represented in curricula *even though this expertise is in high demand by university research groups, national labs, and industry (especially the latter two groups)*.

Survey data for the “emerging” disciplines are presented in Table 3, with the specific disciplines being listed in the first column. The emerging disciplines in the first column include the fusion engineering sciences of plasma-material interaction/divertor through high power/pulsed power electrical engineering, whereas the last three disciplines in the first column—multi-phase plasmas, plasmas in extreme conditions and micro-plasma and plasma medicine—are primarily non-fusion disciplines. The columns and definitions of the data are the same as those in Table 2. As for the core disciplines, these data show that the university responses for strong demand and strong curricula are comparable for several disciplines. However, some disciplines have a demand that is significantly stronger than the curricula, namely, magnets, tritium handling, and system, safety, and design. Also, we note that the core disciplines have curricula metrics between 8 and 17, whereas all but one of the metrics for the fusion engineering disciplines are between 0 and 6. We also note that no strong curricula are identified by our strength metric for magnets and tritium handling and that only one strong curriculum is identified for system, safety and design. Thus, the curricula in the fusion engineering disciplines are not as strong as those in the core disciplines described in Section 3.1.

The responses for strong demand from the universities, labs, and labs plus corporations are shown in the third, fourth, and fifth columns, and the highest demands in each area are highlighted in yellow. The metrics for high responses in demand over strong curricula are shown in the sixth, seventh, and eighth columns for the three areas. The highest ratios (disparity between demand and supply) for each area are highlighted in pink. There is a fairly strong distinction in the data between the fusion engineering sciences and the non-fusion sciences. Whereas much of the highest demand for the university research groups is in the non-fusion sciences, the labs and corporations have very low demand in these areas. Likewise, for the non-fusion sciences, the need metrics are high from the universities and low from the labs and corporations. Due to the relatively weak demands and needs from the national labs or corporations in the non-fusion disciplines, it is difficult to recommend these areas as having top priority.

Key Finding 6: As a whole, the fusion engineering sciences are in high demand but are poorly represented in the academic curricula. We find it difficult to single out a few of these areas as being the most important for workforce development. Based purely on the demand and need criteria, the area of system, safety, and design and the area of high power/pulse power electrical engineering show the most need for labs and corporations. Plasma material interaction/divertor, although being the strongest area in the curricula, also has the highest total demand (21 high marks over the three areas). Three comments were received about the importance of materials and/or divertor research, further evidence of significant need.

Purely on the basis of the survey numbers, one could argue that there is little need for workforce in magnets or tritium handling, since the labs do not presently have strong demand for these areas. On the other hand, no strong curricula have been identified in these areas. However, based on the stated vision of FES to start a fusion nuclear science program and to be ready to decide on a Fusion Nuclear Science Facility in a decade, these disciplines will become important needs of the Office of Science in the near future. Indeed, one cannot achieve fusion energy without significant developments in fusion engineering science. They will be thus be important gaps that need workforce development, starting now, since it would take of order a decade to build up new programs.

3.3 *Charge 3: What are disciplines identified in the previous two bullets for which the DOE national laboratories may play a role in providing needed workforce development?*

Tables 2 and 3, as previously discussed, present the summary of survey data for curricula strength and workforce demand in core and emerging disciplines. The last two columns of these tables summarize university and lab identifications of both core and emerging disciplines for which labs may play a role in providing the needed workforce development.

Table 2: Reduced survey data for core disciplines

Core Sciences	Q1 Strong Curricula (# of institutions scoring 4 or 5)	Q2 Strong Demand (# of univ scoring 4 or 5)	Q2 Strong Demand (# of lab scoring 4 or 5)	Q2 Strong Demand (# of lab/corp scoring 4 or 5)	Univ Demand/ Curricula (Q2_univ / Q1)	Lab Demand/ Curricula (Q2_lab/ Q1)	Lab_corp Demand/ Curricula (Q2_lab_corp / Q1)	Q3 Labs contribute strongly (universities 4 or 5)	Q3 Labs contribute strongly (labs 4 or 5)
Theory/modeling MFE	15	11	3	8	0.73	0.20	0.53	13	5
Theory/modeling HEDLP/IFE	9	8	3	4	0.89	0.33	0.44	17	4
Theory/modeling Discovery	17	19	1	3	1.1	0.06	0.18	9	3
Experiment MFE	15	11	3	6	0.73	0.20	0.40	18	4
Experiment HEDLP/IFE	10	10	3	4	1.0	0.30	0.40	23	5
Experiment Discovery	15	17	1	2	1.1	0.07	0.13	10	3
Diagnostics MFE	8	9	2	7	1.1	0.25	0.88	19	4
Diagnostics HEDLP/IFE	9	7	3	4	0.78	0.33	0.44	20	4
Diagnostics Discovery	10	16	1	2	1.6	0.10	0.20	9	3

