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Advanced Molten Halide Salt Valves Operation Demonstration

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Abstract. To ensure confident molten salt flow operations within Generation 2 concentrating solar power (CSP) and other advanced >700°C molten salt-based power systems, for Gen 3 CSP and Gen 4 Nuclear Energy (NE), an advanced flow control valve is required. This paper investigates development of two molten salt flow control valves (FCV) for operational demonstration of bellows-style and quick-change packing designs. This innovative high-temperature molten salt valve, with nominal operation at 750°C and 11 bar has been demonstrated using FLiNaK and a ternary chloride molten salt. This work details the general design and flow testing of a bellows-seal FCV. This design includes an integrated closed-loop thermal control system to ensure robust design for freeze-thaw cycles. The design of both valves includes advanced thermal management with ceramic fiber (CF) heaters as well as a novel heat pipe valve stem. This investigation details the development of two high-temperature molten salt test systems that tested these valves up to 750°C and at 11 bar operational pressure. The valve test performed within the Flowserve Corp. Villach test loop employed a DOE Gen 3 CSP (20%NaCl/40%MgCl2/40%KCl by mol. wt. %) ternary chloride salt, while the Kairos Power Isothermal batch test system used FLiNaK (LiF-NaF-KF) as the salt chemistry. The results indicated nominal operation for the two valve systems without the heat pipes at 750°C though with the inclusion of the novel valve stem incorporating these, the temperature gradient along the bonnet was reduced by as much as 210°C, to improve thermal management performance and operational reliability.

Keywords: Chloride and Fluoride Molten Salts, Valve, Heat Pipe, Test Loop

1. Advanced Valve Design Features

1.1 Overview

This project was facilitated for concentrating solar power (CSP), Generation 3 systems, capable of attaining 720°C temperatures [1], among other energy sources which require super-heated liquid, which is then pumped through a network of pipes and transported to the power station to generate electricity. Molten salt is a high-temperature heat transfer fluid (HTF), capable of delivering and storing hot-liquid thermal energy storage (TES) energy because it retains its viscosity, as opposed to water, which converts to steam under such extreme temperatures. Molten salt also provides a more consistent temperature throughout the power plant during energy collection and delivery. Proportional FCVs serve as the piping-system gatekeepers for delivering this harvested energy to the production side of a power plant. These valves are continually confronted with extreme temperatures, pressures and flow rates, and oftentimes, extraordinarily low outdoor temperatures. Valve freezing and thawing due to the vagaries of weather can create expanding and contracting materials resulting in power production weaknesses in power block systems. Molten salt flow valves must maintain constant heat transfer and fluid flow, despite severe temperature variabilities to facilitate overall, confident consistent power systems operations that can support a stable and climate emissions-reduction electric grid. The team has developed an advanced molten salt valve (Figure 1) with strategic design features, such as a heat pipe valve stem, a Star-Pac flow metering system as well as quick-change packing canister which not only dramatically improves the flow control performance of FCVs, but also improves the ability to perform operations and maintenance (O&M) within one hour versus the need of having to cut out and maintenance the valve, which previously could take days of downtime.

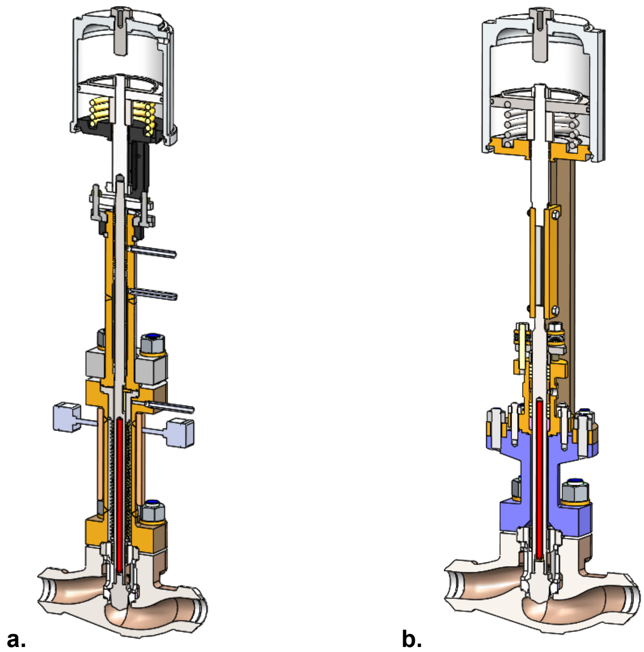

Figure 1. *Advanced molten salt valve a. Bellows design and b. Quick-change packing design*

