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Elements of Successful and Safe Fusion Experiment Operations*

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Abstract - A group of fusion safety professionals contribute to a Joint Working Group (JWG) that performs occupational safety walkthroughs of US and Japanese fusion experiments on a routine basis to enhance the safety of visiting researchers. The most recent walkthrough was completed in Japan in March 2008 by the US Safety Monitor team. This paper gives the general conclusions on fusion facility personnel safety that can be drawn from the series of walkthroughs.

I. Introduction

The Safety Monitor Joint Working Group (JWG) is an international group of fusion safety and facility operations professionals. The JWG mission is to complete a walkthrough visit of fusion facilities that will host foreign researchers to verify that occupational safety is enhanced for these visitors and for the staff as well [1,2]. This work is part of US Department of Energy exchanges; the tour is listed in the DOE Coordinating Committee of Fusion Energy (CCFE) version 27-10, the safety monitoring tour for the US-Japan Cooperation. This work is also sponsored by our fellow researchers in Japan through the Japanese Ministry of Education, Culture, Sports, Science and Technology. Every two years a tour is conducted where fusion safety representatives walk through fusion facilities and review the safety precautions at the selected facilities. Each visit has provided some noteworthy practices and examples of safety in fusion operations. After performing several of these walkthroughs, some key practices have been recognized. These safety practices are described here.

II. 2008 JWG Visit to Japan

- University of Tokyo – Graduate School of Frontier Sciences
  - Kashiwa campus – TST-2 Tokamak, University of Tokyo Spherical Tokamak (UTST), Ring Trap Experiment (RT-1)
- Kyoto University
  - Yoshida Campus – Low Aspect Torus Experiment (LATE)
  - Uji Campus – Heliotron J
- Tsukuba University – GAMMA-10
- Tohoku University
  - Aobayama Campus – DTALPHA, TU-Heliac
- Kyushu University – QUEST –Experimental Spherical Tokamak, Helicon
- Osaka University –
  - Gekko Laser – Institute of Laser Engineering
  - Li Loop – Graduate School of Engineering
- National Institute for Fusion Science – NIFS
  - Large Helical Device (LHD)
  - Superconducting Laboratory
  - Fusion Engineering Laboratory
- Japanese Atomic Energy Agency (JAEA) – Naka Fusion Institute, Fusion Research and Development Directorate
  - JT-60
  - Superconducting Magnet
  - RF Heating
  - Fusion Neutronics
  - Tritium Processing
  - JEBIS Facility

III. Japan's Change in Approach to Safety

The U.S. team observed some fairly significant changes and improvements to many, if not all, of the facilities toured during this visit as compared to the 2004 review. After our previous visit in February 2004, Japanese national universities were converted into independent corporate entities. One result of this change was that the universities are now subject to Japan national rules for occupational and industrial safety. As a result, the research staff took a more prominent role in all aspects of safety for the facility operations and research. The emphasis on safety is now as important to national research as the research itself. In fact, in many instances, a research scientist is now the head of safety for a facility with primary duties for health and safety

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and a reduced role in day to day research. This approach was further evident in review of organizational structures and physical review of facility and plant. While there were dedicated safety professionals in some of the larger facilities, the majority of responsibility for safety is placed on the research scientists. It is considered paramount to and essential toward proper conduct of operations. We observe that this also provides for an environment in which the revered research scientists are also seen as leaders by example in safety and research. This approach is significantly different than the U.S. approach to safety which is more of an "enforcement" climate with safety professionals providing oversight, review, and implementation of safety programs for the research staff.

The Japanese professors and researchers stated that compliance with some of the national laws and rules was expensive, but overall we noted the facilities were cleaner, less cluttered, and tools were better organized. There was better attention to gas cylinder safety, more safety signs had been placed, and more attention to general industrial safety than in past visits. As always, the facilities with larger annual operating budgets tend to have more safety provisions. It is a well known, but not quantified, safety principle that well-run, safe facilities are cleaner, more productive, and more efficient than facilities that do not practice safety [3].

