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Fusion in the Era of Burning Plasma Studies: Workforce Planning for 2004 to 2014

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This is the final report of a panel set up by the U.S. Department of Energy (DOE) Fusion Energy Sciences Advisory Committee (FESAC) in response to a charge letter from Dr. Raymond Orbach (Appendix A), asking FESAC to "addresseds the issue of workforce development in the U.S. fusion program." This report, submitted to FESAC March 29, 2004 and subsequently approved by them (Appendix B), presents FESAC's response to that charge.

KEY WORDS: Fusion energy; fusion science; fusion workforce.

EXECUTIVE SUMMARY

This report has been prepared in response to Dr. R. Orbach's request of the Fusion Energy Sciences Advisory Committee (FESAC) to "address the issue of workforce development in the U.S. fusion program." The report addresses three key questions: what is the current status of the fusion science, technology, and engineering workforce; what is the workforce that will be needed and when it will be needed to ensure that the U.S. is an effective partner in ITER and to enable the U.S. to successfully carry out the fusion program; and, what can be done to ensure a qualified, diversified, and sufficiently large workforce and a pipeline to maintain that workforce? In addressing the charge, the Panel considers a workforce that allows for a vigorous national program of fusion energy research that includes participation in magnetic fusion (ITER) and inertial fusion (NIF) burning plasma experiments.

The surveys of the universities, national laboratories, and industrial laboratories indicate that approximately 1000 persons hold full-time positions that involve fusion research. The fusion research community is found to be less diverse in terms of gender and race than the general population of physicists in the U.S. The age distribution of the fusion faculty shows a larger fraction of older persons than the national distribution of physics faculty. This imbalance is more evident at institutions with the largest and most active fusion research groups. At the national and industrial laboratories, 1/3 of the permanent staff is 55 years or older. Extrapolation of the data obtained to the projected start date for ITER shows that 100 retirements amongst senior scientific staff at universities, national laboratories, and industrial laboratories are likely. The institutions engaged in fusion research predict a need for an additional 150 full-time staff and 100 Ph.Ds researchers over the next 10 years. This implies a potential need to bring 350 new individuals into the fusion program over this longer

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period. It is significant that over the next 2–4 years the personnel needed to support the growing ITER and NIF activities at the largest institutions are expected to be found through internal reassignments.

Since roughly half of the fusion Ph.D. recipients in the past decade have found employment in fusion research, the recent Ph.D. production-rate of 25–30 Ph.Ds/year appears to be sufficient to maintain the present size of the fusion workforce over the next 2–4 years. However, in the 2008–2014 interval the combination of predicted retirements and new hiring will require that 210 permanent positions be filled. This implies an average hiring rate of 42 Ph.Ds/year. Since this figure exceeds the current total Ph.D. production-rate in the fusion-related fields, an increase in fusion Ph.D. production seems necessary to implement the plans outlined in previous FESAC reports. However, it is critical that the process of new job creation begin now; both to encourage students to enter and remain in the field and to facilitate the intellectual continuity of the field.

Over the past decade, the Office of Fusion Energy Sciences (OFES) has continued to support a limited number of graduate and postdoctoral fellowships in fusion science. OFES has also developed new programs such as the Plasma Physics Junior Faculty Fellowship, the Innovative Confinement Concepts program, the partnership with NSF to support basic plasma science, the partnership with National Science Foundation (NSF) to support plasma related NSF Frontier Centers, and the OFES-supported Fusion Science Centers. These proactive policies by OFES have led to a revitalization in basic plasma physics research and the initiation of a diverse range of small and medium-sized basic plasma physics groups around the country. OFES's development of these programs was in response to the recommendation of the National Research Council's Plasma Sciences Committee. This Panel believes that it is time for OFES to build on the successes of these programs and to sustain a national burning plasma fusion science program in the U.S. through a carefully balanced combination of short-term and long-term strategies. This list of strategies, each of which carries equal importance, includes:

Short Term

- Performing an expanded, comprehensive assessment of the fusion workforce at the national laboratories with the goal of developing a five to ten year hiring plan.
- Optimization of operations of existing large experiments to foster student-training opportunities with both affiliated and external academic institutions.
- Implementation of periodic reviews of existing graduate and postdoctoral fellowship programs as well as the junior faculty program to ensure that they are competitive and meet current needs.
- Develop programs in coordination with professional societies that enhance the visibility of fusion researchers.
- Creation of a jointly-funded professorship similar to the recently developed NIF professorship.

Long Term

- Implementation of outreach programs at all educational levels with the goal to attract a diverse group of students into pursuing a career in fusion science and engineering.
- Continuation of support of fusion research programs at universities, with a particular emphasis on experimental programs that will train individuals with hands-on experience.

In summary, this Panel concludes that important steps must be taken now by OFES to maintain the intellectual continuity of the field and to ensure an adequate number of fusion scientists and engineers in the period 5–10 years from now when ITER and NIF become fully operational.

INTRODUCTION

In July, 2003, the Fusion Energy Sciences Advisory Committee (FESAC) was presented with a charge from Dr. Raymond Orbach, Director of the Department of Energy's Office of Science to "address the issue of workforce development in the U.S. fusion program," This charge consists of three key questions:

- *Where are we*? Assess the current status of the fusion science, technology, and engineering workforce (e.g., age, skill mix, skill level).
- *Where are we going*? Determine the workforce that will be needed and when it will be needed

in order to ensure that the U.S. is an effective partner in ITER and to enable the U.S. to successfully carry out the fusion program.

- *How do we get there*? Provide suggestions for ensuring a qualified, diversified, and sufficiently large workforce and a pipeline to maintain that workforce. The suggestions should be things that are reasonable and within the control of the Office of Science.

In responding to the three components of this charge, the FESAC Workforce Development Panel (henceforth referred to as the ‘‘Panel’’), developed three guiding principles to motivate its deliberations:

(a) Ensure the ‘‘continuity of intellectual infrastructure’’ for the field.
(b) Ensure that sufficient professionals are available to maintain a vigorous domestic program that is similar in size and scope to the current program and the inclusion of a strong research program in burning plasmas centered on the NIF and ITER devices.
(c) Ensure that the workforce pipeline is adequate to maintain a healthy, diverse, and flexible base of highly qualified persons capable of continuing the development of fusion energy sciences.

The Panel has performed a detailed assessment of the current U.S. fusion energy workforce to obtain a ‘‘snapshot’’ of the faculty, university researchers, and national and corporate laboratory researchers that comprise the community of fusion scientists. Then, through a second round of surveys, the community provided the Panel with projections of both the short-term (up to 3 years from the present) and long-term (up to 10 years from the present) workforce requirements to successfully pursue a domestic program of fusion energy research with a strong burning plasma component. The report combines all of this information and uses this data to develop a forecast of the fusion energy workforce for the next decade.

For the remainder of this section, the methods used to gather information regarding the current workforce are discussed. Following that, the report will discuss the definitions used to categorize the fusion workforce throughout the data acquisition process.

METHODOLOGY

As discussed in the introduction to this section, in gathering data for this report a variety of sources was used. The primary data gathering tools used by the Panel were a variety of survey forms. Survey forms (denoted Workforce Panel institutional surveys—WPS) were sent to universities, university-based research laboratories, and national and corporate research laboratories involved in fusion energy research.

In the institutional surveys, 55 educational institutions, the DOE national laboratories and two corporate laboratories (general atomics and boeing company) were identified as survey targets. Among the universities, complete responses were obtained from 30 institutions (55%) and partial data was obtained for another five institutions (constructed using the UFA database and/or the Panel’s own investigations of online and other information sources). The national laboratories and corporate laboratories also responded positively to this survey process. Detailed data was gathered on primarily OFES-supported persons in these institutions and partial data was obtained for NNSA-funded positions.

From these institutional surveys, the Panel estimates approximately 1000 persons are involved in fusion research. This total includes magnetic fusion energy (700) and inertial fusion (300)—both inertial confinement fusion (ICF) and inertial fusion energy (IFE) persons. This total includes approximately 100 university faculty, 125 university researchers, and the remainder at national and corporate laboratories. These persons are predominantly Ph.Ds in physics—specifically, plasma physics.

Additionally, the Panel also conducted an internet-based survey (Workforce Panel Online—WPO) in which individuals were asked a series of questions regarding their background and training in plasma physics. The purpose of this second-tier survey was to gather information that could not be obtained from the broader, institutional surveys as well as to crosscheck the numbers obtained by the institutional surveys. The online survey had 395 respondents or roughly a 40% response rate from the fusion community. The responses from the online survey are generally consistent with the age, gender, and racial data obtained from the institution surveys. This is highlighted in Table 1, below. This gives the Panel confidence in using information

Table 1. Comparison of Responses from Institutional and Online Panel Surveys

	Institutional Survey	Online Survey (± 5%)
Average age (years)	50.1	56.1
Diversity (%)		
White	85.7	89.2
Non-white	14.3	10.8
Gender (%)		
Male	93.3	94.1
Female	6.7	5.9

from both surveys to draw conclusions about the current status of the fusion workforce.

Given the relatively small size of the fusion energy community, as compared to other areas of science, the Panel believed it was necessary to compare its data with larger databases. As indicated earlier, the current fusion workforce is dominated by persons with advanced degrees in physics. Consequently, the Panel chose to compare its data against physics doctorate data in two long-running NSF surveys, "Characteristics of Doctoral Scientists and Engineers in the United States" and "Science and Engineering Doctorate Awards" for the years 2001 and 2002, respectively. Because the NSF has conducted these surveys for over 20 years, the Panel felt these databases provided the most reliable and consistent information against which to compare its measurements. Additionally, the Panel also compares its data to that of the American Institute of Physics (AIP). It is also noted that in 2003, the University Fusion Association (UFA) conducted a demographics survey of the fusion faculty. The Panel also compared its data against that obtained by UFA. A summary of these different data sources is presented in Table 2.

Definitions and Classifications

In order to ensure clarity throughout; this report, the Panel has adopted a number of classifications for persons in the fusion community. This report presents those classifications here.

University faculty—The Panel identifies university faculty as tenured- or tenure-track faculty members at educational institutions. While the Panel recognizes that research personnel (sometimes classified as Research faculty) at educational institutions play a pivotal role in the training of future fusion scientists, the definition, role, and responsibilities of research personnel can vary widely from one institution to another, whereas the role and duties of tenure-track faculty is generally consistent. Additionally, it was the consensus of the Panel that the hiring of tenure-track faculty represents an important, long-term commitment to fusion energy sciences by an educational institution. By contrast, Research faculty appointments are often funded through external (i.e., non-university) sources and, in the event of termination of funding, those positions could be eliminated.

University researchers—This category is used to identify all other persons working in fusion energy research at educational institutions that were not in tenured or tenure-track positions. This includes all persons at university-sponsored and university-affiliated research laboratories with the exception of the Princeton Plasma Physics Laboratory (PPPL), which is a national laboratory.

National laboratory / corporate laboratory researchers—This final category is used to identify researchers involved in fusion energy research at the Department of Energy (National) laboratories and corporate laboratories (e.g., General Atomics Corporation).

Throughout this report, the Panel also classifies the technical expertise of personnel in the fusion community using six research and technical areas required for the successful participation in burning plasma experiments. These six areas were defined in the FESAC report, "A Plan for the Development of Fusion Energy" (March, 2003). These areas are:

Table 2. Summary of Data Sources used Throughout this report

Reports	Database size	Notation
Workforce panel institutional surveys	800	WPS
Workforce panel online survey	400	WPO
Characteristics of Doctoral Scientists and Engineers in the United States-2001, NSF report NSF-03-310	13,000	NSF
Science and Engineering Doctorate Awards—2002, NSF Report 04-303	21,000	
2002 Academic Workforce report	11,000	AIP
2002 Society Membership Profile American Institute of Physics	11,000	
ge distribution of fusion science faculty and fusion science Ph.D. production—University Fusion Association, 2003	100	UFA

Theory. simulation. basic plasma science—experiments, theory, and computational work in fundamental topics in plasma physics and plasma engineering.

Configuration optimization—experiments, theory and computational work, and technological and engineering work in the development of alternative plasma confinement schemes.

Burning plasmas—any type of research and engineering/technology development for direct support of burning plasma activities.

Materials science—research, engineering, and technology development for plasma-facing materials.

Engineering science/Technology development—all types of plasma engineering and plasma technology developments to support the domestic program of fusion energy research including on-going and burning plasma experiments.

Power plant development—specific research activities that focus on the scientific and technological areas for the successful design of a fusion energy power plant.

Workforce Report

The remainder of this report is presented in four sections. In the following three sections, a response is given each of the three charges—"Where are we?", "Where are we going?", and "How do we get there?". This is followed by a summary of the report and concluding comments. There are three appendices to this report that contain: a copy of the workforce charge letter (Appendix A), copy of the FESAC letter endorsing this report (Appendix B), and selected comments from the workforce survey forms (Appendix C).

WHERE ARE WE?

Workforce Charge—Part 1: Where are we? Assess the current status of the fusion science, technology, and engineering workforce (e.g., age, skill mix, skill level).

In this section of the report, the Panel presents a summary of its findings regarding the current state of the fusion community in the U.S. Data was gathered from a number of sources ranging from institutional surveys of universities, university-based research laboratories and national and corporate research laboratories to a direct survey of the fusion community using an internet-based survey.

Based upon the results of these surveys, several key findings are obtained about the status of the fusion energy workforce. These are summarized below and are discussed, in detail, throughout this section.

