NEW DEVELOPMENTS IN DUAL FLUID TECHNOLOGY

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ABSTRACT

The patented Dual Fluid technology consists of an innovative reactor concept and a fuel purification system. In the reactor core, two different fluids – a uranium-chromium eutectic and lead – share the functions of fissioning and heat transfer. The technology combines all the advantages of Generation IV, such as inherent safety and overcoming nuclear waste. The main advantage is that the technology promises the lowest energy costs of any generator. This can lead to significantly cheaper production of electrical energy, as well as to the synthesis of fuels and basic chemicals, to a level that can undercut the price points of fossil fuels.

The path to series production began in January 2021 with the founding of the company in Vancouver, Canada. The construction of the prototype reactor is currently being planned, and completion depends primarily on successful financing. The licensing processes in Canada are characterized by the competence of the nuclear regulatory authority and the political will for successful technology implementation.

INTRODUCTION

Today's nuclear technology offers significant potential for improvement: light-water reactors can only convert about one percent of the natural uranium extracted into electricity. The remaining 99% must be disposed of as waste, which increases costs and reduces acceptance. However, because nuclear energy is particularly low-emission and scalable, many players are now trying to improve it. The concepts of the so-called Generation IV focus on safer and more flexible reactors that produce less waste.

But just about all Generation IV designs are versions of concepts conceived in the middle of the last century. Dual Fluid technology, by contrast, is a truly new development. The innovation lies in using two liquids in the reactor core: One is carrying the fuel, while the other extracts the heat. This allows for optimization of both liquids to their respective function: Highest density of fissionable material in the fuel liquid and highest heat transfer and density in the coolant. These high densities allow the core to be built in a fraction of the size compared with all other current and Generation IV types.

With the compactness of the core, the amount of required structural materials reduces accordingly, leading to a much broader selection of materials that have not been applied in nuclear technology so far because of their high costs. These highly corrosion-resistant materials allow in turn a much higher operation temperature, up to 1000° C. The high operating temperature, together with the compactness of the system, brings the decisive advantage of unprecedented power density. While fulfilling all the goals of Generation IV, Dual Fluid's design does reach far beyond this.

- It potentially reduces the cost of electricity, hydrogen, and synthetic fuels to a fraction,
- it extends the limits to growth and decarbonizes the world economy, and
- it burns nuclear waste, it is inherently safe and emission-free.

Due to its very hard neutron spectrum, a Dual Fluid reactor can burn any fissionable material, including thorium or natural uranium. Furthermore, a core meltdown or uncontrolled power excursion is impossible due to its self-regulation without external intervention.

A small Dual Fluid core with a capacity of 600 MW_{th} (called DF300 for 300 MW_e) needs fuel replacements only every 25 years. It generates electricity at about half the cost of fossil-fuel plants. A DF300 core operates about eight to ten times more efficiently than current light water reactors. Power density and efficiency increase further with larger cores. This makes the Dual Fluid reactor the most efficient energy source ever designed.

Efficient energy production goes hand in hand with a very good ecological profile, due to the system's compact size and the small amounts of fuel needed. Total lifetime emissions of a Dual Fluid power plant fall below current nuclear power and even wind power. Dual Fluid could even be used to completely decarbonize our economies within a few decades and to start a new phase of productivity growth.

Unlike nuclear fusion, Dual Fluid is fully achievable with available technology and materials. The DF300 prototype is expected to be operational before the end of the decade.

THE DUAL FLUID PRINCIPLE

The fuel (green in Fig. 1) enters the cylindrical core region from the bottom sides through the so-called plenum, a distribution system connected with the fuel tubes, and leaves it on the top side of the reactor (not shown). The lead coolant (blue) enters the plenum from the bottom, flows through the tubes in the plenum into the space between the fuel tubes in the core region where it takes up the heat and also leaves the core region on top. A part of the lead branches also into a blanket region where it reflects the neutrons, further improving the neutron economy. Fig. 1 shows also a metallic exoskeleton to support the inner core structure.

This distribution system guarantees an optimum thermal contact of fuel and coolant in the core region while still keeping both liquids separated. This way the heat can be removed much more effectively than in the molten salt reactor, where the ineffective heat removal requires the fuel to be diluted. For a Dual Fluid core, the heat removal is so effective that no dilution at all is required: the fuel could be pure fissionable material. However, as the melting point for pure Uranium is at 1130 °C, some admixture of Chromium and possibly other metals is needed, though the concentration will be still very high. In total, the power density will be a factor of about 10x higher compared with other reactor cores.

For the fuel, a mixture of U-Cr but also other mixtures are possible, as described in patent WO2020088707 (https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2020088707). More details about materials and applications, though for the "big" model of 1500 MW_{el} are published in Ref. [11]. Note that, as opposed to the publication, salt is not considered as fuel anymore.