The quick-change packing configuration is intended to reduce maintenance costs and serve as an alternative and/or additional seal barrier for bellow seals, which rupture when actuated with frozen salt present, and is costly to maintain and replace. The quick-change packing system also minimizes human error and installation inconsistencies during O&M. Both packing and bellows designs will be developed from the basis of the current Flowserve *Valtek Mark One* valve platform which has been proven globally in highly corrosive and high-temperature applications for over 50+ years. Prior to 2019 there were no reliable chloride, fluoride or carbonate molten salt valves on the market capable of attaining consistent long-term operation approaching 750°C. The design incorporates multiple purge ports to allow inert gas buffer layers between the bulk liquid and the packing materials. This improves the reliability of the materials, particularly with respect to thermal cycling. Another major valve reliability issue is internal salt freezing which can cause thermal-mechanical stress on valve stems. The novel heat pipe design addresses this freezing issue by using the hot working fluid as a heat source. This component passively transmits heat internally through the valve stem to the packing area, maintaining a constant internal temperature through the bellows and extended bonnet areas. [2]. The heat pipe valve stem was filled with an alkali metal (i.e., sodium or NaK) to achieve the operating temperature range. Employing a valve stem heat pipe keeps the valve hot if hot salt is present while allowing for enhanced freeze-recovery and reduced O&M.

1.2 Heat Pipe Valve Stem Development

One of the key challenges to designing, manufacturing, and operating a high temperature valve for a working fluid with high melting point is maintaining the internal wetted areas of the valve including the packing, bellows, and valve stem guides above the melting temperature of the fluid. Freezing salt within the valve, or actuating the valve with regions of frozen salt, could result in severe structural damage and an immediate loss of seal integrity. However, certain areas of the valve actuation system including the connection yoke and packing must also be kept at a lower temperature than the fluid flowing through the valve. An ideal temperature gradient can therefore be envisioned along the axis of the valve stem where the valve body and seat operate up to the process fluid temperature, the guides, bellows, and packing operate just above the melting temperature of the molten salt, and the yoke area connecting the valve stem to the actuator operate at much lower temperatures. This can be accomplished through external heat tracing, but reliable and precise feedback control is required to respond to varying process and ambient conditions without temperature excursions.

Instead, the valve stem heat pipe concept developed by Sandia takes advantage of a heat pipe within the valve stem in combination with other trace heating to maintain temperatures within the extended bonnet just above the melting temperature of the molten salt automatically as shown in Figure 2. Depending on the design of the heat pipe it could extend from within the valve body up through the packing to transfer trace heat applied around the valve body up through a completely insulated extended bonnet, or it could be positioned throughout the extended bonnet and end just short of the valve body to transfer heat applied somewhere along the extended bonnet throughout the internal surfaces of the valve.

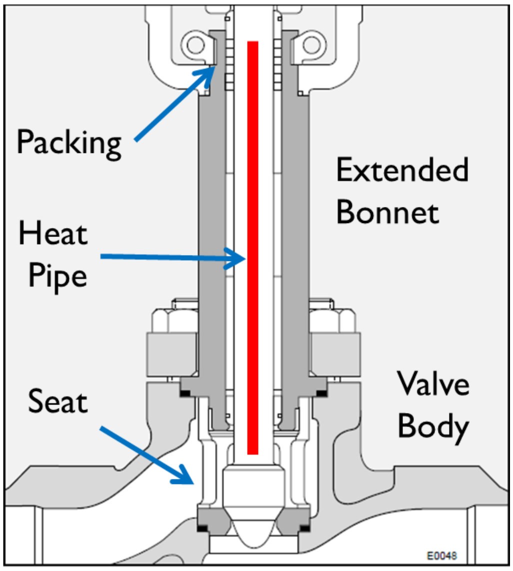

Figure 2. *A diagram of a valve stem heat pipe integrated into a standard valve body with an extended bonnet*

The three key stages of heat pipe design for this application include identification of possible working fluids, evaluation of operating limitations based on working fluids and geometric constraints, and finally a detailed analysis of several designs to assess their performance. At least three preliminary designs were developed and evaluated with partners at Flowserve to assess performance with and without their existing self-contained thermal management system, integration costs for any design changes required to the valve body and bonnet, and potential impact on first- and nth-of-a-kind costs of the valve. The preference was for a design that could be developed as a drop-in replacement for existing valve designs, eliminating the need for a highly instrumented thermal management system, the cost of the valve can be brought down to that of standard valves with a multiplier for corrosion-resistant materials.