Table 3: Reduced survey data for emerging disciplines

Emerging Disciplines	Q1 Strong Curricula (# of institutions scoring 4 or 5)	Q2 Strong Demand (# of univ scoring 4 or 5)	Q2 Strong Demand (# of lab scoring 4 or 5)	Q2 Strong Demand (# of lab/corp scoring 4 or 5)	Univ Demand/ Curricula (Q2_univ / Q1)	Lab Demand/ Curricula (Q2_lab / Q1)	Lab_corp Demand/ Curricula (Q2_lab_corp / Q1)	Q3 Labs contribute strongly (universities 4 or 5)	Q3 Labs contribute strongly (labs 4 or 5)
Plasma material interaction / Divertor	10	10	3	8	1.0	0.3	0.8	13	5
Magnets	0	4	0	3	inf	0	inf	12	4
Blankets/Structures	4	5	2	5	1.3	0.50	1.3	11	5
Control	5	4	1	5	0.8	0.20	1.0	13	4
RF Engineering	6	6	1	6	1.0	0.17	1.0	16	4
Tritium handling	0	2	0	0	inf	0	0	14	5
System, safety and design	1	3	2	6	3.0	2.0	6	14	6
High power / pulse power electrical engineering	6	6	3	9	1.0	0.5	1.5	14	4
Multi-phase plasmas (plasmas in solids, liquids, etc.)	5	6	0	1	1.2	0	0.20	8	2
Plasmas in extreme conditions (relativistic, radiation/pair-dominated, strongly magnetized, etc.)	6	12	1	2	2.0	0.17	0.33	15	3
Micro-plasma and plasma medicine	4	6	1	2	1.5	0.25	0.5	6	0

The responses in Table 2 indicate that all core areas have a high workforce demand and that labs may play a role in the needed workforce development in these areas. For the Discovery Plasma Science, both universities and labs indicate a smaller positive response than for MFE and HEDLP/IFE program elements. This response is consistent with the greater role of universities in Discovery Plasma Science programs compared to that of national labs.

Regarding the emerging disciplines data in Table 3, with few exceptions both universities and labs indicate that labs may play a role in needed workforce development. This positive response includes the areas of Magnets, Tritium handling, and System, safety, and design, which were identified as having a weak curricula base, and the broad category of fusion engineering science, which was noted to have high demand. The exceptions comprise lower levels of positive responses for Multi-phase plasmas by both universities and labs and for Micro-plasma and plasma medicine by universities. There were no positive responses by labs for the latter category.

As was noted by the 2004 Fusion Workforce Planning report, workforce development at the graduate level is predominantly a university function, while post graduate efforts are more appropriate for laboratories. Several comments in our recent survey reinforced this. Laboratories, however, must play a larger role in graduate programs when the research requires large-scale facilities or when the research, e.g., tritium systems development or activated materials analysis, is not appropriate for the university environment.

Key Finding 7: There is general recognition that national labs can play a role in workforce development for the emerging disciplines, especially for those in fusion engineering sciences.

3.4 *Charge 4: Specific recommendations for programs at the graduate student or postdoc levels that can address discipline-specific workforce development needs.*

The subcommittee has carefully considered how to respond to this charge question. We have identified, in the previous charge questions, that disciplines related to fusion engineering sciences are those that appear to face the largest challenges. In large part, these disciplines have emerged in the FES-supported fields because these fusion engineering science challenges *are* the next great issues facing fusion energy science research, and there has been a more than decade-long reduction in support for these disciplines. Additionally, this subcommittee did an evaluation of the current Office of Science and FES-sponsored programs for graduate students and postdocs.

