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Suspending failure: temporalities, ontologies, and gigantism in fusion energy development

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Tracing the history of terrestrial fusion energy to a giant multinational experimental fusion facility under construction reveals a series of consequential failures, re-evaluations of once defunct designs, but also persistence. To account for how this vast enterprise, dogged by failure, endures, I suggest that different ontological narratives re-orientate the enterprise both temporally and vis-à-vis different forms and valences of failure. Thus the rhetoric of mission-driven project vies with that of open-ended, present-focused experiment: the former is positioned as the crucial solution to the threat of climate change; the latter 'bakes in' virtuous failure as integral to creative practice. Visionary promise moves to a focus on the meanwhile. Finally, the sheer unfurling size to which attention is constantly drawn offers a disorientating spectacle, denying perspective or closure and acting to suspend judgements of failure.

For nearly a century, nuclear fusion energy's glittering promise has been that it is potentially limitless (a seawater-derived fuel), cheap (ditto), safe (no meltdowns or link to nuclear weapons), and clean (no fossil fuels). 'Potentially' bears a heavy weight here,[1] but with the existential threat of climate change now driving global energy agendas, governments and private enterprise are trying to push fusion energy's development towards commercial viability: producing electricity for the grid. ITER is the huge, multinational facility being built in France as 'an experimental campaign' to 'prove the feasibility of fusion as a large-scale … source of energy'.[2] Although the name started life as an acronym for International Thermonuclear Experimental Reactor, the preferred explanation now is that '*iter*' is Latin for 'the way', indicating the path towards fusion energy.

But also for nearly a century, fusion energy's development has been dogged by disappointment and delays, leading to the quip that it is 'always twenty years away', never quite but almost within reach; a latter-day myth of Tantalus perhaps, although Promethean fire is usually the myth of choice. ITER's progress has similarly been bedevilled by repeated overruns of cost and time. If operation starts when planned (see

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below), it will be fifty years since Gorbachev proposed the project to Reagan during their 1985 summit. It was approved the following year.

My emphasis here is on the temporalities of failure, principally how ITER manages to persist in spite of or, as I argue here, because of certain failures such that absolute failure is suspended. ITER is legitimated through the invocation of certain forms of failure and enrols some registers of failure to displace others. This process highlights how different tropes of failure may variously be summoned for different effects, act, be resisted, or have unfurling reverberations. My aim is to trace what various forms of failure do and how different narratives and ontologies (e.g. 'mission-driven project' or 'open-ended experiment') serve to re-orientate the enterprise both temporally and vis-à-vis different forms and valences of failure.

A related theme of scale weaves through these discussions. Thus 'nuclear energy … incorporates the most miniature abstraction … with the most gigantic abstraction (… technological apocalypse)' (Stewart 1993: 102; see Street, this volume, for a discussion of scale conflation in mobile diagnostic devices). Stewart is discussing fission. Although apocalyptic meltdowns are not possible with fusion – the reaction would simply stop – it also embraces the subatomic and gargantuan in terms of the material, social, and financial assemblage needed to achieve the nuclear reaction. Scale also suggests further layers to how different kinds of failure are perceived, experienced, or forestalled. A harried engineer, faced with tight deadlines for devising a specification from high-level designs and lacking 'look-up' tables for a 'first-of-a-kind' component, apprehends failure very differently from senior managers tasked with portraying the project's stately progress. The mesmerizing vastness of this behemoth also acts to preclude judgement.

I approach the question of how failure, in this instance, does not fail through four related interventions: one is methodological, two are ethnographic, and the fourth is analytical. Thus my fieldwork during the pandemic period of 2020-2 was also experimental. Because I was initially unable to visit ITER as planned, the Communications Department (Comms) kindly arranged online conversations with staff members, most of whom were working from home – a novel experience for us all – while waiting for restrictions to lift. Initially, I was introduced to senior, long-term staff. As they recommended other people, I had repeated long conversations and email exchanges about careers and life histories with current and former employees, including physicists (ranging from junior to retired), engineers, and professional support staff.[3]

I usually asked about tensions and compromises, waiting to see if and how ideas of failure emerged. One former employee observed that certain themes in senior management accounts (e.g. the unity of ITER's staff and the multiple kinds of social and scientific/technical experiments that it represented) often reflected Comms' and former director generals' dexterity in weaving upbeat organizational narratives for staff as much as for external eyes. Comms might be seen as the organization's formal storytellers. I also drew on archives, media accounts, scientific papers, EU reports, and ITER's own external website both to triangulate and to amplify accounts, and because many informants were also intrigued by fusion's history as something that shaped both ITER and fusion developments elsewhere.

This might be seen as 'patchwork ethnography' (Günel, Varma & Watanabe 2020): long-term fieldwork involving multiple sources in response to constraints on more immersive research. I still worried, however, about what felt more like failed ethnography. How, after all, could I observe interactions, understand social practices, attempt anything approaching a thick description from a Zoom call? It took me a while to listen and learn from many of my informants that their complaints of 'silo' working, stress, and professional anxieties being unheard (see EU 2021; European Commission 2019; Madia & Associates, LLC 2013) made their own experience of working there anything but 'thick'. It also reaffirmed how failure can be apprehended and expressed very differently at organizational or personal levels. Indeed, many cited the fragmented, hierarchical system as one cause of delays and technical problems, suggesting a very distinct organization from CERN (the European Council for Nuclear Research), where Roy (2012) describes co-operation between areas of expertise as the norm, such that it takes a 'crisis' to reveal difference. In contrast, 'thin description' (Brekhus, Galliher & Gubrium 2005; Jackson 2013) became both method and a central ethnographic concern: tensions between faultlines of difference and the emphasis on collaboration that foregrounded, in the words of a senior engineer, 'One ITER! One team!'

