Re-searching the Land of Penguins: Antarctica 1

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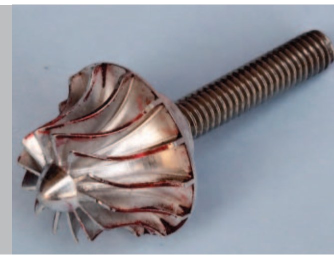

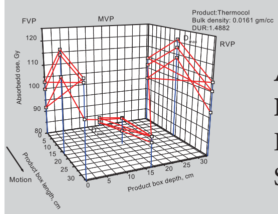

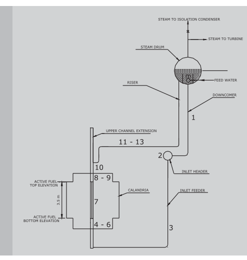

Re-searching the Land of Penguins: Antarctica

Rupali Pal and Bhushan Dhabekar
Radiological Physics & Advisory Division
Health, Safety and Environment Group

This article is a narrative describing the activities and valuable experiences of the authors during their 35th Antarctic Expedition. The interest and dedication of Indian scientists who participate in these expeditions every year for the quest of science and excellence is undeterred by the extreme living conditions and hardships faced on the icy continent. In this expedition, the authors conducted extensive surveys for radiation mapping in and around the 'Bharati' station, Antarctica and have collected several samples of water, soil and rock for analysis. These are being probed for their radioactivity content using various analytical techniques. A scientific report based on the outcomes and observations will be published in the near future.

The journey to the southernmost continent

It was a clear sunny morning on November 29, 2015 at Cape Town, South Africa. We were already on cloud nine as we sat inside Ilusion-17 ALCI flight ready to take off for Novo airport in the Schirmarcher Oasis in Antarctica. It was a matter of pride to be among the 150 scientists from different countries across the world, who were off to the Land of Penguins for a purpose. Three hours of flying, and having crossed the 60^{0}S latitude, it was made to dawn on us by the pilot that we were now at the point of no return as we were swiftly heading towards the bottom of the globe!! Leaving all uncertainties behind, geared up in our polar suits, we were about to step on the pristine icy continent, untouched by civilization. Although the landing on the stark white icy runway without a radar system was very smooth, the fear and excitement made us skip our heart beats. The first step on the glistening white ice felt like stepping on the moon!! The landscape looked exceptionally beautiful, the azure sky above and various shades of ice and snow everywhere (Fig.1). The summer here was freezing cold with temperatures of about -10 ^{0}C. After the initial exuberance of trying to capture the first glimpse of the barren, icy and uninhabited planet in our cameras receded, we had cold feet, literally, thinking of our survival for the next three – four months in this hostile environment of the land beyond this earth.

Indeed, about 98 % of the continent is covered with thick ice sheets which were formed 25 million years ago and holds about 75 % percent of all fresh water on the Earth. The average thickness of the ice sheet is about 1.9 km with highest being 3.6 km at the poles. If all the ice on this icy continent melts, the sea level will rise by about 60 m! The inner regions of the continent receive an average of 5 cm of precipitation each year, primarily in the form of snow. The piling up of the snow for a million years has made Antarctica a cold desert.

Antarctica, although a 'no man's land', is governed by the Antarctic Treaty adopted in 1961 by twelve countries, which inducted India in 1983 as its fifteenth consultative member. The treaty requires that information among countries be shared openly, the research carried out here is for peaceful, non-commercial purposes, and that no development/testing of weapons takes place. As per Antarctic treaty, the station needs to be manned throughout the year. It has several policies laid out towards conserving the Antarctic environment. Almost 30 countries have constructed about 69 research stations in different parts of Antarctica. The first Indian expedition was led by Dr. S. Z. Qazim in 1982. It was a proud moment when our tricolour was first hoisted in the continent and India established a permanent station in Antarctica. This was a wooden hutment called 'Dakshin Gangotri' established in 1984, which was built on a glacier, which later submerged in

Fig.1: Glistening Antarctic Landscapes

ice. The second Indian station 'Maitri' was commissioned in 1989 and the third 'Bharati' in 2012.