Therefore, although this subcommittee will respond to this charge and make specific recommendations for graduate student and postdoc programs, it is done in the context of programs that are supported by FES and with the recognition that these recommendations will be most successful if there is also a vibrant and active community of university, laboratory, and corporate researchers with deep expertise in these disciplines. Moreover, one of the challenges in addressing the gaps in disciplines identified in Charges 1 and 2 is not only to have strong research programs, but to also have a strong academic curriculum of advanced courses so that students have an opportunity to gain in-depth knowledge of their field.

Key Finding 8: Having curricula of sufficient depth and breadth, and more critically, having the faculty members to teach those courses are necessary criteria to complement programs for graduate students and postdocs. Programs such as joint lab-university faculty appointments or DOE-wide programs to support faculty in "gap disciplines" (similar to programs funded by National Science Foundation in space plasma sciences, DOE – Nuclear Engineering University Programs, or the Nuclear Regulatory Commission's Faculty Development Program) may help to provide the intellectual infrastructure to make programs aimed at graduate students and postdocs successful and sustainable. In addition, DOE national laboratories can play a significant role in enhancing the educational experience of advanced graduate students by providing long-term research opportunities in close collaboration with their academic advisors.

4 Recommendations in Response to the Charge Questions

Based on our Key Findings 1-8 and the community input, a set of specific recommendations has been formulated by the subcommittee to address discipline-specific workforce development needs. The specific recommendations are described below in two broad categories: the first category focuses on curriculum development and classroom education, while the second category focuses on research training to meet the workforce development needs, involving both academic institutions and national labs.

4.1 Recommendations on Curriculum Development and Classroom Education

Recommendation 1: *Establish periodic summer schools for graduate students and postdocs on fusion engineering sciences.* Because of the identified need for expertise in the fusion engineering science disciplines (e.g., magnets, tritium handling, etc.), it is clearly necessary to enhance the skills of students in these areas. As has been done in many other fields of science, summer and winter schools can be effective tools to provide this additional training. It is proposed that an "enhanced summer school" could be an extended experience – say two to four weeks – that involves both theoretical and experimental training opportunities for students. These schools can be jointly held with relevant disciplines, such as material sciences for "PMI/divertor", superconductor technology for "magnets", and nuclear sciences for "system/safety/design". Experts from academic institutions and national labs, both domestic and international, could be invited to provide the desired lectures. Course materials (and classroom videos, when feasible) should be made available online.

Recommendation 2: *Establish a consortium among national labs and academic institutions to enhance graduate student training and develop curricula for plasmas diagnostics and fusion engineering sciences.* A proposed consortium of academic institutions can share best practices in teaching and research focused on emerging areas that have both high demand and where there are critical gaps. National labs can play an important role in this consortium as key stakeholders and provide guidance on general technical areas of demand and needs for training. This consortium is intended to provide a network of institutions where the smaller programs could benefit from their interaction with larger institutions and leverage their expertise and best practices in academic curriculum development. Such a network could greatly leverage the expertise of its members to develop the broad curricula needs in the emerging disciplines.

4.2 Recommendations on Research Training

The recommendations in the second category address the workforce development needs in research training. Recommendation 3 is to directly support such activity through a research award program, while Recommendation 4 has two parts: one part about enhancing university programs that are connected to the national labs, and the other part about supporting training programs at national labs to directly involve academic institutions.

Recommendation 3: *Establish a renewed program to encourage graduate students and postdocs to pursue fusion engineering sciences.* This component of the FES program has seen significant funding challenges in the last decade. Correspondingly, students have chosen not to pursue this area. However, the survey results show a particularly strong need for a renewed effort in the fusion engineering sciences. A targeted graduate and postdoc research award program in areas of fusion engineering sciences could help to address this discipline gap.