After extensive heat pipe modelling [3], which considered a number of performance limitations, the final heat pipe design parameters for both bellows valve and quick packing valve were determined according to Table 1, while Figure 3 shows the fabricated heat pipes right after leak and shakedown testing, just prior to insertion within each of the valves.

Table 1. *Heat pipe design parameters for bellows valve and quick packing valve.*

	BELLOWS VALVE	**QUICK PACKING**
Working Fluid	Sodium	Sodium
Heat Pipe Envelope	Inconel 600	Inconel 600
Operating Temp.	500 – 750 °C	500 – 750 °C
Power at 720 °C (Against Gravity)	40 – 425 W	40 – 425 W
Power 720 °C (Gravity Aided)	1100 – 1425 W	1100 – 1425 W
Active Length	13.38 in.	12.25 in.
Diameter	0.495 in.	0.495 in.

Figure 3. *Picture of bellows valve heat pipe (left) and quick-change packing valve heat pipe (right) provided by ACT*

2. Experimental Validation

2.1 Experimental Valve Test Development – Isothermal Batch System

To demontrate the performacne of the valves, two prototypes were fabricated and tested within two new molten salt test systems. Experimental validation was facilitated under constant flow within the Villach test loop, and under batch process flow between two tanks within Kairos isothermal-batch test unity (ITU) system. of the Gen 3 ternary chloride salt as well as a FLiNaK (LiF-NaF-KF) salt, used for applications in nucelar energy molten salt reactors (MSRs). The design phase of the Isothermal Batch Flow Unit consisted of a two tank design, Figure 4a where the team evaluated the bellows valve with a FliNaK molten

Salt. A double flanged vessel, which will allow for testing of wetted and vapor gasket materials, along with dip tubes that serve as a transfer pipe for shuttling molten salt from tank to tank. These vessels required in-house custom fabrication, with pressure hydro-testing to accommodate the ASME BPV code thermal-derated strength requirements. The design intent was to install the high temperature test valve in the crossover line, where the valve was located above the vessel to allow for complete salt drain back after each respective test, Figure 4b.

a. 

b. 

Figure 4. *a. Isothermal Batch Test System and b. Installed prototype valve within the crossoverline and externally heated with ceramic fiber heaters.*

The team was able to complete the mechanical and electrical assembly ahead of schedule to facilitate commissioning and test operations. Here, cold and hot commissioning was performed with attention to safety and designed test sequences for salt, transfer and valve actuation operations. The transfer line connecting the tanks is a 3/4", 0.083" wall stainless steel tube. Mass flowrate of the salt was determined by weight changes in the load cells on the tanks. System parameters are listed in Table and simplified schematic can be seen in Figure 191 with the location of the valve within the Kairos Power Isothermal Batch test system in Figure 192.

Table 2. *General ITU parameters for valve testing.*

Parameter	Value	Unit
Maximum Operating Pressure	10	psig
Operating Temperature Range	500 - 750	°C
Salt Mass	145	Kg
Transfer Line Inner Diameter	1.48	cm

2.2 Experimental Valve Test Development – Flow Loop System

To assess Gen 3 ternary chloride motlen salt flow at 750°C and up to 11 bar pressures, the team developed a 2 in. Sch. 80 pipe molten salt test loop, Figure 5. As shown in Figure 5 the original structure was kept where piping was assembled with flanged connections that included multi-material spiral-wound gaskets from Flexitallic. For this system the team installed 3 different heat trace zones around each of the prototype valves as well as pressure and flow sensors, mounted in line with the valve. During heat trace assembly, it was found that attaching the mineral insulation (MI) cabling had some challenges due to housings being very small and the flanges and screws reducing the free body areas. Further details of the construction of both this and the Kairos Power molten salt test systems can be found by Armijo et al. [3].