These encounters generated two kinds of ethnographic interventions into failure. First, the ethnography below briefly describes ITER through the eyes of staff before moving to terrestrial (as opposed to solar) fusion energy's long history, which reveals a series of consequential failures that shape ITER now. Thus, the continuing lack of a first-principles theoretical model for the most dependable fusion device to date dictates reliance on a scaling law correlating size with success. Size is also determined by the maturity of supporting technologies and industry. In the 1990s, before billionaires funded projects once the preserve of government,[4] ITER's proposed design necessitated multinational funding. This led to diplomatic haggling over siting, management, and construction contracts to maximize each country's return in terms of increased capacity, prestige, and expertise (Åberg 2021). Dividing the complex manufacture of giant, high-precision components across multiple firms globally has been partly responsible for overruns. And yet, despite being 'after failure' in the sense of repeatedly overshooting budgets and schedules, ITER persists.

The second intervention therefore considers how absolute failure is suspended. One route is the relatively simple, if expensive, re-baselining of deadlines and costs. But attention is also diverted from ITER as a mission-driven project to a focus on the present. Gigantism appears again but as an achievement as vast components are filmed majestically traversing the world before being winched delicately into place while progress is indexed by rollcalls of tonnages, populations, nations, and soaring walls. Finally, the idea of experiment is invoked as an open-ended process where failure plays a virtuous role (Corsín Jiménez 2014; see also Bruckermann, this volume), thus re-crafting the object of failure.

The final contribution is to ponder the extent to which this ethnography can be neatly tethered to one literature or another. Thus, at first sight, this account of ITER appears to be in conversation with energy studies as well as science and technology studies. But each of these has particular orientations to failure that in turn appear ethnographically deployed to different effects. The effect is disorientating. Ethnographic description enfolds potential analysis, forestalling the distance afforded by perspective. Thus, echoing recent concerns in energy studies about anticipating planetary cataclysm through non-fossil fuels[5] (Boyer 2014), ITER staff often position fusion as vital for decarbonization, whether alongside renewables or as the only pragmatic solution (see Windsor 2019 for a summary of this position). Again, invocation of ITER qua experiment implicitly casts failure as essential for scientific progress – unexpected outcomes simply grist to the knowledge mill (Firestein 2016). My main emphasis is therefore on the rhetorical work performed by these appeals, rather than a dissection of (for example) energy communities and inequalities or how ITER's research and development programme speaks to the vagaries of scientific knowledge production (Pickering 1995). In a bid to find adjacent purchase rather than an approach that has been ethnographically disappeared, studies of infrastructure prove fruitful. Again there is a repertoire of approaches for thinking through failure (see the introduction to this volume), but the subfield also offers the heuristic of suspension as a generative ontic condition (Carse & Kneas 2019; Gupta 2015; Marrero-Guillamón 2020). Weaving this through the implications of size and experimental open-endedness suggests that empirical and theoretical assessments of failure alike may be at once inevitable, impossible, and ultimately suspended.

In sum, this essay offers an understanding of failure that extends Carroll, Jeevendrampillai, Parkhurst and Shackelford's (2017) 'general theory' that failure is when something does not work as intended, reorganizes social relations in the future, and is always a negative moral accusation. The ethnographic unfolding of failure in ITER's case indicates how failure may be: negatively *and* positively valenced; apprehended differently according to scale; determined by and productive of plural temporalities; invoked by different ontological representations of the enterprise; and something (looming apocalypse) that galvanizes action. Finally, ITER invites consideration of how and why certain failures endure and do not fail.

ITER: a very large machine

An hour's drive from Aix-en-Provence, where many of ITER's staff live, the 180-hectare site began to be carved out of a thickly forested hillside in 2005, terraced banks levelling the undulating terrain. It is still wrapped by forest with snow-capped mountains in the distance (Fig. 1).

Provence was a distinct attraction for many working at ITER, alongside high salaries and what informants often termed fusion energy's 'humanitarian' promise. Responsibility for uprooting families, especially those with non-Francophone partners and children, can weigh heavily on scientists and engineers taking up a post. Highly qualified partners often find themselves unemployed, isolated, and having to deal with 'all the shit, and in French!' Some parents worry whether to send their children to ITER's international *lycée* in nearby Manosque or choose schools in more cosmopolitan Aix – at the risk, some say, of disapproval from bosses for seeming to opt out of the 'One ITER! One team!' ethos. The effect, a young physicist observed, is to increase the pressure on staff for 'all this to work', meaning not only ITER but also the lives and careers entangled with it.

A sleek administrative building housing a canteen overlooks the central 42-hectare building site, where some components, too colossal to be transported along the specially strengthened and widened roads from Marseille, have been made in situ. Assembling the fusion device began in 2019. Despite still being a construction site, it seems a world away from the 'tin hut in the woods' that was the first office of a newly arrived physicist in 2009, who described his feet freezing in the winter while summer temperatures soared to 40°C. After extensive underground work, the device's seven-storey building is now complete; a cheeringly visible sign, some say, of progress. Others fret that the building is already too small to house 'the zoo' of pipes and wiring or that buildings are just 'a low-hanging fruit' deflecting attention from subsequent phases.

Senior staff observed that such is ITER's magnitude it is beyond the financial, scientific, engineering, and industrial capacities of a single country. It is therefore

Figure 1. Aerial view of the ITER site during construction in 2018. Oak Ridge National Laboratory. (Wikicommons)

international in terms of how it is funded and managed as well as being a node in a global network of commercial fusion industries at different degrees of readiness, other approaches to fusion energy (Ball 2021), national and supranational governments, physics and engineering research establishments (see Collins 2004; Galison 1987; Haas 1992; Knorr Cetina 1999; Latour & Woolgar 1986; Roy 2012; Traweek 1988). Size is regularly, reverently enumerated on ITER's website and by many of my interlocutors: 23,000 tonnes of steel (often rendered in Eiffel Towers as the unit of measurement since this is France), 100 football fields in extent, thirty-five countries representing 85 per cent of global GDP, 1 million components built across three continents, and temperatures that will reach 300 million °C. These recitations make the enterprise knowable by inventory but conceal the uncertainty in articulating those various elements – steel, heat, and labour – let alone integrating the components into one machine, emulating attempts to meld different disciplines, industries, government bureaucracies, and national interests into one team.

