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The Impact of Disruptions on the Economics of a Tokamak Power Plant

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Abstract — *Tokamaks are often considered to be a leading candidate for near-term, cost-effective fusion energy, but these devices are susceptible to sudden loss of confinement events called disruptions. The threat of disruptions has garnered serious attention in research for the next generation of burning plasma experiments, such as ITER, but has received little treatment in economic studies of magnetic fusion energy. In this paper, we present a model for quantifying the effect of disruptions on the cost of electricity produced by a tokamak power plant (TPP). We outline the various ways disruptions increase costs and decrease revenues, introduce metrics to quantify these effects, and add them to a levelized cost of electricity (LCOE) model. Additionally, we identify several rate-limiting repair steps and introduce a classification system of disruption types based on the time to return to operations. We demonstrate how the LCOE model can be used to find the cost of electricity and the requirements for disruption handling of a TPP, and we further highlight where future research can have a strong impact in neutralizing the "showstopping" potential of disruptions.*

Keywords — *Tokamak, economics, disruptions.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

The tokamak is widely considered one of the most promising paths to near-term fusion energy, as illustrated by the global cooperation on the ITER project,[1] various national efforts (notably STEP[2] in the United Kingdom and CFETR[3] in China), and private sector ventures, such as Commonwealth Fusion Systems[4] and Tokamak Energy.[5] The tokamak fusion energy pathway typically is described as a near-term burning plasma experiment (for example, ITER and SPARC), followed by a prototype fusion pilot plant (for example, DEMO and ARC) that will culminate in a viable tokamak power plant (TPP) using a deuterium and tritium (D-T) fuel cycle.

Questions remain about whether the next generation of experiments will retire the risk of disruptions, a potential showstopper for TPP viability. Disruption is a catch-all term for instances when the plasma confinement is catastrophically lost, resulting in a fast dissipation of the plasma's thermal and magnetic energy into the surrounding vessel and structure of the machine. Other magnetic fusion concepts can also experience sudden loss of confinement events like disruptions,[6] but the threat is acute for TPPs because of the relatively large current and thermal energy carried by the plasma in power plant–scale devices (>15 MA and >1 GJ for DEMO[7] and 7.8 MA and 0.13 GJ for ARC).[8] These events are benign in small tokamaks with little stored energy, but they can occasionally cause material degradation in high-performance devices.[9]

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Disruptions are not rare. A study of discharges from JET (which operates $\approx$40s-long discharges) between 2011 and 2016 found unintentional disruptions ended 16% of all discharges.[9] For higher-performance discharges, the figure was nearly 50%, while for low-performance and commonly run scenarios, this was about 3%.[9] A more recent study of the 2019 to 2020 JET campaigns found a disruption rate of 32% for high-performance discharges.[10] The disruption rate per shot in ITER for high-performance discharges will need to be far lower, because in the absence of emergency disruption mitigation actions, a single disruption might cause irreparable, mission-ending damage.[11] The challenge for ITER is exacerbated by the 12× to 15× longer pulse length compared to JET, which dramatically increases the time over which the control system must succeed. Disruptions in TPPs are unlikely to pose a threat to human life, but they could render TPPs unprofitable.

There is little prior work studying how the presence of disruptions will affect the viability of commercial fusion power. Fusion pilot plant scoping studies, such as for the ARC,[8] ARIES-AT,[12] advanced compact tokamak,[13] and DEMO[14] concepts, acknowledge the significance of disruptions and discuss the distance to disruptive limits, but they do not address the effect of disruptions on the economics of the concept.

Over the past several years, some authors have attempted to draw greater attention to the disruption problem for TPPs. Boozer has highlighted the difficulty of anticipating disruptions, controlling burning plasmas, mitigating disruptions, and finding a compromise between disruption-resilience and tritium production goals for TPPs.[15,16] Eidietis summarized the state of disruption research, probed the additional disruption handling challenges faced by TPPs, and discussed a few novel proposals for a disruption resilient design.[17] A key emphasis of the Eidietis paper is that research for disruption handling must take the same priority as plasma core performance and heat extraction.

Despite concerns about disruptions among physicists, quantitative economic analyses of magnetic fusion energy[18–25] almost universally ignore these phenomena. Parsons showed that the data-driven disruption predictors available today are likely accurate enough to reduce costs for future TPPs,[26] but did not address how much of a cost reduction is needed for TPPs to be competitive economically. Qualitative analyses of the potential role of fusion energy in decarbonizing or decarbonized energy grids also make no mention of disruptions.[27,28] The only published economic analysis involving disruptions is from Takeda et al., which simulated the revenue generated by a single DEMO-like power plant using historical data from a U.S. energy market between 2011 and 2015.[21] That paper's findings are not broadly applicable because of its unrealistic model for disruption effects (a random 10-day outage), the specific choice of a DEMO-like TPP, a speculative tokamak plant cost model, and the reliance on data from the 2010s to project the economic performance of a TPP in the future.

In this paper, we present a quantitative model for the cost of electricity from a TPP as a function of the disruption rate and other disruption-related parameters. Section II describes the general characteristics of the disruption handling problem in a TPP. In Sec. III, we adapt the widely utilized levelized cost of electricity (LCOE) model to explicitly include disruptions, and in Sec. IV we derive the relevant metrics. In the process of deriving these metrics, we present a categorization system for disruptions based on the rate-limiting recovery steps and timescales to return to operation for a TPP. Section V illustrates how this model can be used to identify disruption handling requirements for a hypothetical TPP and identifies areas where research today could have the most impact in addressing the disruption problem. Finally, Sec. VI summarizes the findings and underlines the need for further research related to disruption handling.

II. DISRUPTION HANDLING IN A TPP

As stated earlier, disruption is a generic term for the sudden, rapid loss of confinement in a tokamak. A variety of mechanisms can cause disruptions, including magnetohydrodynamic instabilities, human error, and pieces of the wall falling into the plasma. These various contributing factors can interact with one another in nonlinear ways, eventually resulting in a macroscopic instability that destroys the nested magnetic surfaces that confine the plasma. Modern, high-performance, elongated plasmas require both passive and active stabilization. As we will show, disruption handling will be significantly more challenging for TPPs compared to today's tokamaks.

Disruption handling can be decomposed into four pillars: avoidance, mitigation, resilience, and recovery. Disruption avoidance will be a much different problem than that experienced in current tokamaks because TPPs will operate in just a single, thoroughly modeled state (or small set of states) with a significantly more challenging control environment (for example, strong plasma self-organization and fewer diagnostics). This creates reasons for both optimism and pessimism. Moving from today's avoidance challenges to those faced by a TPP will not be a difference in degree but a difference in kind.

If a disruption cannot be avoided, three events happen in succession: the thermal quench (TQ), current quench (CQ), and runaway electron (RE) phase, as shown in Fig. 1. The stochasticization of the magnetic field lines during disruptions causes rapid (≈ 0.1 to 10 ms) transport of heat from the plasma to the wall.[29] Plasma-facing components (PFCs) can experience an extreme heat flux (up to ≈ 1 GW/m^2[30]) that erodes solid tiles in the divertor and launches debris into the chamber. The dynamics of the TQ are not well understood, but this phenomena will likely remain a major threat for TPPs because of the large thermal energy density of the plasma ($\approx$ MJ/m^2 of surface area) and short TQ duration ($\approx$ ms) expected on these devices.[8,31]

After the TQ, the remaining "cold" ($\approx$ eV) plasma has a much greater resistance (resistivity goes as $T^{-3/2}$). The current drive sources cannot maintain the current in this vastly higher resistance regime, resulting in a sharp decay of plasma current, referred to as the CQ. Ideally, the current is dissipated as thermal energy via ohmic heating, which is slowly radiated, convected, or conducted out of the plasma. The timing of the CQ is critical, however; a CQ that proceeds too fast or too slow results in $\mathbf{j} \times \mathbf{B}$ forces in the PFCs and vacuum vessel (VV) via eddy currents or halo currents,[32] respectively. These forces (potentially up to MN on ITER[33]) are capable of causing enormous stress far beyond standard operating conditions.

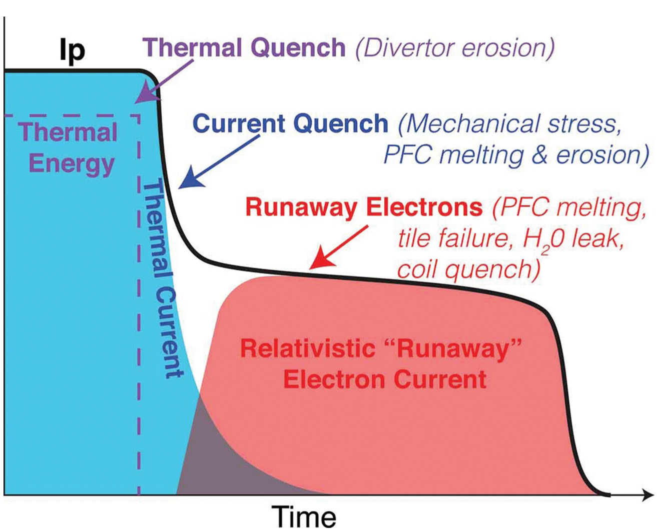

Fig. 1. The three phases of a typical disruption in a high-performance tokamak shown in terms of the thermal energy (purple), total plasma current (black), ohmic/thermal plasma current (blue, shaded) and RE current (red, shaded) (courtesy of Ref. [17]). The vertical axis is shared by both current and thermal energy.

