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ITER SAFETY CHALLENGES AND OPPORTUNITIES

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ITER SAFETY CHALLENGES AND OPPORTUNITIES

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Abstract/Summary

Results of the Conceptual Design Activity (CDA) for the International Thermonuclear Experimental Reactor (ITER) suggest challenges and opportunities. "ITER is capable of meeting anticipated regulatory dose limits,"[1] but proof is difficult because of large radioactive inventories needing stringent radioactivity confinement. We need much research and development (R&D) and design analysis to establish that ITER meets regulatory requirements. We have a further opportunity to do more to (a) prove more of fusion's potential safety and environmental advantages and (b) maximize the amount of ITER technology on the path toward fusion power plants.

To fulfill these tasks, we need to overcome three programmatic challenges and three technical challenges. The first programmatic challenge is to fund a comprehensive safety and environmental ITER R&D plan. Second is to strengthen safety and environment work and personnel in the international team. Third is to establish an external consultant group to advise the ITER Joint Team on designing ITER to meet safety requirements for siting by any of the Parties.

The first of three key technical challenges is plasma engineering - burn control, plasma shutdown, disruptions, tritium burn fraction, and steady state operation. The second is the divertor, including tritium inventory, activation hazards, chemical reactions, and coolant disturbances. The third technical challenge is optimization of design requirements considering safety risk, technical risk, and cost. Some design requirements are now too strict; some are too lax. Fuel cycle design requirements are presently too strict, mandating inappropriate T separation from H and D. Heat sink (vacuum vessel, cryostat, biological shielding) requirements are presently too lax; they should be strengthened to ensure that maximum loss of coolant accident (LOCA) temperatures drop.

"Iter" means "the way" in latin. ITER must be "the way" toward fusion's future. Considering current physics machines, the Burning Plasma Experiment (BPX), a nonnuclear steady state tokamak (SST), and a 14-MeV neutron source, ITER must still provide about half the safety and environmental understanding to make a demonstration fusion power plant (DEMO) attractive from the safety and environmental standpoint.

Introduction

This paper discusses the opportunities ITER presents us in safety and environment and the major challenges with some thoughts on overcoming them. Complete[1,2] and summarized[3,4,5] safety assessments of the ITER CDA design exist. Rather than duplicate them, I pursue the general picture and most critical future opportunities and challenges. I want to persuade you to increase your attention and commitment to improve ITER from the safety and environmental perspective.

The next section details ITER's opportunities in working toward fusion's excellent safety and environmental potential. Then, I discuss ITER's challenges in two parts - programmatic and technical.

ITER Opportunities

When we make ITER successful, imagine what a powerful step it will be toward making fusion a keystone of mankind's energy supply. Consider a potential future newspaper editorial:

"ITER SUCCESS SHOWS FUSION ENERGY IS SAFE AND CLEAN"

(where?,2015) In a press release today, the ITER project noted 10 years of successful operation of the world's first nuclear fusion reactor. Although ITER does not produce electricity, its operation shows that fusion reactors can be operated safely. Radioactive tritium fuel has been successfully confined. Tests with ITER show no hazard from meltdowns or runaway nuclear reactions. ITER engineers say that the upcoming fusion demonstration power plant will be even safer since it will be built with low activation materials recently developed. These new materials will reduce the amount of waste by allowing recycle of most materials.

We and our successors can accomplish this, but it will not be easy. Fusion power plants should be passively (or inherently) safe, with minimal effluents, and with waste managed by recycling and near-surface burial.[6,7] To go where we want to go, we have to examine ITER's general role toward fusion power plants.

ITER's role in answering major technical questions

ITER's success is a necessary, but insufficient condition to allow fusion to provide energy for our children and grandchildren. The four main magnetic fusion technical issues show that ITER has an essential role in fusion development.

1. Confinement physics and engineering
2. Burning plasma
3. Fusion nuclear technology
4. Fusion nuclear materials

Each of these issues contains several safety and environmental aspects. ITER has a role in resolving each, but its role in fusion nuclear technology cannot be transferred elsewhere. Such a transfer would mean building another machine between ITER and a DEMO.

Between now and DEMO, the U.S. plans to have these major projects - existing physics machines, BPX, a nonnuclear steady-state superconducting tokamak (SST), ITER, and a high-fluence 14-MeV neutron source.[8] Fig. 1 shows how I think these projects should contribute to providing the understanding sufficient to make the DEMO fusion power plant attractive from the safety and environment standpoint. Fig. 1 tries to account for the information to be gained from associated smaller support facilities. Later parts of the paper detail the safety issues.

