AN INNOVATIVE IN-CORE SODIUM LOOP FOR IRRADIATION OF MULTIPLE SAMPLES AT HIGH TEMPERATURES: DESIGN AND DEVELOPMENT

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ABSTRACT

An innovative test loop is conceptualized, designed and developed without any active pump for irradiation of multiple samples at high temperatures in sodium. The U-tube loop is capable of removing ~ 5 kW of heat generated due to gamma heating and to maintain the desired temperature within ± 2°C in the specimen chamber. This loop can be used to conduct an experiments on multiple samples at any temperature within the range of 300-650°C irrespective of reactor primary coolant temperature. Specimens can be tested in Na environment and also other liquids like NaK, Pb could be thought off. The design confirmation is done for the complexity involved like balancing level fluctuation, liquid free level height control, level measurement and manufacturing challenges. Full scale loop manufactured with SS-316LN is to be tested in water to verify the loop, sensors and other hardware & software's performance. Water will be replaced by Na to carry out the out-of-pile experiment on the loop for verification of thermal hydraulics and structural behaviour before placing it in the Fast Breeder Test Reactor (FBTR). Due consideration is given to hand over the same U-tube loop with minor adjustments to Jules Horowitz Reactor (JHR).This paper presents the design and experimental challenges involved in implementing the envisaged idea of innovative U-tube loop.

1.0 Introduction

An irradiation test facilities are very limited in the world in contrast to the requirement of large and different kind of test data. Testing of multiple samples in the reactor during a single campaign at desired temperature can assist in the generation of an irradiation material test data. This material test data is essential for numerical simulation of structural materials, fuel pin behaviour and studying fuel safety issues. Indira Gandhi Centre for Atomic Research (IGCAR) is developing advanced structural materials like D9I and ODS alloys to attain higher burnup in future fast breeder reactors including a metallic fuel test reactor. Fast Breeder Test Reactor (FBTR) is serving as an excellent facility for research and development for irradiation of fuel and structural materials. In addition to FBTR as material test facility, the international material test reactor (JHR, Jules Horowitz Reactor) would be utilized for generating irradiation data. In this direction development of special specimen holder/dedicated facility gives high emphasize for testing of both fuel and structural materials at different temperatures in the available experimental canals. The development of such facility has a good potential in Fast Breeder Reactor (FBR) research programs for testing a specimen at different temperature value irrespective of reactor primary coolant temperature. An innovative design of U-tube in-core sodium loop is conceptualized to fulfil the design requirement of very small size. Even though the flux available in FBTR at the location of the loop is lower, good temperature control can be obtained in the flowing sodium of loop by external means. The design of the innovative U-tube loop is conceptualized which works without any active pump and have no disturbance to the reactor during an experiment. Mathematical modelling is done to know the dynamic behaviour of U-tube sodium loop which gives more insight into the height of fluctuation, level fluctuation pattern and control of level fluctuation about equilibrium position. Also water experiment is conducted with an acrylic U-tube set-up to validate numerical results in addition to the demonstration of the conceptual design in context with dynamic behaviour. From mathematical modelling and experiment, it is established that the volume/pressure regulation is essential to run the loop in a controlled manner. Full scale U-tube sodium loop is manufactured with SS 316 LN material. Experimental validation was carried out in water for full scale loop for dynamic simulations. The full scale loop would be used for testing in sodium to verify thermal hydraulics and structural mechanics studies. It is planned to introduce the loop in FBTR for the multi sample irradiation data generation. Subsequently the loop would be finalized for conducting an experiments at JHR after incorporating operational experience at FBTR.

2.0 Need of *Innovative* U-tube Loop

The primary objective of the loop is material/fuel testing in the presence of neutron flux at different temperatures in the sodium environment. In JHR the primary coolant is water whereas in FBTR it is liquid sodium. Sodium undergoes violent chemical reaction with air and water. Sodium reacts readily with water or steam to form sodium hydroxide and hydrogen. This reaction is highly exothermic and produces large amounts of energy. Due to safety concerns in JHR (sodium loop in the water) it is required to have a double walled loop filled with gas in annular gap. This would provide on-line sodium leak monitoring for early detection and to take quick corrective action. Also total sodium inventory is limited by a 9 litre in the loop.