Although various multibillion costs are bandied about in the media (€22 billion is the commonest), the precise cost is unknowable. Approximately 90 per cent of contributions are being delivered 'in-kind' as manufactured components to increase technological capacity across countries and industries. And therein lie many of the current challenges as political and industrial interests have multiplied aims and demands that complicate and, some suggest, compromise the central mission. Other ITER staff cast such political decisions as an irritant but only to be expected in a programme of such extent and a challenge to be overcome.

In 2007, ITER's initial deadline to begin operations was re-baselined to 2016. But in 2014, a trenchant internal report on ITER's poor management (Madia & Associates, LLC 2013) was leaked by the author of a *New Yorker* article detailing ITER's ambition and problems (Khatchadourian 2014). Both report and article are cited by staff as a switchpoint leading to the appointment of a new director general who overhauled management and again re-baselined the project. It also marked when Comms became more adept at internal and external narratives. These not only chronicle ITER's progress but also offer re-framings of what it is, adding to the primary goal multiple forms of experiment that also index 'real-time' successes. One frequent declaration from senior staff was: 'ITER is not just a physics experiment. It's a human, political, geopolitical, sociological … experiment. It is one experiment and it is many experiments in one!' But while many enthusiastically adopted these new narratives of wonder, there are others who disputed them as deviations from the central mission and, as one informant caustically suggested, served to 'bake in' failure as integral to experimental creativity. While projects may fail, he, like others, said that invoking the open-endedness of science and the possibilities offered by failure was a 'get out of jail free card' for organizational challenges (see EU 2021; European Commission 2019).

After two reschedulings, the operation date was now 2025 with 2035 as the target for achieving ITER's main aim of net energy, never previously achieved. Net energy, also called burning plasma, means the fusion reaction produces more energy (qua fusion power) than is injected into it. After this crucial second phase, the machine will be reconfigured (see Hackett, Conz, Parker, Bashford & DeLay 2004) to test other materials, operating regimes, and the ability to self-generate tritium, an essential fuel for burning plasma. Tritium, currently only available via certain fission reactors, generates short-lived radioactive waste. France's nuclear regulator is closely involved in ITER's progress.

The enterprise's sheer complexity meant 2025 was likely to slip. It meets Flyvbjerg's criteria for major (multibillion-dollar) programme delays: non-standard technology and designs, scope change, and multi-actor decision-making which 'produce failure upon failure' (2011: 322). Indeed, in 2021, the then director general said 2025 was no longer technically feasible because of COVID (Simon 2021). Since then, following the director general's death and various problems assembling the machine, the new director general, appointed in September 2022, has suggested that 2035 is a more likely date (AFP in Saint-Paul-Les-Durance 2023; Silver 2023). EUROfusion's 2012 roadmap[6] shows ITER as both the successor to JET, a European experimental reactor, and a vital input to the 'DEMO' stage, the precursor to commercial reactors. This roadmap showed electricity being delivered to the grid by 2050 to meet EU decarbonization goals. EUROfusion's 2018 roadmap no longer has dates[7] and the EU now recognizes that ITER's 'potential role in the decarbonisation of the energy landscape post 2050 is very significant' (European Commission 2019; see also Nicholas *et al.* 2021). By any reckoning, this is an enterprise that vastly exceeds particle physics experimental cycles (Pickering 1995; Roy 2012; Traweek 1988), its duration even greater if seen as part of a century-long experiment to achieve usable fusion energy.

Views about ITER's feasibility from staff, the media, different political parties, and sometimes the wider fusion community are mixed and strong. These reactions largely illustrate MacKenzie's 'certainty trough' (1998), where those closest to a technology are keenly aware of uncertainties, those involved in promoting or managing it express confidence, while those at a distance, who may be rivals or politically against it, again highlight problems. Thus ITER staff with management overviews underscore that this is a 'first-of-a-kind' device, unknown territory in many domains. Such resistance to analogy has a similar effect to appeals to vastness; both explain away, by making inevitable, unmet deadlines and budgets. Underestimating time and cost alongside poor scoping and specifications are common features of 'megaprojects' in order to get them started, after which failure becomes endlessly recalibrated (Flyvbjerg 2011). Nonetheless, confidence soared when, in February 2022, JET, reconfigured to mimic ITER's nuclear phase, doubled its 1997 world record for maintaining fusion to 5 seconds.

Again, following MacKenzie's model, renewable energy proponents tend to cite the same cost escalation, delays, and experimental scope modifications as indications that manmade fusion energy is uncertain at best, unfeasible at worst (e.g. Dittmar 2019). Similarly, there have been broadsides from former plasma physicists (e.g. Jassby 2018), who often seem to charge ITER with not doing what it is not designed to do (providing electricity for the grid). But an unexpected take was provided by an advocate of privately funded fusion energy enterprises: 'Even though we're in competition, we don't want ITER to fail because it's so high profile; it would be read as a failure of fusion, not this organization and device. ITER's failure would affect us all'.

Staff's experiences of working on loosely specified designs to unachievable deadlines – before reschedulings and a design review corrected errors and provided more detail – were different again. Anxiety was portrayed as overwhelming, sometimes manifesting in physical and mental illness. ITER's persistence was thus encountered very differently by many working there, for whom working to immovable deadlines, with concerns often unheard, was intensely stressful. For those close to uncertainty but who are invested in fusion's success, the experience can be traumatic.

A brief history of fusion energy

In a wittily erudite paper combining Shakespearean quotation with musings on how Icarus's failure to reach the sun could have helped him build a better flying machine,[8] Cambridge astrophysicist Arthur Eddington identified the sun's endless energy as nuclear fusion: two light elements (hydrogen) merging to produce a heavier element (helium) – and energy (1920: 20). At very high temperatures, hydrogen changes from a gas to a plasma, in which kinetic energy merges the atomic nuclei, releasing energy: fusion power (World Nuclear Association 2022). So far, so uncontrolled. The problem with controlled fusion, from which electricity can be derived, is that it requires intensely high temperatures, plus a confined plasma of adequate duration and density. No material can withstand such heat.