Safety features

As the core contains mainly liquids, the reactivity coefficient is deeply negative. An effect already known from the molten salt reactor is its self-regulation – the fission rate and therefore the heat production always follows the power extraction. For the Dual Fluid reactor, the temperature coefficient is so negative that this load-follow feature is instantaneous and no active power regulation is required. This is also the most important safety feature. If no heat is extracted, e.g. by a failure of the cooling system, the reactor core remains critical with a power production that just balances the passive heat removal. The temperature always remains at 1000 °C.

The only possibility to change the temperature is a change in the fuel composition. If the nominal temperature is increased this way, a second passive safety feature known from the molten salt experiment at the Oak-Ridge lab comes into play – the melting fuse plug. This actively cooled drainage tube freezes the fuel and therefore stops the drainage in normal operation. In case of a power outage or overheating of the fuel the frozen fuel in this section melts and the entire core is drained to subcritical tanks.

Costs for prototype and serial production

Dual Fluid will significantly reduce the cost of nuclear power for several reasons:

- the entire system is significantly more compact than current light water or molten salt reactors and thus enables serial production in the controlled environment of a factory,

- it operates under normal pressure and there is no need for positive pressure containment,
- as decay heat is passively removed, there is no need for an emergency cooling system,
- it reduces the amount of fuel needed to a fraction.

The development costs for the prototype of a DF300 reactor amount to approximately 6 billion US$ (time horizon: approx. 8 years). Including the manufacturing facility for serial production, a total of double-digit billions will be required (total time horizon: 13 to 14 years). A higher capital outlay would accelerate the prototype development to approximately 6 years and series production to 8 years. Development of the DF1500 model with its fuel recycling system (the pyrochemical processing unit, PPU) will require investments again in the low double-digit billion range. It is planned to finance this development from the revenues generated from the first DF300 sales.

Levelized Cost of Energy (LCOE) comparison

Electricity costs are usually compared using the Levelized Cost of Energy (LCOE): To calculate the LCOE, all amounts invested for building, fuelling, operating, and decommissioning a power plant over its entire technical lifetime are summed up and divided by the total output of electrical energy, again over the entire technical lifetime of the power plant. Table 1 shows an LCOE comparison of Dual Fluid with today´s nuclear power, coal, and gas.

LCOE values for wind and solar power are comparable to coal or lower, depending on the location and system used. However, an LCOE comparison would be misleading, because solar and wind power require high additional costs for storage and grid expansion. Most importantly, they cannot supply the base load that is essential for any power grid.

The LCOE values of Dual Fluid are significantly below the values of other thermal power plant types: Compared to coal and nuclear today, DF300 will halve the electricity costs. DF1500 reduces costs further. The taxation of carbon dioxide emissions further increases the price advantage of Dual Fluid.

Hydrogen and synthetic fuel production costs

Current steam reforming from methane and similar processes are CO_2-intensive and consume fossil fuels. With the high temperature of a Dual Fluid reactor, emission-free hydrogen can be produced from water by catalytic thermolysis at high efficiency.

Already the DF300 can produce hydrogen at a price that competes with current steam reforming: 1.2 – 1.5 ¢/MJ. The DF1500 will lower that price to 0.9 – 1.0 ¢/MJ. For comparison: Emission-free hydrogen from wind power costs 4 – 8 ¢/MJ.

Hydrazine (N_2H_4) is a liquid fuel with properties similar to benzine (including toxicity). Produced by nuclear energy, it becomes an affordable alternative to petroleum products for use in transport. It can be combusted in piston car and truck engines and aircraft turbines after their minor modifications.

The large DF1500 can provide hydrazine at a price competitive with today's oil-based fuels: 0.6 – 1.1 ¢/MJ, depending on the process used.

On a per-energy basis, the hydrazine-producing Dual Fluid facility can compete with oil production costs equal to or higher than 40 US$ per barrel. On a per-weight as well as on a per-distance basis, only oil fields suitable for primary oil recovery (e.g. Middle East) can compete. These resources are expected to be depleted first and soon.

BUSINESS CASE AND PRODUCT PIPELINE

The development timeline is shown in Fig. 2. The DF300 powerplant units will be offered at a price of around USD 3,000 per kilowatt. This will allow buyers to earn a net return of approximately 9% IRR at a 40 USD/MWh power sales price. The purchase price includes fuel supply for approximately 25 years. After this period, Dual Fluid will take care of the removal of the used fuel and the delivery of new fuel.

The Dual Fluid reactors are to be identical to each other and will have undergone type approval to minimize the approval process for the customer. Serial production is to be set at 50 units per production line per year. In today's currency, the sale of all reactors produced would generate potential revenues of USD 45 billion per year.