- The U.S. fusion energy workforce is generally dominated by persons that hold the doctorate in physics.
- The U.S. fusion energy workforce is composed primarily of white males with a median age of 50.
- The U.S. fusion workforce is less diverse both in gender and in ethnicity than the overall physics community.
- Approximately 1/3 of the U.S. fusion energy workforce is currently aged 55 or older.
- The fusion faculty is generally older than the rest of the fusion workforce and other physics faculty with 36% above age 60.
- At the major fusion institutions (those with the largest personnel and hardware infrastructure), the fusion faculty is older than the total population of fusion faculty.
- The majority of recent fusion faculty hires (within the last decade) have occurred at institutions that do not have large fusion infrastructures, including several predominantly undergraduate institutions.
- The production of plasma science and engineering doctorates has fallen steadily for over a decade from over 60 Ph.Ds/year in the early 1990s to below 35 Ph.Ds /year in the last two years.

The Panel's response to the first part of the charge is presented in four sections: the demographics of the current U.S. fusion energy workforce, the skills mix of fusion researchers, the production of new fusion researchers, and the paths taken to become a fusion researcher.

The U.S. Fusion Energy Workforce

Through the use of the methodology and classifications defined in "Methodology" and "Definitions and classifications", the Panel proceeded to gather data on the current fusion energy workforce. This section of the report details the data obtained from the WPS.

Educational Level of the Fusion Energy Workforce

The data obtained by the Workforce panel attempted to identify all persons working in technical positions in the fusion energy program. This included persons ranging from electrical engineers with a Bachelor's degree as their highest degree to theoretical plasma physicists working at a Ph.D.-granting university. Overall, the fusion energy community is strongly dominated by persons with Ph.Ds at both the universities and the national laboratories. The national laboratories have approximately 27% non-Ph.Ds working in fusion energy research. Because of the predominance of Ph.Ds in the field, much of the remaining data compares the population of Ph.Ds among the faculty, university researchers and national/corporate laboratory personnel.

Gender and Racial Diversity in the Fusion Energy Workforce

Two areas in which the fusion energy community faces a challenge are in the gender and racial diversity of the field. For context, it is a well-known fact that both the gender and racial diversity of the U.S. physics and engineering communities are considerably lower than the U.S. population.[1] However, in both of these areas, among the population of Ph.D. researchers, the fusion community falls below the population of the remainder of the physics doctorate population. Tables 3 and 4 document the information on gender diversity and racial diversity within the fusion community, respectively.

Table 3 gives a breakdown of male and female Ph.D. researchers in each of the three categories: faculty, university researchers, and national/corporate laboratories. It then gives the overall breakdown of male and female Ph.D. researchers within the survey database. The final line gives the relative population of male and female Ph.Ds within the overall Physics and Astronomy community.

Table 4 follows the same pattern as Table 3, but describes the racial diversity—white vs. non-white population—of the fusion community. It is noted that the total numbers in the two tables are not the same. This is because some persons responding to the survey chose not to provide all of the requested information. Furthermore, it is noted that the institutional surveys did not specifically ask for a breakdown of non-white persons by ethnicity.

However, in the online survey information on race was collected. The categories used in this survey were the same classifications used by the U.S. Government for the Year 2000 Census. Approximately 94% of the respondents to the online survey provided information on race. With the exception of the categories White (89%) and Asian (10%), all other racial categories (American Indian/Alaska Native, Black or African American, and Native Hawaiian or Asian Pacific Islander) have under 1% in each. Those persons identifying themselves as Hispanic (independent of racial category) represented approximately 3.5% of the survey respondents. Again, these percentages are generally consistent with the overall physics and engineering population and are, in fact, slightly lower.

With an aging workforce as noted at the beginning of the Section "where are we?", it is important that the fusion community make every effort to tap into all parts of the population of the United States. Such a change in the demographics of the fusion community is a challenge that faces the entire science and engineering community. In this respect, fusion has the potential to become a leader of the scientific community by developing methods to broaden the diversity of its research community.

Table 3. Distribution of Fusion Ph.D. Personnel by Gender

Gender Diversity	Males # (%)	Females # (%)
National/Corporate Labs[a]	362 (94.3%)	22 (5.7%)
University faculty[a]	106 (97.3%)	3 (2.7%)
University research staff[a]	114 (94.2%)	7 (5.8%)
Fusion total	582 (94.8%)	32 (5.2%)
Physics and astronomy[b]	92.5%	7.5%

[a]WPS.
[b]NSF2001.

Table 4. Distribution of Fusion Ph.D. Personnel by Race

Racial diversity	White (%)	Non-white (%)
National/Corporate Labs[a]	325 (84%)	61 (16%)
University faculty (tenure-track)	75 (86%)	12(14%)
University research staff[a]	104 (86%)	17(14%)
Fusion total	504 (85%)	90 (15%)
Physics and astronomy[b]	81.5%	18.5%

[a]WPS.
[b]NSF2001.

Age Distribution of the Fusion Energy Workforce

Perhaps the single greatest challenge faced by the fusion community is the fact that this community, like many other areas of physics and engineering,

[1]See, for example, "Women, Minorities, and Persons with Disabilities in Science and Engineering: 2002"—NSF 03-312.

has a rapidly aging workforce. Regardless of any other considerations, over the next 10–15 years, this single fact will place considerable stress on the fusion community and will have the greatest impact on the maintenance of the "intellectual capacity" of the field. Furthermore, this trend is not restricted to fusion, but will impact almost all other areas of physics and engineering. Even in the most positive future scenarios, the fusion community will face intense competition from other fields to attract highly qualified and trained personnel to accomplish the important scientific and technical challenges faced by this field.

Table 5 summarizes the mean and median ages of Ph.Ds in the fusion community. The data indicates that among the university faculty, university researchers and national/corporate researchers there is consistency in the average age of fusion researchers. This is even borne out in a comparison of the data obtained from the institutional surveys (WPS) and the online survey (WPO). The average age among the university researchers is noted to be slightly lower than in the other two categories. This is most likely due to the predominance of recent doctoral recipients at universities as compared to national laboratories.[2]

However, when a detailed analysis of the age distribution of the fusion community is performed, just examining the mean or median age is not enough to draw the correct conclusion. Therefore, the Panel sought to compare the distribution of ages among both the university faculty and the research staff to the physics community as a whole.

Fusion Faculty First, consider the fusion faculty as compared to physics faculty. This data is summarized in Figure 1 and Table 6. It is first noted that, as a group, the population of physics faculty is older than the physics population.[3] This can be seen in the skewness in the ages in the physics faculty in Table 6. This skewness is measured by considering the percentage of persons below age 40 with the percentage of persons above age 60. In the total physics population, these two categories contain 21% and 20%, respectively. Among all physics faculty, this shifts to 16% and 32%, respectively, thus indicating that physics faculty are indeed older than the overall physics population. Among the fusion faculty, this measure becomes 17% and 36%, respectively. This suggests that the fusion faculty is slightly older than the population of physics faculty.

In Figure 1, the details of the age distribution of the fusion faculty are presented. Here, the percentage of persons from the fusion faculty, physics faculty, and total physics population are presented for each age category in bins of five years from age 35 to 65. This data shows that for younger faculty, persons below age 35 and persons aged 40–44, the percentage of fusion faculty falls well below the physics faculty. By contrast, in the older age categories 60–64 and over 65, the percentage of fusion faculty is somewhat higher than the physics faculty. Both of these facts point not only to the aging of the fusion faculty, but also strongly suggests that newer faculty have not been hired to replace retirees.

To gain additional insight, the Panel analyzed the faculty at major fusion institutions. Figure 2 shows a comparison of the age distribution of fusion faculty at eight major fusion research institutions compared against all fusion faculty. The age distribution at major institutions is slightly more skewed than the total population of fusion faculty—the percentage of persons below age 40 is 12% (compared to 17% for all fusion faculty) and the percentage of persons above age 60 is 38% (compared to 36% for all fusion faculty). Additionally, well over 1/3 of the fusion faculty at major institutions are between ages 50 and 59. By contrast, the population of all faculty below age 40 at major institutions is less than the population of persons between ages 50 and 54. Thus, over the course of the next 10–15 years, the fusion community could face a drastic reduction in the number of faculty and potentially in the quality of future fusion graduates at its largest and traditionally most pro-

Table 5. Mean and Median Ages of Ph.Ds in the Fusion Community

	Mean age	Median age
University faculty[a]	52.7	53
University researchers[a]	45.1	46
National/corporate labs[a]	48.0	49
Total fusion (WPS)[a]	51.5	50
Total fusion (WPO)[b]	56.1	49

[a]WPS.
[b]WPO.

[2] Source: "Initial Employment Report of 2001 and 2002 Physics Ph.D. Recipients" from the AIP, 68% of physics Ph.D. postdoctoral assignments were at academic institutions while 23% were at government laboratories.

[3] Source: "Enrollments and Faculty in Physics", a presentation given by Roman Czujko, Director of the Statistical Research Center of the AIP, June, 2002—available from the AIP Website.

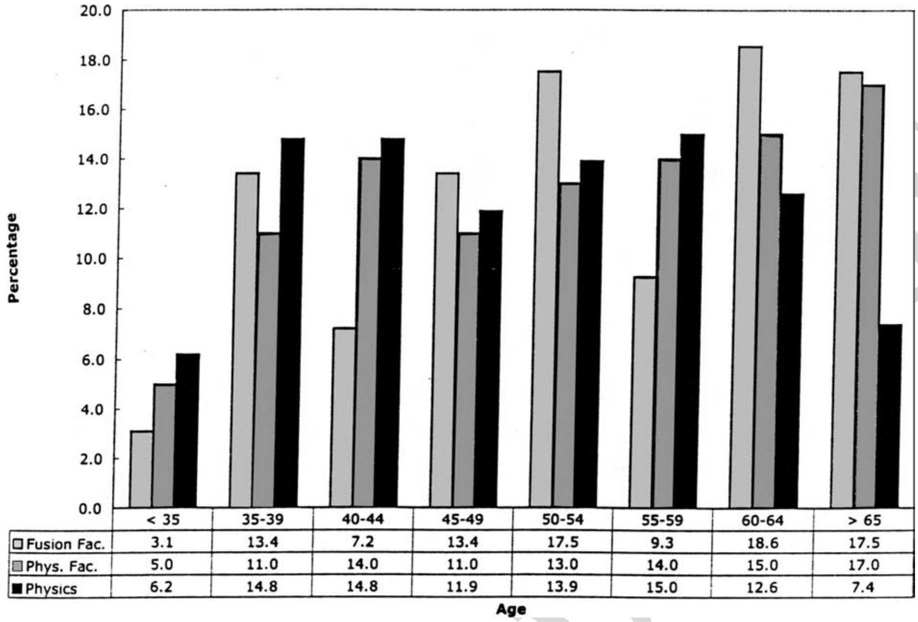

Fig. 1. Age distribution of the fusion faculty compared to the physics faculty[3] and the overall physics population (NSF2001). The data is plotted for age categories from below 35 to over 65 using the format from the NSF and AIP databases. [Source: WPS, UFA]

Table 6. Skewness of the Fusion Faculty data

	Fusion faculty*	Physics faculty**	Physics population**
Percentage below age 40	17	16	27
Percentage above age 60	36	32	18

Source: *WPS/UFA, **NSF

ductive institutions. However, an examination of the data for all of the fusion faculty shows that this trend is not isolated to the major institutions, but will affect the entire fusion faculty and, indeed, the entire physics faculty within the next 5 to 10 years.

Additionally, there is not a clear indication that retiring fusion faculty will be replaced. Presently there are 35 fusion faculty members who are aged 60 and older. When asked about possible new hires over the next 5 years, universities indicated between 15 and 20 hires. However, during those five years another 9 faculty members will enter the over 60 category. This suggests a replacement rate of retiring fusion faculty of less than one and possibly as low as 50%. These losses of the most senior and experienced members of the fusion community will come at a critical moment for the fusion program, a time when a highly trained population of experienced researchers is needed to interpret results from both NIF and ITER.

Finally, the Panel also sought to identify those institutions that have hired new, younger fusion faculty members who are recent Ph.D. recipients. Here, the objective is to identify hiring trends at universities. This data is presented in Table 7. The data is sorted by the year in which the faculty member received his or her Ph.D.—not by year of hire. Additionally, the universities listed are each person's current employer. This table includes a total of twenty Ph.D. recipients from 1991 through 2003. One half of the persons listed (denoted by asterisks) have received the Department of Energy Plasma Physics Junior Faculty Award.

It is clear from the data presented that some of the major institutions (MIT, Princeton, and University of Texas) from Figure 2 are not shown in this table. Furthermore, with the exception of University of Wisconsin (3 hires) and Auburn University (2 hires), all the remaining institutions have had one hire in a fusion-related field. Additionally, the majority of these institutions do not have large-scale fusion infrastructure—in terms of experimental hardware, experience or personnel—and often these newer faculty are the only person, or one of two people, involved in fusion research at their institution.