The fusion community needs a special effort to learn as much safety and environmental information as possible from existing physics machines. This is

SAFETY AND ENVIRONMENTAL ISSUE

Provide burn control and passive plasma shutdown
Control disruptions, including runaway electrons
Provide high tritium burn fraction in plasma
Demonstrate true steady state operation (lower failure rates)
Develop and demonstrate attractive divertor
Develop and demonstrate attractive blankets
Resolve worst-case magnet movement concerns
Design a passively (or inherently) safe power plant
Develop Low Activation Materials
Demonstrate tolerable tritium inventory and control
Demonstrate tolerable operational effluents
Demonstrate tolerable personnel doses
Develop decommissioning and decontamination practices, including waste recycling and near-surface burial
Evolve appropriate safety and environment regulatory approach

PROJECTS' CONTRIBUTIONS

Fig. 1. Projects' contributions to providing understanding sufficient to make the DEMO attractive from the safety and environmental standpoint

especially true once JET and TFTR use tritium. Strong magnets, especially the superconducting magnets in Tore Supra and T-15, should help us start to resolve the issues of offnormal magnet movement and arcs. Such occurrences threaten radioactivity confinement and provide an undesirable common cause failure.

Future physics machines, BPX and SST, will extend the safety information provided by current machines. A 14-MeV neutron source will help develop advanced materials, especially low activation materials. Fig 1. includes some double counting: the 14-MeV neutron source will help work toward passively safe power plant via developing low activation materials.

Even optimistically considering what these projects can provide, there is still a tremendous safety and environmental role for ITER. ITER bears roughly half the responsibility of getting from where we are to where we have to be for a DEMO. No other machine will combine near-reactor-scale plasmas, superconducting magnets, modest neutron fluence (1-3 MW-yr/m²), and significant nuclear test volume (> 10 m³). If the final ITER design lacks one or more of these basic features, we will need yet another machine before an attractive DEMO.

For example, one cannot depend entirely on a 14-MeV neutron source to develop advanced low activation materials. Such a source will have low test volume and high fluence, but probably not have an exact D-T fusion neutron spectrum. It will provide end-of-life radiation damage data, such as the onset of breakaway swelling. We also need the complementary testing capabilities of ITER with higher test volume

and modest true fusion fluence. Versus a 14-MeV neutron source, ITER would allow tests of more candidate alloys and provide a definitive comparison between non-fusion-plasma neutrons and other neutron testing environments. We need materials testing in both ITER and in a 14-MeV neutron source.

Where does ITER stand versus its safety role?

Fig. 1 shows what ITER should contribute, but how are we doing? Fig. 2 shows a mixed picture. At 1-3 MW-yr/m² fluence, ITER should provide most of what we need from it for blanket testing and advanced materials. The CDA design blanket test volume is less than what the test planners really want and need. Therefore, Fig. 2 shows that ITER's fulfillment of blanket and materials testing is only 90%

Some areas have not received adequate attention, including how to test advanced post-ITER divertors in ITER, what the personnel doses and safety would be, and how to decommission and decontaminate ITER.

Plasma engineering safety issues have not received sufficient attention. These include burn control, offnormal plasma shutdown, disruption control, tritium burn fraction, and true steady state operation. Steady state operation is a safety issue because it promotes lower failure rates.

Fig. 2 shows my judgement of ITER improvement if current design and R&D trends continue. The physics R&D plans, if fully funded and implemented, would put ITER where it should be in most of the plasma engineering safety areas. Still, the "voluntary" nature of

ITER SAFETY AND ENVIRONMENTAL ISSUE

- Provide burn control and plasma shutdown - active
- passive
- Control disruptions, including runaway electrons
- Provide modest tritium burn fraction in plasma
- Allow true steady state operation (lower failure rates)
- Develop attractive divertor (via test program)
- Develop attractive blankets (via test program)
- Resolve worst-case magnet movement concerns
- Passive safety - natural convection cooling during LOFA
- minimize temperature during LOCA
- avoid major chemical transients
- Develop Low Activation Materials (via test program)
- Demonstrate tolerable tritium inventory and control,
especially fuel cycle and plasma-facing components
- Demonstrate tolerable effluents (operation, maintenance)
- Demonstrate tolerable personnel doses
- Develop decommissioning and decontamination practices
- Evolve appropriate safety and environment regulatory approach

ITER STATUS VERSUS NEED

☒ accomplished in the CDA
 ☐ would be accomplished in the EDA given present trends
 ☐ need to do more

Fig. 2. ITER's accomplishments versus its need to resolve safety and environmental issues for DEMO attractiveness and ITER licensing

physics R&D may inhibit full implementation of the R&D plans. Thus, Fig. 2 shows less than 100% for most of the plasma engineering safety issues.