In some cases, the toroidal current does not completely dissipate and instead concentrates in a high-energy beam of electrons traveling at relativistic speeds. REs can cause minor damage to PFCs in today's high-performance devices, but are considered by some to be the greatest threat to next-generation tokamaks because of their potential to damage the device (melt PFCs, puncture cooling systems, and damage the magnetic coils) coupled with the lack of experimentally proven solutions to the problem.[17]

One can attempt to mitigate the damage of disruptions by preemptively injecting a large amount of cold matter into the plasma to rapidly cool the discharge via dilution or radiation. Unfortunately, the disruption mitigation strategy for ITER is still under development[34] because it has been found to be difficult to simultaneously address the consequences of the TQ, CQ, and RE phase.

Ideally, a TPP would be designed to be completely resilient to disruptions, but it is unknown if this is possible. Although the total stored energy in TPPs is not very large compared to the thermal capacity of the surrounding material, the timescales of the TQ, CQ, and RE beam impact can be extremely quick. More work is needed to demonstrate that TPP concepts in the literature provide the required structural integrity, heat transfer characteristics, and tritium breeding ratio in a cost-effective manner. This challenge is exacerbated by imprecision in current models of disruption consequences, especially for TQ heat flux.

Finally, disruption recovery will not be trivial in a TPP. The superconducting magnets and the nuclear environment inside the VV necessarily add significant complications to any recovery action. We will show in Sec. IV.A.2 that even modest repairs could take weeks.

Now that we have clarified the challenge of disruption handling on a TPP, we will introduce a model for quantifying the effect of these phenomena on the cost of electricity.

III. ASSESSING THE IMPACT OF DISRUPTIONS ON FUSION ELECTRICITY COST

The LCOE is a commonly used metric for estimating the average revenue per unit of electricity required for a power plant to break even on all investment and operational costs. More precisely, the LCOE is the discounted sum of costs over the power plant's lifetime divided by the discounted sum of electricity sold during that time,

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} (I_t + M_t + F_t)(1+r)^{-t}}{\sum_{t=1}^{n} E_t(1+r)^{-t}} \quad , \tag{1}$$

where

n = total plant lifetime in years from the beginning of construction to end of decommissioning

I_t = investment cost during year t

M_t = operations and maintenance (O&M) cost

F_t = fuel cost

r = discount rate (the annual rate at which the future value of money is adjusted relative to the present value to account for the time value of money, e.g., interest rates, opportunity costs, etc.)

E_t = annual electrical energy production.

The LCOE does not account for taxes, externalities, "imbalance fees" imposed when a power plant fails to complete an electricity production contract, and variations in energy production within a year. Nevertheless, it provides a helpful estimate of the average cost of electricity required for the plant to be economically viable.

We parameterize the LCOE to account for disruptions as

$$\mathrm{LCOE}_{\mathrm{disrupt}} \approx \frac{\sum_{t=1}^{n} (\boldsymbol{k_{I,t}} I_t + \boldsymbol{k_{M,t}} M_t + F_t)(1+r)^{-t}}{\sum_{t=1}^{n} E_t (1+r)^{-t} (\boldsymbol{f}_{\mathrm{cons}})(\mathbf{1} - \boldsymbol{f}_{\mathrm{recov}})(\mathbf{1} - \boldsymbol{P}_{\mathrm{damage}}(\boldsymbol{T}(\boldsymbol{t})))} \quad , \tag{2}$$

with the capital cost scaling factor $k_{I,t}$, O&M cost scaling factor $k_{M,t}$, fraction of electrical power produced at the more conservative operating point f_{cons}, fraction of operating time lost due to disruption recovery actions f_{recov}, total amount of the time by the end of year t that the tokamak has been in operation $T(t)$, and probability that by year t the plant will have been forced into an early shutdown due to disruptions $P_{\mathrm{damage}}(T(t))$. The new terms have been emphasized in bold. The only costs not affected by disruptions are the fuel costs, which are likely negligible relative to the capital and O&M costs of a TPP.[20]

The disruption-aware LCOE equation [Eq. (2)] includes a capital cost multiplication factor $k_{I,t} \geq 1$ and an O&M cost multiplication factor $k_{M,t} \geq 1$. We catalog the ways disruptions can increase both capital and O&M costs in Table I. It is difficult to estimate the likely range of these multipliers because no TPP design study has seriously factored disruption handling into its concept. This is a key area of uncertainty for the LCOE of TPPs.

IV. EFFECT OF REDUCED REVENUES

Disruptions reduce revenues in three primary ways, as summarized in Table II. We consider each in turn.

IV.A. Reduced Electricity Production Because of Outages

IV.A.1. Modeling the Effects of Outages

Disruptions will cause outages in energy production. These outages can be smoothed by onsite energy storage, but the total volume of electricity sold per unit time during that year will decrease. The relevant metric for this effect in the disruption-aware LCOE model is the fraction of lost operating time due to disruption recovery, f_{recov}.

Utilities will almost certainly require a TPP to have relatively little operational time interrupted by disruption-induced outages.[20] Failure rates in most industrial applications typically follow one of four trends over time: flat, increasing, decreasing, or "bathtub-shaped" (i.e. relatively high failure rates early and late in life). For a TPP, machine aging could cause disruption rates to increase over time, but more operator experience could counteract this effect. Until we have empirical evidence from running a TPP, it is unclear what the trend will be in practice. For simplicity and tractability, we will assume a constant disruption rate over time.

To estimate the fraction of planned operational time lost due to disruption recovery on average, we model the change in population of operational TPPs N_{op} and TPPs recovering from disruptions N_{recov} as

TABLE I

Metrics Capturing the Increased Capital and O&M Costs for a TPP in the Disruption-Aware LCOE Model and Contributing Factors*

Metric	Definition	Factors Increasing Costs
k_I	Capital cost scaling factor	More resilient structure, PFCs Greater insurance costs Added regulatory burden More capable actuators Complex disruption mitigation system Increased tritium breeding capability Added diagnostic costs Remote inspection and/or repair systems Software complexity
k_M	O&M cost scaling factor	Additional systems to maintain More rigorous inspections Higher labor, material, and equipment costs

*For the disruption-aware LCOE model, see Eq. (2).

TABLE II

Three Metrics Quantifying the Reduction of Revenues Caused by Disruptions as Utilized in the Disruption-Aware LCOE Model*

Metric	Definition	Factor Reducing Revenues
f_{recov}	Fraction time spent on recovery	Less electricity sold during outages
P_{damage}	Probability of early shutdown	Shortened plant life due to disruptions
f_{cons}	Fraction electrical power from conservative plasma	More conservative plasma produces less electricity.

*For the disruption-aware LCOE model, see Eq. (2).

$$\dot{N}_{\mathrm{op}} = -pN_{\mathrm{op}} + \frac{N_{\mathrm{recov}}}{\langle\tau_{\mathrm{recov}}\rangle} \tag{3}$$

$$\dot{N}_{\mathrm{recov}} = pN_{\mathrm{op}} - \frac{N_{\mathrm{recov}}}{\langle\tau_{\mathrm{recov}}\rangle} \ , \tag{4}$$

where p is the probability of disruption per unit time and $\langle\tau_{\mathrm{recov}}\rangle$ is the average recovery time. This system of coupled ordinary differential equations approaches a steady state of one TPP operational for every $p\langle\tau_{\mathrm{recov}}\rangle$ undergoing unscheduled maintenance due to a disruption. Therefore, the fraction of operational time we expect any given TPP to spend recovering from disruptions is approximately

$$f_{\mathrm{recov}} = \frac{p\langle\tau_{\mathrm{recov}}\rangle}{1 + p\langle\tau_{\mathrm{recov}}\rangle} \ . \tag{5}$$

If we require that a TPP spend relatively little time recovering from disruptions ($p\langle\tau_{\mathrm{recov}}\rangle \ll 1$), Eq. (5) can be simplified to $f_{\mathrm{recov}} \approx p\langle\tau_{\mathrm{recov}}\rangle$. We plot f_{recov} in Fig. 2 over a range of p and $\langle\tau_{\mathrm{recov}}\rangle$. In terms of the LCOE, we account for outages by multiplying the volume of electricity per year by $1 - f_{\mathrm{recov}}$.

Separate from the LCOE model, we can identify an upper limit on allowable disruption rate given $\langle\tau_{\mathrm{recov}}\rangle$ and a maximum tolerated fraction of operating time spent on disruption recovery $f_{\mathrm{recov,max}}$ (where $f_{\mathrm{recov}} \le f_{\mathrm{recov,max}} \ll 1$). This can be useful in exploratory studies where a full LCOE model is unnecessary but $f_{\mathrm{recov,max}}$ can be estimated.