Trained at Yale, Lyman Spitzer worked with Eddington before moving to Princeton, where, in 1951, he hit on suspending the plasma in a magnetic mesh, calling his device the 'stellerator' to evoke the idea of containing a star. The main challenges were how to create sufficiently high temperatures and how to know if they had been achieved, let alone a consequent fusion reaction. Given the energies involved, it was not possible to see or measure what was happening in the vessel – accurate diagnostic tools had not yet been developed. With limited funding available, the American Energy Agency funded Spitzer's machine in 1953 while rejecting another device, based on similar principles: the Perhapstron. Hearing of American investment, British physicists successfully sought even greater government funds to construct the world's first large-scale fusion reactor, ZETA. In turn, Soviet and US physicists found newly willing state funders to help them maintain pace with the British. Cold War competition and secrecy spurred fusion on.

But in 1956, Igor Kurchatov, the Soviet chief nuclear physicist, visited ZETA and spoke about Soviet fusion research. This was the first startlingly public move to declassify fusion research, which was inadvertently boosted shortly afterwards. ZETA started operations in 1957. Despite the director's cautious statement (Cockcroft 1958) that what appeared to be a successful thermonuclear reaction may have been caused by other factors, he was harried into opining that fusion was 90 per cent likely. This was exultantly reported by the press in January 1958 as a breakthrough in fusion energy.

The triumphant jingoism of the reporting (the *Daily Mail*'s headline ran: 'Our scientists Sputnik the Russians – for peace. A sun of our own and it's made in Britain!') was perhaps over-compensating for the Suez Crisis two years earlier and Britain's first 'faltering on the world stage' (Jon Agar quoted in Pease 2008). After a public withdrawal of the claim that ZETA had achieved fusion, the press began using the word 'failure' (Hillaby 1959: 5; Watson 2006: 291), even though the project was not aiming for fusion, only creating high temperatures and controlling the plasma. Alan Gibson, a ZETA physicist, perspicaciously observed, 'I think what the press couldn't get their heads around was the fact that the scientists didn't know' (quoted in Pease 2008). Although ZETA produced major advances in plasma theory and measuring techniques, it is remembered for something that was essentially a failure of witnessing and communicating, rehearsing the point that scientific method is as bound up with how something is observed and persuasively made known publicly as with the 'doing' of experiments (Haraway 1988; Shapin & Schaffer 1985). In 2019, the *Financial Times* again dismissed ZETA as having failed to do something it had not set out to do: 'Zeta closed down in 1968 having failed to produce any useful energy' (Cookson 2019). Nonetheless, the PR fiasco accelerated fusion research's declassification, jump-starting global collaboration (Herman 1990), thereby suggesting that some failures can be positively, if inadvertently, generative. Certainly this is how ITER's website tells the story (Arnoux 2018).

Despite fusion's seeming imminence, it failed to materialize in the 1960s. Several different devices to confine plasma, including Spitzer's stellerator, were in play in various laboratories, indirectly in competition, including the Soviet 'doughnut-shaped' tokamak (Fig. 2).

The difficulty, as ZETA's announcement illustrated, was knowing what was happening inside the machines. By 1965, the tokamak was producing significantly better plasma performance than any other device (Herman 1990: 81). Initially, as with ZETA, the figures were disbelieved since they contradicted theoretical predictions (Herman 1990: 84). Eventually, however, ZETA's new measuring techniques confirmed that 10 million °C had indeed been reached with plasma confined for a good duration: 'up to 20 thousandths of a second' (Herman 1990: 96; see also Forrest 2011). Although the tokamak consistently proved better than other devices, theoretical physics could not explain why it so reliably created such good plasma performance. The one clear thing indicated by the device's results was that the larger the plasma, the more likely fusion was to occur, which meant a big machine. Twenty years later, Harold Furth, an American fusion physicist, observed that all improvements made in the intervening period 'had been arrived at by "brute force" … [with no] advances in the theory of plasma behavior' (Herman 1990: 168).

These developments presented an acute challenge for other laboratories. If they opted for fully understanding the physics, they might never move towards the goal of energy production, but choosing to pursue a particular device too early might prove a

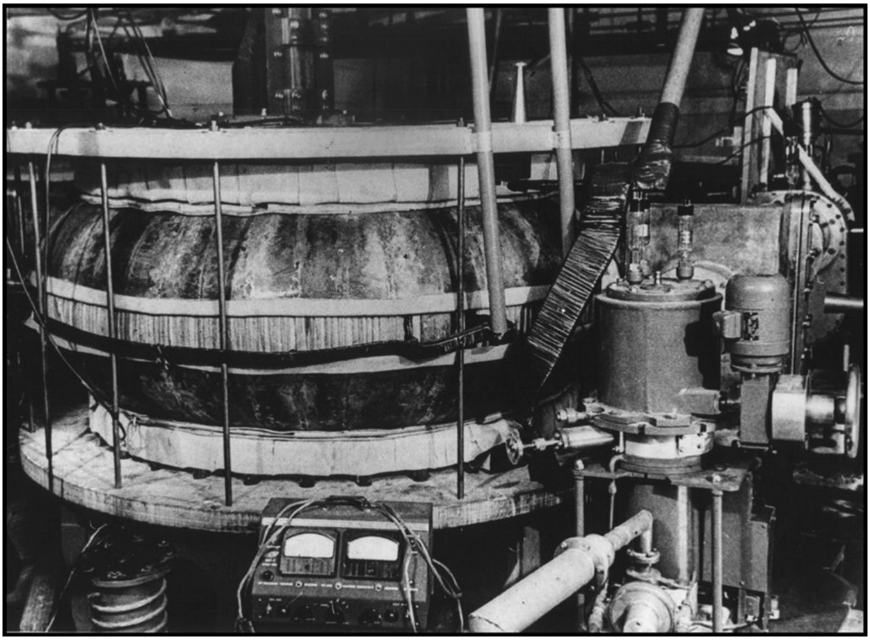

Figure 2. The world's first tokamak device: the Russian T1. (Wikicommons.)

dead end (Herman 1990: 77) and other options would have been starved of funding. One by one, the 'big players' of the United States, Europe, and Japan chose pragmatic uncertainty, building larger tokamak reactors and shutting down or cannibalizing other kinds of devices (e.g. the stellerator) that had not yet proved themselves. JET was 100 times larger (100 m^3) than the next largest machine then in operation. ITER, also a tokamak, is 830 m^3 and designed to produce between five and ten times more fusion power (500 MW) than injected thermal power (50 MW). However brief, this is the crucial moment that will generate vital diagnostic data. As the physicists like to say, 'All you need is one good plasma, one good shot'.