Adopting the high aspect ratio design (HARD) suggested by J. Perkins would improve ITER.[9] HARD would make it possible to achieve steady state operation in ITER, with attendant major benefits in nuclear testing. My evolving assessment of HARD is that it appears safer, primarily because of lower stored plasma energies due to lower plasma currents. The plasma chamber wall area in HARD is also slightly smaller, decreasing the in-vessel tritium inventories. HARD does have safety penalties of faster vertical instability growth rates and higher stored magnet energies. On balance, the HARD design point appears safer than the CDA design.

If instead we move in a direction opposite from HARD, ITER becomes physically larger with more plasma current. An increase in size increases radioactivity inventories and probably stored magnet energies. An increase in plasma current increases stored plasma energy and associated disruption effects.

Most of the work implied in Fig. 2 must be done before ITER receives regulatory approval for construction - even if one ignores ITER's role in building toward an attractive DEMO power plant. Gaining regulatory approval for ITER from the standpoint of ensuring burn control (especially of an ignited plasma) and offnormal plasma shutdown will be difficult. At minimum, serious attention is needed to model the consequences of all possible burn control scenarios. Initial ITER operation must be carefully

planned to avoid damaging surprises. The ITER operation license may be conditional on showing that D-T ITER operation falls within expected performance ranges, especially with regard to offnormal plasma shutdown behavior.

Regulators will also demand assurance of tritium inventory and control, effluents, and other nuclear safety issues. Gaining regulatory approval for ITER will be unlike anything the fusion community has yet attempted.

ITER must play a dominant role in building the case for fusion energy from the safety and environmental standpoint. There is much to do just to build the regulatory data base. If we overcome the challenges summarized in the next sections, ITER will fulfill its opportunity to be "the way" toward fusion's future.

Programmatic Challenges

An underlying programmatic challenge in ITER is its international nature. Different countries have differing safety and environmental regulations. Physical laws do not change at national boundaries, but legal laws and regulations do. More importantly, fusion programs have differing attitudes and strengths toward safety and environment. The U.S. program takes a roll-backward view of ITER, starting with a broad sense of where fusion energy must go. Other Parties programs generally use a roll-forward view. The U.S. has more complete assessments of potential fusion power plants than the rest of the world combined. This is particularly true of safety and environment.

I detect a growing global awareness that the case for fusion energy includes, in large measure, its safety and environmental potential. If so, the way is clear to surmount some challenges leftover from the CDA. The primary programmatic ones are as follows.

1. We must have an international safety and environment R&D plan for ITER. We lack this today. Even with the CDA approach of trying to place all safety and environmental R&D questions with corresponding component R&D plans, there are gaps.

Key gaps include radioactivity confinement, [2] activation product behavior, offsite radioactivity dose codes, and a comprehensive failure rate data base. (Many tritium confinement issues are in the Fuel Cycle plan.) The U.S. ITER Home team has recently established safety as a separate ITER category. In the coming months, I will produce a comprehensive safety and environment R&D plan that I hope will be the blueprint for the needed international plan.

2. We must have strong safety representation in the new ITER Joint Team, reporting to either the Director or one of the deputies.

The ITER Engineering Design Activity (EDA) will have 3 design sites, 4 home teams and many governments (U.S., USSR, Japan, and several European countries). In spite of this organizational complexity, we need integration, efficiency, and innovation to solve problems. Accordingly, there must be a strong safety staff in ITER, with perhaps 2 full-time safety professionals at each design site, including a safety head in San Diego. This staff would work together to help

the rest of the design team solve problems and plan and oversee safety-related R&D.

Safety cannot just be the responsibility of safety experts. Most of the design analyses needed to support safety assessments and most of the underlying component R&D must be done by non-safety professionals with non-safety budgets. Safety must involve the entire ITER community.

3. We must have an external consultant group of safety regulatory experts to work with the ITER Joint Team to ensure that ITER could be sited in any of the Parties.

We face complex siting and regulatory challenges and the ITER Joint Team will need effective safety and environmental review. Fig. 3 is my proposal for a schedule and approach for ITER siting and regulatory approvals. Admittedly, I am more familiar with U.S. procedures and requirements so the proposal will need international adjustments. We need to start domestic and international discussions on siting and regulatory approvals.

The design team needs reference site information sometime late in 1993. Each Party should provide a reference site for EDA design purposes, to clarify where the Parties may build ITER. These reference sites will not necessarily be the same sites later formally proposed as construction sites, but they should represent what the Parties are considering. This will narrow the present uncertainty in external initiator parameters, regulatory dose limits, and permissible design standards. We cannot de-couple

Fig. 3. Possible schedule for ITER siting and regulatory approvals considering U.S. safety and environmental approval procedures

design of a large nuclear project from potential sites. It would be wastefully expensive to simultaneously design to satisfy the worst German aircraft impact, the worst Dutch flood, the worst Japanese earthquake, the worst American lawsuit, and everybody's toughest regulations.