For example, consider a DEMO-like TPP with a 4-month-long maintenance time.[35] Let us assume we can tolerate up to $f_{\mathrm{recov,max}} = 10\%$, which is comparable to 3% to 6% the unplanned capability loss factor of the world's nuclear power industry,[36] and further assume 95% of disruptions are correctly predicted and perfectly mitigated (meaning that maintenance is only required after an unmitigated disruption). In this scenario, the 4 months of unscheduled maintenance is only needed on average once per 20 disruptions, averaging out to a recovery time per disruption of $\langle\tau_{\mathrm{recov}}\rangle = 0.2$ months. Applying Eq. (5) leads to a disruption rate limit of $p < 6.67$ year^{-1}, which for reference is about five orders of magnitude lower than the disruption rate on JET, $p \approx 5 \times 10^{-5}$ year^{-1}. This provides a concrete target for TPP design optimization. In Fig. 3, we plot the maximum allowable disruption rate for a range of $f_{\mathrm{recov,max}}$ and $\langle\tau_{\mathrm{recov}}\rangle$.

IV.A.2. Classes of Disruption Responses

Not all disruptions will require the same recovery steps. A list of possible steps needed to restart a TPP after a disruption is shown in Table III, along with approximate timescales based on a conservative extrapolation from today's technology and practices. These actions are listed in the approximate order of occurrence.

Given the order of steps needed to do various repairs, the combinations that can be done in parallel, and the timescales for these steps, we propose a classification system for disruptions based on one or two rate-limiting recovery steps in each case. These are shown in Table IV.

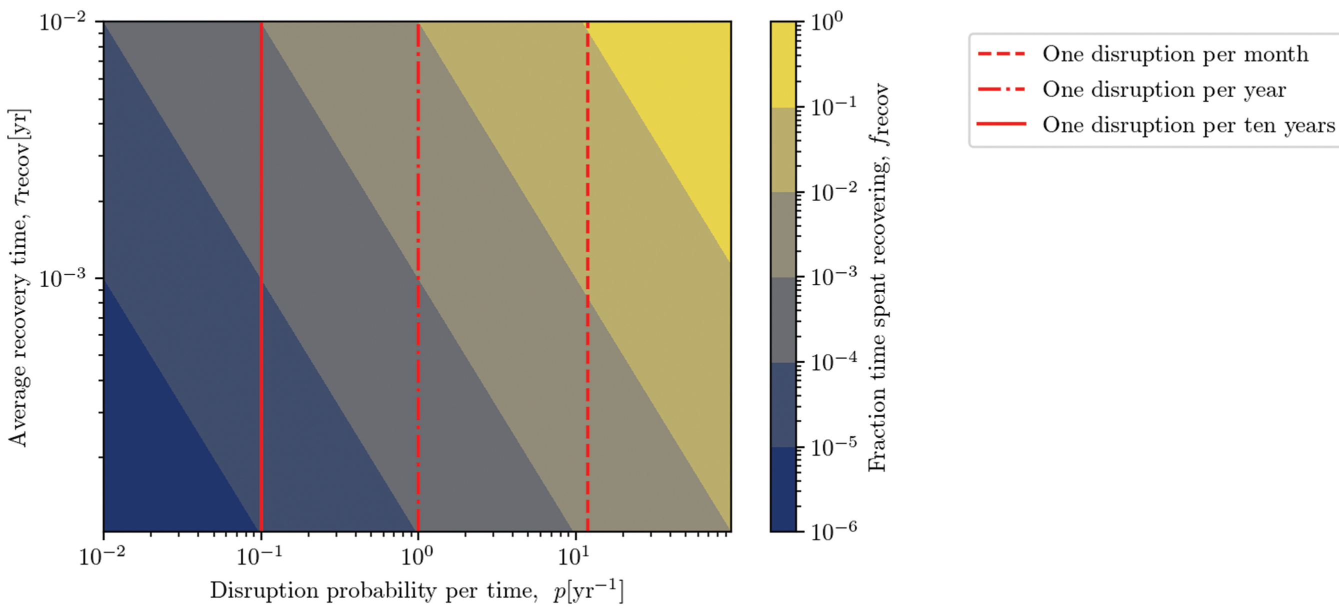

Fig. 2. Expected fraction of operation time lost to disruption recovery f_{recov} of a TPP based on the approximation of Eq. (5).

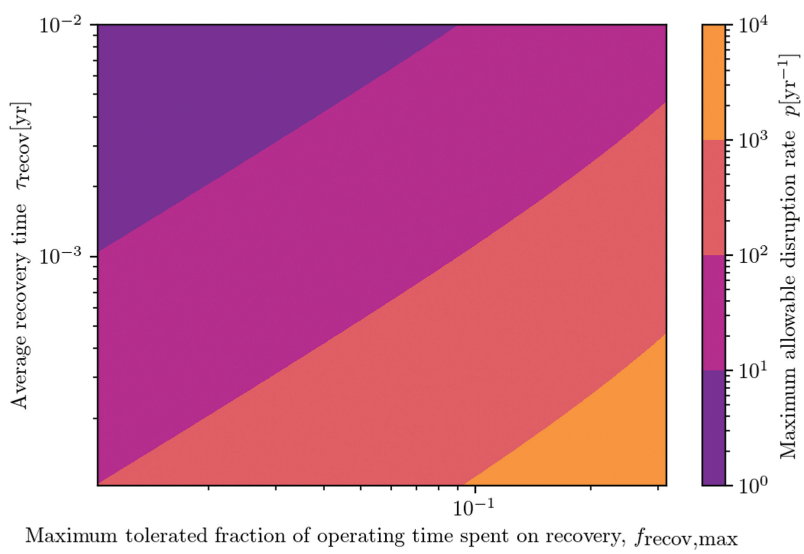

Fig. 3. Maximum allowable disruption rate p of a TPP over a range of a tolerated fraction of downtime $f_{recov,max}$ and average disruption recovery time $\langle\tau_{recov}\rangle$. Note that each color represents a range of disruptions rates spanning an order of magnitude.

The timescales are all approximate, but the rate-limiting steps have significant scale separation.

IV.A.2.a. Class A: Immediate Restart

In the best case scenario, the disruption is avoided by a safe shutdown, leaves no lingering damage, and the cause of the disruption is both immediately identifiable and correctable. This is represented in Table IV as a Class A disruption response. Under these hypothetical circumstances, the discharge could be restarted in as little time as it takes the current drive system to be reset.

IV.A.2.b. Class B: Damage Assessment and/or Wall Conditioning

Given the threat disruptions pose to the device's health and the limited diagnostic set, it is unlikely that a TPP operator would be willing to risk a Class A immediate restart. Melting, crack formation, or deformation of the PFCs caused by a disruption could lead to more disruptions in subsequent

TABLE III

Potential Steps After a Disruption Listed Along with Approximate Timescales Based on Current Technology and Practice*

Recovery Step	Limitation(s)	Approximate Timescale
Current drive system reset	Engineering design, pulse length	Minutes
PFC cool down	Cooling power	<Minutes
RCA	Complexity of device, human validation	Days to weeks
Radiation cool down	Activation of interior, shielding of remote systems	Minutes to years
In-vessel inspection	Engineering design	Minutes to hours
Remove impurities, excess gas in VV	Baking time, operating temperature	Hours
Charge/recharge TF magnets	Heat exchange capacity, magnetic energy, L/R time, tolerated temperature gradient	Hours (insulated magnets) or weeks (noninsulated)
Thermal cycle of cryostat	Heat exchange capacity, tolerated temperature gradient, thermal inertia	Weeks
Implement, certify software fix	Software engineering and validation	Days to weeks
Ex-VV maintenance	Accessibility of cryostat, activity of device	Days to ∞
In-VV maintenance	Engineering design of remote system, PFCs	Hours to ∞

*Not all of these actions are required after a disruption, and some can be done in parallel.

TABLE IV

Classification of Disruption in a TPP-Based Response Timescale*

Class	Response	Recovery Time (τ_{recov})	Main Constraint(s)
A	Immediate restart	Minutes	Current drive system reset
B	Damage assessment, wall conditioning	Hours	Radiation and temperature cool down, “cleaning” discharges
C	RCA	Days	Human validation
D	Minor repairs	Weeks	Simple remote repair, charge/recharge magnets
E	Significant repairs	Months	Warm/cool cryostat, remote repair
F	Major repairs	Years	Repair major components
G	Early plant closure	∞	Irreparable damage

*The class of recovery caused by a particular disruption depends on the characteristics of the predisruption plasma state, tokamak design, mitigation system design, and disruption dynamics.

plasma operation via uncontrolled impurity accumulation or injection events. A TPP could find itself in a vicious cycle where damaged PFCs lead to more frequent disruptions, which further worsens the wall condition until the TPP can no longer sustain a stable burning plasma.