The space available for inserting the loop in FBTR is Ø 100 mm and in JHR is Ø 90 mm, which are material test facilities to be used for conducting the experiment is very small. The major challenge is to design the loop in small effective area of around 80 mm in diameter with all necessary components viz. Specimen chamber, heater, cooler, pump, and instrumentation. At present, no pump system is available to satisfy the condition of small size, process requirements along with the safety concerns. Electromagnetic (EM) pumps generally used for sodium are also not available in the required design constraints of size. Hence, an innovative design of U-tube loop is conceptualized to fulfil the design requirement. In the U-tube loop, there is no active sodium pump (EM pump or other type of pumps) and it can be accommodated within the space available in both FBTR and JHR.

3.0 Working Principle

When pressure is applied to one side of U-tube, that level will go down and the level on the other side will rise until the difference between the heights are equal to the pressure head. The height difference is proportional to the pressure and to the density of the liquid. U-tube loop is based on this fundamental principle, a continuous alternate differential pressure is applied in two limbs which provides the oscillatory motion of the liquid contained in the tube. Limbs of U-tube loop are enveloped by concentric tube with an annular gap between them which acts as a heat exchanger with sodium in an inner tube and heating/cooling medium in annular

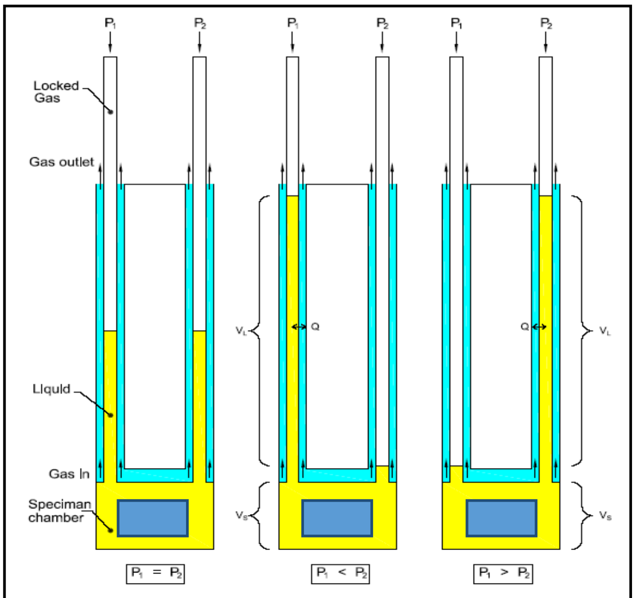

Fig 1. Schematic for working principle

space between the two tubes. Specimens are kept at the bottom of the loop (inside the specimen chamber). The schematic of working principle is shown in Figure 1. Upper end of the two legs of U-tube loop are connected with the piston cylinder arrangement through a tube filled with locked gas. Piston cylinder assembly pressurize/depressurize the legs of the loop which leads to the oscillatory motion of the liquid contained in the loop. During the working liquid is oscillating in an inner tube whereas heating/cooling medium is flowing through annular space between the two tubes. Liquid in one leg is in top position and simultaneously in other leg it is at bottom most position. Heat is exchanged between liquid filled with leg and gas in the annular space to get the desired temperature of liquid in the leg and subsequently of specimen chamber. When sodium oscillates in the two legs of tubes it takes away heat from the specimen chamber and rejects to the sodium-gas heat exchanger. Specimen chamber is kept at the lowest position of the U-tube.

The liquid volume in the filled leg (V_L) should be greater or at least equal to the liquid volume in the specimen chamber (V_S) so that full specimen chamber is swept by cooled/heated liquid. To make liquid level to oscillate in the U-tube loop a special actuator mechanism is designed and manufactured.

4.0 Actuator Mechanism

The actuator mechanism consists of an electrical motor, gear box, coupling, crank-slider mechanism, double acting pneumatic cylinder, Variable Frequency Device (VFD) control (shown in Figure 2). A reduction gearbox (25:1) is used to reduce the motor RPM at the first stage. The crank connects with the driven shaft of the gearbox. Crank with slider mechanism converts the rotary motion of the shaft into translatory motion. The other end of the slider is connected with the piston rod of the double acting pneumatic cylinder. Both end ports of the double acting pneumatic cylinder are connected to the two legs of the U-tube loop filled with liquid (bottom) and gas (top).