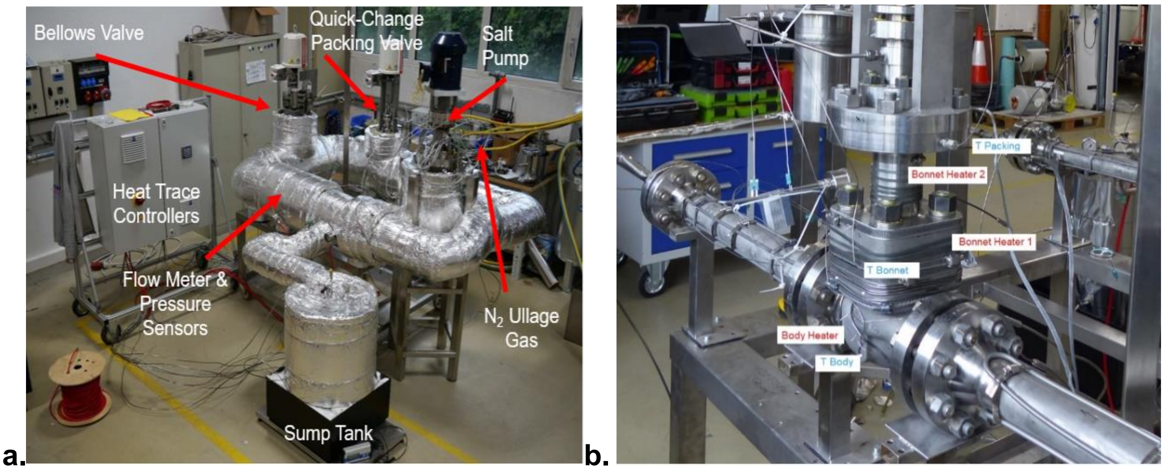

Figure 5. *Completed Flowserve Villach 750°C Chloride Molten Salt Flow Test Loop*

2.3 Valve Experimental Results & Discussion

The test campaigns consisted of salt flow passing through the 2 in. piping within the flow test loop and salt passing back and forth through the valve, between the two tanks of the Kairos ITU up to 1,000 times at the temperature set points: 750°C → 530°C → 750°C → 530°C. The results of the ITU testing can be seen in Figure 6 where during steady operations, the temperature profile of the valve can be seen where the valve, and its integrated assembly (i.e. flanges, ceramic fiber heaters, etc.) operated as designed without leaks or significant corosion issues. As shown in the results, there was three times it was cooled down to ambient.:

1. Thermocouple troubleshooting
2. Post-Phase 1 external inspection
3. Upon removal for system

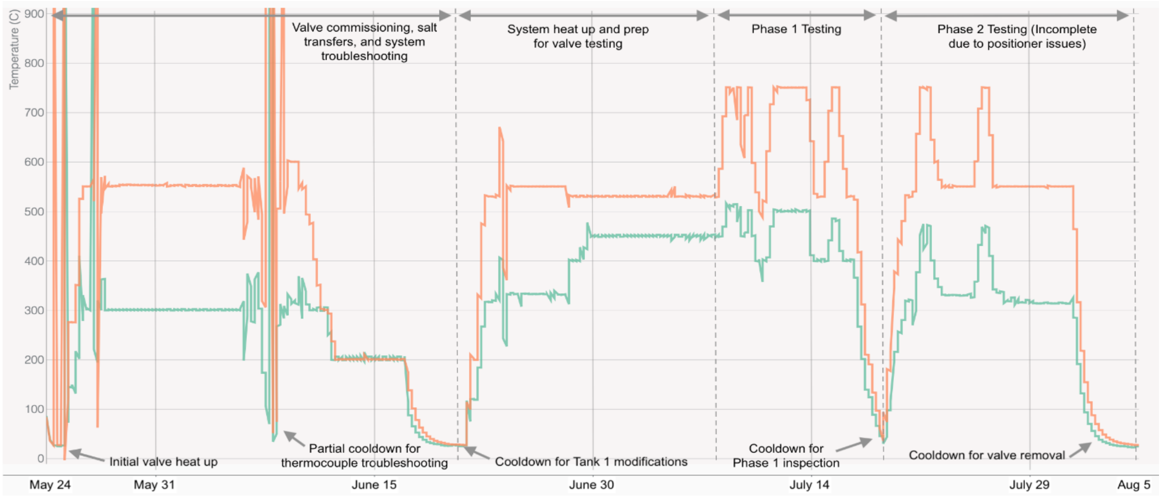

Figure 6. *Operating Temperature Life of the Flowserve valve while installed on ITU. Orange line is the body temperature (TE-219). Green line is the bonnet (TE-218)*