Therefore, the TPP operator would want a way to inspect the damage after a disruption. This could be done in one of two ways: low-energy plasma operation and optical sensing. The first approach entails running low-energy and low-current discharges in a variety of configurations (limited, diverted with variable strike point) and detecting correlations between the location of heat load deposition and variations in impurity levels. The power and current of the discharges could be carefully stepped up in subsequent discharges as confidence grows in the condition of the PFCs. The downside of this approach is that damage may only become apparent during high-power and high-current discharges.

Optical inspection techniques could also be used to check the PFC conditions. Two examples of such systems are the 8-m-long articulated inspection arm deployed on WEST between discharges[37] and the in-vessel viewing and metrology system (IVVS) under development for ITER.[38] The latter is designed to provide measurements of surface erosion down to the 0.1-mm scale via laser metrology.

The challenge for the optical inspection systems is the presence of both a high dose rate in the vessel due to activation and the strong toroidal field (TF). Articulated inspection robots with cameras have been demonstrated to tolerate up to a $\approx$ 1000-Gy dose and dose rates up to $\approx$ 70 Gy/h,[39] but this will likely not be appropriate for a TPP with metal walls, which will have dose rates >1000 Gy/h in the vessel immediately after shutdown and remain above >100 Gy/h for a year or longer.[40,41]

The IVVS system is a promising model for TPP in-vessel inspection because it is more radiation resistant. Tests of the piezoelectric motor have shown no degradation with a dose rate up to 2.5 kGy/h and a total dose of almost 5 MGy.[42] The IVVS is also compatible with a strong toroidal field, which might prove a challenge for articulated robots, but this device may not be able to detect smaller features such as narrow cracks. For the sake of concreteness, we will assume that an IVVS-like remote inspection system can be designed to deploy and retract on the order of hours after the disruption occurs in order to complete a damage assessment.

Another source of potential delay in recovering from a disruption is wall conditioning. After a disruption, impurities can be implanted or adsorbed into the walls. These impurities can leak out when the wall heats up during a subsequent discharge, either degrading the plasma performance or causing another disruption. Wall conditioning for ITER will be accomplished by running specialized cleaning discharges.[43] Nonstandard cleaning discharges will be needed for tokamaks with superconducting magnets because traditional baking and glow discharge cleaning techniques are not compatible with energized TF magnets.[44] This cleaning challenge in TPPs may be mitigated by their high wall temperature, which helps desorb impurities. We wrap the inspection and cleaning steps into the Class B disruption response in Table IV.

IV.A.2.c. Class C: Root Cause Analysis

Post-disruption recovery could also be delayed by the time it takes to complete a root cause analysis (RCA). Given the complexity of the TPP's autonomous plasma controller and limited in-vessel diagnostics, it is unlikely that the cause of the disruption will be immediately identifiable and correctable. In the best case scenario, the RCA finds that no fixes are needed until the next maintenance period. We guess that these analyses would take on the order of days to complete and be certified by upper management. This appears as a Class C disruption response in Table IV. This delay could shrink to hours given sufficient diagnostic coverage and streamlined procedures, but it could extend to weeks if the validation procedures are cumbersome.

IV.A.2.d. Class D: Minor Repairs

In-vessel maintenance would be required if damage accumulates and/or if a faulty in-vessel component is causing disruptions. This is included as a Class D disruption in Table IV. As with remote inspection, this task is challenging because of the temperature, radiation, ultra-high vacuum, and magnetic field.[45] It may be possible to design robotic systems that could operate in such conditions using actuators, such as hydraulics, piezoelectric motors, and cable systems, but such a design would likely force compromises that have not yet been explored in detail. In-vessel components would need to be codesigned with the limited manipulation capabilities of the robot in such an environment.

The current generation of remote maintenance technology, such as those used in JET[46] and those to be deployed for ITER,[38] cannot operate while the TF magnets are charged. Magnet discharge time can be relatively quick for insulated TF magnets if a large power supply voltage is utilized. Simulations of the ITER toroidal field coils finds charging times on the order of 1 h.[47,48] Similar timescales have been achieved on KSTAR.[49] Noninsulated magnets, by contrast, have far longer charging times due to the radial current path. Power supply voltages above a volt or two drive radial currents that produce large amount of joule heating, potentially leading to a quench. This challenge is significant for TPP-scale noninsulated TF magnets because of the time scales with the linear size to the fourth power.[50] The charge time could be reduced by increasing the heat exchange capacity of the magnets and cryoplant, reducing the L/R time of the magnets, tuning radial resistance in situ, and intentionally quenching the magnets at some significant fraction of the original current.

IV.A.2.e. Class E: Significant Repairs

The recovery time could potentially stretch to months if the repairs require that the cryostat go through a temperature cycle. The large thermal inertia of tokamaks causes the cycle time of superconducting tokamaks such as KSTAR[51] (and likely ITER as well[52]) to take weeks. The main limiting factor to warm-up and cool-down times for the TF magnets

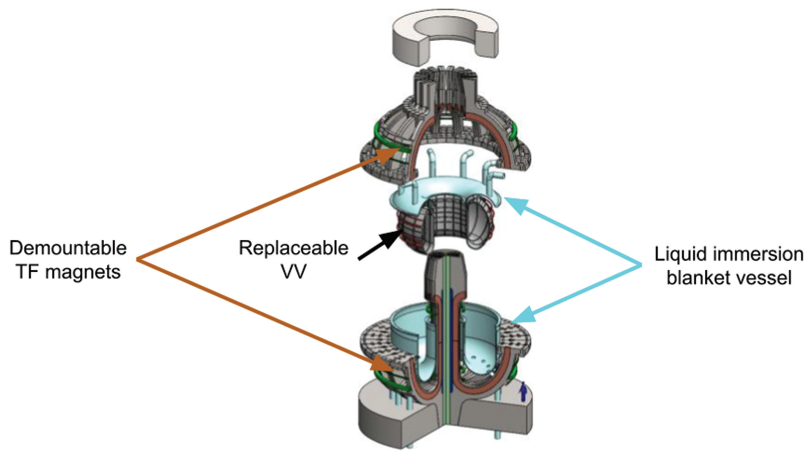

Fig. 4. ARC-class tokamak designs utilize demountable TF coils, a drainable liquid immersion blanket, and a replaceable VV (adapted from Ref.[8]). These innovations could speed up repair timelines by enabling easier access to the interior of the TF cage, however they remain at early stages of technological development.

is the stress due to differential thermal expansion. Therefore, one could hasten the thermal cycle times by designing the magnets to tolerate larger thermal gradients, adding cooling channels, and increasing cooling/warming power capacity. Optimizing these factors to minimize the thermal cycle time of superconducting magnets will require tradeoffs with respect to other magnet and cryoplant goals that have not been fully explored.

The remote maintenance systems deployed on JET[46] and that are in development for ITER[38] are quite sophisticated, but still lack the capability and speed of a human worker. Remotely replacing the PFCs in JET required a 16-month shutdown with 18-h shifts running 7 days a week.[53] Replacing all the blanket modules in ITER could take up to 2 years[38] and 6 months for DEMO.[35] Part of the challenge for these devices is that all remote systems and components must fit between gaps in the fixed TF cage. The ARC concept[8] attempts to hasten repair times by utilizing both demountable TF coils and a drainable liquid blanket, as shown in Fig. 4, to enable vertical maintenance. These could be impactful innovations, however, more research is needed to assess the feasibility of these technologies and explore the tradeoff between the flexibility of repairs and the robustness to disruption forces. Regardless, a commercial TPP will require faster repair/replace timelines than are possible on current devices. The time consumed by the repairs will only add to the delays brought on by the cryostat temperature cycle time.

IV.A.2.f. Class F: Major Repairs and Class G: Early Plant Closure

A worrying sign from current operational experience is that major tokamak repairs for even non-superconducting devices can take years. The NSTX-U tokamak's operational history illustrates how tokamaks can suffer years-long operational delays even when disruptions are not responsible.[54,55] Devices like NSTX-U are an imperfect point of reference because they are not commercial projects, but the nuclear energy industry offers many examples of how complex, capital-intensive energy projects can be beset by years of delays for repairs or upgrades.[56]

The most significant threat to the longevity of the plant are the electromagnetic (EM) forces, such as those caused by asymmetric vertically displacement events rotating at the VV's resonant frequencies.[57] RE beams and TQ heat fluxes will almost certainly be stopped by the PFCs and/or blanket modules, which are designed to be replaceable. Therefore, Class F and Class G recoveries will only be caused by damage from EM forces.

The impacts of disruption Classes A through F are included in the disruption-aware LCOE model [Eq. (2)] through term f_{recov}. Early shutdowns due to Class G disruptions are captured by P_{damage}, as is described in the next section.