A gap still remains, however, between observation and what can be predicted. As Mike, a physicist, explained, there is a good understanding of what is happening inside a tokamak, 'the physics is mature, *but* there's no validated first-principles model of how tokamaks will perform'. There have been numerous computer simulations of burning plasma in labs globally, 'but', Mike continued, 'you still have to do it, right? I mean … you don't know what you're going to get until you actually try it'.

ITER's chief engineer, employed there since 1989, described how that theoretical uncertainty was overcome and ITER's design determined. 'There was then, and still now, ambiguity about plasma performance and characteristics … We cannot predict the ITER machine purely based on physics, the ambiguity is so large'. This is where, he said, the scaling law comes into play, combining engineering and physics. The scaling law uses existing tokamaks' performance data, correlating that with each machine's engineering parameters to produce a parametric model. With such a model, it is relatively straightforward to calculate what happens if a machine is (for example) doubled in size: does performance also double or change by another factor?

But regression analyses that drive extrapolations from parametric models assume unproblematic input data sets and, Mike went on,

> Anyone I've ever talked to who's done one of these studies shakes their head, because you can't unravel all the interdependencies between the various parameters. They're the ones who are the most nervous, because they … went through the exercise, of trying to get a line to go through that data that means something. And of course you never know if you're missing a key parameter in your scaling relationship, so there's a lot of uncertainty. So a scaling law is a guess.

Another physicist concurred that 'physics uncertainty is hidden by engineering parameters'. In the 1990s, the initial design was 'big ITER', which, Mike said, 'would have worked even if it didn't work', meaning that the aim of net energy would have been met, even if the machine had failed to achieve its goal of 'ignition': self-sustaining fusion. Another way of explaining the larger design's attraction was that it offered higher error margins to compensate for uncertainty. He used the conditional tense because the conservative design was rejected by political funders as too expensive. The current machine is half the size with reduced aims, but the shrunk design reduces error margins and intensifies the challenge of housing necessary components. Some believe the increased complexity has cost more than the original.

The scaling law fillets proliferating complexity into a reductive predictive model to transcend gaps threatening progress. Inherent uncertainty is disappeared into the form: a statistical law that seems objective, although all statistical analyses assume an explanatory structure (Cartwright 1989; see also Lahsen 2005: 898). The scaling law thus rehearses the familiar argument that social relations and uncertainty are typically folded into forms of quantification. What emerged from the scaling law was not just a huge machine but also the fiendishly complex orchestration of multinational participation across different sectors: industry, academia, governments.

Politics: selling and fragmentation

Pieter, ITER's knowledge manager, did his Ph.D. and postdoctoral research in plasma physics at JET before moving his family to France. As he liked to say, he was ITER's first employee. Since then, he has participated in the political and technical negotiations over design, siting, and construction and had robust views on the politics surrounding ITER. He showed me a PowerPoint slide he had made illustrating the painfully protracted process of selecting a site from those offered by member countries: ragged, exhausted men are hauling a large ship into harbour.

Like many of ITER's physicists, he had learned enough engineering to be able to translate and arbitrate between the disciplines. This was a source of pride when he was asked to comment on specifications from an engineering perspective but also a rueful acknowledgement that: 'I'm no longer a pure-bred physicist and I'm also not a pure-bred engineer, so if you go too deep into anything, I get lost'. Nonetheless, although he laughingly called himself an administrator, he saw his work as 'still related to fusion and the vision of making fusion a reality' and was eagerly looking forward to having 'my toy' to play with, a common diminutive that made this enterprise intimately knowable. He might be retired by the time the device is fully operational, but it's still a goal that shaped his doggedness in finding ways to keep the project on track. Pieter explained that ITER's design is partly an artefact of other technologies' maturity, and so is about twenty to twenty-five years ahead of other devices.

> In comparison, the tokamak's a more robust, big, Russian-kind-of-beast machine. When it was first made, it produced results that were a factor of 10 better than what everyone else had managed and therefore everyone put themselves on tokamaks. That's why JET's a tokamak and ITER's a tokamak … That doesn't mean a fusion power station has to be a tokamak. It has to be something ITER-like.

The tokamak remains the likeliest option to achieve net energy, even while recent computing advances mean other stalled devices, such as the stellerator, have been revived. Pieter continued that new superconducting technologies are enabling fusion devices currently being designed to be smaller, although, he observed, their development time is usually underestimated. Thus, by the time these machines are built, they, too, are unlikely to incorporate the latest technologies. The sheer complexity and duration of building a fusion reactor, whatever the design, means a certain obsolescence by the time it appears is almost inevitable.

Multi-government participation in the 1990s to construct the giant reactor both enabled and complicated the idea of building a machine to get 'that one good plasma'. As recounted by ITER staff, additional aims were introduced, and political funders had to be enticed with narratives of certain ambition. 'The biggest problem we have in "big" fusion', Pieter said, scare quoting 'big' with his fingers, 'is that only governments will invest in this and governments are subject to the … [*he grimaced*] natural flows … Politics!' By 'natural flows', he explained, he meant changing governments with different views about fusion energy. Here I touch on two effects: the need to 'sell' fusion and the multiplication of ITER's aims, both of which contributed to labels of failure that have haunted the ITER project's development and construction.