Upon initial heat up, the thermocouple readings were noticed to be functioning unexpectedly with an unusual temperature profile. It was operated in this orientation for a couple weeks until the system was cooled down for one of the vessel modifications, at which time the thermocouple readings were troubleshoot and placement was reverified. Nominal Phase 1 test campaign operation results however can be seen in Figure 7 where the valve was able to operated stabally, and without leaks at approximately 750°C.

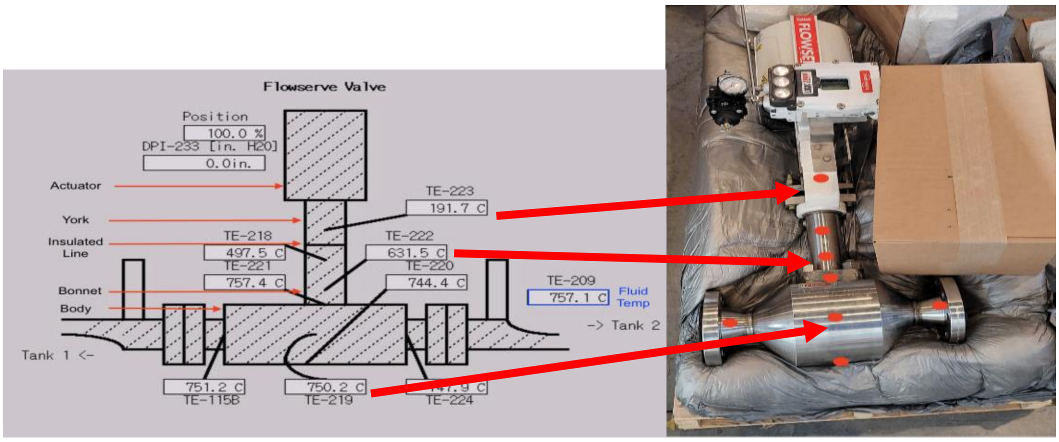

Figure 7. *Temperature profile of the Flowserve valve during testing with setpoints at 750°C based on thermocouple locations shown for reference*

The results for the first flow loop test campaign are shown in Figure 8, which presents two relatively rapid thermal transient tests where both assessments included an approximate 7-10 hour hold. After the valve was installed into the system, it was operated at a temperature range between 530-752°C. The valve underwent rapid thermal cycles of the bellows valve with the heat pipe valve stem were also facilitated to assess the potential for leakages, as well as to characterize thermal distributions throughout the valve subcomponents. Through each successive test, extensive leak checks were performed. A promising find was after the salt cooled in the system and no leaks were found showing the solidifying of the salt in the system had no immediate adverse effects. Overall, the bellows valve performed as predicted in terms of the temperature profiles.