IV.B. Reduced Electricity Production due to Early Shutdown

Disruptions could also decrease electricity production by forcing an early plant closure. The irreplaceable components on a TPP (for example, TF magnets) can be thought of as having an "acceptable damage budget." We write the proportion of the damage budget that is consumed per unit time of operation as

$$\tau_{damage}^{-1} \equiv p\langle d\rangle \ , \tag{6}$$

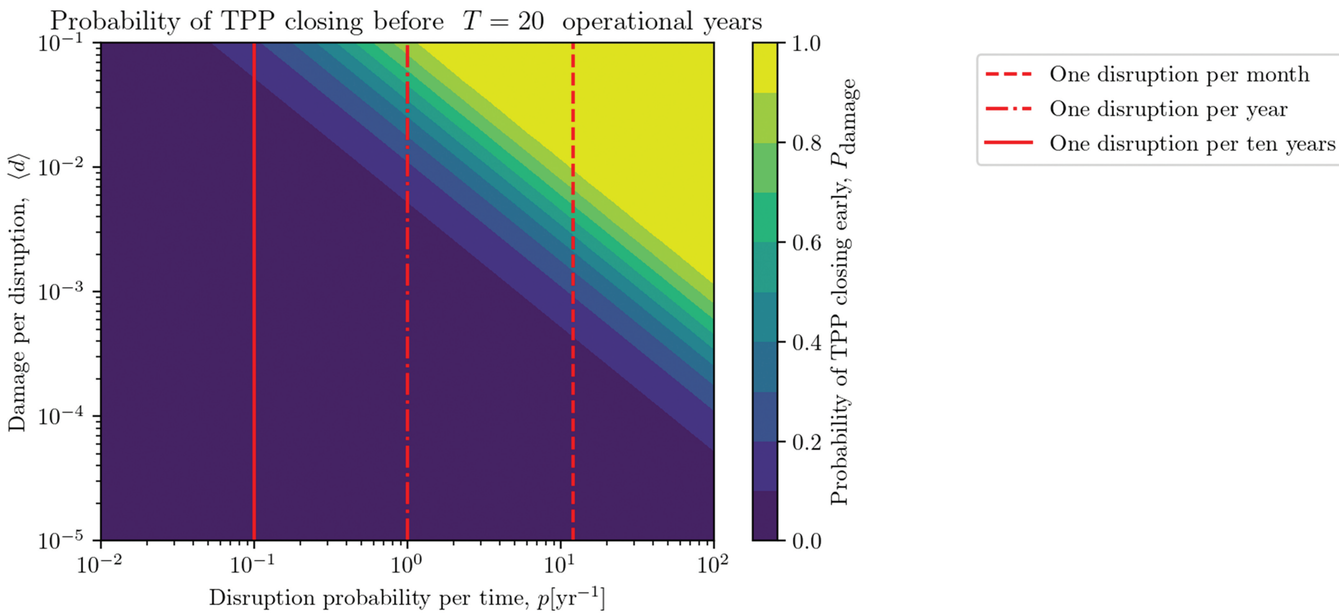

Fig. 5. Probability P_{damage} that a particular TPP is operating after an operational lifetime of $T = 20$ years for disruption rate p and an average damage per disruption $\langle d \rangle$.

where p is the probability of disruption per time and $\langle d \rangle \in [0, 1]$ is the average damage per disruption as a proportion of the acceptable damage budget. For example, if every disruption is a Class G event that renders the device inoperable, then $\langle d \rangle = 1$.[a] We refer to τ_{damage} as the characteristic damage time.

For a population of N TPPs, the number that are lost due to damage per unit time dt is approximately

$$dN = -N\tau_{\mathrm{damage}}^{-1} dt \ , \tag{7}$$

from which we recognize that population decays exponentially. The probability that a particular TPP does not complete its target operational lifetime of T is

$$P_{\mathrm{damage}}(T) = 1 - \exp\left(-\frac{T}{\tau_{\mathrm{damage}}}\right) \ . \tag{8}$$

We see that both $P_{\mathrm{damage}}(T)$ and T/τ_{damage} can be used as figures of merit for this source of reduced revenues. Figure 5 shows P_{damage} after $T = 20$ years of operation for a range of p and $\langle d \rangle$.

[a] This may be the case for full current discharges of ITER. A conservative estimate indicates that a RE beams impact even during a mitigated full-power disruption could consume the entire ITER disruption budget.[34]

The effect of accumulated damage enters the LCOE by decreasing the expected electrical energy by a factor of $1 - P_{\mathrm{damage}}$. Because the LCOE model is written in terms of calendar years, the total time the tokamak has been operating by the end of year t is $T(t) = (t - t_0) f_{\mathrm{duty}}$, where t_0 is the year that energy production begins and f_{duty} is the fraction of the calendar year during which the TPP is producing fusion energy.

Given the large capital cost of TPPs,[20] utilities operating such a device will require that the probability of an early plant closure be very small. Therefore, we can state a design requirement $P_{\mathrm{damage}} \leq P_{\mathrm{damage,max}} \ll 1$, where $P_{\mathrm{damage,max}}$ is the maximum probability of an early plant closure the utility is willing to tolerate. This leads to strict requirements for disruption probability and damage per disruption. Consider a plant with a power-producing lifetime of 20 years, a utility that tolerates $P_{\mathrm{damage,max}} = 0.1$, and assume that $\langle d \rangle = 0.01$. In this case, the maximum allowable disruption rate is $p < 11.5$ -year^{-1}. We plot the maximum allowable disruption rate p for a range of $P_{\mathrm{damage,max}}$ and $\langle d \rangle$ for the case of $T = 20$ year in Fig. 6.

IV.C. Reduced Electricity Production due to a More Conservative Operating Point

We include the effect of potentially needing to operate at a more conservative plasma state with

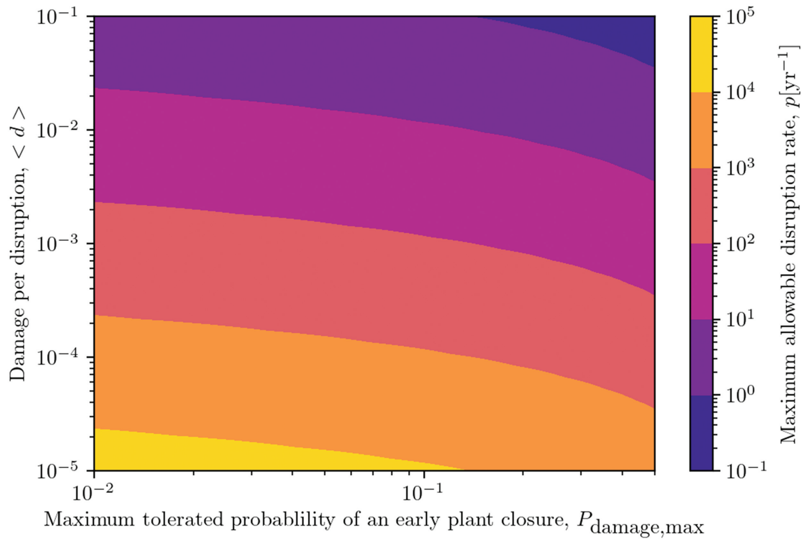

Fig. 6. Maximum allowable disruption rate p of a TPP with an operational lifetime of $T = 20$ years across a range of P_{damage} and $\langle d \rangle$. Note that each color represents a range of disruption rates spanning an order of magnitude.

a scaling factor $f_{\text{cons}} \in [0, 1]$, which represents the fraction of electricity production achieved in practice compared to the disruption-free operating point. Over time, f_{cons} could approach 1 as operator experience enables higher performance or go to 0 as disruption-induced damage forces more conservative operational choices.

V. DISCUSSION

V.A. Exploring the LCOE of an Example TPP

Here, we demonstrate how the disruption-aware LCOE model [Eq. (2)] can be utilized to show cost scaling due to disruptions and to set disruption handling requirements. We will task ourselves with the goal of achieving LCOE $<$ \$100/MWh, given the baseline characteristics of a nondisruptive case shown in Table V. Fusion electricity will likely need to achieve this cost target to be competitive in the most expensive energy markets around the globe.[58] We assume a constant capital cost during the construction phase and constant O&M and fuel costs. In Figs. 7, 8, and 9, we explore the LCOE as a function of two parameters per plot while keeping the rest at the nondisruptive baseline value. We see in Fig. 7 that the designers can afford to increase the capital cost scaling factor k_I significantly more than the O&M cost scaling factor k_M. In Fig. 8, we find that the plant can achieve the LCOE cost target with $f_{\text{recov}} \approx 20\%$ lost operating time due to disruption recovery if there is no change to the output electrical power ($f_{\text{cons}} = 100\%$). But reducing the electricity output to $f_{\text{cons}} = 0.8$ also reduces the maximum f_{recov} within the \$100/MWh goal to $\approx 5\%$. Therefore, we see that reducing power even modestly may put significant pressure on other disruption-related

TABLE V

Baseline Characteristics of the TPP Used to Show the Disruption-Aware LCOE in Eq. (2) and in Figs. 7, 8, and 9*

Characteristic of TPP	Variable	Baseline Value (No Disruptions)
Electrical power	P_{electric}	500 MW
Construction time	$n_{\text{construct}}$	5 years
Target lifetime of plant	n_{lifetime}	20 years
Duty factor	f_{duty}	80%
Annual capital cost during construction	I_t	4×10^8 \$U.S. dollars
Annual O&M cost	M_t	5×10^7 \$U.S. dollars
Annual fuel cost	F_t	5×10^6 \$U.S. dollars
Real interest rate	r	7%
Capital cost scaling factor	k_I	1
O&M cost scaling factor	k_M	1
Fraction time spent on recovery	f_{recov}	0
Fraction electrical power from conservative plasma	f_{cons}	1
Probability of early shutdown	P_{damage}	0
LCOE	LCOE	76 \$U.S. dollars/MWh

*In this scenario, O&M and fuel costs are only accrued after the construction phase ends during the operational lifetime of the plant.

