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Prospective research and development for fusion commercialisation

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ABSTRACT

As well as the mainstream activities aimed at delivering DEMO to meet the high-level targets and timetable outlined elsewhere, there is a parallel stream of research investigating and developing technology to provide alternative and risk-mitigating options for DEMO and/or a fusion power plant, targeting the delivery of commercially viable fusion energy. This programme is termed Prospective Research and Development (PRD). The focus is on research into promising alternative technologies that do not form part of the main DEMO programme due to their current readiness level or higher programmatic risk due to development uncertainty, but which offer the potential for improved reactor performance in the long-term, and/or risk mitigation in case the baseline options cannot be validated. These alternatives may naturally, if achieved in time, be re-adopted into the DEMO programme. As well as the technological challenges, fusion has to meet social and economic requirements. Therefore in complement to research on technology, there is research into the socio-economic factors which are anticipated to impact the wider adoption of fusion: future energy system modelling, public awareness and attitudes towards fusion, energy policies, etc. This work helps to indicate important factors which must be considered in the longer term if fusion is to become a widely-accepted and -deployed future energy source, and therefore provides a view of "market pull" for the requirements the technology programme must meet to be successful.

1. Introduction

Although the main focus of the EUROfusion technology programme is aimed at the realization of DEMO as a fully-integrated demonstrator of fusion power plant technologies, in the long term fusion must be commercially competitive and attractive to investors [1]. EUROfusion research therefore has two additional strands: Socio-Economic Studies (SES), which investigates potential future energy markets to assess the role of fusion within them, and social attitudes to fusion, to provide an assessment of "market pull" and ensure that fusion meets future needs; and Prospective Research and Development (PRD), which aims to develop alternative technologies which cannot be relied upon to be ready in time for DEMO, but which are targeted at improving plant performance for more commercially-attractive designs once DEMO has proved that fusion electricity is viable. In addition, PRD carries out risk-mitigation research on technology not currently foreseen for DEMO, such as ion-heating and current drive systems, in case they are required once the DEMO physics scenario (currently electron-cyclotron heating-based) is fully developed and integrated. These alternatives may naturally, if achieved in time, be re-adopted into the DEMO programme.

The main programmatic objectives of PRD are:

- To take immature technologies which may benefit fusion in the longer term, identify how they would integrate into a power plant, and develop them as options for DEMO (if ready in time) or for prospective customers of fusion. This also covers some risk mitigation options for DEMO where relatively well-developed alternatives to the primary DEMO choice exist.
- To identify long-term programmatic risks and start mitigation research: for example the identification of required supply chains etc.
- To enable scale-up and industrialisation of production and processes
- To encourage innovation in the wider European fusion programme
- To provide a structure and focus for assessing new ideas and encouraging bottom-up ideas with integration advice

For research to fall within PRD there should be a foreseeable path to applications of the work and an identifiable technology development

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programme, with stated goals to be achieved to allow progress to be assessed, that may ultimately result in a useable system.

Taken as a whole the global fusion research programme contains many interesting ideas and avenues, of which only a subset can be explored in a single funding programme. Therefore the PRD programme also maintains a "watching brief" on external developments.

2. Improving the commercial attractiveness of fusion

The end-point of the Roadmap to Fusion Electricity is to establish the commercial attractiveness of fusion power, by demonstrating its generation on a power-plant-relevant scale and developing suitable technologies for its implementation [1]. EU-DEMO (referred to as DEMO in this paper) is fundamentally intended to be a relatively low-risk power plant prototype based on the best available current data and employing performance margins (through conservative assumptions on technology and physics performance, to reflect the gaps between "best-possible" laboratory performance and that reasonably expected from an integrated component) so that there is some confidence that it can achieve its high-level operational targets. It is aimed at closing many technical gaps simultaneously and is closely tied to the ITER timeline, as ITER is intended to provide critical input to the design and operation [2]. Taking these constraints into account, DEMO is not aimed at a design which will provide competitively-priced electricity, which we should not in any event expect from a first attempt to integrate fusion technology into a coherent whole.