In the past, scientists from BARC have participated in the 8th, 9th and 10th and 29th expeditions for generating baseline data on natural radioactivity in soil and water near the 'Maitri' base. In this 35th expedition, efforts were made to extend these surveys and measurements to the regions around new Indian station named 'Bharati' and various islands around the Larsemann hill region which houses the station. Also, with recent developments in online detectors and communication facilities, it was planned to install Indian environmental Radiation Monitoring System (IERMON) for online gamma radiation monitoring along with other instruments. It is well known that, cosmic radiation is higher at the poles with the neutron fluence being 4-5 times more at the poles than at the equator as reported by UNSCEAR 2000. Therefore, cosmic ray dosimetry was introduced in this expedition.

We were fortunate to be deputed from BARC in this expedition to Bharati station for carrying measurements towards the following objectives:

(i) Gamma and neutron radiation dose measurements at different locations around Bharati station using passive dosimeters,

(ii) Collection of soil and ice samples from different locations around Bharati

(iii) Collection of water samples for Tritium analysis

(iv) Measurement of natural radioactivity levels in the atmosphere due to Radon and Thoron

(v) On-site background gamma spectrometry using portable gamma spectrometer

(vi) Continuous measurement of gamma and neutron dose rate by installing on-line instruments. Training to NCAOR members stationed at Bharati for the day-to-day operation of the instruments and periodic transfer of data to BARC.

The journey to the icy continent begins at National Centre for Antarctic and Oceanic Research (NCAOR), Goa under Ministry of Earth Sciences which organizes these expeditions to Antarctica each year. More than 20 institutes from all over India, participate in the Indian Antarctic Program. The research includes topics ranging from atmospheric, biological, environmental and earth sciences, glaciology to human physiology and medicine. Prior to the expedition, the proposed projects were evaluated by a panel of judges and were shortlisted at NCAOR, Goa. From BARC, project proposal was defended by Dr. A.K. Bakshi, Principal Investigator of the project. Selected candidates undergo stringent medical test at AIIMS and high altitude acclimatization and mountaineering training provided at Auli, Uttarakhand under the guidance of Indo Tibetian Boarder Police (ITBP).

Our batch was warmly welcomed by the Station leader of 'Maitri' station at the Novo airport and we boarded the huge tanker-like snow vehicle called “PistenBully” (Fig.2). After a journey of 10 km from the Novo runway, covered in an hour, we were at the Indian station 'Maitri'. This is situated on the rocky mountainous region in Antarctica called Schirmacher Oasis with Priyadarshini lake, a freshwater lake, as a landmark. The stay at 'Maitri' for a few days was a mid-way halt on the way to our final destination 'Bharati' station, which is about 3000 km away from “Maitri”. A chartered Basseler plane, with a capacity to carry about 1500 kg load (persons + cargo inclusive) (Fig.3), took about 10 hours to reach Progress runway, built by Russians, near the 'Bharati' station. The ride further on snow vehicles and snow scooters, smooth and exuberant, brought us to 'Bharati' which looked similar to a space station with the scientists draped in polar clothing weighing 7 kg, almost looking like astronauts!

Fig.2: PistenBully snow vehicle

Fig.3: Basseler plane

Life at Bharati Station

BARC had participated in the previous Antarctica expeditions with the base station at 'Maitri'. During this 35th expedition (November, 2015 – February, 2016), we got the opportunity to be stationed at 'Bharati' for the first time. Built with a German architecture base, the station comprises of 33 steel containers housing quite a few fully automated systems; most importantly, it can boast of a 'zero waste discharge'. There is a stark difference between the two Indian stations; while Maitri has the warmth of Indian culture, Bharati is an upgraded version - modern and technologically superior (Fig.4).

Fig.4: Indian Station 'Bharati' in Antarctica

Abiding by the mandates of the Antarctica Treaty, Bharati station has an efficient non-polluting waste treatment protocol. The solid waste, including the kitchen waste, is segregated into glass, plastic, paper (duly compacted) and tins. It is packed, sealed in drums and sent back to South Africa via the ship for disposal. The waste water from the kitchen and toilet goes through the waste water treatment process in huge tanks. The sludge is separated, packed and sealed into drums for disposal at South Africa, while the treated water is purified to drinking water quality and discharged into the sea. For drinking and other household purposes, sea water is pumped in for desalination followed by reverse osmosis. Water usage is optimally restricted owing to the high cost of operation of the plant which uses generators running on Aviation Turbine Fuel (ATF).