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IV. Best Practices in Safety

Some of the best practices are not new ideas; some are time-honored approaches that give superior results across industries. The insights described here arose from facilities visited; some are university machines, others are large national experiments. There are obvious differences in annual funding levels across this variety of machines, but the safety best practices are true for all types of fusion experiments (magnetic versus laser, large versus small, university or government). The best practices are described below.

A) Commitment to safety. This issue has been recognized for decades as being essential for safe operations [4]. Our experiment operations [5,6,7] and JWG safety walkthroughs have shown this to be true for fusion experiments as well as for general industry. Senior management of the facility must be personally and visibly involved in safety and hold the staff accountable for safety performance [8]. In many laboratories, safety may be an enforced priority due to laws or regulations. However, the desire for safe operations, to have safety included in all levels of the experiment, is necessary for a successful program. Managers must fund safety activities, project leaders must take responsibility for safety implementation, and the researchers, students, and staff must work safely, following the rules. The monetary commitment to safety does not need to be large. There is a need for staff training, inspections, and some safety equipment, but these costs are not large, perhaps 1-3 percent of the annual operating costs. Periodic reviews of the experiment after it is modified or augmented for new research, or overhauled for maintenance, are needed for safety.

A positive safety attitude is beneficial for several reasons besides the moral obligation to provide a safe workplace. First, safer experiments also tend to operate better and give better data. There are several explanations for this – with more carefully installed equipment and less hasty, jury-rigged equipment the machine tends to function better, and well designed, installed, and maintained equipment rarely leads to fires, arcs, or other downtime. Another reason is that a safer experiment tends to give a better appearance to visitors, including the visitors who provide funding for scientific research. Safer experiments also build morale, demonstrating that the staff is valued and that they work as part of a well-managed enterprise. Good morale leads to higher productivity and staff members keeping an awareness of nascent, incipient faults and unsafe situations.

B) Cleanliness is important to safety. Fusion experiments have shown that keeping tools properly stowed, and equipment clean and in good working order means getting better data results from operations. Obviously, stowing tools, small parts, steel gas cylinders [9], and equipment when operating magnetic fields is a best practice for safety and operations. Cleanliness and orderliness next to the experiment often means faster and easier maintenance work, especially when an experiment has many diagnostic devices installed. Some diagnostics require tuning and calibrating before and after each experiment campaign, so providing the space to access and properly work on the equipment is a best practice. Facility cleanliness is also very important for fire safety. While fusion experiment fires may be primarily electrical in origin, leaving debris and clutter in a lab room or near an experiment can allow a small electrical fire to spread.

Fire safety is a concern for many types of research facilities. Some data assessment of research areas gave these values for incipient fires: laboratory rooms, 0.12/year; mechanical equipment rooms, 0.007/year, computer rooms, 0.004/year; and offices 0.073/year. Large fires that grow from incipient (smoldering) fires are few, giving large fire frequencies on the order of 1E-04/year [10]. Fusion experiment fire safety concerns are similar to other industrial and technical facilities.

C) Personnel accountability. Well-run facilities keep track of persons on site and persons away from the site. During experiment operations they keep track of persons in the experiment hall. This does not mean that a sophisticated personnel access control system is necessary. A status board with labeled tags or magnet markers is sufficient and inexpensive to denote who is in the experiment hall. Experiments using high power need more stringent access

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control measures, such as locked doors. Experiments with high power shots that emit high levels of radiation, experiments that use tritium, etc., may require an electronic access control system.