Recommendation 4a: *Enhance participation of academic institutions in large FES projects and FES international collaborations – particularly in the areas of advanced diagnostic and materials development.* The central theme of this recommendation is to increase the training and preparation of graduate students and postdocs early in their career to gain experience working on large devices. A potential benefit of this approach would be to increase "ownership" of diagnostics and scientific leadership at large devices (including NIF and ITER in the future) and increase the effectiveness of translating knowledge in materials development (including plasma-material interactions, plasma-facing components, blankets, magnets, and structural materials) by university research groups, who can also have local experiments or test devices to support development in these targeted areas of advanced diagnostics and fusion engineering science. Continued local activities are important since, as noted by the 2012 FESAC Panel on International Collaboration in FES Research[2], participation in distant projects poses challenges for students and faculty who are taking and teaching courses. The increased participation can help avert the crisis of shrinking fusion research at universities. These emerging areas have been identified from our survey as high in demand and as areas where universities in partnership with national labs can have significant impact. In this way, graduate students and postdocs can benefit from training at their local universities and also at labs and corporations. We note that multiple universities already play key roles in diagnostics at all major US facilities, but we encourage further expansion of this mutually beneficial collaboration, e.g., into materials science areas. It could be enabled by a targeted FES competition open to university proposals, similar to what has occurred periodically for NSTX.

Recommendation 4b. *Establish a focused program at national labs to support graduate students and postdoctoral researchers in advanced diagnostics and in targeted emerging engineering science areas, including nuclear materials.* National labs and large academic institutions can partner with smaller fusion groups (as indicated in Recommendation 2) to address gaps in emergent research areas, thus offering opportunities for graduate student and postdoc mobility. For example, a rotation program could be implemented in which a postdoctoral researcher spends time (e.g., one year) in a national lab and another year at a partner university and thus

[2] FESAC: International Collaboration in Fusion Energy Sciences Research: Opportunities and Modes During the ITER Era (2012);

enable effective knowledge transfer to both the university and also participating graduate students. Furthermore, graduate students can enhance their academic and research experience at a university by spending an extended period, e.g., six months, on unique infrastructure facilities at national labs in the areas of fusion engineering sciences or advanced diagnostics. Such research should have strong and direct connections to their academic advisors and home institutions.

5 Final Comments

In general, the subcommittee finds that the scientific disciplines supported by FES are in a state of flux. In the core areas of MFE, HEDLP/IFE, and discovery plasma science, the field *currently* has generally stable academic programs with good productivity of graduate students and postdocs. But, there is also a very clear downward trend that could threaten the long-term viability of the US leadership in plasma and fusion energy sciences. In emerging areas, the picture is much less clear. Some areas, such as Plasma-Materials-Interface/divertors, are recognized as important future disciplines for the field, and there is an effort underway to develop the academic programs and curricula in these areas. In other areas of fusion engineering sciences, although there is recognition of the importance and value of these disciplines (e.g., control, magnets, tritium handling, etc.), it is unclear whether the academic institutions are prepared to support these fields.

Additionally, most of the disciplines with shortages are most appropriately covered in engineering departments. To quote one respondent: "Heavily engineering-based disciplines will not be the basis for a hire in a physics department." The relatively small number of engineering departments with strong MFE and IFE programs, some of which are shrinking, will need to be supported and expanded to meet future workforce needs. Any programs tailored to fill these gaps will need to be targeted to meet specific mission needs; we note that proposals focused on practical applications may not fare well in general competitions judged on the basis of fundamental scientific interest, which tend to favor high impact physics publications. A bright spot in this report is that while there are lingering concerns about support of discovery plasma science, this area is, and is likely to remain, an important part of the academic portfolio.

As this report is being prepared, FES is also undergoing a major strategic planning activity. While this strategic planning activity references many of the same reports that this subcommittee has used, it is likely that new strategic priorities will emerge from this process that could modify the mix and priority of disciplines that were under consideration by this subcommittee.