It is critical for the community to understand there is a substantial number of fusion faculty that are under age 45 who are distributed among many

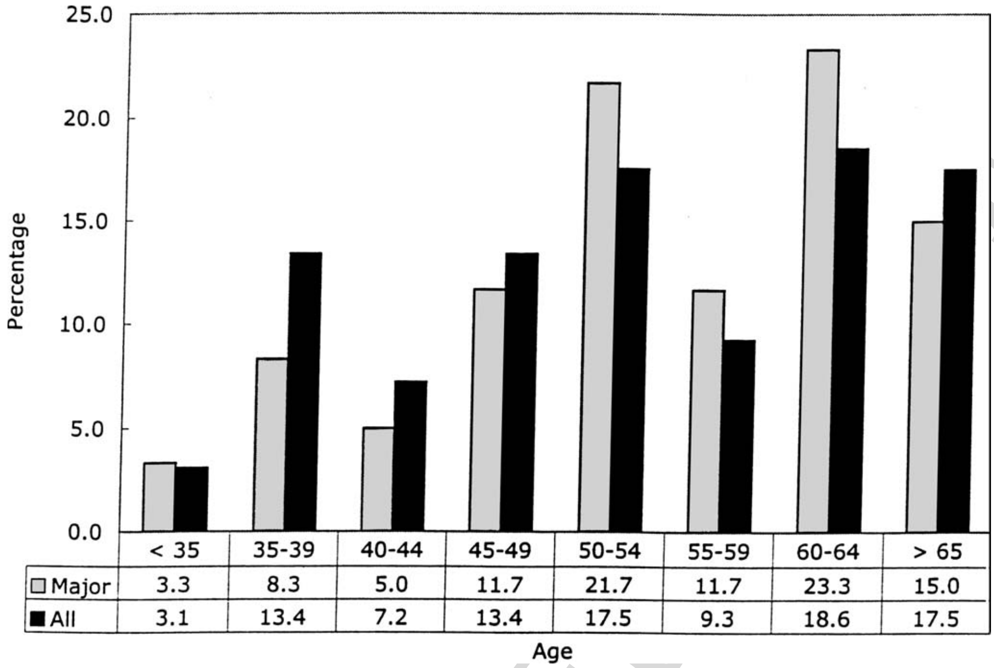

Fig. 2. Age distribution of the fusion faculty at eight major fusion research institutions (Columbia, MIT, Maryland, Princeton, Texas, UCLA, UCSD, and Wisconsin) compared to all fusion faculty. Combined, these eight institutions represent just over one-half (60 out of 109) of the total number of fusion faculty. The data is plotted for age categories from below 35 to over 65 using the format from the NSF and AIP databases. [Source: WPS, UFA]

smaller institutions and who are actively pursing research. Given the aging of the fusion faculty at all institutions, and especially at the major institutions, and the potential that retiring faculty may not be replaced, these younger faculty members represent a valuable, but often overlooked resource for the fusion community. As the fusion community engages in a process of self-assessment and prioritization, all segments of the fusion community should be encouraged to participate in this important process.

Table 7. University Hires of Recent Ph.D. Graduates—Sorted by Year of Ph.D.

University	Year of Ph.D.
UC—Los Angeles[a]	2001
Columbia University[a]	2000
UC—Irvine[a]	1999
University New Mexico	1999
Utah State[a]	1999
Auburn University	1996
University Wisconsin[a]	1995
University Maryland	1993
New Mexico Tech[a]	1993
Auburn University	1992
Hampton University	1992
University Montana[a]	1992
University Nevada-Reno[a]	1992
Southeast Louisiana	1992
University Washington	1992
University Wisconsin	1992
University Wisconsin	1992
West Virginia University[a]	1992
Florida ASan Diego[a]	1991

[a]Recipients of the DOE Plasma Physics Junior Faculty Award. [Sources: WPS, UFA, OFES Website.]

Ph.D. Fusion Researchers Among the fusion researchers at both university (~100 persons) and national/corporate laboratories (~600 persons), there is a somewhat more even age distribution than among the university faculty. Nonetheless, there are indications that over the next 10–15 years, this group will also be facing serious challenges. The distribution of ages among the fusion research population is shown in Figure 3.

As discussed in the Section "Age distribution if the fusion energy workforce," the predominance of the age category under 35 is largely due to the population of recent doctoral degree recipients that work in both laboratory settings. By the following age category, 35–39, much of this large population of younger persons has become dispersed. As in the faculty data, there is a substantial peak in the

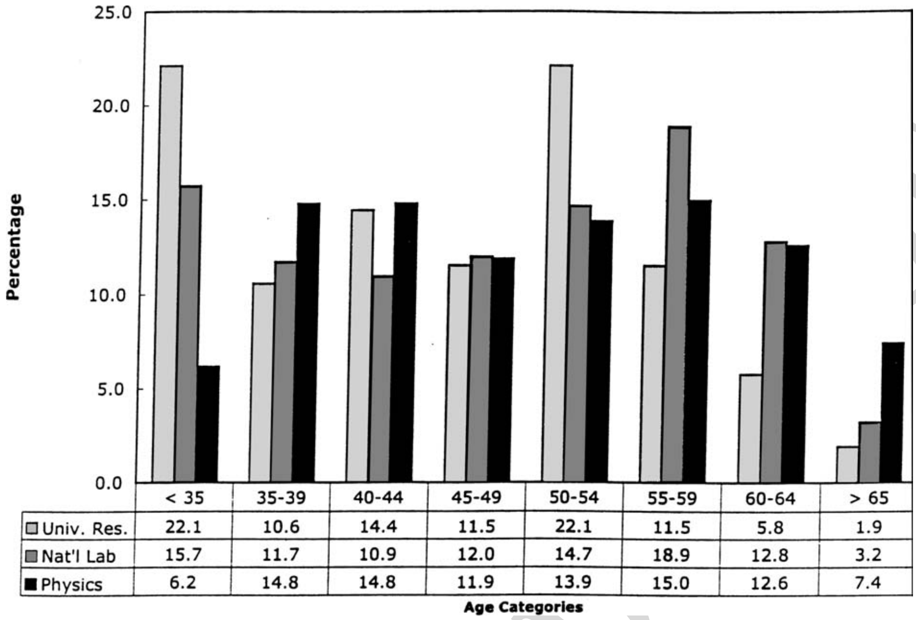

Fig. 3. Age distribution of the fusion research personnel at university and national/corporate laboratories. The data is plotted for age categories from below 35 to over 65 using the format from the NSF and AIP databases. [Source: WPS]

population between ages 50 and 60, although this is not as pronounced as in the faculty data.

Non-Ph.D. Fusion Researchers Up to this point, this report has focused on Ph.D. fusion researchers, however, there is a significant population of trained staff and engineers that have either Bachelor's or Master's degree as their highest level of education. Data on this population was obtained from the national and corporate laboratories since those organizations generally have a much larger technical staff than is present at universities. This section discusses the demographics of the fusion technical staff.

A summary of the age, racial, gender, and degree distribution of the non-Ph.D. technical staff degree recipients is presented in Table 8. The results show many similarities to the fusion Ph.D. population. Like the fusion Ph.D. population, the technical staff is a predominantly white male population although the percentage of women on the technical staff is considerably higher than among the Ph.D. population. The mean and median ages of this technical staff are also comparable to that of the Ph.D. population. The primary contrast between the technical staff and the Ph.D. researchers is that the technical staff is overwhelming dominated (by almost 3:1) by persons with engineering degrees as compared to physics degrees.

Finally, as shown in Figure 4, another important contrast between the technical staff and the Ph.D. researchers is the overall distribution of persons by age. This distribution appears not to have the same skewness as the Ph.D. data and may point to the more fluid nature of the technical staff. In other words, there is not yet a specific definition of a "fusion engineer". The technical staff is composed of persons with a wide range of engineering skills including mechanical, electrical, and nuclear engineering. Therefore, these are persons who bring specific technical skills to the fusion community. The Panel expects that, in general, these persons could be brought into the fusion program without specific training in plasma science. By contrast, the majority

Table 8. Summary of Demographic Information on the Non-Ph.D. Technical Staff in Fusion

		Non-Ph.D. staff # (%)
Age	Mean	45
	Median	48
Race	White	136 (92.5%)
	Non-white	11 (7.5%)
Gender	Male	129 (87.7%)
	Female	18 (12.3%)
Degree	Physics	35 (23.8%)
	Engineering	112 (76.2%)

[Source: WPS]

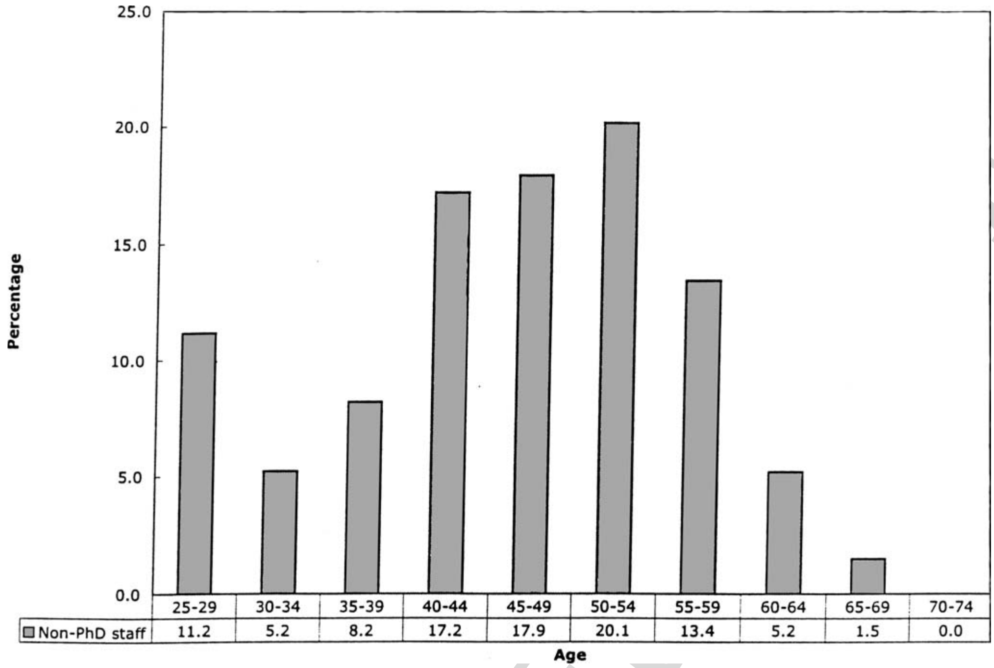

Fig. 4. Age distribution of non-Ph.D. fusion technical staff.

of the Ph.D. researchers who enter the fusion program are expected to have plasma science or engineering training.

Skills Mix of Fusion Researchers

In addition to the number and demographic makeup of fusion researchers, it is also important to know what skills these persons contribute to the profession. This information was collected in part from the online survey and from a separate skills assessment survey distributed by the Panel.

In the online survey, the Panel sought to identify the types of positions held by persons in the U.S. fusion workforce and how those persons classified their work activities. The results of the online survey are summarized in Table 9 and Figure 5, below.

First, in Table 9, the distribution of the fusion workforce by job classification is shown. As indicated in the earlier sections, it is clear that the majority of the fusion workforce is located at university, national, and corporate laboratories. It is also apparent from the number of persons in senior positions (e.g., full professors or senior research scientists) that this reflects the age distribution of the fusion community.

In addition to the data gathered from the online survey, the Panel also collected information from various laboratories and universities to obtain a more detailed picture of the technical skills utilized by different parts of the fusion community. Using the definitions presented in Section "Definition and Classification", these six skills areas are:

- Theory, simulation, and basic plasma science,
- Configuration optimization,
- Burning plasmas,
- Materials science,
- Engineering Science/Technology Development,
- Power Plant Development

As part of this survey, the Panel asked organizations for both the current number of personnel involved in these six areas as well as their projected needs in the short term (up to 18 months) and long term (10 years). In this section of the report, the Panel

Table 9. Distribution of Fusion Workforce by Job Classification

Job Title	Percentage of total workforce
Post-doctoral researcher	5.4
Faculty (non-tenure track)	2.7
Assistant professor	1.5
Associate professor	1.5
Professor	8.1
Professor emeritus	2.1
Research scientist or engineer	36.1
Senior research scientist or engineer	30.1
Program manager / project leader	12.3

[Source: WPO]

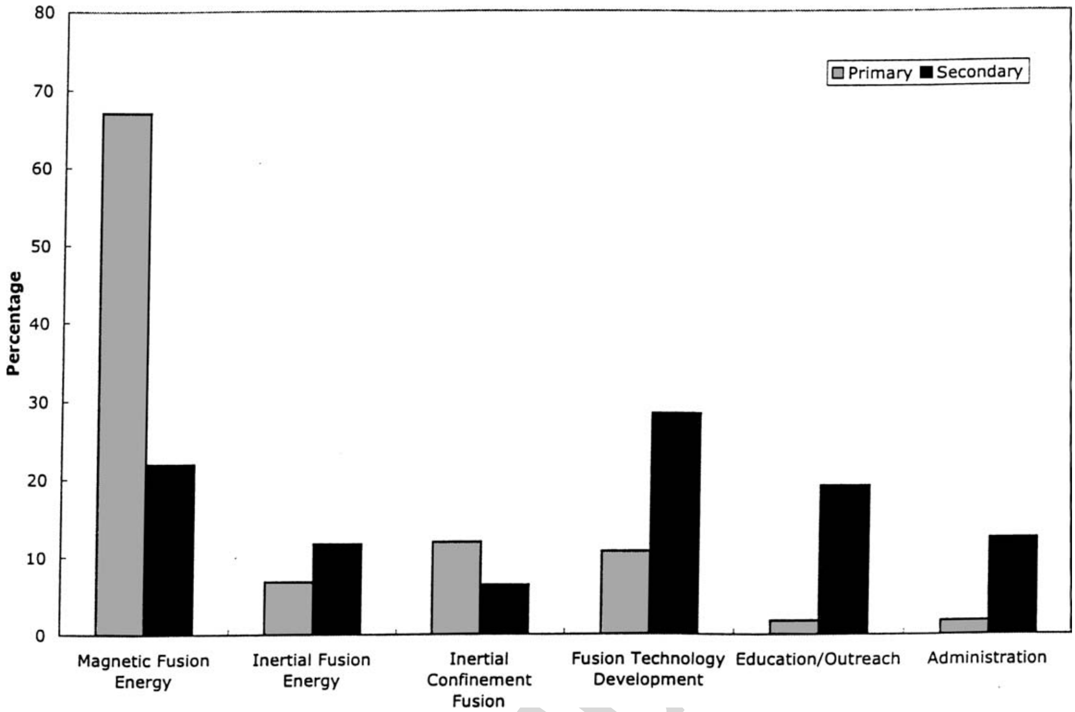

Fig. 5. Distribution of fusion research personnel by primary and secondary work activities. [Source: WPO]

focuses on the current workforce In the Section, "Where are we going?" of this report, the short- and long-term personnel needs will be discussed in greater detail.