Corresponding to this, the U.S. should complete the initial public scoping process for an Environmental Impact Statement (EIS), narrow potential sites to a short list for later EIS analysis, and identify a preferred alternative. The preferred alternative would be our reference site for international design efforts. U.S. law and DOE Orders require EIS-type planning for a project like ITER.

There are ever increasing requirements for documentation of safety and environmental characteristics of large projects. Documentation in the ITER EDA will be a major and critical task, building on C. Flanagan's documentation leadership during the ITER CDA.

Technical Challenges

ITER will be a major transition from slightly radioactive machines (JET, TFTR, BPX) to something with true nuclear safety concerns. We must make that transition safely and at optimum cost. I quote from T. Kletz, page 135.[10]

"Remember that if it costs

\$1 to fix a problem at the conceptual stage
It will cost

\$10 at the flowsheet stage

\$100 at the line diagram stage

\$1,000 after the plant is built, and more than

\$10,000 to clean up the mess after the accident."

For ITER, I add another stage,

\$100,000 to resurrect the fusion program and rebuild public support for fusion after an accident - money we won't have available to spend.

Today, we are at the \$1-10 stage since there are still conceptual design questions unresolved (divertor) but most flowsheets exist (such as tritium fuel systems). After the EDA, we will be at the \$100 stage. Delays increase costs to improve ITER from the safety and environmental perspective.

Plasma engineering

There are five key plasma engineering safety issues - burn control, plasma shutdown, disruptions, tritium burn fraction, and true steady state operation. Surmounting these adequately to license ITER will require more work. (Steady state operation is not a licensing issue, but is an attractiveness issue.)

Burn control: The ITER plasma is thermally unstable in most of its modes. If burn control equipment fails, the temperature will increase until a beta limit is exceeded, triggering a worse-than-normal disruption. The fusion power and wall heat flux scale roughly as beta squared; the stored thermal energy in the plasma scales roughly as beta. Burn control work started in the CDA.[11] Now, detailed work is needed in these areas: profile-dependent studies, control theory, partial validation of the models by current tokamak experiments, equipment design, failure frequency estimates, assessment of burn control failure effects on plasma-facing components (PFC) components, and plans to recover from damage states.

Plasma shutdown: ITER will be the first tokamak combining hour-long pulses and much radioactivity.

This means that one can get into trouble during a single pulse if the plasma is not shutdown when safety demands. The divertor has little margin in handling the high heat loads even when everything is operating correctly. When coolant or burn control systems fail, the plasma must be shut down, preferably without a hard disruption. The allowable time to act depends on the exact design. The CDA assessment was that we should aim for shutdowns in about 1 s.[1] An appropriate goal would be an active system with 1 s response, backed-up with a passive safety feature with 1-5 s response. The active system would protect against machine damage (also protecting the public). If the active system failed, the passive one might not protect against machine damage, but would still keep the accident from propagating outside the divertor - thereby protecting the public. Although there have been discussions on emergency plasma shutdown,[11,12] more work is needed, as for burn control.

Disruptions: The issue of disruption tolerance is generally well known and included in R&D plans. There are two less appreciated aspects. First is the relatively high severity of disruptions caused by equipment failure, either burn control (see above) or coolant ingress. Preliminary analysis suggests that "the intensity of the disruption induced by a coolant ingress accident is from two to three times greater than a disruption that is not induced by a coolant ingress accident." [13] The second under-appreciated aspect is the feedback of PFC choice on the severity of the disruption itself.[14]

Burn fraction: The total onsite ITER CDA tritium inventory is 5.7 kg-T during the low fluence, carbon-PFC physics phase and 4.3 kg-T during the modest fluence, tungsten-PFC technology phase.[1] The reference early dose for ITER tritium is 0.5 mSv/g-T released to the environment. Given the public early dose limit of 100 mSv, the maximum tolerable tritium release is about 200 g-T. The tritium in components associated with the torus is 2.5 kg-T (physics phase) or 0.8 kg-T (technology phase) primarily because of tritium in the PFC. (Besides the PFC inventories, these torus-related inventories include tritium in systems intimately connected to the torus, such as the pellet injector and primary vacuum pumps.) The tritium in Fuel Cycle systems is about 1.6 kg-T. A robust radioactivity confinement is needed to limit the worst-case releases below 200 g-T.

My colleagues at the INEL Fusion Safety Program and I are not comfortable with the prospects of licensing ITER in this situation. Tritium inventories must be lowered by (a) increasing the tritium burn fraction, (b) optimizing the PFC material choice,[14] and (c) optimizing tritium design requirements with an innovative view (next subsection).