The economics of fusion power are non-trivial but have previously been examined for DEMO-like devices during the European Power Plant Conceptual Study [3]. To start such an analysis, a plant concept is first required, covering the many plant systems and site layout, to examine the drivers of costs and performance (Fig. 1). This concept can then be used as a framework for identifying options for reducing costs and assessing the impacts of incorporating new technologies on the whole plant. It also allows consideration of the transferability of data generated by ITER and DEMO to the concept: is the physics scenario the same? Are further technological developments or test devices required? What additional or alternative materials are needed?

Ultimately a fusion power plant needs to be a reliable source of electricity generation. Any risk of unplanned downtime, or particularly any off-normal event which has a risk of damaging in-vessel components and requiring a shutdown for inspection and replacement, will mean that prospective operators are likely to require a risk premium on top of the nominal cost of electricity to offset their capital risk. Since fusion is principally still a research project, fusion supply chains are not well established, although some major steps have been taken for ITER, for example the large-scale production of superconducting wire. Identifying crossover applications of fusion and related technology – including development tools, computer modelling, manufacturing and material joining techniques, etc. – would help to secure relevant supply chains and allow further development of such technology without the reliance on fusion funding. These will not alone make fusion commercially viable, but they reduce the need for the current fusion research programme to carry out all technology maturation work and supply-chain development alone. They also help industrial engagement by showing short-term benefits to close involvement with a high-tech research programme.

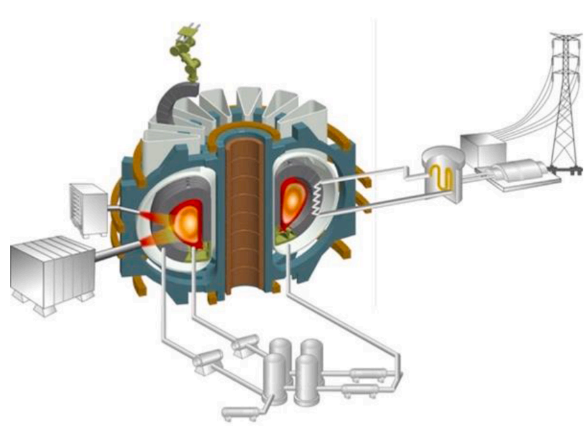

Fig. 1. A conceptual fusion power plant with auxiliary systems, including maintenance, heating and current drive, tritium breeding, and balance of plant. Consideration of all such systems is important when determining the plant economics. Image: EUROfusion.

Broadly, considerations of how to reduce the cost of fusion fall into a number of categories:

1. *Technology and materials to improve overall plant efficiency and attractiveness*

   These are replacements for existing components and materials, which extend the lifetime of the component or allow expansion of the operating conditions, increasing reliability and thermal efficiency. They should not require major reintegration or redesign, and could be qualified through progressive introduction and testing on DEMO. Example: development and qualification of new radiation-damage resistant alloys to allow higher temperature blanket operation. Currently it is envisaged that DEMO will act as a Component Test Facility for the breeding blanket [4]. While operating with a near-full coverage "driver" blanket, which must be installed from day-1 to achieve tritium self-sufficiency and extract the thermal power and convert this in electricity, it will also be used to test and further develop, in a limited number of dedicated segments, more advanced breeding blanket concept(s) that have the potential to be deployed in a future first of a kind (FoaK) fusion power plant (FPP). The idea to test advanced blanket concepts in a reactor operating with a conservative breeding blanket design is not new. Early considerations were already given to this in the 80's (see for example [5,6]).
2. *Reduction of direct costs*

   For example the development of crossover applications of fusion technology, spurring the development of wider supply chains and allowing the fusion programme to buy common technologies and processes back in rather than develop technology entirely internally. This should allow the reduction of fusion capital costs with relatively straightforward introductions of new technologies through partnership with industry. In addition, it allows industry to develop complementary technologies in parallel, reducing fusion development costs.
3. *Reduction of operational and decommissioning costs*

   These are developments that alter how a plant is maintained for improvements of efficiency, for example the development of blanket designs allowing crushing to reduce storage requirements in the hot cell, or designs which allow easier disassembly into waste streams. These examples would require redesign of the remote maintenance facilities and systems and hence changes to the plant design
4. *Plasma scenarios and technologies for increasing power density*

   New plasma scenarios which meet power plant stability requirements but allow higher fusion power density are obviously attractive if they can be achieved without significant impact on other component lifetimes, and this area includes the development of e.g. high-field magnets as well as, for example, higher elongation plasmas which boost performance through a compound effect of increased current, higher density, and so on. Also high bootstrap current plasmas which reduce current drive requirements. However higher power density requires improved first wall, divertor, and/or structural materials to handle the increased loads, and possibly new maintenance strategies. This potentially leads to the plant design requiring extensive re-integration.
5. *Innovative plant concepts*

   For example, what happens if we aim for optimisation of plant availability and design around that target? If we consider different power cores such as stellarators? Changes of concept mean major redesigns of many systems.