Fig 2. Actuator mechanism assembly

5.0 Dynamic Studies of the U-tube Loop

Dynamic studies are carried out on the U-tube loop mathematically as well as conducted experiments to demonstrate the level oscillation behaviour in two legs. The velocity maxima and minima of piston do not occur at the crank angle of ± 90 ° if driven by crank through connecting rod, as it depends upon connecting rod length and crank radius. Also compression and expansion of gas in two sides of double acting pneumatic cylinder is not same in terms of positive and negative pressure generated due to equal volume change. These effects in addition to other uncertainties in manufacturing of the two legs of the U-tube can lead to unbalanced level

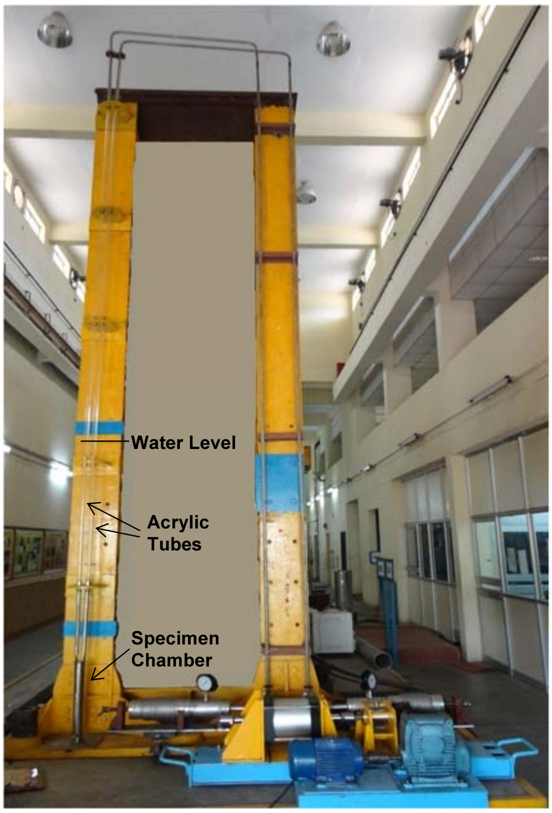

Fig 3.Experimental set-up for dynamic studies

oscillations in the two legs of the loop. Balanced level oscillations in the two legs are desired to enhance/utilize the heat transfer capacity of the heat exchanger. Also understanding the level oscillation behaviour in the two tubes is necessary to control & run the loop in more efficient and controlled manner.

An experiment is conducted with water in two legs of the loop with actuator mechanism (shown in Figure 3). Acrylic (transparent) tube is used for manufacturing the two legs of the U-tube loop to study the level oscillations. The unbalance is observed in the level of oscillations in the two legs and also it is found to be difficult to control the height of an oscillation in the loop. From an experimental observations liquid oscillation velocity is limited to 3 m/s from the cavitation point of view.

Mathematical modelling is done to understand the dynamic behaviour of the U-tube loop. The dynamic behaviour of the oscillating system of U-Tube with equal diameter column actuated by the piston cylinder arrangement is analysed. Here the liquid is at bottom portion only and the rest of the length of the tubes is filled with gas. The pressure difference in the two legs produced by a double acting pneumatic cylinder leads to level oscillations in the two legs of the loop. This pressure difference is calculated based upon cranking-piston motion equation [1] which gives the piston pin position with respect to crank angle (see Figure 4).

$$x = r\cos\theta + \sqrt{l^2 - r^2\sin^2\theta}$$

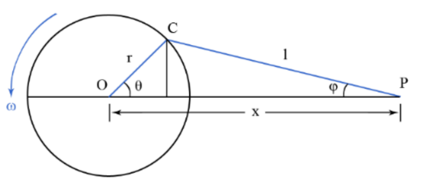

Fig 4. Slider-crank mechanism

Due to piston motion change in volume in the two sides of double acting double acting pneumatic cylinder takes place which leads to the development of differential pressure in the two legs of the loop [2, 3]. The governing equation taken for the numerical investigation is (also see Figure 5)