The ITER CDA tritium burn fraction is about 2.6%. The tritium processing system inventory (1.6 kg-T) will scale slightly less than linear with burn fraction. If we can increase the tritium burn fraction to 10% by a combination of physics parameters and engineering solutions, the 1.6 kg-T would drop to roughly 500 g-T. Also, the non-PFC portions of the torus-related tritium inventory will also scale roughly with the burn fraction. We cannot know the burn fraction with certainty, but we can start trying to optimize physics parameters with burn fraction in mind. If physics does not give us a burn fraction of 10% (or higher), engineering can help. With their colleagues, A. Livshits[15] and S. Cohen[16] suggest using permeation in the divertor/pumping duct walls to increase the effective tritium burn fraction. J. Brooks and colleagues suggest helium self-pumping,[17] to preferentially trap He on the walls of

the divertor or vacuum ports, increasing the effective tritium burn fraction. These ideas might be profitably used together.[18] We need to aggressively pursue these innovative schemes so we can use them in ITER.

Nuclear engineering

We can improve the nuclear safety characteristics of ITER while simultaneously lowering true cost. The ideas in this paper and previously suggested to improve ITER safety[19] follow the approaches that T. Kletz[10] suggests for improving chemical industrial facilities based on his long experience. Kletz notes that these approaches reduce net cost because of fewer active safety systems and less component testing.[10] Surely we in ITER are clever enough to use passive safety and user-friendly suggestions for the chemical[10] and fission[20] industries.

Divertor: In the ITER CDA, we found the highest single tritium inventory and the worst activation product hazard come from the PFC. Separately, I discuss PFC safety issues.[14] Carbon PFC leads to very high tritium inventories, 2 kg-T in the ITER CDA[1] plus more in carbon tile waste processing. During worst-case long-term LOCAs, 600 ± 100 C (first wall) and 700 ± 100 C (divertor) for 7 days,[1] C-steam reactions could produce undesirably high amounts of hydrogen gas, with explosion potential. (This adds to the short-term production of hydrogen from C-steam during the immediate cool down from operating temperatures. The CDA controlled this short-term production by limiting C operating temperatures.) Tungsten PFC leads to high activation

product mobilization during worst case LOCA's. We now know that beryllium PFC leads to significant beryllium mobilization during worst case LOCA's. And, during long-term LOCA's, Be-steam reactions could produce undesirably high amounts of hydrogen gas, with explosion potential.[14]

We do not yet have a clear solution to PFC safety issues. We must expand our attention to PFC engineering and provide a way to test post-ITER divertors in ITER. One design requirement in ITER that would help would be reduction of worst-case LOCA temperatures and durations by proper heat sinks and passive heat transfer during accidents. Estimates for worst-case LOCA temperatures vary considerably, primarily because of differing assumptions about the ultimate heat sink and heat transfer through the vacuum vessel, cryostat, and biological shield. The range of answers in current LOCA calculations suggest we may lower the worst-case LOCA temperatures by 100 C, or perhaps even 200 C.

Activation product improvements: Fig. 4 shows possible reductions in worst-case activation product doses from various improvements. Both tokamak dust and high temperature oxidation volatility (during LOCA) contribute to these doses; hence reducing either reduces the total. The CDA assessment[1] shows intolerably high early doses (4.4 Sv) during a worst-case LOCA without any credit for radioactivity confinement or filtration. Thus, ITER fails the passive safety test and needs a robust radioactivity confinement to protect the public and gain regulatory approval. The W-steam reaction dominates mobilization of activation products. Since the CDA, a new assessment of the tungsten radioactivity inventory[21] shows dose

Fig. 4. Possible reductions in activation product doses and tritium inventories

reductions. Larger reductions are possible if maximum LOCA temperatures are reduced and if the tungsten tokamak dust inventory were dropped from 10 kg-W to 1 kg-W by dust control equipment during operation. Fig. 4 shows that these improvements would lower even worst-case activation product doses to about the 100-mSv consensus tolerable limit for maximum public dose. ITER would be passively safe from the activation product standpoint.

Tritium inventory improvements: Fig. 4 also shows possible reductions in key tritium inventories. New assessment of the tritium inventory in tungsten PFC shows reductions from CDA assumptions.[22] D. K. Sze and co-workers have pointed out several non-optimum tritium design specifications.[23] The extreme isotope separation in the CDA Fuel Cycle systems does not appear needed. (It may not even be feasible.) Relaxing these requirements will reduce cost and reduce tritium inventories.[23] Based on discussions with Sze, I think full implementation of his ideas will cut Fuel Cycle inventories in half. Finally, changing the physics phase PFC material from carbon to tungsten will reduce tritium inventories. Unlike activation products, the improvements I identify here do not yet appear sufficient to reduce tritium inventories enough to make ITER passively safe from the 100-mSv ITER CDA criterion. Further innovation is needed for that. Still, these improvements would reduce the most vulnerable tritium inventories (Fuel Cycle, PFC) by an order of magnitude versus the CDA.