6. *Integration into coherent plant design*
   Fusion systems are highly integrated: what are the consequences of improved performance from a particular plant system on the rest of the plant? If we identify ways to ease the limits imposed by the operating stresses on a particular system, what new limits on overall performance come into play? Is the development of additional systems required to gain the benefit of new technologies?
7. *The place of fusion in future energy scenarios*
   What is the market pull and public acceptability of fusion, and how do these help to shape the high-level requirements for fusion power systems? For example, what are the impacts of risks from outages of systems and what cashflow interruptions will an investor accept? Should fusion target steady-state operation or is a pulsed system acceptable? These questions are chiefly approached through the socio-economic studies (SES) work package.

In addition to these questions, component designs must be allowed to be influenced by commercial concerns, rather than the best tolerances that can be achieved: they must be "designed for manufacture". More work is required on what tolerances can be permitted inside a tokamak. For example it is unrealistic to think that blanket segments can be aligned to millimeter precision, and retain that alignment through many thermomechanical cycles, but what is permissible? Can we develop innovative construction techniques that impact construction logistics? For example, if segmented superconducting coils could be manufactured (e.g. as for ARC [REF]), this would allow factory construction of coil segments in bulk and remove the need for coil-winding facilities on-site, and would also simplify the assembly of the device. Can blanket segments be designed to allow removal of breeder material and then crushing of the remainder to reduce storage requirements, or for easier disassembly to the same end?

It will also be important to reduce overall complexity, for example by limiting the number of sub-systems such as different heating and current drive methods, and increasing standardization of parts (for example monoblocks in the divertor, and internal elements of blanket segments) to take best advantage of bulk manufacture. In this way – designing for low cost from the outset – there may be some deviation from a design optimized for physics performance or coolant flow, but the overall capital cost reduction may outweigh these concerns: more detailed analysis of acceptable tolerances and deviations and their impact on plant output is required.

Some of the issues where further thoughts are required between DEMO and a commercial fusion power plant design are summarized in Table 1. Commercialisation requires significant scale-up and cost reduction of supply chains that already exist at lab-scale to supply "one-off" products [7]. Given the lack of fusion-relevant test environments, there is also no well-developed prototyping cycle. In addition, the move from fusion as a research project to an industrial project requires very different management and design skills from the current lab-based research environment.

Table 1
Fusion supply chain status.

Element	Status
Supply of materials	Many materials in development at lab scale or not produced in bulk (steels, 10s of tonnes)
Formation of material	Manufacturing methods in development at lab scale; joining technologies require nuclear qualification
Supplier engagement	Tier 1 (customers/stakeholders) consulted Tier 5/6 (basic materials suppliers) initial engagement Rest of supply chain not yet engaged
Logistics	Some components too large to transport
Supply of skills	Being built up including industrial involvement
Design readiness	Integration of plant systems incomplete; initial work on plant layout carried out; no consideration yet of logistics of build
Quality Control/ Inspection	Specifications and manufacturing stream not yet settled
End of life	Separation of waste in consideration; design not yet finalized

We know from work on DEMO that the overall machine size is strongly dependent on magnet technology and that the achievable power density is equally-strongly limited by the divertor solution [8]. The economics of fusion power are influenced by the plant thermal efficiency (a function of materials, balance of plant, blanket), availability (materials, component lifetimes, pulse length through cyclic stress and temperature variation, maintenance strategy), and recirculating power (coolant pumping, HCD power). The targets in PRD are aimed at developing options to improve these current limits on fusion commercial attractiveness.