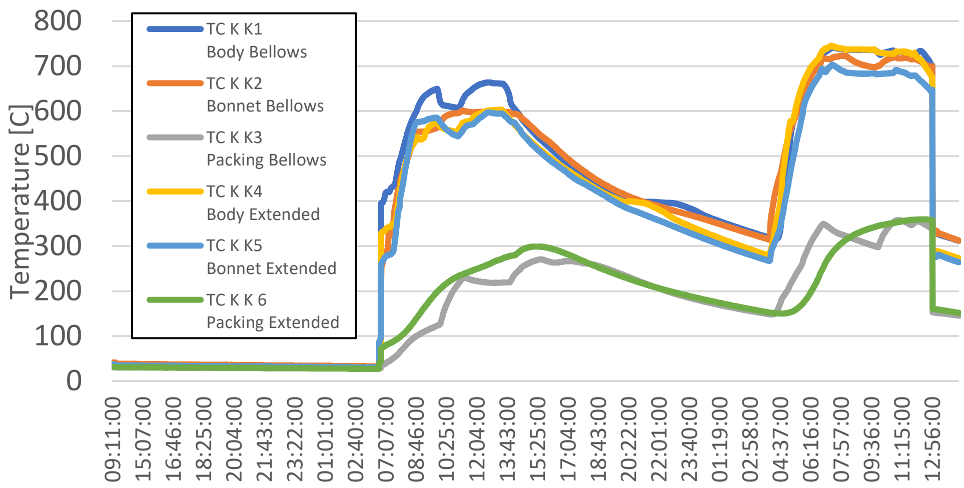

Figure 8. *Operating Temperature Life of the Baseline FCV while installed on ITU. Orange line is the body temperature (TE-219). Green line is the bonnet (TE-218)*

During thermal cycling, the FCV temperatures increased from 200°C to 550°C within two hours. During that time thermal expansion was observed with both the test loop lines as well as with the elongated portions of the bonnet, though without any salt or ullage gas leaks detected. Afer the rapid cycle test occured, the residual heat of the salt charged in the loop allowed for a slow ramp down in temperature throughout the night. The system was later reheated (Figure 9) for re-melt around 550°C.

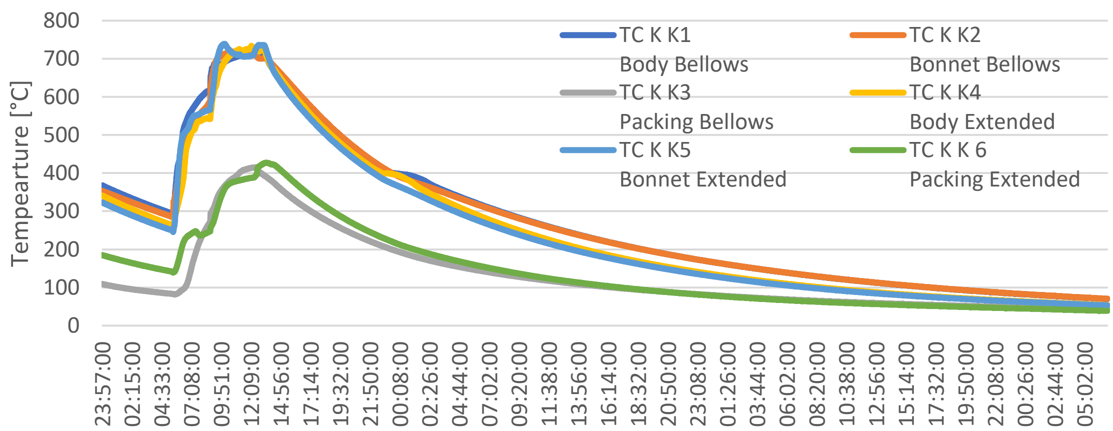

Figure 9. *August 4th Testing and Weekend Cooling of the System*

3. Conclusions

Two novel, advanced halide molten salt valves were designed and tested for reliable operation up to 750°C, for a 20%NaCl/40%MgCl2/40%KCl by mol. wt. % ternary chloride salt for CSP applications and FLiNaK molten salt for nuclear energy applications. The designs featured a heat pipe valve stem passive thermal management system to mitigate large thermal gradients, and to improve high-temperature operational performance and reliability, as well as a quick-change packing canister to reduce O&M down-times to hours instead of days/weeks for a CSP power plant. Two valves were designed, fabricated and tested at the Flowserve Corp. Villach test loop as well as the Kairos Power ITU and found nominal performance, particularly after post-test materials inspections. Both the fluoride salt ITU and the chloride salt flow loop, were developed to be high-temperature, record setting salt test systems that saw both valves produce leak-free results with minimal corrosion less than 30 µm/yr., with real-world pressure variations up to 11 bar under 750°C operation. The development of this new advanced molten salt FCV, which is cross-cutting across multiple types of heat transfer fluids allows for improved resilience of operation as well as bankability of high-temperature/higher-efficient industrial systems. The features of the advanced valve are also backwards compatible with Gen 2 CSP and Gen 4 NE systems to make them too more resilient, to help improve warranties and reliability of respective systems.

Data availability statement

The data for this research work can be accessed directly from the authors.

Underlying and related material

Related materials can be obtained directly from the authors.

Author contributions

All author’s listed at the beginning of this article contributed to this work.

Competing interests

The authors declare no competing interests.

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