$$m\ddot{z} + c\dot{z} + kz = -\Delta p/\rho g$$

Where $m = l/2g$ & $c = 16\vartheta_m l/gd^2$

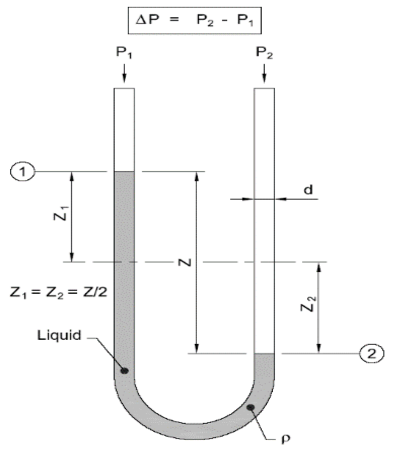

Fig 5. U-tube

Central difference method (numerical integration) is used to solve the above equation for the U-tube loop [4]. Dynamic studies are carried out at 2m/s and 2.5 m/s velocities of liquid fluctuation about an equilibrium position (the results are shown in Figure 6). Velocity of liquid in two legs is controlled by the motor RPM,

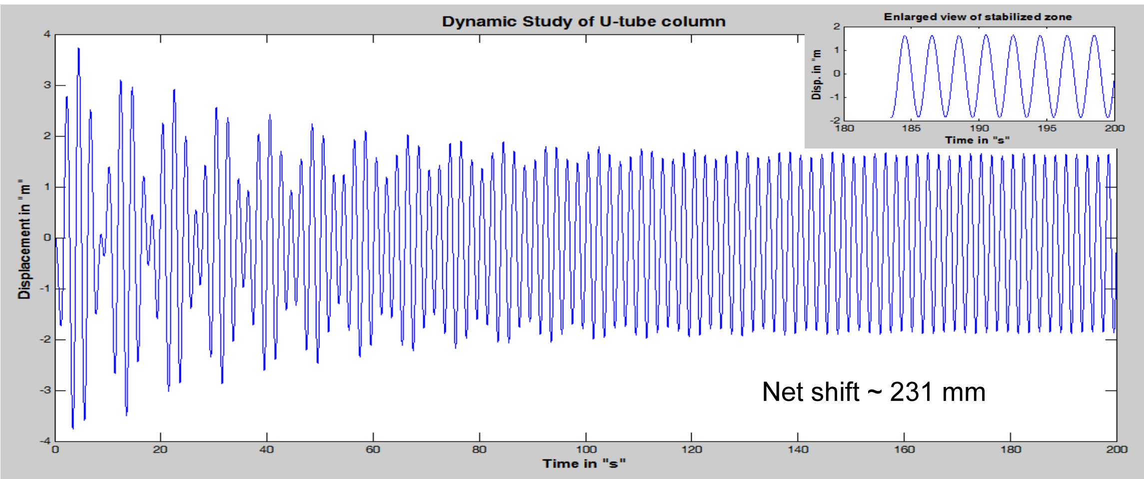

Fig 6. Level oscillations in one leg

reduction gear box and VFD control. The resultant shift is observed about the mean position which implies that there is an unbalanced level oscillation in the two legs. Similar unbalance is there in the experiment also.
From the numerical investigations it is observed that the height of oscillation in the two legs can be controlled by changing the volume/pressure of the system. Figure 7 shows the result of balanced level oscillations in the two legs of the loop after volume/pressure control. Addition of volume in one leg which indirectly affects pressure due to change in volume can be used to balance the oscillation difference between the two legs. Add or reduce equal volume from two legs simultaneously to decrease or increase the height of the oscillation in both legs.