3. Areas of work within PRD

While it is obviously not possible to cover all possible areas of interest, some have greater leverage than others. Specific areas of research currently in the programme include:

- **Advanced divertor concepts**: Integration of newly-developed materials (such as cold-rolled ductile tungsten [9]) and joining techniques into a helium-cooled divertor design concept [10], along with the manufacture of small-scale mock-ups for qualification under representative high heat-flux (HHF) loading. Safety assessment of an integrated helium-cooled concept. Development of a heat-pipe target concept [11] and evaluation of potential performance, and
- **Liquid metal divertors** (LMD) [12]

The longer-term aim with these two areas of divertor studies is to investigate how to transfer them into power-plant-scale systems, with the target of improving capacity to handle excursions from steady-state behaviour (e.g. loss of detachment, ELMs, other plasma instabilities) to expand the space of operating plasma scenarios, and also to seek options which allow longer divertor lifetimes. The technology for DEMO envisages the divertor being replaced twice as often as the blanket: finding options for aligning these lifetimes could increase plant availability from ~85% to ~90%, as well as decreasing the direct cost of replaced components. The other area of interest here (which LMD particularly may offer) is options which are robust against misalignment and so allow greater manufacturing tolerances and more rapid assembly and replacement.

- **Tritium systems**: continuation of the development of a continuous isotope-separation concept [13], and investigations into paths to lithium-6 enrichment [14].

Future fusion power plants will almost certainly need continuously-operating systems, including exhaust separation and vacuum pumping. See also heating and current drive (HCD). These systems have to scale to full plant scale.

- **Magnet systems:** development of high-temperature (HTS) winding pack options for tokamak magnets, including investigations of how to incorporate them into large toroidal-field coils [15,16]. Development of HTS quench-protection modelling and identification of any additional materials requirements.

It is generally acknowledged that high fields are desirable for magnetic-confinement fusion: however, the DEMO magnet design rules eliminate this possibility – properties of superconductor aside – due to the stresses in the coils. An examination of the geometry of HTS-specific winding packs, which differ from LTS, and the additional requirements on e.g. the quench-protection systems, should allow the definition of materials requirements to make use of the potential for high fields, possibly including novel structural options like carbon fibre.

- **Balance of plant:** further investigation of alternative balance of plant cycles, primarily supercritical CO_2 options [17].

Thermal electricity generation efficiency depends on the temperature of energy extraction. Alternative cycles are of interest to investigate what is required to achieve higher efficiencies or even make use of high-temperature heat extraction for process chemistry applications if suitable blanket materials become available.

- **Breeder blanket:** development of dual-coolant lithium lead (DCLL) concept [18], in particular the identification of specific requirements for the concept including permeation barriers [19], which may have cross-over applications in other power plant systems. Investigation of other blanket concepts (e.g. HCLL) where synergies allow.

The current cost and limited availability of beryllium means that eliminating it from breeder blankets is of potential interest for fusion. DEMO will investigate WCLL (water-cooled lithium-lead) options, but other lithium-lead options are available which are potentially more suitable for high-temperature operation if appropriate tritium-breeding ratios (TBRs) can be achieved. The DCLL concept also eliminates water from the blanket/reactor, potentially improving safety and reliability (corrosion, activation, tritium generation and leakage). These are best approached from the perspective of a conceptual system design to identify requirements such as corrosion or permeation barriers, and flow-channel inserts. Knowledge gained from DEMO on cost-reduction (particularly through elements of design for manufacturing) can transfer.

- **Advanced steels:** scale-up of advanced steel and oxide-dispersion strengthened (ODS) steel manufacture, and further optimisation (composition, heat-treatment) of these steels taking into account advanced manufacturing methods [20,21].

Novel steels (such as ODS) may allow higher-temperature operation within the blanket, and novel manufacturing techniques (such as 3D printing methods and powder metallurgy) may allow complex designs to be produced with fewer manufacturing steps and less wastage than traditional manufacturing methods. The microstructure of the materials in question also lend themselves poorly to traditional machining and joining methods. However the properties of materials produced using these methods leave much to be desired, and basing compositions on those of steels designed for more usual forging routes is probably wrong. The optimisation of these approaches requires work, that will have to take into account the need to meet licensing regulatory specifications and design criteria for structural materials and fabrication processes.