We end this report by providing a few final points as input to the strategic planning process that provide an important context for the analysis presented in our report. These are "global" issues of importance to FES, and the subcommittee hopes that these points will be considered as complementary to our recommendations.

a. *Educational pipeline*

A complete picture of the scientific workforce must be understood in the context of the broader educational pipeline. There are many reports that discuss the challenges of training highly-qualified individuals in the so-called STEM (science, technology, engineering, and mathematics) fields. We believe that a robust workforce for FES requires a wide pipeline that starts with pre-college activities and ends with strong employment opportunities. This pipeline should also tap into the full potential of the American populace, with opportunities to attract women and groups that are traditionally under-represented in STEM fields.

b. *Role of strong coupling between academia, national labs, and industry*

The subcommittee notes that there is a very strong coupling between academia, the national labs, and industry in the areas supported by FES. As noted above, in the U.S. magnetic fusion program, while the largest tokamak, DIII-D, is located at a company, a national lab houses the spherical tokamak NSTX, and a university houses the tokamak, Alcator C-Mod. The majority of the other magnetic fusion concept devices are located at universities. In low temperature plasma science, while much of the fundamental research is done at universities, the field is driven by needs of the large plasma processing industry.

Because of this diversity of professional opportunities, universities often seek to provide a strong, fundamental training in plasma science that provides students with the skills to pursue careers in academia, national labs, or industry. Subsequently, the specific disciplines that students are exposed to at universities are largely dependent upon the expertise of and research support provided to faculty members. Therefore, some critical disciplines that are identified in this report may not only require the assistance and support of national laboratories, but may also necessitate new opportunities at universities.

c. *Importance of establishing and supporting faculty in the emerging disciplines*

Programs to enhance workforce development for graduate students and postdocs do not function without excellent faculty who not only can teach curricula in emerging disciplines but also perform research directly in these areas to provide research training for graduate students and postdocs. Creating new faculty positions in these areas can be facilitated by programs like joint lab and university appointments, followed by financial support over a relatively long period.

As a final comment, the subcommittee notes that a healthy and strong FES program requires each of its program areas to be healthy and strong and, therefore, the emphasis on one program area cannot be at the expense of other program areas. It is crucial to maintain overall stability and balance in order for FES to achieve its mission over an extended period of the time.

Appendix A: Charge on Assessment of Workforce Development Needs in Office of Science Research Disciplines

Department of Energy
Office of Science
Washington, DC 20585

February 19, 2014

To: Chairs of the Office of Science Federal Advisory Committees:
Professor Roscoe C. Giles, ASCAC
Professor John C. Hemminger, BESAC
Professor Gary Stacey, BERAC
Professor Mark Koepke, FESAC
Professor Andrew J. Lankford, HEPAP
Dr. Donald Geesaman, NSAC

From: Patricia M. Dehmer
Acting Director, Office of Science

Charge: Assessment of workforce development needs in Office of Science research disciplines

The Office of Science research programs have a long history of training graduate students and postdocs in disciplines important to our mission needs as part of sponsored research activities at universities and DOE national laboratories. In addition, the Office of Workforce Development for Teachers and Scientists supports undergraduate internships, graduate thesis research, and visiting faculty programs at the DOE national laboratories.

We are asking the assistance of each of the Office of Science Federal Advisory Committees to help us identify disciplines in which significantly greater emphasis in workforce training at the graduate student or postdoc levels is necessary to address gaps in current and future Office of Science mission needs. As part of your expert assessment, please consider:

- Disciplines not well represented in academic curricula;
- Disciplines in high demand, nationally and/or internationally, resulting in difficulties in recruitment and retention at U.S. universities and at the DOE national laboratories;
- Disciplines identified in the previous two bullets for which the DOE national laboratories may play a role in providing needed workforce development; and
- Specific recommendations for programs at the graduate student or postdoc levels that can address discipline-specific workforce development needs.

Please submit to me, no later than June 30, 2014, a letter report describing your findings and recommendations. These results will be used to help guide future activities and investments.

If you would like to discuss the charge, please do not hesitate to contact me (patricia.dehmer@science.doe.gov). Thank you very much for your help with this important task.

Printed with soy ink on recycled paper

Appendix B: Letter to Subcommittee Chair from FESAC Chair

Department of Physics
West Virginia University
(304) 293-3422 Morgantown WV 26506-6315

March 19, 2014

Professor Hantao Ji
Department of Astrophysical Sciences
Peyton Hall, Room 106
Princeton University
4 Ivy Lane, Princeton, NJ 08544
Tel: (609) 258-1014
Email: hji@princeton.edu

Greetings, Prof. Ji,

As you know, FESAC has been given an important charge to recommend academic programs, student training, and in-need discipline support for our field. You are keenly aware that workforce development in science is a priority and fusion science workforce development is in dire need of increased attention and tangible action by the federal government.