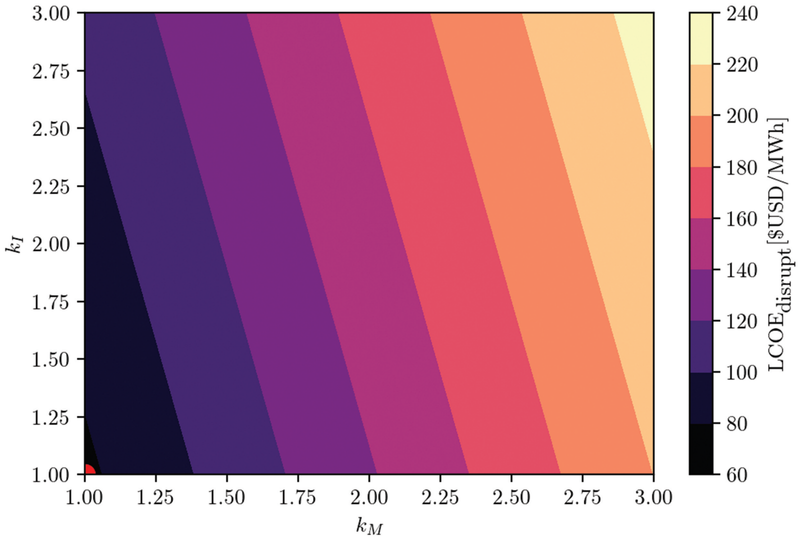

Fig. 7. LCOE of n TPP (Table V) for various values of O&M cost scaling factor k_M and capital cost scaling factor k_I. The baseline case (no disruptions) is shown in red.

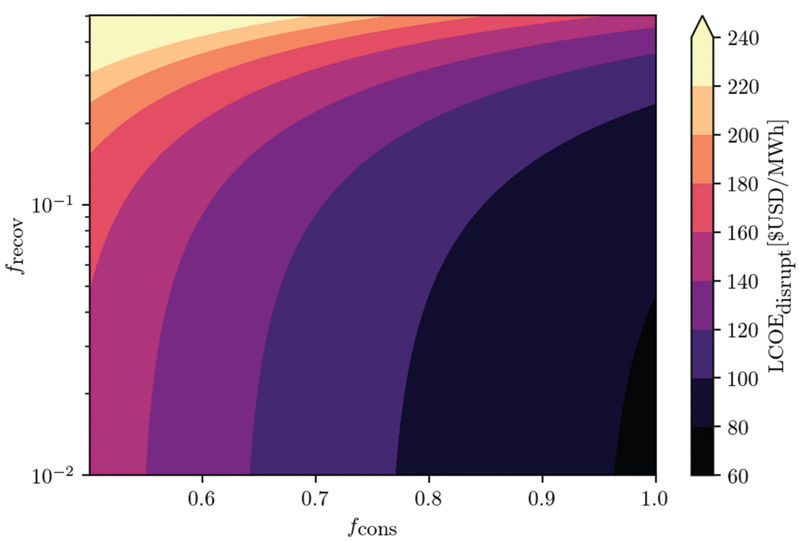

Fig. 8. Dependence of the LCOE of a TPP (Table V) on the fraction of operating time lost to disruption recovery f_{recov} and the fraction of target electrical power produced in order to keep sufficient margin to disruptive instabilities f_{cons}. The baseline case (no disruptions) is below the horizontal axis at $f_{\text{recov}} = 0, f_{\text{cons}} = 1$.

parameters. Figure 9 shows that LCOE varies strongly with the characteristic damage time for $\tau_{\text{damage}} < 30$ years.

The effects of all the disruption-related parameters on the cost of fusion electricity compound, leading to a very narrow space within which we can reach our < $100/MWh goal. For example, one such design has the parameters $k_I = 1.5$, $k_M = 1.25$, $f_{\text{recov}} = 0.03$, $f_{\text{cons}} = 0.99$, $\tau_{\text{damage}} = 200\,\text{year}$, and $n_{\text{lifetime}} = 50$ year. In this scenario, a disruption rate of one per day entails [by Eqs. (5) and (6)] $\langle\tau_{\text{recov}}\rangle = 45$ min and $\langle d\rangle = 1.4 \times 10^{-5}$. These are extreme requirements.

V.B. General Comments on TPP Design

The analysis of the LCOE of a hypothetical TPP in the previous section illustrated the significant challenges disruptions pose to the economics of a TPP. Research and innovations are urgently needed to make strict disruption handling requirements achievable. In Table VI, we show a list (by no means complete) of potentially impactful research and/or engineering developments along with the directly relevant figure of merits. These developments could improve the viability of a wide range of TPP designs.

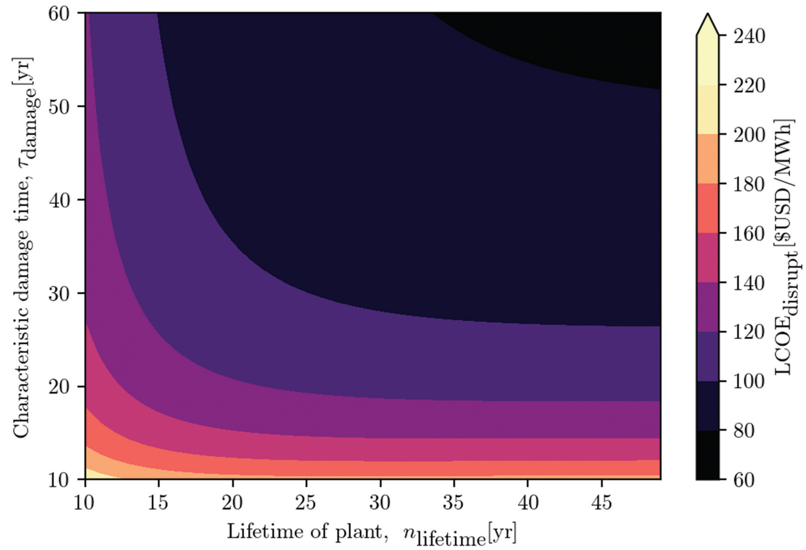

Fig. 9. LCOE of a TPP (Table V) as a function of the characteristic damage time τ_{damage} and target lifetime of plant n_{lifetime}, where $\tau_{\mathrm{damage}}^{-1} \equiv p\langle d\rangle$ [Eq. (6)]. The baseline case (no disruptions) is above the vertical axis at $\tau_{\mathrm{damage}} = \infty$.

TABLE VI

List of Potentially High-Impact Physics, Technology, and Engineering Developments with the Directly Relevant Figures of Merit Indicated with a X*

Potentially High-Impact Development	k_I	k_M	f_{recov}	f_{cons}	P_{damage}
Improved mitigation solutions	X	X	X		X
Demountable TF magnets		X	X		X
Replaceable VV		X	X		X
Disruption-resilient, low-activation PFCs		X	X		
Quickly replaceable PFCs		X	X		
Liquid immersion blanket		X	X		
Liquid sandwich VV[59]		X			X
EM pellet injector[60]		X			X
RE mitigation coil[61,62]		X			
Stable TPP-relevant plasma scenarios			X	X	X
Improved disruption modeling			X	X	X
Advanced plasma control algorithms			X	X	X
Robust disruption predictors[63–65]			X		X
Remote optical inspection device			X		
Faster magnet charge/recharge			X		
Quicker cryostat temperature cycle			X		

*We note that the multidimensional optimization required for a TPP allows for developments relevant to one metric to be used in a tradeoff to improve other metrics (for example, a better mitigation solution could make operators more confident operating closer to instability boundaries, reducing f_{cons}).

Given the integrated nature of the disruption handling problem and the remaining uncertainties, it is beyond the scope of this study to determine whether high-field or low-field concepts are more robust to disruption–related costs. High-field TPP design points tend to be at lower plasma current and offer a larger distance to zero-dimensional disruptive limits (for example, density, pressure, current) compared to low-field TPPs, but the more compact size results in higher current and energy density. The optimal tradeoff between these considerations is unclear at this time, but could be identified by pairing the LCOE model presented here with appropriate physics, engineering, and cost models.