Phased design: The current CDA has a physics phase and a technology phase. The physics phase has carbon tiles for the PFC surface. This is to be changed to tungsten coating for the technology phase. The first wall, blanket, and shield would not be changed between phases.

There are proposals to increase the difference between phases, to change the first wall, blanket, and shield. One proposal would be to install a full size DEMO-relevant blanket for an extended operation phase (as opposed to test modules). This seems impractical. Any DEMO-relevant blanket would require some other coolant than the presently envisioned low temperature, low pressure water. Changing all the contaminated heat transport systems (coolant pipes, heat exchangers, valves, pumps) seems difficult. The safer direction would be to minimize changes between operation phases.

Blanket: The CDA safety assessment was neutral regarding the safety trade-off between breeding and not breeding.[1] Quoting from this assessment:

"Breeding tritium in ITER has the safety advantages of reducing tritium transportation shipments to the site and probably decreasing the activation/decay heat inventory. Neutrons absorbed in breeding materials are not activating steel nor generating tritium in neutron absorber materials like boron."[1] Y. Gohar informs me that new ANL analyses quantify the decay heat from a non-breeding blanket as an order of magnitude higher during the first month into a transient. A non-breeding blanket would thus have significantly higher LOCA temperatures than the CDA design.

"Breeding tritium in ITER has the safety disadvantages of increasing the tritium inventory in the blanket (especially in the beryllium multiplier), inclusion of the blanket tritium recovery system, and increased throughput in the Fuel Cycle system."[1] We now know that Be-steam reactions pose significant hydrogen generation risks in the blanket, especially if porous beryllium is used.

On balance, it is still not clear whether a breeding blanket is a safety plus or negative.

Neutron fluence: Safety hazards are not a strong function of ITER fluence. (They are a strong function of materials, e.g., tungsten versus beryllium versus carbon for PFC.) Lowering the fluence from 3 MW-yr/m² to say 0.3 MW-yr/m² would have little safety advantage, other than those related to the associated issue of including the breeding blanket. The tritium inventories would be essentially unchanged. Activation product hazards are dominated by short-lived isotopes like Re-186 and W-187 that build up quickly during machine life.

Bakeout/conditioning - helium coolant: High temperature water poses overpressure concerns within the torus and within the radioactivity confinement.[2] To control this and limit costs, the CDA strategy is to prohibit water temperature above 150 C. Thus, vacuum bakeout and conditioning at 180 C (metals) and 350 C (carbon) must be done by some way other than hot water, such as lengthy draining of the machine and replacing it with helium. (This approach invites stress corrosion cracking and delays. This strategy may fail for several reasons.) We may even need hot PFC temperatures during operation. Water temperatures exceeding 150 C would decrease machine safety, increase pressures, and increase cost. This increases the amount of steel, hence increasing cost, increasing decay heat (higher LOCA temperatures), and decreasing tritium breeding. The radioactivity confinement would turn into a pressure-tight costly radioactivity containment.

A better strategy might be to use helium during operation. Helium could provide the high bakeout/conditioning temperatures without the steam flashing problems of hot water. Helium coolant is far more reactor relevant than water - as evidenced by the clear trends in U.S. commercial fusion reactor studies. Helium coolant temperatures would be a better temperature and chemical compatibility match for solid breeders. We could use helium coolant for the first wall and blanket/shield if we provide adequate vacuum/PFC leak tightness. Going further and using helium coolant for the divertor requires solving difficult heat transfer problems.

Radioactivity confinement: Regulatory approval of ITER as presently envisioned will require a robust radioactivity confinement to limit public doses. The R&D items associated with confining fusion activation products are not in the ITER CDA R&D plans. The fusion-specific R&D needs arise from the isotope and chemical conditions unique to the ITER design.

Magnets: Another fusion-specific confinement question is magnets. The CDA magnet design philosophy is appropriate - keep any damage from offnormal events to the magnet system itself. We must plan the work to produce a solid regulatory case that offnormal magnet movement or arcs cannot fail radioactivity confinement. Similarly, we need to show that the common mode failures from such movement (breaking many coolant pipes and releasing cryogenics) are limited. Regulators will be familiar with design practices and analyses for fission radioactivity confinements. The stored energy in fusion magnets is a new issue that will invite close regulatory scrutiny.

Maintenance

Most of the time, ITER will be in some type of maintenance mode rather than normal tokamak operation. As the ITER design matures, it will be neces-

sary to assess personnel safety and potential damages from maintenance failures.