Virtová and Vostal (2021) suggest that inflated claims to attract grants for proposed research projects are now so widespread that no one expects projects to achieve their initial aims; failure is therefore not so much unexpected as par for the course. The problem intensifies with something of ITER's size. In order to court funding commitment, the ultimate prize is offered of fusion as a 'potential source of safe, non-carbon emitting and virtually limitless energy',[9] which obscures the fact that ITER is only a necessary step towards that. With such a long time-frame, Comms and other staff observe the difficulties of maintaining ITER's profile in the press. Several times, the 'mystery' of CERN's media success (see Roy 2012: 294) was commented on, where, 'as soon as somebody *farts* at CERN, it's on the BBC. It's unbelievable', or, 'CERN are doing fantastic work, but if you want to check what they've really done for mankind, the only thing you can really come up with is the internet', playing into the very claim that other staff quietly say plagues perceptions of ITER. Eduardo, the configuration manager, rolled his eyes as he summarized the problem:

> The fusion world's always had to deal with this: you have to sell things to politicians … Even now we're doing the same thing with promises for unlimited energy for mankind. But in the end we're not producing any energy for mankind! ITER consumes energy for mankind!
>
> In some cases you're setting the ultimate objective, but you're asking for money for a specific device, which is just a step to reach it … And I have this impression that sometimes people miss this difference.

Pieter added that fusion energy availability should end oil wars and, for this reason, a previous director general had hoped for a Nobel Prize – for peace. He grinned. The capacity for disappointment, and media misreporting of failures, as happened with ZETA, is thus inscribed in the conflation of long-term end goals and exactly what each stage entails, although ITER's website now precisely qualifies its claims.

On the other hand, an inability to distinguish between real advances and what sound like major milestones can work to ITER's advantage. 'First plasma' is literally just that, the first time a newly built device reaches the heat necessary for a low-power plasma to appear. It is, as Eduardo says, 'really just a flash, a pouf! of light, nothing exciting at all from a physics point of view'. But, like others, he is keenly aware of how well 'first' resonates with politicians and the global media. For him, ITER's first plasma indicates something different. The project's efforts are, he says, 'focusing on first plasma [because] the full machine needs to be in place for that. That can happen while other components … are still being developed'.

Physicists and engineers wring their hands at the early political decision to spread manufacturing contracts across member countries to raise overall capacity (Åberg 2021), which, in turn, sharpens the possibility of mismatched components. In 2022, when I wrote this, the issue was 'live' as numerous sections, often from different manufacturers and each requiring staggering precision, were being assembled.[10] The tension here was between required accuracy and the disaggregation of construction to different countries and industries, each with their own ways of doing things. As just one example, each of the nine, orange-segment shaped steel components, which slot together to form the seamless vacuum vessel, measures 10 by 5 metres and is 6 centimetres thick but needs to be accurate to within 2 millimetres. The insistence on dividing these components' production between different manufacturers was described succinctly by one senior staff member as 'insane', and at greater length, but with the same sense, by others. Having sorted out different understandings of 'tolerance', in terms of margin, and different quality standards, the current preoccupation is how to construct the machine when (for example) some components have arrived that cannot be fitted together, are delayed, or appear out of sequence. 'At least', an engineer laughed, 'everyone is using metric!', referencing NASA's 1999 disaster when a spacecraft shattered because both metric and imperial units of measurements had been used by different teams (Kerr 1999). Despite the frustration with things going wrong, resulting from earlier decisions, such stories are told with a certain dramatic panache, with the narrator either highlighting how their ingenuity was central to overcoming obstacles, laughing at the absurdity of certain situations, or just giving a shrug of acceptance. The improvisation, serendipity, and intuition that Rheinberger (2005: 6) casts as central to the experimental process appeared in many of the ingenious workarounds devised by Pieter and his colleagues.

This is where failure becomes both inevitable and impossible. As they described it, staff are firefighting the effects of earlier and ongoing political decisions to maximize benefit to national industries and cut costs. One physicist believed such cost-cutting could be fatal. Another laughed hollowly at the 'many experiments in one' tag, observing that one might with more validity say that ITER had clearly shown international collaboration did not work; a point repeated by another physicist, who muttered that the only way to get things done was through war or market competition.

Others were more optimistic. But even those who criticized the project internally noted that because of the political involvement, there had also been clear wins. The simple fact of peaceful collaboration between countries with diplomatically strained relations was frequently cited as an extraordinary achievement: 'a reverse Tower of Babel!', as an enthusiastic Comms member claimed. Additionally, from a low start, the fusion industry had matured and grown, performance levels had been raised across the board, and many engineering innovations had had positive knock-on effects. Pieter cited global capacity for superconducting wire fabrication doubling because of ITER's requirements, thus reducing the cost of MRI scanners. This is the 'real-time value' to which Comms, Pieter, and others said they had little luck drawing media attention.

The enchantment of size

The history of both fusion and ITER rehearses influential studies of experiment and laboratory practice highlighting non-linear knowledge production that mangles together (Pickering 1995) machines, politics, organizational orders, ideas, and social relations (Latour 1987; 1992; Latour & Woolgar 1986; Law 1994: Pickering 1995; Rheinberger 2005) in constructing experimental apparatus (Collins 2004; Galison 1987) and producing facts. Failure here is the puzzle to be explained: for example, through the 'dance of agency' between these various elements (Pickering 1995). But there is no sense of failure being positively or negatively valued, as suggested by the various responses above to descriptions of ITER as an experiment, perhaps because its 'experiment' is rather a test or 'mission' to prove and refine the viability of fusion energy. Roy's (2012: 299) observation that the development of accelerator systems moves from discovery and expansion to validation, precision, and consolidation is useful here, speaking to alternating temporalities of openness and closure. In the context of ITER, each carries different valences of failure. Corsín Jiménez's observations on prototypes incorporating 'virtuous failure' and acting as figures of suspension and expectation work equally well for ITER when cast as an experiment 'never quite accomplishing its own closure' (2014: 385).