In Table 10, the distribution of fusion personnel involved in magnetic fusion energy research at several major fusion research organizations is shown. Here, the Panel attempted to identify both "internal" personnel and "external" personnel that contributed to the research efforts. The data in Table 10 shows that, at present, the fusion community is heavily focused on configuration optimization studies, studies of burning plasmas, and basic plasma science, Additionally, the data shows that the "internal" laboratory personnel (totaling around 400 persons) are heavily leveraged with outside personnel (just under 200 persons).

Production of New Fusion Researchers

So far, this report has focused on the demographics of those persons that are currently in the U.S. fusion energy workforce. At this point, we consider the production of new fusion Ph.D. researchers. As part of the institutional surveys of universities, the Panel obtained data on the current graduate student population. The Panel also sought to identify historical trends in Ph.D. production by comparing its data to various NSF databases.

First, the Panel notes a steady decline in the production of plasma physics Ph.Ds over the past 15 years that is independent of the overall production rate of physics Ph.Ds. This is shown in Figure 6. The curve for physics Ph.Ds shows both periods of increasing (1987–1993) and decreasing (1994–2002) production of Ph.Ds. The corresponding curve for all of plasma physics (including fusion, space, and basic plasma physics) shows a somewhat sporadic behavior in the late 1980s and early 1990s. However, there is a steady decline in Ph.D. production since 1994. It is important to note that among physics Ph.Ds, the total number produced has not exceeded 80 in the past 15 years. Also, the data shows that while the average Ph.D. production rate for the past five years is approximately 45 Ph.Ds/year, for the last three years the production rate has been at or below 40 Ph.Ds/year, Most interestingly, as shown in Figure 7, this long-term decline is student production is strongly correlated to the overall decline in the OFES budget over the same period.

[4] To prevent the over counting of personnel, the "raw" data in this column was reduced by the number in second column in order to obtain the net number of external research participants.

Table 10. Distribution of Fusion Personnel Working in Magnetic Fusion Energy in the Six Skills Area at Major Research Institutions (MIT, PPPL, LLNL, GA, LANL)

	Number of persons from *your institution* who spend > 80% time working on projects at your organization	Number of persons from *your institution* who contribute > 20% time to projects outside of your organization.	Number of persons from *other institutions* who contribute > 20% effort to projects at your organization[4]	Number of persons with temporary positions (e.g., Ph.Ds)	Total
Theory, simulation, basic plasma science	61	8	20	14	103
Configuration optimization	149	61	135	73	418
Burning plasmas	77	18	36	28	159
Materials science	0	0	0	0	0
Engineering science/technology development	27	2	1	0	30
Power plant development	1	0	0	0	1
Total	315	89	192	115	

[Source: WPS]

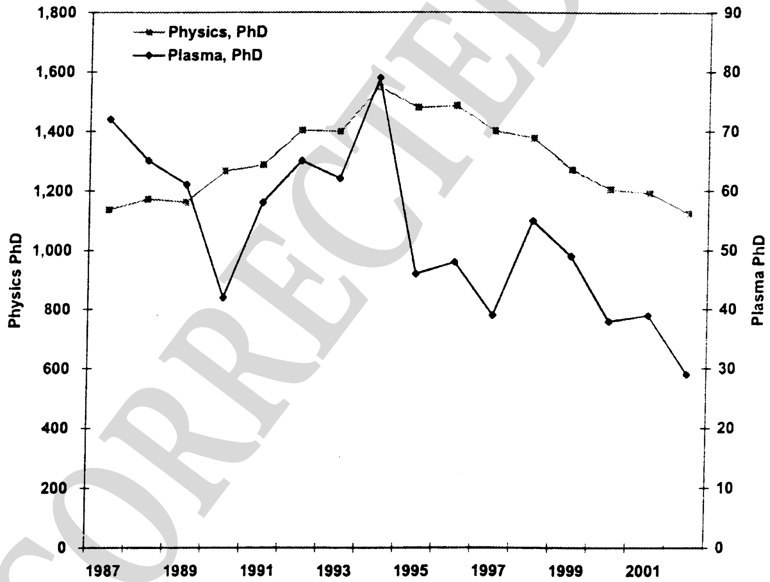

Fig. 6. Total number of graduating physics Ph.Ds as compared to the number of graduating plasma physics Ph.Ds for the period 1987–2002. [Source: "Science and Engineering Doctorate Awards"—NSF: 1998, 2000, 2002]

When examining the Ph.D. student production data in some detail, interesting and potentially disturbing trends are observed. This information is summarized in Table 11. First, from the survey of U.S. universities, there is a population of around 300 graduate students pursuing research in plasma science and engineering. Here, plasma science and engineering is defined as degrees in physics, applied physics or engineering (mechanical, nuclear, electrical, etc.) in which the dissertation topic focused on the plasma state of matter. However, this does not include space plasma or astrophysical plasma research. Of this total number of graduate students, approximately 145 (or roughly 50%) have indicated that they are pursuing fusion-related plasma physics or engineering research. However, it is important to note that the Panel believes that this entire population of plasma science and engineering Ph.Ds—regardless of specific graduate training in fusion—represents the pool of highly trained

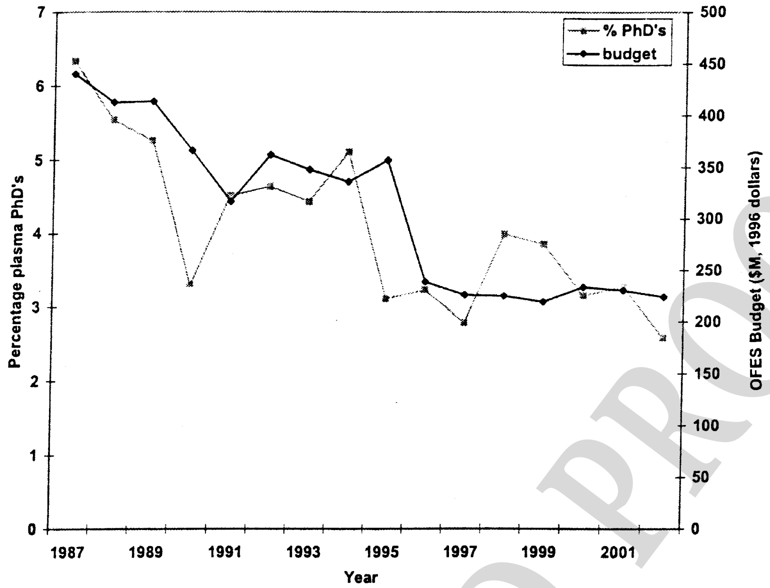

Fig. 7. Percentage of plasma physics Ph.Ds compared to the Office of Fusion Energy Science (OFES) budget for the period 1987–2002. [Source: OFES, "Science and Engineering Doctorate Awards" — NSF: 1998, 2000, 2002]

persons that can be tapped to work in fusion science and the next generation of burning plasma experiments.

The Panel's institutional survey gave an estimate of 200 plasma science and engineering graduates or an average graduation rate over the past five years of 40 new Ph.Ds per year. It is noted that this estimate is generally consistent with an average production rate of plasma physics Ph.Ds of 45 Ph.Ds per year as obtained from the NSF data [see Figure 6].

Of those 200 graduates in the past five years identified by the Panel, the survey data indicates that 30, (15%) took permanent positions in a fusion-related field, another 30, (15%) took post-doctoral positions in a fusion-related field, and an additional 30 (15%) took a position in a non-fusion related plasma science or engineering field. The data suggests that roughly one-half (90 persons) of the recent plasma science and engineering Ph.Ds took positions outside of any area of plasma science and engineering.

Given a 50% "loss" of recent Ph.Ds, an important question is whether or not there is an overproduction of plasma science (and fusion) Ph.Ds. Certainly in an era of shrinking budgets for fusion science—as has occurred for most of the past 15 years—only a limited number of new permanent positions have become available at national laboratories. Simultaneously, those declining budgets have also caused the reduction and termination of fusion experiments at a number of universities. Consequently, there are only a limited number of options for recent graduates who seek to remain within the plasma science and engineering profession.

This loss of 50% of new plasma Ph.Ds therefore should be carefully considered. From one point of view, this loss is a measure of the funding pressure that exists within the fusion program. That is, highly trained students are produced by universities but, upon graduation, there may be no positions for these students. Furthermore, this loss also repre-

Table 11. Current Graduate Student Population in Plasma Science and Engineering

Current number of graduate students pursing any type of plasma science or engineering research	300
Current number of graduate students pursing fusion-related research	145
Graduation rate in plasma science and engineering (1999–2003)	200 (40 Ph.Ds /year)
Percentage of recent Ph.D. graduates obtaining permanent positions in fusion over past 5 years	15%
Number of recent Ph.D. graduates obtaining post-doctoral research positions in fusion over past 5 years	15%
Number of recent Ph.D. graduates obtaining a position in non-fusion plasma science or engineering	15%

sents a drain on the intellectual capacity and continuity of the field. By contrast, the unemployment rate among new physics Ph.Ds in recent years has been typically under 3% within 3 months of graduation.[5] Therefore, it is likely that persons who, either by choice or circumstance, leave plasma science and engineering, will find employment. Finally, as a measure of quality, it may be desirable for the field to have a high "loss rate." This ensures that the best, brightest, and most enthusiastic of the new plasma science and engineering doctorates enter professional careers in the field.

To conclude this section, the Panel considered data collected from current students as part of the online survey. Here, 49 graduate students (15% of the 300 identified graduate students) responded to the survey. While this is a not a large sample size, the Panel believes it is sufficient to gauge some of the attitudes of the current plasma science and engineering graduate population. In particular, the Panel was interested in their perception of possible career paths and employment opportunities in plasma science and fusion.

In Table 12, data is presented on the perception among current graduate students of finding permanent employment in fusion science or fusion engineering related fields. It is observed that there is almost an even split among those graduate students who believe there are very good to excellent opportunities and those who believe there are poor or very poor opportunities.

This result is borne out when the students were asked to comment on their possible career paths, as indicated in Table 13. Students were asked to state the likelihood that they would pursue a career in fusion science or engineering or in some other area of plasma science or engineering, The clearest result is that current graduate students are undecided about what career paths they may eventually pursue. It is also of interest to note that only about 1/3 of the respondents to either question definitively stated that they would pursue a career in either fusion or plasma science and engineering.

Table 12. Perception of Current Graduate Students of Finding Permanent Employment Opportunities in Fusion Science or Engineering

	Employment Prospects (#)
Excellent	5
Very good	8
Good	20
Poor	11
Very poor	5

[Source: WPO]

Table 13. Possible Career Choices of Current Graduate Students—Would Students Choose to pursue a Career in These Areas?

	Fusion science or engineering (#)	Plasma science or engineering (#)
Yes	18	16
No	6	14
Undecided	24	19

[Source: WPO]

The Path to Becoming Fusion Energy Researcher

In this final section, we discuss the influences that led persons to pursue careers in fusion energy sciences and engineering. This data was gathered as part of the online survey [Source: WPO]. The Panel's motivation behind this portion of its survey was to identify those factors that have lead the current members of the U.S. fusion workforce to pursue this career and to help guide the recommendations that will be presented by the Panel in "Conclusion" Section.

Three key questions were raised by the Panel (summarized in Figures 8—10):

1. When did persons first learn about fusion? [Figure 8]
2. Where did persons first learn about fusion? [Figure 9]
3. What were the key influences that led persons to pursue fusion? [Figure 10]

In addressing Question 1, it is clear that the vast majority of persons first learned about fusion energy at the university level as shown in Figure 8. This then strongly corresponds to the response to Question 2 in that the vast majority of persons stated that they first learned about fusion at school. This is shown in Figure 9. However, books and popular science journals are indicated as other sources where persons first learned about fusion. This suggests that expanded steps could be taken to introduce the concepts of fusion science and engineering earlier in the educational process.

[5] Source: "Initial Employment Report: Physics and Astronomy Degree Recipients of 2000 and 2001"—American Institute of Physics.