Each Office of Science Federal Advisory Committee has been asked to help the Office of Science identify disciplines in which significantly greater emphasis in workforce training at the graduate or postdoc levels is necessary to address gaps in current and future Office of Science mission needs. These might be disciplines that are not well enough represented in academic curricula and disciplines in which the high demand, nationally or internationally, results in difficulties in recruitment and retention at U.S. universities and at the DOE laboratories. Specific recommendations for programs at the graduate-student level or postdoc level that can address discipline-specific workforce development needs are solicited. June 30, 2014, is the deadline for the FESAC response.

The full scope and other details can be found in the attached letter. I would like you to serve as chair of the FESAC panel that will address this charge. To provide you major assistance carrying out the panel's response to this charge, Ed Thomas (Auburn Univ) will serve as Vice Chair. Ed chaired the 2004 Workforce-Assessment FESAC panel that serves as an important reference document for today's charge (also attached). After hearing back from you, I would like the two of us to invite the other members of the panel via a message from my email address and pass the communication responsibilities over to you, with you, me, and Sam Barish collaborating regarding the Panel's process. Could you respond by Friday noon of this week to confirm or decline this invitation?

Respectfully,

Mark E. Koepke

Mark E. Koepke, Professor, FESAC Chair
Department of Physics and Astronomy
West Virginia University
Mark.Koepke@mail.wvu.edu

Plasma Physics Laboratory Office 304-293-4912 FAX (304) 293-5732 E-MAIL mkoepke@wvu.edu

Appendix C: Membership of the FESAC Subcommittee on Assessment of Workforce Development Needs

Jean Paul Allain	University of Illinois at Urbana-Champaign
Lee Berry	Oak Ridge National Laboratory
Rich Groebner	General Atomics
Amanda Hubbard	Massachusetts Institute of Technology
Hantao Ji (Chair)	Princeton University and Princeton Plasma Physics Laboratory
Ray Leeper	Los Alamos National Laboratory
Ed Thomas (Vice Chair)	Auburn University

Appendix D: Survey Form and Community Responses

The subcommittee has designed the survey form for easy responses to questions directly relevant to the charges. The disciplines with emerging opportunities were selected based on the 2007 FESAC Priorities, Gaps, and Opportunities Report on research gaps identified in the magnetic fusion energy sciences, as well as perceived emerging disciplines from Discovery Plasma Sciences.

We distributed this survey form though organizations like APS DPP, GPAP, and UFA, as well as a list of principal investigators of research projects funded by FES. We received 73 completed surveys in total from the U.S. institutions, including 54 from universities, 9 from national labs, and 10 from corporations. There were additional 4 completed surveys from foreign institutions, but were not included in the statistical analyses for this report.

We enclose both the survey form and cover letter to this appendix.

Your name:		**The name(s) of the insitution, department, or group that you are representing:**	
If your instituion is an academic institution, how did the number of faculty and students in your institution/department/group evolve over the past dacade? (3 - increased, 2 - about the same, 1 - decreased, 0 - not sure)			

Disciplines	How well are disciplines represented in YOUR academic curricula, if your institution is an academic institution? (1-5) (5 - strongly represented) (1 - poorly represented) (0 - not sure or N/A)	Which disciplines are in high demand now or anticipated in the future, in YOUR institution/ department /group? (1-5) (5 - high demand) (1 - low demand) (0 - not sure or N/A)	Which disciplines may national labs help provide needed workforce development? (1-5) (5 - labs contribute greatly) (1 - labs do not contribute) (0 - not sure or N/A)	**Additional comments, concerns, and recommendations**
Established Disciplines				
Theory/modeling				
MFE Sciences				
ICF/HEDP Sciences				
Discovery Plasma Sciences (Basic, Low-Temperature, Space/Astrophysical Plasmas)				
Experimentation				
MFE Sciences				
ICF/HEDP Sciences				
Discovery Plasma Sciences (Basic, Low-Temperature, Space/Astrophysical Plasmas)				
Diagnostics				
MFE Sciences				
ICF/HEDP Sciences				
Discovery Plasma Sciences (Basic, Low-Temperature, Space/Astrophysical Plasmas)				
Disciplines with Emerging Opportunities				
Plasma material interaction / Divertor				
Magnets				
Blankets/Structures				
Control				
RF Engineering				
Tritium handling				
System, safety and design				
High power / pulse power electrical engineering				
Multi-phase plasmas (plasmas in solids, liquids, etc.)				
Plasmas in extreme conditions (relativistic, radiation/pair-dominated, strongly magnetized, etc.)				
Micro-plasma and plasma medicine				
Other Disciplines with Emerging Opportunities				
Discipline 1				
Discipline 2				
Discipline 3				
Discipline 4				
Discipline 5				
Discipline 6				