One under-appreciated personnel safety question is maintenance of ex-vessel parts of heat transport systems. The steel/water coolant systems for the first wall, blanket, and shield should be possible to maintain via manned access - as assumed in the CDA. These systems are similar to fission reactors, except for possibly higher stress corrosion from repeated bakeout/conditioning cycles. Yet, the divertor has different, exotic coolant systems - Cu/water, Nb/water, or Mo/water. Their corrosion/erosion rates are likely much higher than for steel/water. Without R&D, we cannot know that such systems can be maintained via manned access - as imprudently assumed in the CDA. Nb/water seems to have the lowest corrosion/erosion rate for the high velocity water divertor.

Effluents

The CDA safety assessment[1] showed that effluent releases to the environment can be adequately limited. However, new information suggests that tritium permeation into PFC coolants will be worse than assumed in the CDA.[11] We now expect permeation in the kCi/day range, requiring tritium removal from such water coolants. (Tritium removal from helium would probably be easier - another argument for shifting from water to helium, subject to leak-tightness and heat load resolution.)

Conclusions

The abstract at the beginning of this paper already summarizes the conclusions. There are challenging times for any large, radioactive project. Dedicated team work, involving the entire ITER community, will make ITER succeed. If we meet the challenges described in this paper, we will improve the climate for innovation and solving technical challenges. We will also be assembling the tools to walk through the difficult regulatory minefield toward ITER approval.

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ITER SAFETY CHALLENGES AND OPPORTUNITIES

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Abstract/Summary

Results of the Conceptual Design Activity (CDA) for the International Thermonuclear Experimental Reactor (ITER) suggest challenges and opportunities. "ITER is capable of meeting anticipated regulatory dose limits," [4] but proof is difficult because of large radioactive inventories needing stringent radioactivity confinement. We need much research and development (R&D) and design analysis to establish that ITER meets regulatory requirements. We have a further opportunity to do more to (a) prove more of fusion's potential safety and environmental advantages and (b) maximize the amount of ITER technology on the path toward fusion power plants.

To fulfill these tasks, we need to overcome three programmatic challenges and three technical challenges. The first programmatic challenge is to fund a comprehensive safety and environmental ITER R&D plan. Second is to strengthen safety and environment work and personnel in the international team. Third is to establish an external consultant group to advise the ITER Joint Team on designing ITER to meet safety requirements for siting by any of the Parties.

The first of three key technical challenges is plasma engineering - burn control, plasma shutdown, disruptions, tritium burn fraction, and steady state operation. The second is the divertor, including tritium inventory, activation hazards, chemical reactions, and coolant disturbances. The third technical challenge is optimization of design requirements considering safety risk, technical risk, and cost. Some design requirements are now too strict; some are too lax. Fuel cycle design requirements are presently too strict, mandating inappropriate T separation from H and D. Heat sink (vacuum vessel, cryostat, biological shielding) requirements are presently too lax; they should be strengthened to ensure that maximum loss of coolant accident (LOCA) temperatures drop.

"Iter" means "the way" in latin. ITER must be "the way" toward fusion's future. Considering current physics machines, the Burning Plasma Experiment (BPX), a nonnuclear steady state tokamak (SST), and a 14-MeV neutron source, ITER must still provide about half the safety and environmental understanding to make a demonstration fusion power plant (DEMO) attractive from the safety and environmental standpoint.

Introduction

This paper discusses the opportunities ITER presents us in safety and environment and the major challenges with some thoughts on overcoming them. Complete [1,2] and summarized [3,4,5] safety assessments of the ITER CDA design exist. Rather than duplicate them, I pursue the general picture and most critical future opportunities and challenges. I want to persuade you to increase your attention and commitment to improve ITER from the safety and environmental perspective.

The next section details ITER's opportunities in working toward fusion's excellent safety and environmental potential. Then, I discuss ITER's challenges in two parts - programmatic and technical.

ITER Opportunities

When we make ITER successful, imagine what a powerful step it will be toward making fusion a keystone of mankind's energy supply. Consider a potential future newspaper editorial:

"ITER SUCCESS SHOWS FUSION ENERGY IS SAFE AND CLEAN"

(where?, 2015) In a press release today, the ITER project noted 10 years of successful operation of the world's first nuclear fusion reactor. Although ITER does not produce electricity, its operation shows that fusion reactors can be operated safely. Radioactive tritium fuel has been successfully confined. Tests with ITER show no hazard from meltdowns or runaway nuclear reactions. ITER engineers say that the upcoming fusion demonstration power plant will be even safer since it will be built with low activation materials recently developed. These new materials will reduce the amount of waste by allowing recycle of most materials.