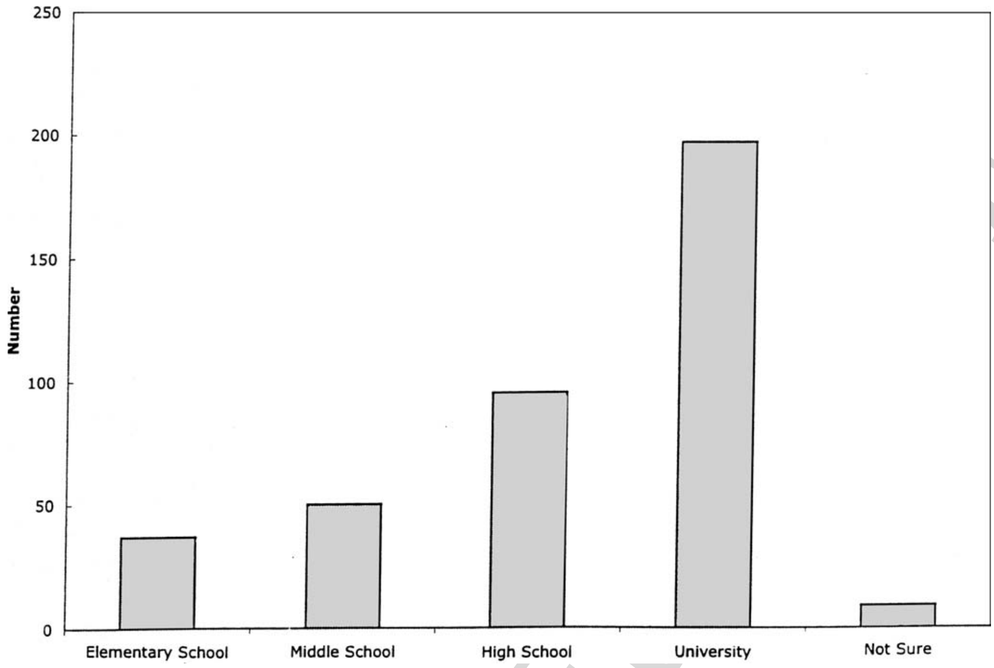

Fig. 8. When did persons first learned about fusion energy.

It is noted that in the comments made by some of the current students and post-docs who participated in the survey that the internet also plays an important role in educating students about fusion. This was one source that was not directly examined by the Panel. (It is interesting to note that even with several panel members younger than age 40, and two members 35 or younger, our perspective of the field can be very different from the younger members of the fusion community. In a research community whose popula-

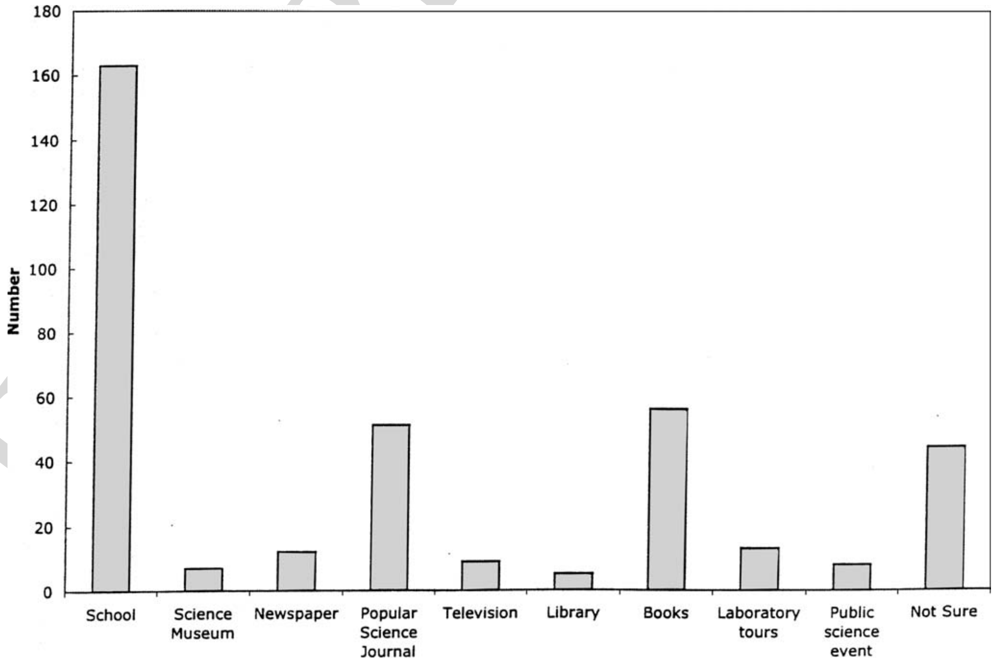

Fig. 9. Information source where persons first learned about fusion energy.

tion is dominated by persons above aged 50 or above, this is an extremely important fact that should be carefully considered when decisions about the future direction of field are under discussion).

Finally, the key influences on an individual's decisions to pursue a career in fusion science is shown in Figure 10. It is interesting and reassuring to note that the two dominant reasons for persons to pursue fusion as a career have been the intellectual challenge presented by the field and its long-term energy mission to create a new global energy source.

While these two influences point to the lofty goals of the fusion community, it is very important to note the role that university faculty and the university research staff can play in influencing persons to pursue careers in fusion. This is where direct actions by the fusion faculty can strongly influence the future workforce. This points to the importance of maintaining a strong and diverse university faculty in order to maintain the pipeline of qualified persons who pursue careers in fusion.

Summary

In summary, the U.S. fusion energy workforce reflects the characteristics of the larger U.S. physics workforce. It is a predominantly white male workforce with a median age of 50, but it is slightly older and generally less diverse in gender and race than the overall population of physics doctorates. Moreover, the production of new plasma science and engineering Ph.Ds has been in decline for over a decade leading to a production rate of approximately 35 Ph.Ds/year over last two years. However, the Panel firmly believes that fusion community should view this an opportunity to take on an important leadership role in the scientific community by developing innovative solutions to address the demographic challenges that will be faced by most of the U.S. physics and engineering workforce over the next decade.

WHERE ARE WE GOING?

Workforce Charge - Part 2: "Where are we going? Determine the workforce that will be needed and when it will be needed in order to ensure that the U.S. is an effective partner in ITER and to enable the U.S. to successfully carry out the fusion program."

If "where we are" is some indication of the current state of affairs, then "where we are going" is an indication of its derivative. In the following section, the panel discusses the needs for the fusion program in the short term (3 years) and in the long term (10 years). As in the Section "Where are we," these projections are based upon our analysis of surveys and comments from the community at large.

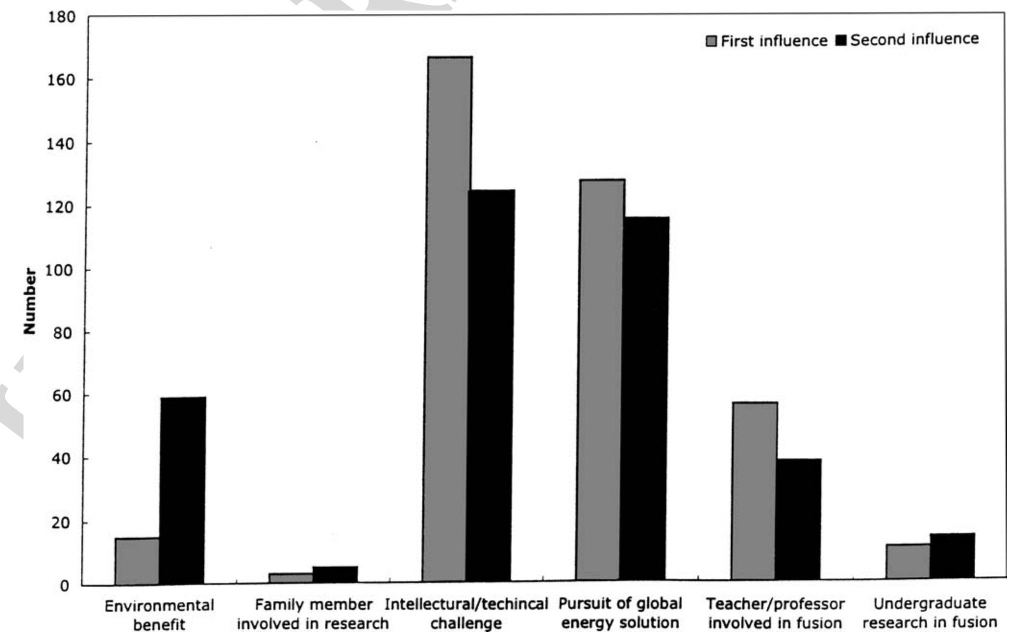

Fig. 10. Primary and secondary influences that lead persons to pursue careers in fusion energy.

Based upon the data gathered, there are three major factors that will influence the future needs of the fusion workforce. First is the participation in ITER and NIF, the two currently planned burning plasma experiments. Clearly, these two large projects will place a significant demand on both the financial and technical resources of the fusion community. Second, are the relative roles played by fusion science and basic plasma science in shaping the near-term and long-term future of the community. These determine the scientific direction of the field and strongly influence the long-term career opportunities for persons in the field. And third, and perhaps most importantly, the fusion energy budget. All three of these areas are strongly coupled and wield significant influence on the workforce requirements for the fusion program. This coupling can be observed in both the outflow of persons from the field at the end of their careers and, more critically, the inflow of persons at the beginning of their careers.

In the end, we are a disparate community driven by at least three missions: basic plasma science, fusion energy science, and a burning plasma goal. The workforce for the future will have to be tuned to meet these sometimes disparate needs. If we were only interested in a burning plasma or only in basic plasma science, we would have very different workforce needs (and very different budgets).

The Panel finds three major concerns regarding the direction we are going. The Panel recommendations for addressing these concerns are presented in part 3: "How do we get there?."

1. *Short term needs* (*up to 3 years from the present*): Results of the workforce surveys indicated that in the short term, persons will likely be redirected from their current activities to begin making contributions to burning plasma research activities. It is assumed that positions created by retirements would be replaced.
2. *Long term needs* (*up to 10 years from the present*): Results of our workforce survey indicate that in 10 years our workforce will need to increase from 1000 to 1250 in order to fulfill our burning plasma mission (ITER and NIF) while keeping the base program intact, This represents a 20–25% increase in the total number of both the magnetic fusion *and* inertial fusion personnel. This growth would start approximately 4 or 5 years from the present at a rate of up to 35 plasma science and engineering Ph.Ds per year and an additional 20 technically trained persons per year.
3. *Undergraduate recruitment*: The fresh plasma Ph.Ds of 2014 are the freshmen of 2004. We need to make an effort to recruit/enthuse/inspire young people *today* so that they choose plasma physics and fusion energy science as a career.

The Future U.S. Fusion Workforce

The U.S. fusion program, in both MFE and ICF/IFE is about to embark on the next logical step in the development of fusion energy, the construction of "burning plasma experiments." These are the international ITER project for MFE and the NIF project for ICF, with direct relevance to IFE, To determine the workforce requirements for the fusion program, the Panel conducted a second round of surveys of the fusion community.

In this survey, the Panel asked major university laboratories and the national/corporate laboratories to make projections of their workforce requirements (number of persons) and the skill areas needed by those persons. In these surveys, the respondents were asked to project both short-term and long-term personnel needs for their programs under the assumption of "successful U.S. participation in a domestic fusion program that includes a burning plasma component in the context of the 35 year development path endorsed by FESAC."[6] Based upon these responses, the Panel has developed a projection for the workforce needs and a possible skill mix of the fusion energy workforce over the course of the next decade.

The Panel reiterates that this is a projection that is based upon the reported needs of the fusion community The Panel has developed what it believes to be a conservative projection for the future fusion energy workforce. This projection assumes full participation in burning plasma experiments (ITER and NIF) while maintaining the basic programs that underlie them (i.e., allowing the basic science programs to remain at their present level of activity). In its deliberations, the Panel has attempted to separate questions of funding profiles from the questions of the size and diversity of the

[6] This is text from the "Skills Survey". A copy of this survey form may be found in Appendix D of this report.

workforce, while recognizing that these are not independent quantities. The results presented here will be constrained by the conditions noted above. Changes in the budget profiles or the needs of the burning plasma experiments or basic science programs will, obviously, modify the workforce needs.

In the "Skills Survey", the respondents were asked to provide information on the six research and technical areas required for the successful participation in burning plasma experiments (ref. Section "Definitions and Classification"). The reader is reminded that these areas are:

- Theory, simulation, and basic plasma science
- Configuration optimization
- Burning plasmas
- Materials science
- Engineering Science / Technology Development
- Power Plant Development

The data presented in the following two sections ("Short term needs: Present to Three years" and "Long term needs: 10 years") represent a summary of the responses for both the short-term and long-term needs of the fusion community. Here, the projections are made for the national and corporate laboratories (here, the MIT Alcator C-mod project is included) since most of the responses were from those organizations, However, since those organizations currently employ over 70% of the current U.S. fusion energy workforce, the Panel believes that these results give a good indication of the future state of the U.S. fusion energy community. Although all of the national laboratories did not respond to the survey, those that did respond are among the four largest employers (MIT, PPPL, General Atomics, and LLNL—representing over 50% of the total workforce) in the fusion community. It is further noted that the vast majority of the responses came from organizations within the MFE community while only limited data was received from the IFE/ICF communities. While the two parts of the community indicated generally similar needs, there are larger error bars on the IFE/ICF data ($\pm 12\%$) as compared to the MFE data ($\pm 4\%$).

Short Term Needs: Present to 3 Years

In the short term, defined as a period from the present to three years from now, there is no clearly defined need for an additional number of persons in the fusion community. The respondents to the skills survey suggested that a redirection of current personnel—primarily from configuration optimization studies to burning plasma studies would be sufficient to maintain their current programs while meeting the demands of an expanding burning plasma component. Table 4, below, indicates the overall changes in personnel from the six different skill areas over the next three years for the MFE community. As noted above, the data for the IFE/ICF community has much larger error bars, but the overall picture is the same—there is essentially zero growth expected in terms of the total number of persons required. These results indicate that any persons that retire would be replaced in order to keep the total number of persons constant. This redirection of personnel in the short term clearly has consequences on hiring and student production. This will be discussed in Section "Demand for fusion scientists."