VI. CONCLUSION

Avoiding disruptions in a TPP has been compared to driving a car on an icy, foggy road[15]; the control system's ability to observe and react to potential catastrophes is severely limited. Perhaps a better analogy is flying a fighter jet through a tunnel. The operator must rely on a technology suite significantly restricted by other mission-critical constraints to avoid crashes. The safest way to abort the mission would be to slow down, but this could take too long if an obstacle is fast approaching. Repairs after a crash landing could stretch to months or longer because of the complexity and inaccessibility of the machine.

In this paper, we provide a quantitative estimate of the impact of disruptions on the economics of TPPs. We derive a model for the LCOE [Eq. (2)] that illustrates how the cost of fusion power scales with several disruption-related parameters. We identify several key figures of merit: k_I, k_M, f_{recov}, f_{cons}, and P_{damage}. Although we focus on the tokamak, where the disruption problem is severe and has been well studied, this LCOE model can, in principle, be applied to any magnetic confinement concept that experiences disruptions, such as stellarators.

In addition to the LCOE model, we identify two important design constraints: low fraction of operating time lost to disruption recovery ($f_{\mathrm{recov}} \leq f_{\mathrm{recov,max}} \ll 1$) and low probability of early closure ($P_{\mathrm{damage}} \leq P_{\mathrm{damage,max}} \ll 1$). These can be used in lieu of the more complex LCOE model to estimate the space of maximum allowable disruption rate, recovery time, and damage per disruption. The fusion pilot plant design review process, as called for by a recent National Academies report,[66] should consider including these constraints as evaluation criteria for magnetic confinement devices.

We also introduced a classification for disruptions in TPPs using D-T fuel and superconducting TF magnets in terms of the recovery timescale, ranging from an immediate restart to catastrophic failure, based on the technology and practices of today. This illustrates the severe constraints facing disruption recovery actions.

We applied the LCOE model to a hypothetical TPP and found that the disruption handling requirements for achieving <$100/MWh LCOE are extreme. Finally, we identified several areas where further research and development can ameliorate costs associated with disruption handling.

The threat of disruptions does not preclude the tokamak as a fusion power plant at this stage, but the related challenges must be addressed urgently. Disruption handling must be considered among the core priorities of tokamak research programs today alongside core-edge integration, divertor heat exhaust, and tritium breeding. Many complex industrial products operate routinely with extremely low failure rates, such as commercial airliners, nuclear power plants, and satellites. If we reorient tokamak research today to more forcefully address the disruption problem for TPPs, we can potentially head off a showstopper for the tokamak fusion energy pathway.

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Data Availability Statement

Data and code are available at https://github.com/andrew-maris/disruptions-tokamak-economics (DOI: 10.5281/zenodo.8044908).

References

1. B. BIGOT, "ITER Construction and Manufacturing Progress Toward First Plasma," *Fusion Eng. Des.*, **146**, 124 (2019); https://doi.org/10.1016/j.fusengdes.2018.11.052.

2. H. WILSON et al., "STEP—On the Pathway to Fusion Commercialization," *Commercialising Fusion Energy: How Small Businesses Are Transforming Big Science*, IOP Publishing (2020); https://doi.org/10.1088/978-0-7503-2719-0ch8.

3. Y. SONG et al., "Engineering Design of the CFETR Machine," *Fusion Eng. Des.*, **183**, 113247 (2022); https://doi.org/10.1016/j.fusengdes.2022.113247.

4. A. CREELY et al., "Overview of the SPARC Tokamak," *J. Plasma Phys.*, **86**, 5 (2020); https://doi.org/10.1017/S0022377820001257.

5. A. SYKES et al., "Compact Fusion Energy Based on the Spherical Tokamak," *Nucl. Fusion*, **58**, *1*, 016039 (2017); https://doi.org/10.1088/1741-4326/aa8c8d.

6. Y. XU, "A General Comparison Between Tokamak and Stellarator Plasmas," *Matter Radiat. Extremes*, **1**, *4*, 192 (2016); https://doi.org/10.1016/j.mre.2016.07.001.

7. R. WENNINGER et al., "Advances in the Physics Basis for the European DEMO Design," *Nucl. Fusion*, **55**, *6*, 063003 (2015); https://doi.org/10.1088/0029-5515/55/6/063003.

8. B. N. SORBOM et al., "ARC: A Compact, High-Field, Fusion Nuclear Science Facility and Demonstration Power Plant with Demountable Magnets," *Fusion Eng. Des.*, **100**, 378 (2015); https://doi.org/10.1016/j.fusengdes.2015.07.008.

9. S. GERASIMOV et al., "Overview of Disruptions with JET-ILW," *Nucl. Fusion*, **60**, *6*, 066028 (2020); https://doi.org/10.1088/1741-4326/ab87b0.

10. C. SOZZI et al., "Termination of Discharges in High Performance Scenarios in JET," presented at the 28th IAEA Fusion Energy Conf. (2021).

11. M. LEHNEN, P. ALEYNIKOV, and B. BAZYLEV, "Plasma Disruption Management in ITER," International Atomic Energy Agency (2018); http://inis.iaea.org/Search/search.aspx?orig_q=RN:49093244,number:IAEA-CN–234.

12. C. KESSEL et al., "The ARIES Advanced and Conservative Tokamak Power Plant Study," *Fusion Sci. Technol.*, **67**, *1*, 1 (2015); https://doi.org/10.13182/FST14-794.

13. R. BUTTERY et al., "The Advanced Tokamak Path to a Compact Net Electric Fusion Pilot Plant," *Nucl. Fusion*, **61**, *4*, 046028 (2021); https://doi.org/10.1088/1741-4326/abe4af.

14. G. FEDERICI et al., "Overview of the DEMO Staged Design Approach in Europe," *Nucl. Fusion*, **59**, *6*, 066013 (2019); https://doi.org/10.1088/1741-4326/ab1178.

15. A. H. BOOZER, "Plasma Steering to Avoid Disruptions in ITER and Tokamak Power Plants," *Nucl. Fusion*, **61**, *5*, 054004 (2021); https://doi.org/10.1088/1741-4326/abf292.

16. A. H. BOOZER, "Stellarators as a Fast Path to Fusion," arXiv:2104.04621 (2021); http://arxiv.org/abs/2104.04621.

17. N. W. EIDIETIS, "Prospects for Disruption Handling in a Tokamak-Based Fusion Reactor," *Fusion Sci. Technol.*, **77**, *7–8*, 738 (2021); https://doi.org/10.1080/15361055.2021.1889919.

18. J. SHEFFIELD, "Physics Requirements for an Attractive Magnetic Fusion Reactor," *Nucl. Fusion*, **25**, *12*, 1733 (1985); https://doi.org/10.1088/0029-5515/25/12/003.

19. C. BUSTREO, T. BOLZONELLA, and G. ZOLLINO, "The Monte Carlo Approach to the Economics of a DEMO-Like Power Plant," *Fusion Eng. Des.*, **98**, 2108 (2015); https://doi.org/10.1016/j.fusengdes.2015.02.014.

20. S. ENTLER et al., "Approximation of the Economy of Fusion Energy," *Energy*, **152**, 489 (2018); https://doi.org/10.1016/j.energy.2018.03.130.

21. S. TAKEDA, S. SAKURAI, and S. KONISHI, "Economic Performance of Fusion Power Plant on Deregulated Electricity Markets," *J. Fusion Energy*, **39**, *1*, 31 (2020); https://doi.org/10.1007/s10894-020-00230-z.

22. W. E. HAN and D. J. WARD, "Revised Assessments of the Economics of Fusion Power," *Fusion Eng. Des.*, **84**, *2–6*, 895 (2009); https://doi.org/10.1016/j.fusengdes.2008.12.104.

23. H. CABAL et al., "Fusion Power in a Future Low Carbon Global Electricity System," *Energy Strategy Rev.*, **15**, 1 (2017); https://doi.org/10.1016/j.esr.2016.11.002.

24. J. SCHWARTZ et al., "The Value of Fusion Energy to a Decarbonized United States Electric Grid," arXiv preprint arXiv:2209.09373 (2022).

25. L. SPANGHER, J. S. VITTER, and R. UMSTATTD, "Characterizing Fusion Market Entry via an Agent-Based Power Plant Fleet Model," *Energy Strategy Rev.*, **26**, 100404 (2019); https://doi.org/10.1016/j.esr.2019.100404.

26. M. S. PARSONS, "A Cost-Based Criterion for Implementing Data-Driven Disruption Predictors," *Fusion Eng. Des.*, **191**, 113564 (2023); https://doi.org/10.1016/j.fusengdes.2023.113564.

27. J. ONGENA and G. V. OOST, "Energy for Future Centuries: Prospects for Fusion Power as a Future Energy Source," *Fusion Sci. Technol.*, **61**, *2T*, 3 (2012); https://doi.org/10.13182/FST12-A13488.

28. T. NICHOLAS et al., "Re-examining the Role of Nuclear Fusion in a Renewables-Based Energy Mix," *Energy Policy.*, **149**, 112043 (2021); https://doi.org/10.1016/j.enpol.2020.112043.