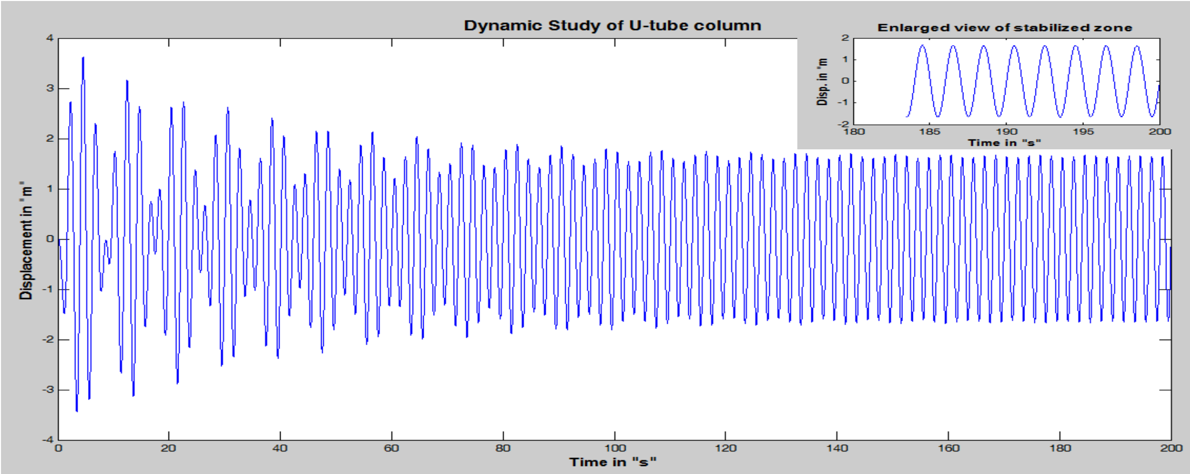

Fig 7. Level oscillation of one leg with bellow control

To fulfill the requirement of volume addition/reduction in two legs independently and simultaneously, two bellows with screw mechanism are added in each leg to balance and control the liquid free level oscillations. Figure 8 shows the final actuator mechanism having bellows in a line of two legs to control the level oscillations. With new actuator mechanism which consists of bellow control an experiment is performed on acrylic U-tube set-up. Initial unbalanced level oscillations in the two legs are balanced with the help of bellows control. Bellows are compressed/expanded as per the requirement with the help of screw mechanism.

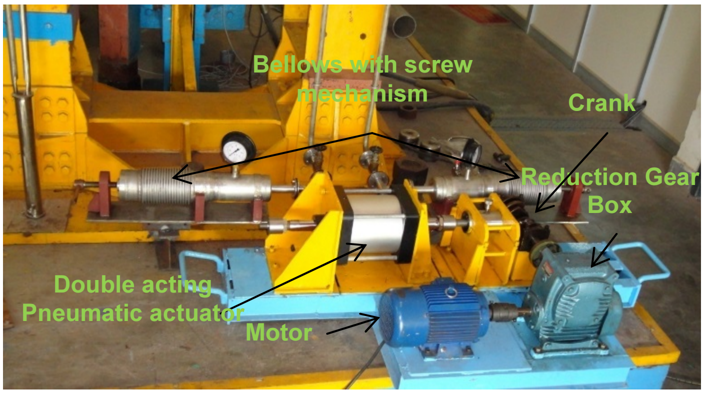

Fig 8. Final Actuator mechanism with bellows control

6.0 Actual Design of U-tube Loop

Actual loop is designed and manufactured with SS 316 LN material to conduct an experiment in the sodium. The loop is designed as per the design requirement of size and the experience gained from dynamic studies carried out with water. The actual loop consists of the specimen chamber at bottom most position (shown in Figure 9). Specimen chamber forms the bottom of U-tube which is having an outside diameter of 19 mm and thickness of 0.8 mm. Concentric tube surrounding the two legs of the U-tube loop is having an outside diameter of 24 mm and

1.25 mm thick. Spacer wire is wrapped between two tubes to maintain a gap between them. Two plenums (see Figure 10) are provided for inlet and exit of the cooling/heating gas to be passed in the annular space (1.25 mm) around the two legs of the U-tube loop. Bottom plenum is just above the specimen chamber and provides inlet of the gas whereas upper plenum for exit of gas is provided at ~2000 mm above the bottom plenum. Zone between bottom plenum and upper plenum calls heat exchanger assembly. Sodium oscillates within the heat exchanger assembly. From specimen chamber to top plenum, all components are enveloped in the tube of inner diameter of 62 mm.

Above the heat exchanger assembly only tubes carrying heating/cooling gas and gas space of two legs of U-tube loop are present. In this location gas envelope is not required hence rods are used to support the loop. Whole loop is hanging from the top with the help of these rods. Two legs of the U-tube loop are provided with special double T-shaped end fitting at the top to facilitate the insertion of the sensor in addition to gas line connection with actuator mechanism and also sodium filling. Bellows are provided at the critical locations to accommodate the differential thermal expansion in the loop. One small diameter tube is provided to insert the thermocouple up to the thermowell located in the specimen chamber. The special level sensor is designed and developed to measure the level oscillations in the small SS tube of internal diameter 17.4 mm during operation of the loop.