Long Term needs: 10 years

In the long term, defined as a period that ends 10 years from now (2014), the landscape for fusion energy research will potentially look very different from today. During that period, the NIF device is expected to become fully-operational. In the 2014 to 2015 time period, the ITER device should be approaching first plasma operations.[7] During that same period of time, almost 1/3 of the Ph.D.-level researchers (200 persons) at the national and corporate laboratories will reach retirement age (65 years or older). Additionally, up to 40 persons of the non-Ph.D. technical staff will also reach retirement age during that, period. For comparison, among the university faculty and university researchers, those percentages will be 45% and 19%, respectively (refer to Figures 1 and 2). With this information, the Panel has made a projection of the workforce requirements for the fusion community over the next decade.

According to the information provided to the Panel, a substantial realignment of the work activities within the U.S. fusion energy science program is expected. This is summarized in Table 15 (MFE)

[7] Dates are based on information provided at the ITER website (www.iter.org). If ITER device is approved in 2004, the projected date for the start of construction would be 2006. According to the ITER schedule, ITER systems testing and integration would begin 66 to 72 months after the construction start date. A target date for first plasma would be approximately 96 months after the construction start date.

Table 14. Projected Percentage Change of MFE Fusion Personnel in the Six Fusion Skill Areas Over the Next three Years.

	Number of persons from your institution who spend > 80% time working on projects at your organization#(%)	Number of persons from your institution who contribute > 20% time to projects outside of your organization #(%)	Number of persons from other institutions who contribute > 20% effort to projects at your organization #(%)	Number of persons with temporary positions (e.g., post-docs) #(%)
Theory, simulation, basic plasma science	−0.25	0.00	0.00	0.00
Configuration optimization	−3.62	−1.37	−6.36	−2.62
Burning plasmas	3.74	1.37	6.36	2.87
Materials science	0.00	0.00	0.00	0.00
Engineering science/technology development	0.12	0.00	0.00	0.00
Power plant development	0.00	0.00	0.00	0.00
Total change	0.00	0.00	0.00	0.25

The Data Indicates That There will most Likely be a Reorganization of Personnel with No Significant Growth in the Total Number.

and Table 6 (ICF/IFE). What is immediately noticeable is strong realignment of personnel from configuration optimization to direct studies of burning plasma phenomena. Another major change in personnel is the projected growth of the engineering science / technology development areas. There is also a small projected growth in the number of personnel working in basic plasma science.

In total (MFE and ICF/IFE combined) the laboratories are projecting a growth in their own staff by roughly 150 persons above their current number of personnel over the course of the next decade. Additionally, these laboratories are also forecasting an increased demand for external personnel and temporary positions of another 100 persons. This would suggest a net increase in the total population of fusion researchers by as many as 250 persons or 25% above the current number of fusion researchers.

However, the total numbers presented in Tables 15 and 16 do not present the complete picture. It is necessary to incorporate potential retirements as well as the mix of new hires in order to determine the workforce requirements for the next decade. The Panel assumes that only 50% of the total number of persons eligible for retirement (100 Ph.D.-level staff and 20 non-Ph.D. staff) actually retire, and that the retirement rate is constant over the next ten years (i.e., 12 retirements/year). When this information is combined with the growth projections above, it is possible to develop a more complete projection of the future workforce.

Table 17 summarizes the total number of new persons that are needed to satisfy the workforce requirements of fusion community between years 4 and 10 of this projection. Personnel are grouped according to their area of technical training; i.e., plasma science and engineering Ph.Ds vs. non-plasma trained technical persons. According to this data, over 350 positions will need to be filled or created. It is noted that this is a *lower bound* since not all of the national and corporate laboratories reported their personnel projections to the panel and university faculty are not included in this analysis. Thus, the number of needed positions could possibly exceed 400.

What is particularly important to note in Table 17 is that roughly 100 of these positions may be filled by persons that are not specifically trained in plasma science and engineering. Indeed, in the areas of engineering science/technology development or materials science, persons with educational backgrounds outside of plasma science and fusion have, and will continue to make, significant and important contributions to the fusion energy workforce.

However, in areas such as basic plasma science and theory or burning plasmas, the Panel believes that in order to maintain the highest scientific quality of the fusion program, the vast majority of these persons should be trained in some area of plasma science and engineering. As the fusion community begins investigations of burning plasma phenomena, highly trained personnel with a very good understanding of plasma physics will be required.

Table 15. Projected Changes of the Number of Fusion Personnel Working in MFE by Six Skill Areas at Major Research Institutions (MIT, PPPL, LLNL, GA, LANL) Over the Next Decade. Persons are Grouped by Four Categories as Shown Below.

	Number of persons from *your institution* who spend >80% time working on projects at your organization	Number of persons from *your institution* who contribute >20% time to projects outside of your organization.	Number of persons from *other institutions* who contribute >20% effort to projects at your organization	Number of persons with temporary positions (e.g., post-docs)
Theory, simulation, basic plasma science	12	3	3	6
Configuration optimization	−21	−10	−31	−20
Burning plasmas	60	24	67	48
Materials science	1	0	0	0
Engineering science/technology development	32	1	11	0
Power plant development	0	0	0	0
Net change	84	18	50	34

[Source: WPS]

Table 16. Projected Changes of the Number of Fusion Personnel Working in ICF/IFE by Six Skill Areas at Major Research Institutions (MIT, PPPL, LLNL, GA, LANL) Over the Next Decade

	Number of persons from *your institution* who spend >80% time working on organization	Number of persons from *your institution* who contribute >20% time to projects outside of your organization.	Number of persons from *other institutions* who contribute >20% effort to projects at your organization	Number of persons with temporary positions (e.g., post-docs)
Theory, simulation, basic plasma science	18	0	4	4
Configuration optimization	0	0	0	0
Burning plasmas	1	1	0	2
Materials science	5	0	2	3
Engineering science/technology development	45	0	0	3
Power plant development	1	0	0	0
Net change	70	1	6	12

[Source: WPS]

However, the increasingly specialized nature of fusion science parallels that of other areas of physics and the ability to cross from one field to another—especially for mid-career persons—can be difficult. Thus, the only way to truly ensure that sufficient numbers of personnel are available is to carry out a vigorous program of recruitment and training to ensure the best and brightest students are attracted to fusion science.

Demand for Fusion Scientists

In the previous section, we have identified the number of persons that are needed to maintain the U.S. fusion energy program over the course of the next decade. We now focus on what steps are required to ensure that these persons are brought into the fusion community.

Table 17. Projected Increases of the Number of Fusion Personnel (Both MFE and ICF/IFE Combined) at Major Fusion Research Institutions (MIT, PPPL, LLNL, GA, LANL) Among the Scientific and Engineering Staffs Over the Next Decade

	Plasma Ph.D.s[a]	Technical and Engineering Staff[b]	Total
Replacing projected retirements	70	14	84
Permanent staff ICF/IFE	20	50	70
Permanent staff MFE	65	35	100
Additional post-docs	45	0	45
Outside participants	50	11	61
Total	250	110	360

[Source: WPS]

[a] Includes plasma physics and engineering Ph.Ds. This includes persons identified in the burning plasma, basic & theory, and configuration optimization categories.

[b] Includes persons in the engineering, material science, and power plant development categories.

Based upon the numbers in Table 17, from year 4 to 10, the *average* rate of hiring should be approximately 42 persons/year in order to have the additional 250 plasma trained Ph.Ds in the program by year 10. The reader is reminded (Figures 6, 7 and Table 11) that although the *average production* of plasma science and engineering Ph.Ds over the last five years is estimated at 40/year, the *absolute production* rate has fallen from 60/year to around 30/year during that 5-year period.

If the recent attrition rate of plasma science and engineering Ph.Ds of 50% remains, the current production rate of 30 Ph.Ds/year is a sufficient number to cover vacant positions created by retirements at both the laboratories and universities over the next three years. If the fusion energy workforce is to expand in a manner similar to that suggested by Tables 15 and 16 and assuming a 50% attrition rate of new Ph.Ds, an increase of the total number of plasma science and engineering Ph.D. graduates to no less than 80 Ph.Ds/year will be required by the year 2008. In order to have a passionate, trained workforce in the future, we need a stable and growing program of student training now.

The question of overproduction or underproduction of new Ph.Ds is one that often dominates the discussion of workforce needs. The Panel firmly believes that some level of overproduction is absolutely essential to ensure that the most highly qualified and enthusiastic persons are brought into permanent positions with the field. Indeed, in every healthy, established area of physics (e.g., nuclear, atomic, condensed matter, etc.)—that is an area with a significant body of accumulated specialized knowledge—Ph.D. production exceeds demand within the area.

The health and vigor of the intellectual enterprise depends on competition at every level of the career chain. For example, although major research universities will compete for Nobel laureates, they would not hire junior faculty without a highly competitive pool of applicants. The vaunted mobility of physics Ph.Ds, most of whom are not working in the area of their doctorate after five years, is nevertheless a highly asymmetric process. The mobility is strictly in the direction of new and unconventional fields. By contrast, nearly everyone in an established field like high energy physics was trained in high energy physics.

If fusion were to become heavily dependent on students trained in other areas, the field would incur a handicap in the progress of the field. That assumes that the requisite education could somehow be provided at this stage and ignores that fact that employers at that level are unlikely to encourage the breadth of education required of graduate students. In no case would we be competitive internationally.

In order to ensure those numbers of graduating plasma science and engineering Ph.Ds, it is extremely important that there are educational institutions that can provide the necessary training for these students. However, as illustrated in Figures 2 and Table 7, the fusion faculty at the "major" fusion institutions (those that have significant funding, personnel, and existing hardware) have *both* the oldest persons in the fusion community and the fewest number of recent hires. Additionally, as discussed in the depth in the Section, "Fusion faculty," these institutions also have indicated that they may not replace faculty positions in plasma science (i.e., a plasma/fusion position may be converted to another field). Thus, the community must turn to those universities—both large and small—that are demonstrating a commitment to fusion science through recent hires, institutional investment in infrastructure, and student productivity to ensure the production of adequate numbers of trained fusion scientists.

It must be cautioned that new faculty hires also have a time constant (as much as six to eight years) before they begin producing new Ph.Ds for the community. Thus, the critical time window for hiring new faculty members to meet the projected demands of the fusion program in eight to ten years is *now*. Delays of three to five years before beginning a new phase of faculty hiring in plasma physics and engineering could cause serious disruptions in the competitiveness of the U.S. fusion energy program.

Supply of Fusion Scientists

Finally, it is clear that the future of fusion energy is in the hands and minds of our students. It is absolutely vital to educate undergraduate physics and engineering majors about fusion and plasma science now since the plasma Ph.Ds of 2010–2014 will come from the current undergraduate student population. We need to make an effort to recruit and enthuse our young people now or else we will loose them to other fields. This is best exemplified by one of the respondents to the Panel's online survey,

> Only rarely are undergrads exposed to fusion, and most of the time, if a student does become involved in fusion at the graduate level, it is because the student happens to be attending a school with an active graduate research program. Nearly every other federally funded physical science research program has embraced undergraduate research as a vital and essential part of the sustained growth of their field, but for some reason, fusion has not caught on.

As noted in Figures 8–10 in the Section "The Path to becoming fusion energy researcher," most persons indicated that they first learned of fusion energy in their undergraduate institution. Additionally, many persons indicated that the while fusion's energy and science goals were strong influences on their decision to pursue careers in fusion, another strong indicator was the influence of a faculty member. Therefore, strong support of university fusion scientists—both on the faculty and at university laboratories—can play a very important role in enhancing the fusion workforce pipeline.

Additionally, the APS Division of Plasma Physics (APS-DPP) and the DOE have several programs to promote interest in plasma physics and fusion especially among undergraduates. The APS-DPP holds a special undergraduate poster session at their annual meeting complete with awards for the best presenters. There were over 40 undergraduate participants at the 2003 meeting. The APS-DPP also fields a slate of "Distinguished Lecturers" who are available to physics departments around the U.S. who are interested in a plasma physics colloquium. The DOE supports the National Undergraduate Fellowship program to expose undergraduates to plasma physics and fusion research over a summer. The DOE Plasma Physics Junior Faculty program has supported several young faculty members at primarily undergraduate institutions.

The DOE also supports strong K-12 educational outreach programs operated by its major laboratories at General Atomics, MIT, and PPPL. These programs and, those at other universities, collectively reach thousands of high school students each year by providing facility tours, educational materials, and in-classroom demonstrations, and exhibitions at area workshops and fairs. Furthermore, plasma physics and fusion educational materials are provided to about 1000 high school teachers each year. The national outreach teams from these institutions organize and present a Teacher's Day and Plasma Expos at the APS-DPP meeting, reaching approximately 100 teachers and 2500 students annually. In addition, Fusion and Plasma Outreach materials are widely distributed internationally in response to requests on fusion education webpages at the various facilities.

However, much more could be done to promote plasma physics and fusion science. Although the DOE generally does not provide direct support for educational programs in the same manner as other federal agencies (e.g., the NSF), much can be done within the DOE structure to support and enhance fusion-relevant undergraduate research opportunities. Furthermore, plasma physics is not represented in physics departments as widely as condensed matter or high energy physics. Physics majors at many institutions can spend 4 years without taking a plasma physics course, or even meeting with a plasma physicist. Once students are in graduate programs in plasma physics, they certainly receive world-class training in most programs.