D) Periodic safety training. Well-run facilities conduct periodic refresher training in safety and other topics. Many of the universities and institutes visited have annual safety training to brief their personnel on safety issues with chemicals, compressed gases, cryogenics, electricity, radiofrequency energy, vacuum, and other pertinent topics. Universities typically also have supervision to observe and tutor the students until they are knowledgeable enough to work without coaching. That is, a permanent staff member, or a graduate student with several years' experience, would coach new student workers on the experiment. Successful facilities often have a 'buddy system' so that no one works alone in the experiment room. With a buddy present, there is a much better chance of having a person sound an alarm if an injury or exposure does occur. Working alone is not permitted at successful fusion experiments.

E) Staff communication. Orderly operations and maintenance rely on good communications. A best practice is to have a 'plan of the day' meeting to inform all personnel at the beginning of an experiment day of the goals, the operations schedule, and the systems to be operated so that everyone understands the plan. The meeting may be formal or informal, but it does need to convey the information to the staff, technicians, student workers, and any visiting researchers. This information also helps the personnel to recognize if something 'just does not look right' during an experiment day so that they can inform the control room or act quickly tot take preventive measures with incipient failures. Cognizant personnel, or 'key' persons, coordinate operations and maintenance to ensure no personnel are placed in harm's way. This is especially important when there are multiple, overlapping activities being conducted.

F) Adherence to fundamental safety principles. Safe facilities follow common-sense safety practices whether these are in the form of regulations or not. An example of these principles is to perform a personal check of systems to verify that they are depowered before conducting maintenance work [11,12]. There are electrical safety regulations in each country but following the safety practice of verifying that any voltage line is de-energized is wise whether a rule exists or not. Safety rules and regulations vary between countries, but the common sense reasons of safety transcend regulations.

G) Daily walkthrough of the facility. Well-run facilities have a cognizant person (a session leader, engineer in charge, or principal investigator) take a brief but thorough walk around the facility to observe and identify conditions that present hazards to personnel or to the investment of the facility, and to briefly identify any major maintenance needs. Past daily walkthroughs have identified roof leaks, coolant leaks, unusual cryogen venting, smells of overheated electrical equipment, inappropriate storage of combustible materials, unsecured gas cylinders, and other concerns at fusion facilities. These walkthroughs are not as formal as a daily inspection with a checklist or written report, but are effective nonetheless.

H) Emergency shutdown. Safe facilities have a 'panic button' or 'kill switch' included in the control system that depowers and shuts down the facility if the operators believe an off-normal event is occurring. Some facilities have this switch in the control room, and some have the control room switch plus additional switches in locations around the machine. It is a best practice to have these switches on experiments and power systems for fast shut down in case of emergency [13]. The shutdown switch can serve multiple purposes – ionizing radiation safety, radiofrequency radiation safety, electrical safety, and magnetic field safety.

I) Pre-shot search. Before commencing pulse operations, a cognizant person will walk around the machine ("sweep the area"), searching the area to verify that no one remains in the experiment room and that the access doors are all securely closed. Besides the possibility of direct ionizing radiation from the plasma, radiofrequency energy can leak from plasma heating systems [14]. It is prudent to verify no one is trying to make a last minute adjustment, "tune up" a diagnostic, or perform some other work just prior to a plasma pulse. This does not require a sophisticated personnel radiation safety system, simply some staff time and attention to detail. In the past, some particle accelerators had personnel exposures due to poor sweeps that did not identify remaining personnel, or no sweeps being performed, before energizing the machine [15]. Removing personnel from exposure situations remains a best practice.

As noted for particle accelerators [16], generally the radiological exposures in fusion facilities are rare. The most serious accelerator accidents have involved suffocation in high voltage tanks, falling objects from rigging, electric shock, chemical incidents, falls from ladders or high platforms. These events and fires are always safety topics for consideration. Unexpected occurrences tend to result in the worst consequences, so emergency preparedness programs are essential.