29. S. MIRNOV et al., "MHD Stability, Operational Limits and Disruptions," *Nucl. Fusion*, **39**, *12*, 2251 (1999); https://doi.org/10.1088/0029-5515/39/12/303.

30. Y. UEDA et al., "Baseline High Heat Flux and Plasma Facing Materials for Fusion," *Nucl. Fusion*, **57**, *9*, 092006 (2017); https://doi.org/10.1088/1741-4326/aa6b60.

31. W. BIEL et al., "DEMO Diagnostics and Burn Control," *Fusion Eng. Des.*, **96–97**, 8 (2015); https://doi.org/10.1016/j.fusengdes.2022.113122.

32. R. SWEENEY et al., "MHD Stability and Disruptions in the SPARC Tokamak," *J. Plasma Phys.*, **86**, 5 (2020); https://doi.org/10.1017/S0022377820001129.

33. M. SUGIHARA et al., "Disruption Scenarios, Their Mitigation and Operation Window in ITER," *Nucl. Fusion*, **47**, *4*, 337 (2007); https://doi.org/10.1088/0029-5515/47/4/012.

34. U. K. M. LEHNEN, S. JACHMICH, U. KRUEZI, and the ITER DMS TASK FORCE, "The ITER Disruption Mitigation Strategy," presented at IAEA Technical Meeting on Plasma Disruptions and their Mitigation, July 2020.

35. O. CROFTS and J. HARMAN, "Maintenance Duration Estimate for a DEMO Fusion Power Plant, Based on the EFDA WP12 Pre-conceptual Studies," *Fusion Eng. Des.*, **89**, *9–10*, 2383 (2014); https://doi.org/10.1016/j.fusengdes.2014.01.038.

36. "PRIS—Trend Reports—Unplanned Capability Loss," Power Reactor Information System, International Atomic Energy Agency (2023); https://pris.iaea.org/PRIS/WorldStatistics/WorldTrendinUnplannedCapabilityLossFactor.aspx.

37. V. BRUNO et al., "WEST Regular In-Vessel Inspections with the Articulated Inspection Arm Robot," *Fusion Eng. Des.*, **146**, 115 (2019); https://doi.org/10.1016/j.fusengdes.2018.11.050.

38. C. DAMIANI et al., "Overview of the ITER Remote Maintenance Design and of the Development Activities in Europe," *Fusion Eng. Des.*, **136**, 1117 (2018); https://doi.org/10.1016/j.fusengdes.2018.04.085.

39. Q. ZHANG et al., "Research Progress of Nuclear Emergency Response Robot," *IOP Conference Series: Materials Science and Engineering*, **452**, 042102, IOP Publishing (2018).

40. A. LOVING et al., "Pre-conceptual Design Assessment of DEMO Remote Maintenance," *Fusion Eng. Des.*, **89**, *9–10*, 2246 (2014); https://doi.org/10.1016/j.fusengdes.2014.04.082.

41. B. BOCCI et al., "ARC Reactor Materials: Activation Analysis and Optimization," *Fusion Eng. Des.*, **154**, 111539 (2020); https://doi.org/10.1016/j.fusengdes.2020.111539.

42. G. DUBUS et al., "Progress in the Design and R&D of the ITER In-Vessel Viewing and Metrology System (IVVS)," *Fusion Eng. Des.*, **89**, *9–10*, 2398 (2014); https://doi.org/10.1016/j.fusengdes.2014.01.012.

43. D. DOUAI et al., "Wall Conditioning for ITER: Current Experimental and Modeling Activities," *J. Nucl. Mater.*, **463**, 150 (2015); https://doi.org/10.1016/j.jnucmat.2014.12.034.

44. T. WAUTERS et al., "Wall Conditioning in Fusion Devices with Superconducting Coils," *Plasma Phys. Controlled Fusion*, **62**, *3*, 034002 (2020); https://doi.org/10.1088/1361-6587/ab5ad0.

45. M. FERRE et al., "Robot Requirements for Nuclear Fusion Facilities," presented at the First Workshop on Fusion Technologies and the Contribution of TECHNOFUSIÓN (2011).

46. G. BURROUGHES et al., "Precision Control of a Slender High Payload 22 DoF Nuclear Robot System: TARM Re-ascending," presented at the 44th Annual Waste Management Conf., Phoenix, Arizona, March 18–22, 2018.

47. R. FAN et al., "Control and Operation Strategy Design of ITER Coil Power Supply System," *Fusion Eng. Des.*, **141**, 15 (2019); https://doi.org/10.1016/j.fusengdes.2019.02.015.

48. B.-H. OH et al., "Design Issues of the TF AC/DC Converter for the ITER Coil Power Supply System," *Trans. Korean Nuclear Soc. Spring Mtg.*, p. 917 (2009).

49. N. SONG et al., "Construction and Commissioning Results of the KSTAR Current Lead System," *IEEE Trans. Appl. Supercond.*, **20**, *3*, 564 (2010); https://doi.org/10.1109/TASC.2010.2040727.

50. N. MITCHELL et al., "Superconductors for Fusion: A Roadmap," *Supercond. Sci. Technol.*, **34**, *10*, 103001 (2021); https://doi.org/10.1088/1361-6668/ac0992.

51. H.-S. CHANG et al., "Operation Results of the KSTAR Helium Refrigeration System," *AIP Conference Proc.*, **1218**, 1476, American Institute of Physics (2010).

52. N. PENG, L. LIU, and L. XIONG, "Thermal-Hydraulic Analysis of the Cool-Down for the ITER Magnets," *Cryogenics*, **57**, 45 (2013); https://doi.org/10.1016/j.cryogenics.2013.05.002.

53. G. MATTHEWS et al., "JET ITER-Like Wall—Overview and Experimental Programme," *Phys. Scr.*, **2011**, *T145*, 014001 (2011); https://doi.org/10.1088/0031-8949/2011/T145/014001.

54. S. GERHARDT, J. MENARD, and C. NEUMEYER, "Overview of the NSTX-U Recovery Project Physics and Engineering Design," *27th IAEA Fusion Energy Conference. Programme and Book of Abstracts*, Report no. IAEA-CN -258 (2018).

55. J. R. PETRELLA et al., "Forensic Analysis of Faulted NSTX-U Inner Poloidal Field Coil," *IEEE Trans. Plasma Sci.*, **46**, *7*, 2653 (2018); https://doi.org/10.1109/TPS.2018.2831919.

56. J. BUONGIORNO et al., "The Future of Nuclear Energy in a Carbon-Constrained World," Rev. 1, Massachusetts Institute of Technology Energy Initiative (2018).

57. T. SCHIOLER et al., "Dynamic Response of the ITER Tokamak During Asymmetric VDEs," *Fusion Eng. Des.*, **86**, *9–11*, 1963 (2011); https://doi.org/10.1016/j.fusengdes.2010.11.016.

58. M. C. HANDLEY, D. SLESINSKI, and S. C. HSU, "Potential Early Markets for Fusion Energy," *J. Fusion Energy*, **40**, *2*, 18 (2021); https://doi.org/10.1007/s10894-021-00306-4.

59. J. FREIDBERG et al., "Liquid Sandwich Vacuum Vessel for Magnetic Fusion," U.S. Patent Application 17/190, 755 (2021).

60. R. RAMAN et al., "Prototype Tests of the Electromagnetic Particle Injector-2 for Fast Time Response Disruption Mitigation in Tokamaks," *Nucl. Fusion*, **61**, *12*, 126034 (2021); https://doi.org/10.1088/1741-4326/ac30ca.

61. H. SMITH, A. BOOZER, and P. HELANDER, "Passive Runaway Electron Suppression in Tokamak Disruptions," *Phys. Plasmas*, **20**, *7*, 072505 (2013); https://doi.org/10.1063/1.4813255.

62. R. TINGUELY et al., "Modeling the Complete Prevention of Disruption-Generated Runaway Electron Beam Formation with a Passive 3D Coil in SPARC," *Nucl. Fusion*, **61**, *12*, 124003 (2021); https://doi.org/10.1088/1741-4326/ac31d7.

63. J. KATES-HARBECK, A. SVYATKOVSKIY, and W. TANG, "Predicting Disruptive Instabilities in Controlled Fusion Plasmas Through Deep Learning," *Nature*, **568**, 526 (2019); https://doi.org/10.1038/s41586-019-1116-4.

64. S. SABBAGH et al., "Tokamak Disruption Event Characterization and Forecasting Research and Expansion to Real-Time Application," *Proc. 28th Int. Conf. on Fusion Energy* (2021).

65. J. ZHU et al., "Scenario Adaptive Disruption Prediction Study for Next Generation Burning-Plasma Tokamaks," *Nucl. Fusion*, **61**, *11*, 114005 (2021); https://doi.org/10.1088/1741-4326/ac28ae.

66. R. HAWRYLUK et al., "Bringing Fusion to the US Grid," Public Briefing, February 17, 2021, The National Academies of Science Engineering and Medicine (2021).

 ANS