However, the panel also recognizes that in order to achieve the long-term goals of the fusion program, it is necessary to have students train on fusion devices. Presently, the number of graduate students doing thesis research on major MFE and IFE fusion devices, especially at the national and corporate laboratories, is nearly zero. A survey of major facilities suggests that perhaps 20 graduate students work on Z (Sandia). The DIII-D (General Atomics) project and NSTX (Princeton Plasma Physics Laboratory) project each report fewer than five graduate students. By contrast, there are 24 graduate students working on Alcator C-Mod (MIT), 13 graduate students at the Madison Symmetric Torus (MST, University of Wisconsin) and approximately 50 graduate students at OMEGA (University of Rochester).[8] The Panel notes that the larger number of students at OMEGA reflects both a mandate by DOE to dedicate 15% of run-time to student projects and a strong educational outreach program that ranges from high school students to graduate students. The Panel believes that the OMEGA approach can serve as a successful model for the fusion community.

In the final analysis, the best way to encourage students to pursue a career in fusion is to demonstrate that the field is one that provides intellectual challenges, well-defined goals and objectives, clear vision and leadership, and long-term career stability. One of our survey respondents sums up the challenge faced when discussing the future of fusion with students:

> As someone who works closely with graduate students, I always feel torn discussing the future of fusion. It is an exciting field with many open problems and with huge potential impact for both science and energy. However, funding is such a forefront issue that I feel to be honest I need to caution potential researchers that they may experience a good deal of volatility in future years... I think this may become an issue for getting the best students into fusion worldwide. As such, the U.S. is in *a* good position provided we maintain our diversity.

[8] Data obtained by direct queries of panel members to the laboratories indicated.

Summary

The U.S. fusion energy program is at a critical juncture. It is difficult to discern a single distinct direction for the future. On the one hand, we are moving forward with our energy mission as participants in ITER, while on the other, we are still a distinctly science-based program. We need to establish and commit to a multi-tiered set of goals. We have done this as a community already by establishing a "three leg" strategy for fusion: plasma science (base program), fusion science (innovation/technology), energy as an international partner.[9] This will mean that different aspects of the fusion program will have different goals and different directions. In the end, the answer to the question, "Where are we going?" depends on who you ask. Workforce members directly involved in ITER will focus on fusion energy as part of an international collaboration. Workforce members in the base program (perhaps working on an innovative confinement concept) will focus on concept exploration. Basic science and concept exploration provides a path for new discoveries and tends to be the part of the program that excites students (undergraduates and graduate students alike). The OFES must actively participate in balancing the three legs of the fusion program to ensure that all aspects of the program—science, technology and energy are advanced in the era of burning plasma studies.

HOW DO WE GET THERE?

Workforce Charge - Part 3: How do we get there? Provide suggestions for ensuring a qualified, diversified, and sufficiently large workforce and a pipeline to maintain that workforce. The suggestions should be things that are reasonable and within the control of the Office of Science.

The current U.S. plans for development of fusion energy through magnetic confinement are presently guided by long-term strategies derived from a broad consensus arrived at by the fusion

[9] From the FEAC (predecessor to FESAC) report entitled, "A Restructured Fusion Energy Sciences Program", January, 1996. "The FEAC recommends, in no priority order, three policy goals: advance plasma science in pursuit of national science and technology goals; develop fusion science, technology and plasma containment innovations as the central theme of the domestic program; and pursue fusion energy science and technology as a partner in the international effort."

community. The nearer term goal has as its centerpiece the participation in the ITER project. This activity is estimated to peak within 10 years (at the start of machine operation) and should continue for yet another decade. On the 35-year horizon, the anticipation is that a magnetic fusion device should begin to make headway as a test component in the U.S. electrical grid. Given this perspective together with the fact that the U.S. is not making plans to build and operate a magnetic fusion burning plasma device in the foreseeable future places a tremendous emphasis on the health and stability of the entire fusion workforce.

The challenge faced by OFES is how to maintain the required number of the highest quality of scientists and engineers engaged in fusion research over these long time scales. While a simplistic view might lead to the conclusion that by supplying sufficient financial resources at moments of crisis the perceived workforce problems can be solved, it is the opinion of the Panel that such an approach is not appropriate in this case. There are many exciting and challenging new fields developing that will attract the attention of the brightest and youngest persons. Fusion research must compete for their attention both at the intellectual and practical level. Persons considering a long-term fusion career must perceive that they can make important technical contributions at the cutting edge of their specialty while maintaining a modicum of financial security to meet their personal commitments.

From the data in the previous sections, it is clear that the need for qualified staff to support ITER and NIF is at a critical junction. The current student production is clearly sufficient for the short term—under the assumption that all vacated due to retirement are immediately filled. The data also suggests that if the fusion program grows in a manner consistent with the projections made by the community as part of this report, the current level of student production over the next 4–10 years will not be capable of supporting the needs of the fusion community. Therefore, decisions made now will have both an immediate and long-range impact on the ability to attract the necessary personnel in sufficient numbers and with sufficient training.

It is crucial that steps are taken to ensure that positions are created at universities and national laboratories so that younger physicists already in the pipeline stay and new Ph.D's with the proper training find sufficient and rewarding career opportunities. At the same time, it is also critical to maintain the university programs that are the source of our workforce. The projected workforce needs indicate that the Ph.D. production rate by 2008 must increase by at least 70%.

In order to do this, the Panel has developed suggestions that fall under the heading of "short term" and "long term." Those suggestions listed as "short term" are designed to attract existing members of the plasma science community (especially faculty and their students) into fusion energy research and development and to prepare for the greater Ph.D. production rate needed 4 to 5 years from now. Those suggestions labeled as "long term" are proposed as means of enhancing the possibility that students that are first-year undergraduates in 2004 become fusion scientists and engineers in 2014 when ITER begins operation. The Panel notes that all of these suggestions are dependent upon maintaining the current number of fusion job positions while creating the new positions suggested by this report.

The Panel believes that the following suggestions are not only reasonable and within the control of the Office of Science but are also critically important. They provide a "big bang for little buck" and will ensure that the necessary pipeline needed is large enough and will remain open for the next ten years and beyond. Finally, the Panel notes that the suggestions presented in the following section are *not* rank-ordered. Rather, the Panel has provided a balanced combination of suggestions that should be implemented by the OFES.

"Short Term" suggestions

As discussed above, the Panel has developed a list of short-term suggestions aimed at positioning the fusion community to leverage its current resources to begin building the personnel infrastructure to support the planned burning plasma experiments. In the short-term, the OFES *should perform* the following actions:

1. Perform an expanded, comprehensive assessment of the fusion workforce at the national laboratories with the goal of developing a five to ten year hiring plan.

- Actively encourage and support the national laboratories in making replacement hires for retiring fusion personnel.
- Develop and implement a plan of job creation and hiring to meet the expanded

responsibilities of the fusion program of maintaining a domestic program while making significant contributions to burning plasma studies.

- Develop a National Laboratory "Young Scientist" program—similar to the Plasma Physics Junior Faculty program—to attract and encourage innovative research in fusion science at the National Laboratories.
- The OFES can exert the greatest influence on the fusion workforce by implementing a program of personnel growth at the national laboratories. Such a move would directly demonstrate long-term federal commitment to and stewardship of the U.S. fusion program and would provide a sense of stability and security for students entering the fusion pipeline. Furthermore, such a commitment could indirectly strengthen the position of fusion faculty and university researchers in maintaining the commitment of educational institutions to plasma and fusion science and engineering.

2. Make full use of existing large experiments by including students and faculty from smaller institutions.

- An early or mid-career award could be created to encourage plasma faculty to become engaged in fusion experiments at larger institutions, with particular emphasis on student training and burning plasma issues.
- Large laboratories could be encouraged to develop partnerships with fusion scientists at smaller institutions as a means of incorporating a wider segment of the fusion community and attracting students to fusion science.

3. Periodically review graduate and postdoctoral fellowship programs as well as the junior faculty program so that they are competitive and meet current needs.

- Consider increasing the stipend or number of awards given in the graduate and postdoctoral programs.
- The DOE Plasma Physics Junior Faculty program could be increased from 3–5 years or perhaps an increased funding level over 3 years could be considered.

4. Develop programs in coordination with professional societies that enhance the visibility of fusion researchers.

- The intention of this recommendation is to make the careers of fusion scientists more attractive to students considering the plasma physics profession.
- For example, the OFES could work with the American Physical Society (APS), American Nuclear Society (ANS) and Institute for Electrical and Electronics Engineers (IEEE) to spotlight national laboratory researchers and university faculty.
- These programs could take the form of awards or lectureships.

5. Create a national laboratory funded professorship similar to the existing NIF professorship.

- Through providing funding and a connection to large experimental facilities, such a program would enhance the attractiveness of new faculty hires in fusion related fields.
- OFES could also use such a program to encourage the hiring of new faculty in fields where new expertise is needed in the future (e.g. materials).

"Long Term" Suggestions

Data from our surveys indicate that one of the dominant factors influencing persons to pursue careers in fusion science and engineering is interaction with members of the fusion community while at the undergraduate level. One can easily speculate that significant interaction with plasma science research before the undergraduate level would also influence a student's career choice. The following suggestions are designed to ensure that the workforce needs in the next 5–10 years are met. In the long-term, the OFES *should perform* the following actions:

1. Support and enhance existing outreach programs at all levels—K-12, undergraduate, and to underrepresented groups.

- Successful OFES programs include the National Undergraduate Fellowship (NUF) program. A complement to this program could be supplemental awards to existing

DOE grants allowing the hiring of undergraduates during the academic year.

- Increase the opportunities for K-12 teachers to perform fusion energy research by working to extend the on-going Office of Science teachers program.
- Encourage major university fusion laboratories and national laboratories to develop partnerships and alliances with regional minority serving institutions (MSIs) to expand the diversity of the fusion community. This could include undergraduate and graduate student research opportunities, lectureships at MSIs, and support of scholarships in plasma and fusion science (e.g., the recently established Robert Ellis Fellowship program that is sponsored by PPPL and managed through the National Society of Black Physicists).
- Encourage the recruitment and retention of women scientists in fusion science. Support scholarships for women in plasma and fusion science (e.g., Katherine Weimer Award for women in Plasma Physics—currently funded by APS and private sources).

2. Expand support of new, fusion-relevant, university-class experimental, theory, and computational research programs, with a particular emphasis on experimental programs.

- The universities are, ultimately, the source of the future fusion energy workforce. Without a healthy, diverse base of university programs in fusion science, the workforce pipeline will be irreparably broken.
- Make use of the Innovative Confinement Concepts program or the Fusion Energy Centers of Excellence program to diversify the number and types of institutions that conduct fusion energy research.
- Consider establishing small-scale, non-toroidal, fusion-relevant basic plasma experiments that address a specific scientific question of relevance to high performance burning plasmas. This could be done as part of an expanded NSF-DOE Basic Plasma Science and Engineering program.
- The critical role of university research is best summarized by the recent National Research Council (NRC) report, *Burning Plasmas—Bringing a Star to Earth:*[10]

The fusion program must be the steward of plasma science in order to maintain the flow of new ideas and new talent into fusion. Although the fusion program has made important contributions to basic physics knowledge in areas such as fluids and nonlinear dynamics, plasma research does not stand out as a priority in long-range planning among physics and engineering departments. Beyond basic plasma research, important university efforts include smaller-scale tokamak and alternate-concept experiments, plus participation in the larger national programs. While the specific projects to be pursued will change as the fusion program evolves, the important role of university research in the U.S. fusion program will continue throughout the era of the burning plasma experiment and beyond.

While the Panel firmly believe that the aforementioned suggestions are crucial for the development of a stable U.S. fusion workforce, we recognize that the fusion community is composed of versions with a wide range of backgrounds. Two groups in particular, non-U.S. citizens and non-plasma physicists have made significant contributions to the U.S. fusion energy program.

Presently, the current U.S. fusion energy workforce consists of U.S. citizens (86%), U.S. permanent residents (5%), and non-U.S. citizens (9%).[11] Since the mid-1990s, the number of physics Ph.Ds awarded by U.S. universities to non-U.S. citizens has exceeded the number awarded to U.S. citizens.[12] However, in 2002, there was a 7.4% drop in the number of student visa issued by the U.S.[13] Whether this drop is a momentary fluctuation or a sign of the future is unknown at this point. If this trend continues, it may not be possible to rely on the international community as a source of trained fusion scientists. The OFES should join with other scientific and professional organizations to monitor this situation.

[10] National Research Council Report, "Burning Plasma: Bringing a Star to Earth", by the Burning Plasma Assessment Committee (BPAC), Section 1.3.F, released September, 2003.

[11] Source: WPO—Online Surveys.

[12] Data from American Institute of Physics— "Enrollment and Degrees Reports", August, 2003.

[13] Data from Department of Homeland Security—U.S. Citizen and Immigration Services Department (formerly, Immigration and Naturalization Services)— "Fiscal Year 2002 Yearbook of Immigration Statistics"

The U.S. fusion community has traditionally embraced persons with a wide variety of backgrounds. In fact, 35% of persons currently working in fusion energy careers have their highest degree in an area of engineering. Where appropriate, the OFES should encourage and facilitate interactions between the fusion researchers and professionals in other fusion-relevant fields (e.g., material science, electrical engineering, etc.).

Summary

The Panel has presented a series of short and long term suggestions to the OFES to address the "issue of workforce development" in the fusion community. These suggestions are based upon the key principle in the development of this report:

> Ensure that sufficient professionals are available to maintain a vigorous domestic program that is similar in size and scope of the current program and the inclusion of a strong research program in burning plasmas centered on the NIF and ITER devices.