J) Emergency response team. Fusion facilities are monitored for several off-normal conditions, including smoke detectors, oxygen monitors, and airborne tritium or other radioactive contamination. A facility can rely on a site or municipal fire department to respond to alarms, but such response can take time, perhaps up to 15 minutes or even longer depending on the location of the fusion facility. Even if the response time is long, all personnel should be trained on how to contact the fire department or emergency

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services in their location. If facility personnel have the proper training, teams of the staff, sometimes called an emergency brigade, can respond to such alarms within minutes. An emergency response team can render life safety actions, first aid, and they can take amelioration actions as well. Fast actions can also reduce losses due to facility damage

V. Past JWG Reports

Typically, each JWG visiting team finds that there are small but constant numbers of visiting researchers to the fusion experiments. Visits can span days, weeks, or months. While collaborative work continues, the JWG will continue to function. At the conclusion of each trip by a JWG team, a report is written about best practices and any areas of possible improvement. The most recent reports are available on the internet at www.pppl.gov/ESH.cfm under the heading US-Japan Safety Monitoring Joint Working Group. These reports have been valuable for the facilities visited, serving as a reminder of the multi-national nature of fusion research, making a reminder of good practices and any safety issues to resolve.

VI. Suggestions for New Laboratories

Following the guidance given here is a positive step for a new laboratory to adopt, or for an existing laboratory to review and perhaps incorporate to enhance safety. For further guidance to establish a safety and health program, there are several avenues open to researchers. Many fusion labs have their own safety manuals available to download from the facility's web site. An example is the web site: http://www.pppl.gov/eshis/ESHD_MANUAL/sm.html.
Another particular type of laboratory with many types of equipment similar to fusion research is a modern semiconductor fabrication laboratory. The semiconductor labs are technological activities and typically have small vacuum systems, compressed flammable gases, high electrical power requirements, small to medium sized radiofrequency heating, and modest field strength permanent magnets. Therefore, the experiences and guidance from a semiconductor lab are worthwhile [17]. Particle accelerators are also very close matches to fusion experiments in terms of equipment and hazards; radiation safety [18] and safety documentation from a facility safety manual [19] are good guidance when preparing a fusion experiment safety manual. Translating a visitor's version of the safety manual into the languages most likely to be understood by visitors is a wise idea. Often, visitors are required to take abbreviated safety training for short visits, training that focuses on the areas of greatest concern for the visitor's tasks.

If just starting an experiment activity, then educating new personnel on the importance of safety is important. Discussing the hazards, reasons for rules, and some past events from similar facilities can be helpful in establishing a positive safety attitude. Busick [20] credited this approach with reducing personnel radiation overexposures at particle accelerators. Some past events in high technology facilities that can serve as examples are documented by Cadwallader [21]. Keeping communication open and acting to resolve safety issues forms the basis that safety is important at a new facility.

VII. Conclusions

The safety monitor JWG will continue to perform biennial inspections of participant facilities and trade safety information between participants. Continued vigilance in personnel safety will help fusion facilities to operate without any serious injuries to visitors or staff. Safe experiments mean incurring the costs of safety training, equipment, and personnel time to follow safe working practices, but it also means very low costs due to personnel injuries and, in general, a more productive experiment. Making fusion experiments more attuned to international researchers will help not only the existing researchers but also the next generation of researchers who will operate the International Thermonuclear Experimental Reactor, the International Fusion Materials Irradiation Facility, and other facilities that will have multi-national staff.

VIII. Recommendations

U.S. Fusion Research Facilities – Possible sites for 2010
- General Atomics (GA)
  - DIII-D Tokamak
- Lawrence Livermore National Laboratory (LLNL) –
  - National Ignition Facility (NIF)
- Idaho National Laboratory (INL)
  - Safety and Tritium Applied Research lab
- Princeton Plasma Physics Laboratory (PPPL)
  - National Spherical Torus Experiment (NSTX),
  - Lithium Tokamak Experiment (LTX)
  - Magnetic Reconnection Experiment (MRX)
- University of Rochester
  - Laboratory for Laser Energetics (LLE)
- Massachusetts Institute of Technology (MIT)
  - Current Drive Experiment CDX-U

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