Actual loop is to be validated with water in place of sodium. A heating source (resistance heater) is inserted from the bottom of the specimen chamber to simulate the actual gamma heat generation in the materials of the specimen chamber during testing in the reactor.

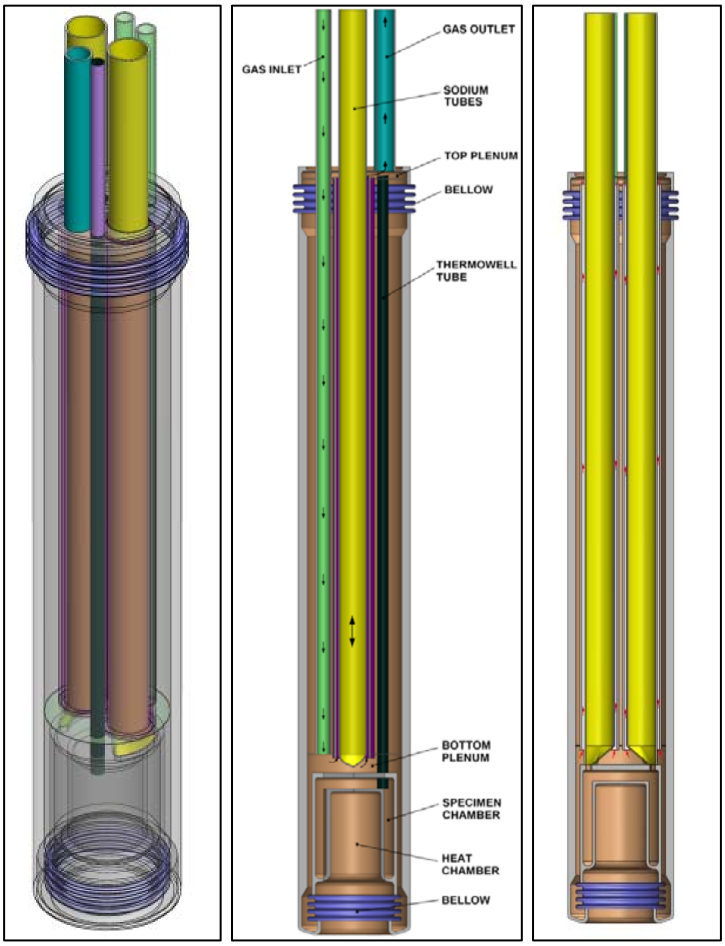

Fig 9. CAD model of U-tube in core sodium loop

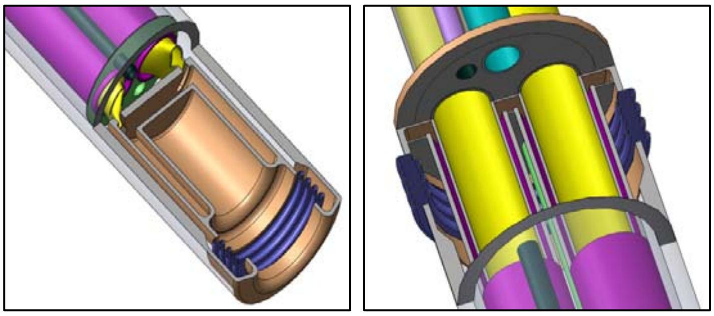

Fig 10. Sectioned view of bottom & top plenum

7.0 Conclusion

An innovative in-core sodium loop has been developed for utilizing the international material test reactor (JHR) for generating irradiation material test data for the future reactor structural materials like D9I & ODS alloys. Multiple material samples can be tested together in the inpile condition during the single campaign itself at the desired temperature. This test loop is conceptualized, designed and developed without any active pump. U-tube loop is conceptualized to take care the space constraints of the test loop. Mathematical modelling and water based experiments have been carried out to study the dynamic behaviour of U-tube loop performance. The development of such facility has a good potential in the FBR programs for testing a specimen at different temperature value irrespective of reactor primary coolant temperature.

8.0 Future Work

- The full scale actual loop will be tested for sodium with long operating hours.
- Manufacturing of the actuator mechanism consisting of SS double acting pneumatic cylinder for high temperature application.
- Automatic feedback control of bellows with the help of level sensors.
- Manufacturing and commissioning of final U-tube loop for FBTR along with peripheral components

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