In the longer term this may include the investigation of e.g. novel ceramics which may meet a number of the requirements mentioned under blankets simultaneously as well as being radiation-damage resistant.

This work (and the materials modelling work below) is aimed at supporting meeting requirements emerging from blanket and balance of plant requirements identified in the work described above.

- **Materials modelling:** use of advanced modelling techniques to develop macroscale tools for engineering use capturing the impact of fusion-spectrum radiation damage (e.g. input into finite element models) and to help guide the development of materials design rules and qualification [22,23].

It seems extremely likely that the data collected from ITER and IFMIF/DONES will be somewhat limited and the probability of experimental uncertainty or data scatter high. The aim of the modelling programme is to provide theory-based underpinnings to materials design rules and experimental design for DONES, to ensure that the maximum information can be obtained from the data. In addition, work is aimed at generating multi-scale models for the impact of atomistic radiation damage structures into macroscopic materials property changes as a function of irradiation fluence and conditions, allowing the inclusion of radiation damage and swelling into multi-physics simulations such as ANSYS, to better predict lifetime behaviour of reactor components.

- **Heating and current drive:** investigation of high-efficiency H&CD options such as photoneutralisation and routes to incorporation into integrated systems [24–28].

DEMO avoids substantial in-plant recirculating current-drive power (and consequent reduction of electrical output) by using pulsed, Ohmic, current drive. The result is high cycling of thermal and other stresses on the in-vessel components during the pulse cycle, as well as a decrease in the available control of the plasma current profile. It would be more desirable from a number of engineering perspectives to achieve steady-state scenarios with very elongated pulse times, but this requires a dramatic improvement in the efficiency of the current-drive systems, and hence in the amount of electrical power needed to drive a given plasma current. The work here is aimed at finding potential routes to achieving this, as well as the extremely high reliability of such systems to operate continuously. In addition, this places requirements on other plant services such as vacuum pumping and maintenance to service the systems: these requirements need to be identified through the development of possible conceptual systems to ensure that the supporting work can be done. Within the PRD programme are studies into negative-ion neutral beam injection (NNBI), both for methods to improve efficiency and reduce caesium use for future reactors and as a potential option for DEMO, and ion-cyclotron (IC) system design and evaluation, also as an option for DEMO.

- **Power plant studies:** Development of systems codes to study the impacts of new technologies on power plant performance and economics, and for rapid developmental iteration and engineering evaluation of potential power plant concepts [29]. Other tasks such as investigation of impacts of system failure rates on overall performance to allow optimisation of maintenance strategies and plant layout as resources allow. This includes **Stellarator Power Plant Studies** (SPPS): development of parameterised magnet, blanket, and physics models to allow the engineering of stellarator power plant concepts to be explored, and the investigation of remote maintenance concepts for such plants [30,31].

This work aims to support a suite of tools for rapid investigation of the impact of different physics and technology assumptions on plant layout and performance, and to maintain a “library” of conceptual sketches of power plant options to support the development of individual technologies. In addition the identification of alternative beneficial plasma scenarios (particularly high bootstrap options, and scenarios using single HCD technologies) will be pursued to provide input into potential experimental programmes.

In general, a structured approach to developing fusion technology and economic concepts needs a view on what a commercial fusion power plant might look like. This is then used as a framework for identifying options for reducing costs and improving economics, and also for assessing the impacts of incorporating new technologies on other systems, the integration costs. It also provides structure for the consideration of the transferability of data generated by DEMO to a power plant. However, this is not necessarily a single concept and the maintenance of variety of options – for example different concepts for different markets – is useful. The power plant studies approach makes use of the existing whole systems approach used for DEMO to capture known interactions and dependencies.

Also in the power plant studies area fall potential gaps in the DEMO programme such as the construction of potential plant failure trees, and optimisation of maintenance strategies – less critical for DEMO then a commercial plant. The impact of manufacturing and assembly tolerances and mitigation options to reduce costs. Possible strategies to ensure minimisation of proliferation risks also come under this area. This could be e.g. modelling of radiation fields within a plant layout to see if the insertion of fissile material into the reactor can be reasonably detected, or if it must be done elsewhere in the supply chain.