(specify disciplines above)

Greetings:

The U. S. Department of Energy – Office of Science has recently charged its advisory committees to perform an assessment of Workforce Development Needs. The focus of this charge is to help "identify disciplines in which significantly greater emphasis in workforce training at the graduate student or postdoc levels is necessary to address gaps in current and future Office of Science mission needs". We, the Fusion Energy Sciences Advisory Committee (FESAC) subcommittee, are asked to respond to DOE in the form of a brief letter report.

We are writing you to request your assistance to help us address this charge for all areas supported by Fusion Energy Sciences (FES) - from fusion energy to low temperature plasma science. In particular, we seek your input to address the three main questions raised by this charge:

1. Which disciplines are not well represented in academic curricula?
2. Which disciplines are in high demand, nationally and/or internationally, resulting in difficulties in recruitment and retention at U.S. universities and at the DOE national laboratories?
3. Are there disciplines identified in the previous two bullets for which the DOE national laboratories may play a role in providing needed workforce development?

We request that you fill out the attached survey and send back to us by Thursday, May 1, 2014 so that we can gather community input and respond to this charge in a timely fashion. This survey is designed only for institutions, departments, and groups, not for each individual. You are sent this request because you are identified to represent your institution, department or group regarding research and education activity supported by the FES programs currently or in a recent past. If there is a more appropriate person who should respond to this survey, please let us know and pass the request to that person. We appreciate your prompt responses by the deadline.

Here are some explanations about the survey. The columns correspond directly to the three main questions listed above. The "disciplines" are presented in two categories in the rows. The first category represents the well-established research areas and the second category represents specific topical areas with emerging opportunities. Please note that "N/A" or "Not Sure" are acceptable answers. For clarification on some of the questions on the survey:

MFE – Magnetic Fusion Energy plasma sciences
ICF/HEDP – Inertial Confined Fusion / High-Energy-Density Plasmas
"Discovery plasma sciences" – relates to work in the areas of basic, low temperature, and space/astrophysical plasmas; research areas that can be characterized as curiosity-driven rather than mission-driven.

Lastly, we welcome any additional comments, concerns, and recommendations regarding workforce development and future workforce needs as part of survey. We also welcome input in the form of separate emails or brief white papers. We appreciate your cooperation and assistance in advance.

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Prof. Edward Thomas, Jr.
FESAC Subcommittee Vice Chair
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Appendix E: Additional Emerging Disciplines Suggested by Survey Respondents

The survey respondents were given an opportunity to suggest additional plasma science and engineering disciplines with emerging opportunities. They are listed in the following two categories:

Fusion Plasma and Engineering Sciences:

- Energy and environmental studies
- Fusion engineering
- Fusion nuclear science
- Fusion nuclear technologies
- Heat removal
- IFE target physics
- Integrated thermofluid/thermomechanical modeling
- Neutronics and nuclear analysis
- Privately funded fusion concepts

Discovery Plasma Science:

- Astrophysical and space plasma (2 entries)
- Atmospheric plasmas (2 entries)
- Antimatter plasmas / anti-hydrogen
- Computational plasma physics
- Dusty plasmas
- Dusty plasmas in astrophysics
- Hydrodynamics (the collisional, unmagnetized limit)
- Intense beam physics and beam-plasma interactions
- Magnetic reconnection (experimental)
- Noctilucent cloud plasmas
- Plasma accelerators
- Plasma metamaterials/photonics
- Plasma nanosynthesis
- Plasma propulsion
- Plasmonics
- Proton therapy
- Saturn ring plasmas