The suggestion made by the panel are intended to grow the population of U.S. plasma and science and engineering professionals from which the fusion community draws its workforce. However, the Panel recognizes the importance of persons trained outside of the United States and those trained outside of fusion science. All of these sources will need to be tapped in order to maintain the fusion workforce.

Ultimately, the future workforce will be shaped by many influences—the immediate availability of employment, the perceived stability of a long-term career in fusion sciences, the scientific progress of the field, the rate of retirements of senior members of the field, and the financial and political commitment of the federal government to the fusion program. The OFES, as the key steward for plasma and fusion science, must take an active role in working with the community to ensure the health and stability of the fusion workforce. The Panel firmly believes that future stability of the fusion workforce depends on a carefully designed, long-term, but continually evolving plan of job creation that is strongly linked with increased enrollments in plasma science and engineering.

The fusion workforce—much like the fusion program itself—is driven by both scientific curiosity and a desire to develop a fundamental new energy source for the planet. However, the fusion community is a disparate one, working towards different goals. The community needs to work to keep its different parts educated about the entire program. Students and new ideas often come from science sector. Progress towards a burning plasma will come from the energy sector. Both aspects of the fusion program will need to be balanced in order to make the necessary progress toward the fusion energy goal.

CONCLUSIONS

The Workforce Panel has provided an analysis of the U.S. fusion energy workforce. The Panel has documented the current state of workforce, queried the community regarding the future personnel requirements, and provided the OFES with suggestions on ensuring that the workforce pipeline is maintained. This report documents the findings of the Panel using carefully considered quantitative methods. However, in its deliberations, the Panel has discussed a number of intangible forces that have a tremendous impact of the fusion workforce. Here, at the conclusion of this report, the Panel presents its concerns.

Plasma physics and engineering in the U.S. is at a moment of transition. The field is about to embark on tremendous new endeavors including burning plasma experiments, new work in plasma astrophysics and high energy density plasmas. But, at the same time, this report has documented that the field is also facing very serious workforce challenges to meet the growing personnel demands of these areas. In the 2001 NRC assessment of the OFES,[14] it was noted that the flow of new scientific ideas between the fusion community and the larger scientific community is limited. One major consequence of this lack of communication is,

> ...the broader scientific community holds a generally negative view of fusion science. This isolation, combined with the generally negative perception of the field, ... endangers the future of plasma science.

The Panel reaffirms this assessment by the NRC. The Panel also notes that as long as this perception remains, the field will face a challenge in attracting new students and maintaining its visibility among the country's leading universities. While it is

[14] "An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program," National Academy of Sciences, National Academy Press (2001).

the responsibility of the plasma science and engineering community to change this negative perception, the OFES can—through programs like the recently established Fusion Science Centers—work with the fusion community to develop program activities that raise the visibility of the field.

In summary, the Panel has responded to the three components of its charge. Through a process of querying both individuals and institutions, the panel has developed projections for the future fusion energy workforce.

From the survey results on the status of the current workforce, the following key results were obtained.

- The U.S. fusion energy workforce, about 1000 individuals, is generally dominated by persons who hold a doctorate in physics;
- The U.S. fusion workforce is less diverse both in gender and in ethnicity than the overall physics community;
- Approximately 1/3 of the U.S. fusion energy workforce is currently age 55 and older, and the fusion faculty is generally older than the remainder of the fusion workforce;
- The production of plasma science and engineering doctorates has fallen steadily for over a decade from over 60 doctorates a year in the early 1990s to below 40 Ph.Ds/year in the last 2 years;

The key conclusions from the projection survey can be summarized as follows:

- The short-term needs will likely be satisfied by redirecting individuals from their current activities to participation in burning plasma activities.
- Over the next decade, up to 100 positions will become available due to retirements.
- Additionally, the long-term needs will require an increase in the total workforce (both MFE and ICF/IFE positions) by roughly 250 Ph.D. level positions or about 25% growth over the next decade.
- This growth would start 4 to 5 years from the present and will require a production rate of up to 42 plasma science and engineering Ph.Ds per year, and an additional 20 technically trained persons per year to cover both retirements and projected program growth.

The Panel suggests that in order to satisfy both the short-term and long-term workforce needs of the fusion program actions must be initiated now. Because of both the strong influence of future job availability on current student production and the five to seven year time response it is critical that OFES develop a long-term, but continually evolving plan to stabilize the fusion workforce pipeline.

Short Term

- Performing an expanded, comprehensive assessment of the fusion workforce at the national laboratories with the goal of developing a five to ten year hiring plan.
- Optimization of operations of existing large experiments to foster student-training opportunities with both affiliated and external academic institutions.
- Implementation of periodic reviews of existing graduate and postdoctoral fellowship programs as well as the junior faculty program to ensure that they are competitive and meet current needs.
- Develop programs in coordination with professional societies that enhance the visibility of fusion researchers.
- Creation of a jointly-funded professorship similar to the recently developed NIF professorship.

Long Term

- Implementation of outreach programs at all educational levels with the goal to attract a diverse group of students into pursuing a career in fusion science and engineering.
- Continuation of support of fusion research programs at universities, with a particular emphasis on experimental programs that will train individuals with hands-on experience.

In conclusion, the Panel finds that the fusion community faces many challenges. But, at this moment in history, plasma and fusion science is at the threshold of making many remarkable advances—in both fusion energy and basic plasma science. All parts of the fusion community and the OFES must rise together to meet these challenges head-on.

A stable, growing program with important, new results from NIF and ITER will, undoubtedly, create incredible excitement about the field and will be the greatest tool for expanding the fusion energy workforce.

Appendix A. COPY OF THE WORKFORCE CHARGE LETTER

July 9, 2003
Professor Richard Hazeltine,
Chair Fusion Energy Sciences Advisory Committee
Institute for Fusion Studies
University of Texas at Austin
Austin, TX 78712

Dear Professor Hazeltine:

The Office of Fusion Energy Sciences has a longstanding interest in the education and training of scientists and engineers needed to satisfy its programmatic goals. Anecdotal information indicates that the age distribution of the largest number of those currently trained and working in the fusion community is between 46 and 60. Other limited data show that the number of students graduating with a Ph.D. in fusion technology is dropping. And, although the number of Ph.D. degrees awarded in fusion science appears to be relatively stable, it is not clear that this trend will continue. With U.S. participation in ITER and plans to work toward having fusion power on the grid in the latter part of this century, there are questions as to whether the current education and training of scientists and engineers will provide the future leaders and researchers required for the U.S. fusion program. This letter provides a charge to the Fusion Energy Sciences Advisory Committee to address the issue of workforce development in the U.S. fusion program.

The key issues that should be addressed are the following:

- Where are we? Assess the current status of the fusion science, technology, and engineering workforce (e.g., age, skill mix, skill level).
- Where are we going? Determine the workforce that will be needed and when it will be needed in order to ensure that the U.S. is an effective partner in ITER and to enable the U.S. to successfully carry out the fusion program.
- How do we get there? Provide suggestions for ensuring a qualified, diversified, and sufficiently large workforce and a pipeline to maintain that workforce. The suggestions should be things that are reasonable and within the control of the Office of Science.

I would like FESAC to report its findings by January 31, 2004.

Sincerely,
Raymond L. Orbach
Director

Appendix B

March 30, 2004
Dr. Ray Orbach
Director, Office of Science
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585

Dear Dr. Orbach:

The Fusion Energy Sciences Advisory Committee (FESAC) has reviewed the enclosed report, "Fusion in the Era of Burning Plasma Studies: Workforce Planning for 2004 to 2014," and submits it to you with its unqualified endorsement.

In response to your charge of July 9, 2003, "to address the issue of workforce development in the U.S. fusion program," FESAC instituted a Panel, chaired by Professor Edward Thomas and consisting of ten scientists from Universities, National Laboratories and industry. The Panel gathered extensive data, through community surveys and other means, before composing its report. FESAC is grateful to Professor Thomas and all the members of the Panel for the careful research, analysis and assessment that are evident in the report.

A prominent finding of the report is that, while the population of fusion scientists is likely to remain close to its present size for the next 2–4 years, without prompt action the following 6–10 years may result in a significant shortage of fusion research personnel. This prediction, based on the present demographics of fusion scientists, takes into account the increased demands of the burning plasma research program as well as a significantly expanded base program.

The Panel report includes detailed recommendations for workforce development in both the short and long terms. FESAC specifically supports the recommendation for "[c]ontinuation of support of fusion research programs at universities, with a particular emphasis on experimental programs that will train individuals with hands-on experience.” FESAC also supports the Panel conclusion that “it is critical that the process of new job creation begin now; both to encourage students to enter and remain in the field and to facilitate the intellectual continuity of the field.”

Yours truly,

Richard Hazeltine

Chair, Fusion Energy Sciences Advisory Committee

Enclosure

Appendix C. Selected Comments from Workforce Surveys. The panel received many comments from the community related to the future workforce that did not address directly the charge we were given. However, we feel that some of the comments were representative of larger community concerns and should be aired. These comments came primarily from the web based survey wherein respondents were given the opportunity to provide commentary. What follows are some selected comments quoted directly from the surveys, grouped into three major categories: the uncertainties of funding, the dichotomy of science vs. energy in our program, and community leadership.

SUPPLY AND DEMAND

It has become clear from reading the results of our survey, that the community perception of where we are going is driven by the current state of the fusion budget (in particular, its rate of change). In good times, there is enthusiasm for the program and optimism for the future. In bad times, it is difficult to plan ahead. At the moment (early 2004), there is a modest upturn in the fusion energy budget (up 5.7%) and promising signs from leadership in Washington (e.g., Secretary Abraham’s 2003 speech noting fusion as a top priority in DOE). However, there is anecdotal evidence that, even now, there are far more applicants than jobs and that a successful career in fusion for a motivated young scientist is far from guaranteed. Three of our survey respondents reported:

> “It is simple economics. More money will attract high quality talent, build bigger graduate programs and the subsequent employment opportunities. There are clear examples in the past. There is plenty of talent in related fields that can be cross trained in plasma physics and bring their own disciplines to the table.”

> “Development of the real possibility of fusion energy relies on steady direction and commitment to goals. Although the breadth of fusion science research in recent years has produced interesting and useful results, investment in a true fusion energy development program is the only path that leads to energy security and human benefit. Thinly applied funding over the pasture of fusion research does not expose a path less traveled by (apologies to Robert Frost).”

> “Unlike IFE, whose funding is grounded in defense issues and is more stable, MFE budgets seem to fluctuate greatly. This is the primary reason I am no longer in MFE (my graduate thesis was in MFE) and instead am doing physics more related to ICF at a national lab. Availability of permanent employment with decent pay is critical to young researchers (especially if they have families), and university programs will continue to lose talent to the national labs if the funding situation does not stabilize.”

SCIENCE VS. ENERGY

There was some anxiety among our survey respondents about the two sided aspect of our program: fusion science with an energy goal. This is a relatively recent change in our program (the late 1990s) and the ramifications are still being felt. It is clear that if fusion were solely an energy program or solely a science program, then the answer to the question “where are we going?” would be quite different.

Some respondents want the program to have more of an energy focus...

> “The U.S. fusion program lost its focus in the mid-90’s when it became a ‘science’ program rather than an energy program. What momentum we had from the successes on TFTR, DIIID, and other Tokamak devices has been eroded by a seemingly endless succession of ‘Next Step’ conceptual studies (including ITER) that have led nowhere despite the technical merit of many as reasonable next step proposals. This has been due in part to insufficient funding support in congress but also to a lack of real commitment to this enterprise as a true energy program at the upper levels at DOE...”

Others prefer more of a basic plasma physics focus...

> "I would like to see the fusion program give more support to basic research on the physics of fusion plasmas. Plasma research is enticing because it calls for broad vision and broad physics knowledge and skills. I have seen the catastrophic results of programmatic, narrowly focused, short-time scale work with pre-ordained attainable milestones, hardly what one in other fields would call research, even if also needed. It not only replaces the fruits of real research, but is repellent to potentially valuable contributes to this field. It is shameful that such research is left by OFES to the NSF."

> "The development of the science as a whole will allow for the necessary bits of creativeness and pure luck that will provide the big breakthroughs necessary to turn fusion into a reality. We need to have diversity in skills and an honest belief in the fundamentals before sincere progress can be made."

LEADERSHIP

A clear direction for the future of the fusion program requires strong leadership. There is a perception among our survey respondents that that leadership is lacking. Other communities are able to speak with one voice (astrophysics, high energy physics) but fusion has many faces (MFE vs. ICF, energy vs. science). Often, the leadership of OFES, DOE, OMB, and Congress have differing views of what the future holds. There are a wide variety of views from the current workforce:

> "Lack of support for the fusion program is not a financial issue but political will. A multi trillion dollar economy can support a substantial program."

> "To me the key on the success of fusion energy in the US is political commitment. Our present program leadership is not strong enough to convince the politicians that fusion energy is worth going after, and keep hiding it as a science program."

> "It is frustrating for professionals working a good fraction of their careers within the community to go the extra mile, often on their own time, to create designs and meet deadlines to serve one arm of the Government (DOE), and then have another arm (often the Congress) simply terminate the project. The signal is there is a distinct lack of coordinated direction. Strong energy leadership in several branches of the Government may be needed to solve this problem."

> "If fusion energy was promoted as much as say a cure for cancer, the public would be pounding down the doors of Congress. Fusion promotion should emphasize the amazing benefits of Fusion as an ideal source of bulk electrical power, benefit for global warming, and the virtually non-existence of waste, compared to *any* fossil fuels (especially coal). It should also emphasize that this is for the future of our children and the world but we have much work to do now to realize the benefits."