The annual cost of manufacturing will be approx. USD 10 billion. Accumulated development costs (approx. USD 20 billion) must be financed from the surpluses. For the time being, the remaining profits will not be distributed to investors, or only to a small extent, but instead will be used to develop further product lines. These are, in particular, the recycling plant (PPU / Pyrochemical Processing Unit), the large variant of the power plant DF1500 (with approx. 1500 MW_{el} in power output), as well as the variant for fuel production DF30G with approx. 30,000 MW thermal capacity, in which carbon and nitrogen-based fuels, as well as basic chemicals for the chemical industry, are to be synthesized. The target cost of energy for the larger variants is about 10 USD/MWh_{el} for DF1500 and 3 – 4 USD/MWh_{th} for DF30G.

In further development steps, new applications for nuclear technology are to be developed, such as nuclear batteries offering a service life of several decades, which could be used in all kinds of mobile applications or small stationary plants.

To ensure that several dozen DF300-class reactors can be sold from the first year of series production, the level of awareness of this technology must increase. This should succeed in particular because Dual Fluid technology is disruptive: it produces energy at a significantly lower cost than fossil fuels while being CO_2 emission-free and environmentally friendly. This message will go a long way towards gaining the necessary support from decision-makers in politics, business, and the media. The planned IPO in the middle of the decade will also raise the profile of Dual Fluid.

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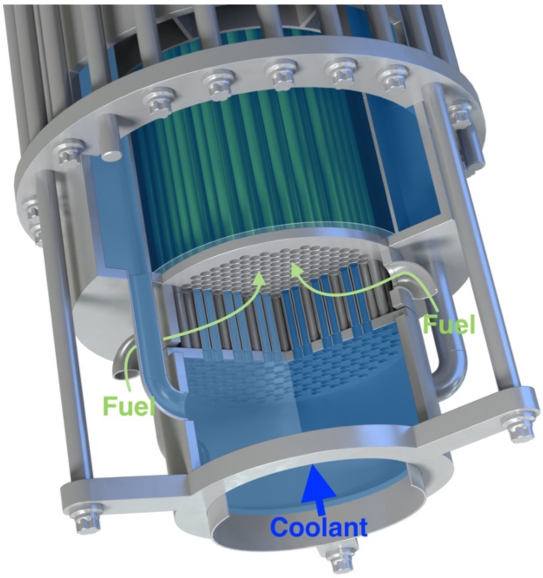

Figure 1: Bottom of the (top/down symmetrical) Dual Fluid core structure. The actual core is the cylindrical part in the middle with the fuel tubes, indicated in green.

	DF300	DF1500	Nuclear today	Coal	Gas CC	Gas OC
LCOE US$/MWh	27	21	65	55	70	95
LCOE US¢/KWh	2.7	2.1	6.5	5.5	7.0	9.5

Table 1: LCOE comparison between different energy generation types (sources except for Dual Fluid: World Bank, 2020). Gas CC = combined cycle, Gas OC = open cycle turbine; Gas OC is easier to regulate and therefore preferred as a backup for volatile solar and wind energy.

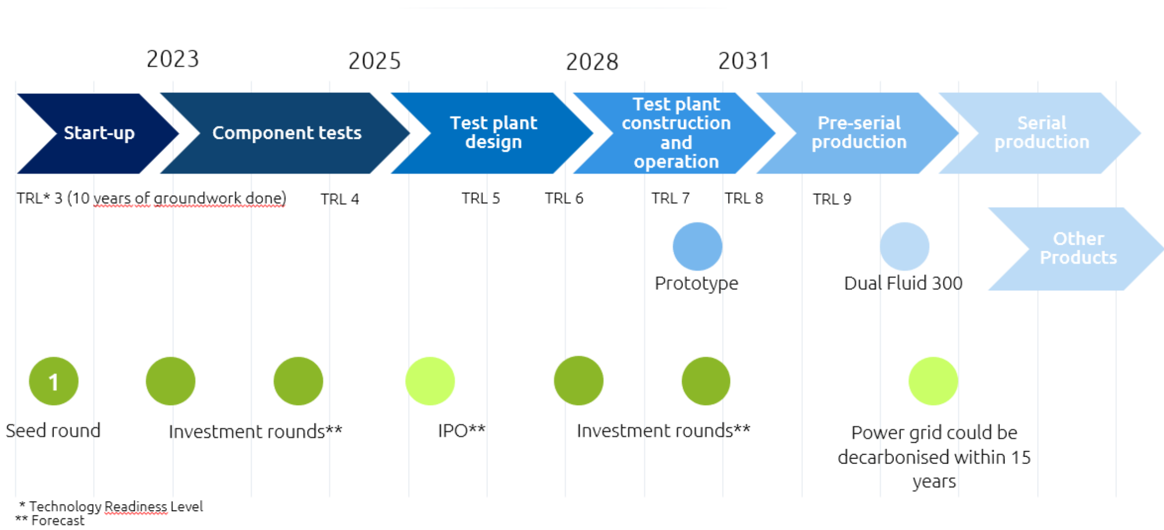

Figure 2: DF300 - Serial production readiness within a decade. The seed round was completed in June 2021.