Other areas to be investigated to see if there is feasible work that can be done include the role of accelerated testing for components, possible alternative fuelling methods, and keeping a wider eye on global programme investigating similar areas such as Li extraction from seawater and enrichment.

4. Socio-economic studies

DEMO will pave the way to the commercialization of fusion in the second half of this century. Nuclear fusion power plants will deliver reliable carbon-free electricity to power a growing global society that will have dramatically reduced the use of fossil fuels. Along with social changes, the global energy system will also develop progressively to meet the demands – both energetic and environmental – that the population places on it. Will nuclear fission power plants still be in operation at the time fusion becomes commercial, allowing fusion commercialisation to draw on extant nuclear technology competence and expertise? Will the transportation sector rely on electric and hydrogen vehicles only? Will the renewables deployment still be largely accepted by the general public when it occupies increasingly-extensive areas of land? What will the role of fusion be in future energy systems? These are some of the questions addressed by Socio-Economic Studies.

Possible alternative evolutions of the global energy system up to the end of the century are studied on the basis of possible actions taken by governments to preserve climate, the evolution of economy and society, technological progress and availability of materials, natural resources and land, for accomplishing different strategic goals [32]. Moving from very optimistic figures depicting a world that has managed to achieve a carbon-free economy at minimum costs, to very conservative ones, showing little change compared to today, conditions for successful fusion deployment that encompass public support, change [33].

The European public awareness and attitude towards nuclear fusion is also constantly monitored in this context. Indeed, the perception that future societies will have about fusion will be the heritage of today's knowledge and attitudes. On these bases, the lay public attitude towards fusion is studied through focus groups, surveys and analyses of social media. All show fusion generally as an appealing environmentally friendly future technology but not still not widely and adequately known, although attitudes vary from country to country.

There are many bodies which produce technology- and economy-based scenarios for future energy supply and use, but few of these include fusion. Incorporating fusion into scenarios as an available future technology changes the outcomes, and provides some confidence that it has a role to play. The insights from this modelling, and from social studies such as World Cafés and questionnaires, on the current perception of nuclear fusion as compared to traditional energy technologies, and people's expectations on energy and climate, then provides the fusion community with a wide picture of the environment in which fusion is meant to play a relevant role in the future. Recommendations on the economic and social measures that fusion power must achieve to be competitive in future energy markets can be derived. These recommendations for market role and social acceptability can have effects on technology choices for DEMO or future commercial power plants in terms of the wider grid systems they must interface with, their cost and size, and perceptions of waste production.

5. Further areas of interest

As well as the research plans described above, the PRD project is intended to provide a framework for discussion of the impact of new technologies on fusion. This includes new concepts and new plasma scenarios, and wider impacts from industrialization readiness and supply chain limitations.

The decarbonisation of the energy sector will stay a formidable task even after the mid of the century. Pushing and preparing for an early availability of fusion energy is the clear goal of the EUROfusion Roadmap. The industrialization of fusion will require significant engagement with industrial partners, building on the groundwork from ITER. Mutual benefits arise from a long term engagement, and this in turn requires a stable financing and programme of corresponding research and development activities.

6. Conclusions

While the next stages of fusion development – ITER construction and operation, and DEMO design and technology integration – are rightfully the focus of the bulk of European fusion research, and still present major challenges to be solved, it is reasonable to look beyond DEMO at the position fusion will take in the future energy market and therefore what features it should offer to be commercially attractive. The evolution of fusion from physics experiment to fully-operational, competitive electricity generation cannot be accomplished in one step and developing options for improving performance and decreasing costs are an important part of the commercial development of fusion.

With SES providing the "market pull" factors and PRD developing promising complementary technology for a second generation of reliable and maintainable fusion power plants, a focus is kept on Mission 7 of the EUROfusion Roadmap: Competitive Price of Electricity [1]. The lessons and challenges from ongoing DEMO integration transfer into identifying the issues that alternative technologies must solve and the impacts on wider plant systems, without the overhead of immediate pressures on complete system integration.

Overall, the DEMO, PRD, and SES programmes aim to offer a comprehensive knowledge base of how to construct and operate a fusion power plant, a suite of technologies for doing so, and confidence that the appropriate market needs can be met.

CRediT authorship contribution statement

R. Kembleton: Conceptualization, Writing – original draft. **C. Bustreo:** Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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