Analysing technoscientific enterprises as infrastructural megaprojects (Carse & Kneas 2019; Flyvbjerg, Bruzelius & Rothengatter 2003) moves us from laboratory practice to big science. Used to describe postwar physics research (Galison & Hevly 1992; Price 1986; Traweek 1988: 2; Weinberg 1961) that relied on colossal machines (accelerators, space telescopes, reactors), big science has, until recently, necessitated (multi-)government funding with all the attendant bureaucracy, accountability, politics, industrial interests, and multiple publics, each with its own version of a job well done. An aptitude for presenting research that appeals to national prestige politics, alongside understanding backstage diplomacy and financial spreadsheets, became necessary skills for physicists leading organizations. Weinberg, who coined the phrase (1961), described science's giant appliances as the modern equivalent of ancient pyramids or medieval cathedrals, suggesting scientists should retreat from such ambition. Nonetheless, such images have wide circulation (Herman 1990; Khatchadourian 2014; Traweek 1988), reinforcing infrastructure's quality of awe and enchantment (Harvey & Knox 2012; Larkin 2013). While I never heard such metaphors, likening usable fusion energy to the Holy Grail was a frequent, if unlikely, simile, bearing in mind the fate of the questing knights. Just as the promise of unbuilt roads in Peru carries an affective capacity to enchant (Harvey & Knox 2012), so do ITER's discursive promises, which take the form of boundless energy and peace among nations, and spur commitment and funding. As Eduardo noted, such claims also pave the way for inevitable failure.

Responding to Gupta's (2015) call to consider infrastructural suspension as a socially productive ontic condition (Marrero-Guillamón 2021), Carse and Kneas (2019) have created a typology of unfinished constructions. Each, they suggest, is freighted with its own temporal effects, or 'timeknots', that need to be disentangled from teleological 'project time', in which linear time unfolds back from completion: an imagined form's materialization. As my ethnography illustrates, such seamless progression masks tensions in orchestrating plural temporalities as multiple actors, techniques, and materials are somehow enmeshed. Two of Carse and Kneas's ideal types are instructive here. One is the idea of shadow histories or paths not taken. Throughout fusion's history, politics, lack of funding, or immature supporting technologies have meant that some designs were not built or built to scale. But with material and technical developments and new private funding (Overton 2020), many of these once 'failed' machines and designs are now being built (Ball 2021), reminding us that the production of technoscientific knowledge can be as inimical to 'project time' as infrastructural megaprojects. From another angle, fusion's rollercoaster fortunes have been shaped by global politics and environmental fears since the 1950s. Equally apt is the notion of a 'suspended present' (Carse & Kneas 2019: 18-20), where delay can 'enroll people in communities of aspiration and anxiety' (Hetherington 2014) framed by 'a temporal orientation defined, on the one hand, by uncertain horizons of project … closure and, on the other, the experience of deferral' (Carse & Kneas 2019: 19). Staff designing and building ITER variously experience anxiety, doggedness, cynicism, and hope.

For many physicists and engineers who are also closely involved with negotiations and administration, and who have committed their career to pushing ITER through, pragmatic determination combines with a keen sense of humour in retelling more farcical effects of political decisions. Early delays were ascribed by Pieter to 'forgetting' that design details needed revisiting and refining after the site was selected, and to the failure to recognize the time needed to clear a forest, level a hillside, set concrete, and establish an organization *ab novo*. Responsibility is excised from this narrative. Such things, as Pieter said, take the time they take. As with other ITER staff, Pieter's deadpan comic delivery acts as a distancing device from certain actions (or lack thereof) while also staking a claim of authority. Some things can be laughed about precisely and only because the person is so close to a given problem and cares about it (see Geissler, Bruckermann, and Mattioli, this volume, for different registers of laughter as responses to failure).

But I end by taking suspension in a different direction inspired by Larkin's evocative phrase that infrastructure may not only be promise and failure (2013: 334) but also 'an excessive, fantastic object that generates desire and awe in autonomy of its technical function' (2013: 333). Repeatedly, ITER's vastness is summoned in YouTube videos, presentations, and recitations of numerical facts. Recognize ITER's place as part of a global collaborative network of laboratories, devices, technicians, scientists, manufacturers, and governments and its reach becomes boundless. To an extent, such magnitude is held up as an accomplishment, something to be wondered at, irrespective of its function. Vastness and complexity are clearly ethnographic concerns, but also raise an analytical question about the possibility of perspective. Stewart's marvellous meditation on the gigantic is enlightening; she writes that it 'envelops us but is inaccessible to lived experience' (1993: 102). '[T]he partial vision of the observer prohibits closure of the object' (1993: 89). Judgement is thus arrested and analytical closure forestalled – suspended.

Ball notes that 'fusion research has shifted from gargantuan state- or internationally-funded enterprises to sleek, image-conscious affairs driven by private companies'

(2021: 363). Perhaps, remembering its Cold War roots, ITER might be seen as the last gasp of high modernist gigantism (Scott 1998: 72), where technoscience is summoned to solve humanity's woes in a spectacular demonstration of formally organized power's capacities. Size becomes performative, projecting an ideal of multinational collaboration (Steiner & Veel 2020), admitting only astonishment.

Suspension

Suspension is at the heart of fusion energy. Exploring the various modes in which suspension appears both foregrounds the temporalities at play in the series of consequential failures that shapes ITER and is productive in thinking how it endures.

The asynchronous development of the various elements comprising experimental projects adds further texture to the non-linear production of scientific knowledge. Thus at different historical junctures, if theory, funding, diagnostic capacity, materials, experimental observations, computing power, and political will are out of step, progress is threatened, sometimes terminally stalled. The longer view suggests some reported deaths are greatly exaggerated. Thus the Perhapstron fell by the wayside; the lack of love in this instance, to borrow Latour's (1992) explanation for a failed technology, appearing as limited funding. But the once-cannibalized stellerator was revivified when building it to scale was enabled by increased computing power. Other devices have similarly been brought back into play as supporting technologies, materials, or alternative funding sources re-coalesce around once-defunct designs. Central to these acts that retrospectively transmute absolute failure into mothballed suspension and then reinvigoration is the work of active memory that sees possibility in new advances being conjoined with once unrealizable ideas and experimental designs. In these cases, attributions of complete failure are indeterminate (see Ringel 2019), open to re-evaluation.