We and our successors can accomplish this, but it will not be easy. Fusion power plants should be passively (or inherently) safe, with minimal effluents, and with waste managed by recycling and near-surface burial. [6,7] To go where we want to go, we have to examine ITER's general role toward fusion power plants.

ITER's role in answering major technical questions

ITER's success is a necessary, but insufficient condition to allow fusion to provide energy for our children and grandchildren. The four main magnetic fusion technical issues show that ITER has an essential role in fusion development.

1. Confinement physics and engineering
2. Burning plasma
3. Fusion nuclear technology
4. Fusion nuclear materials

Each of these issues contains several safety and environmental aspects. ITER has a role in resolving each, but its role in fusion nuclear technology cannot be transferred elsewhere. Such a transfer would mean building another machine between ITER and a DEMO.

Between now and DEMO, the U.S. plans to have these major projects - existing physics machines, BPX, a nonnuclear steady-state superconducting tokamak (SST), ITER, and a high-fluence 14-MeV neutron source. [8] Fig. 1 shows how I think these projects should contribute to providing the understanding sufficient to make the DEMO fusion power plant attractive from the safety and environment standpoint. Fig. 1 tries to account for the information to be gained from associated smaller support facilities. Later parts of the paper detail the safety issues.

The fusion community needs a special effort to learn as much safety and environmental information as possible from existing physics machines. This is

SAFETY AND ENVIRONMENTAL ISSUE

- Provide burn control and passive plasma shutdown
- Control disruptions, including runaway electrons
- Provide high tritium burn fraction in plasma
- Demonstrate true steady state operation (lower failure rates)
- Develop and demonstrate attractive divertor
- Develop and demonstrate attractive blankets
- Resolve worst-case magnet movement concerns
- Design a passively (or inherently) safe power plant
- Develop Low Activation Materials
- Demonstrate tolerable tritium inventory and control
- Demonstrate tolerable operational effluents
- Demonstrate tolerable personnel doses
- Develop decommissioning and decontamination practices, including waste recycling and near-surface burial
- Evolve appropriate safety and environment regulatory approach

PROJECTS' CONTRIBUTIONS

Fig. 1. Projects' contributions to providing understanding sufficient to make the DEMO attractive from the safety and environmental standpoint

especially true once JET and TFTR use tritium. Strong magnets, especially the superconducting magnets in Tore Supra and T-15, should help us start to resolve the issues of offnormal magnet movement and arcs. Such occurrences threaten radioactivity confinement and provide an undesirable common cause failure.

Future physics machines, BPX and SST, will extend the safety information provided by current machines. A 14-MeV neutron source will help develop advanced materials, especially low activation materials. Fig 1. includes some double counting: the 14-MeV neutron source will help work toward passively safe power plant via developing low activation materials.

Even optimistically considering what these projects can provide, there is still a tremendous safety and environmental role for ITER. ITER bears roughly half the responsibility of getting from where we are to where we have to be for a DEMO. No other machine will combine near-reactor-scale plasmas, superconducting magnets, modest neutron fluence (1-3 MW-yr/m²), and significant nuclear test volume (> 10 m³). If the final ITER design lacks one or more of these basic features, we will need yet another machine before an attractive DEMO.

For example, one cannot depend entirely on a 14-MeV neutron source to develop advanced low activation materials. Such a source will have low test volume and high fluence, but probably not have an exact D-T fusion neutron spectrum. It will provide end-of-life radiation damage data, such as the onset of breakaway swelling. We also need the complementary testing capabilities of ITER with higher test volume

and modest true fusion fluence. Versus a 14-MeV neutron source, ITER would allow tests of more candidate alloys and provide a definitive comparison between non-fusion-plasma neutrons and other neutron testing environments. We need materials testing in both ITER and in a 14-MeV neutron source.

Where does ITER stand versus its safety role?

Fig. 1 shows what ITER should contribute, but how are we doing? Fig. 2 shows a mixed picture. At 1-3 MW-yr/m² fluence, ITER should provide most of what we need from it for blanket testing and advanced materials. The CDA design blanket test volume is less than what the test planners really want and need. Therefore, Fig. 2 shows that ITER's fulfillment of blanket and materials testing is only 90%

Some areas have not received adequate attention, including how to test advanced post-ITER divertors in ITER, what the personnel doses and safety would be, and how to decommission and decontaminate ITER.

Plasma engineering safety issues have not received sufficient attention. These include burn control, offnormal plasma shutdown, disruption control, tritium burn fraction, and true steady state operation. Steady state operation is a safety issue because it promotes lower failure rates.

Fig. 2 shows my judgement of ITER improvement if current design and R&D trends continue. The physics R&D plans, if fully funded and implemented, would put ITER where it should be in most of the plasma engineering safety areas. Still, the "voluntary" nature of

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