Two other instances of asynchrony appear. The immaturity of manufacturing knowledge and capacity in the nuclear fusion industries had consequential deleterious effects on ITER's deadlines. However, the relative success in increasing capacity not only had beneficial side effects, but also suggests other current and future fusion enterprises are better placed for swift development. Considered within the broader landscape of fusion energy development, the causes of ITER's failures to meet deadlines may have positive effects elsewhere. Once again, perspective and scale determine whether something appears as a failure or if that judgement is held back, suspended in light of longer histories and global endeavours. The third asynchrony at ITER's heart is the disjuncture between predictive and observational knowledge. Although 'hidden' behind the scaling 'law', the fundamental physics uncertainty perhaps tips this more to the open-ended 'discovery' than the 'validation' between which Roy distinguishes.

Big science and 'projectification' (Carse & Kneas 2019; Jensen, Thuesen & Geraldi 2016) apparently lock failure to dates and budgets that make it visible. But in ITER's case, scope and aims have been redefined, deadlines prove paradoxically lively, and, while absolute costs are unknown, cash contributions have escalated alongside labour and material costs for manufactured contributions-in-kind. The effect is that failure is recalibrated, always twenty years away, always suspended. Advocates' view is that however much fusion's roadmaps and timelines slither to the right, the pressing need for fusion energy will remain: it cannot fail, the need is too great. As noted above, EU policy now envisions fusion energy as part of a post-2050 energy economy.

Finally, an emphasis on meanwhile achievements refocused attention to an expanded present. While some experienced this as the anxiety of deferral or the stress of meeting unfeasible deadlines without knowing they would slip, there was also a distinct celebratory aspect championed by senior management. Here, multinational collaboration is heralded as a triumph, rather than a means to an aim; the declaration that ITER is 'many experiments in one' foregrounds geopolitical 'soft' diplomacy[11] and multinational labour within and beyond ITER that both enable and are produced by it. Again, the notion of experiment rather than project invokes open-endedness, where failure is essential to progress, displacing a missed deadline's negatively framed failure. The spin-offs as a side effect of developing industrial capacity are described as 'real-time value': unfolding effects in the world beyond ITER.

The final mode of suspending failure is again rooted in the present. The decades since Eddington mused on solar fusion's terrestrial possibilities meet estimates of a further forty-odd years to reach usable energy. This is not a time-frame amenable to conventional projects and policy. Indeed, a mode of battling on, trying to circumvent mishaps as they appear, is perhaps a more realistic way of understanding how such megascience projects operate, retreating from their enormous temporal reach to the present and 'the time it takes'. Elsewhere, the insistence on enumeration and evocations of vastness demand wonder at the spectacle, arresting, foreclosing, and thus suspending assessments of failure. Just as some say ITER is 'many experiments in one', so multiple forms of failure follow from the experiment multiple: at once essential, inevitable, impossible, and suspended.

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NOTES

[1] Arguably these claims are slightly disingenuous. Tritium is required for a sustained fusion reaction, is not found naturally, is in short supply, and is radioactive. While tritium's half-life is twelve and a half years, fusion plants will produce large quantities of low- and mid-level radioactive waste to be managed. There are also potential military uses (Carayannis, Draper & Bhaneja 2021).

[2] *https://www.iter.org*.

[3] Senior staff were usually willing to be named, others were keen to be unidentifiable. I have therefore either used pseudonyms or just disciplinary affiliations.

[4] The exception is Bob Guccione, who poured his *Penthouse* millions into a fusion experiment in the late 1970s. Bill Gates and Jeff Bezos are both funding fusion.

[5] Fusion is obliquely represented in energy studies via observations that decarbonizing energy policies rest on still immature technologies. Anthropological nuclear studies are typically concerned with high-energy physics (e.g. Roy 2012; Traweek 1988) or fission: weapons, contamination, and wastes.

[6] *https://www.euro-fusion.org/fileadmin/user_upload/Archive/wp-content/uploads/2013/01/JG12.356-web.pdf* (no longer available online).

[7] *https://www.euro-fusion.org/eurofusion/roadmap/*.

[8] Icarus died, which rather curtailed learning opportunities.

[9] *https://ifmif-dones.es/fusion-energy/about-iter/*.

[10] It subsequently transpired that there were 'dimensional non-conformities' in two of these giant vacuum vessel sectors. Repair strategies are being developed for this and inevitable delays built into the new re-baseline of the schedule (Nuclear Engineering International 2022).

[11] 'Science diplomacy' or 'soft power' are scientific collaborations that maintain links between governments with strained relations (McCray 2010).

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Suspension de l'échec : temporalités, ontologies et gigantisme du développement de la fusion nucléaire

Résumé

En retraçant l'histoire de la génération d'énergie terrestre par fusion jusqu'à un centre multinational géant de fusion expérimentale, l'autrice met à jour une série d'échecs consécutifs, de réévaluations de conceptions précédemment enterrées, mais aussi d'obstination. Pour expliquer comment cette vaste entreprise, plombée par les défaillances, peut perdurer, elle suggère que différents récits ontologiques la réorientent, aussi bien dans le temps que par rapport à différentes formes et valences de l'échec. La rhétorique du projet à mission concurrence ainsi celle d'une expérience sans échéance, concentrée sur le présent : l'une se positionne comme la solution cruciale face à la menace du changement climatique, l'autre « incorpore » des échecs vertueux comme parties intégrantes d'une pratique créative. La promesse visionnaire s'oriente vers un point « entre-temps ». Enfin, l'ampleur du déploiement sur lequel l'attention est sans cesse attirée offre un spectacle déroutant, refusant perspective et achèvement et suspendant les jugements de l'échec.