Discipline and camaraderie are the essential attributes required for harmony at this isolated station and hence a strict code of conduct is to be observed. It is made very clear to the participants during the training sessions at NCAOR, Goa prior to the expedition that there are only two ranks in Antarctica, members and the station leader who is in command of the station. The technical activities started on each day with a mandatory meeting with the station leader sharp at 0900 h. This served a dual purpose, firstly to ensure that all the station members were fine and healthy and secondly, to arrange the logistic support for the scientists to perform their tasks and to discuss routine tasks related to the station operation and maintenance.

The experience at the station was enriching in terms of interpersonal relation-building as well. The fortnightly '*Galley Duty*' roster would be displayed on the board assigning the daily responsibility for the upkeep and maintenance of the station to a team of two persons. The 24 hours galley duty began at 0600 h by helping the chef prepare breakfast for 50 station members. After breakfast, the daily chores like cleaning of the station, including toilets and bathroom, as well as utensils had to be performed. It was then again time to help the chef for lunch and dinner preparations. The Galley duty ended with two hourly patrolling of the station in the night to monitor and note the readings of station emergency systems such as fire alarms, air circulation control, the generator and other installed automatic systems. In the morning at 0600 h, the charge was then relayed to the next two members listed on the roster. This hectic, energy sapping duty was performed by one and all, irrespective of the rank, including the station leader. Another important activity jointly executed by all was the '*Shramdaan*' which entailed offloading of cargo/food rations from the ship and uploading the huge drums of waste generated over the year.

It was not all work, though there were ample resources for entertainment. NCAOR has provided sports and fitness facilities like gymnasium, table tennis and chess. There were special memories of cricket and volleyball played on the concrete helipad, especially of the match when we were unofficial volleyball champions in Antarctica, having beaten both the Chinese and the Russians in the volleyball tournament conducted on the airfield! Yoga sessions were conducted in the mornings along with regular health checkups by the medical doctor. The ‘Entertainment Room’ houses huge LED TV and recliners with a bank of CDs (movies and informative). One could try a hand on the various instruments available such as tabla, harmonium, guitar and drums. An all-religion prayer room resonated with the chant of *bhajans* and *pujas* on every Tuesdays. No opportunity of having festivities was missed, with birthdays and wedding anniversaries being celebrated with the ceremonious cake cutting leading to a small entertainment program. It was a special patriotic moment to be celebrating the Republic Day, thousands of miles away from our homeland, by chorus singing of patriotic songs (Fig.5). The warmth and aroma of the Indian station was shared with 150 guests from different stations and countries by way of a lavish meal. The venue for these celebrations was a beautiful lounge overlooking the blue southern ocean, large drifting icebergs and the never setting sun.

Fig.5: Republic day celebration at Bharati station

Fig.6: Russian station 'Progress' near Bharati

We also visited a few nearby stations such as Russian station Novo near Maitri, Chinese station 'Zongshan' and Russian station 'Progress' near Bharati (Fig.6). The Australian station Davis is as large as a town with over 200 people during summer. It is overwhelming to see the strong feeling of camaraderie among the Antarcticans, with no differentiation in terms of nationality, culture, colour, caste, creed etc. The Chinese were the friendliest.

Though stationed at the bottom of the earth, we were well connected to the other parts of the globe, thanks to the installed communication systems. Wi-Fi and high speed net connectivity, WhatsApp and Skype ensured that we stayed connected with our near and dear ones by means of voice calling and video chatting, albeit with disturbances. Satellite phones were available with a 20 min time slot per month made available to each member. This was a boon to alleviate the feeling of loneliness and isolation that slowly sets in as the days pass.

Work beyond hardships is worship

Working in Antarctica is a milestone in itself as it requires tremendous determination and grit to work against the odds with limited means and tools. The true spirit of research surfaces, as innovations with available resources are needed at every step to perform the tasks at hand in the very harsh environment.

The unpredictable weather further adds to the hardships. Our instruments, which were to be sent by air cargo to 'Bharati' before our arrival, were unfortunately still lying at Maitri Air base. This meant we had to tow them along, making our official cargo weigh a whooping 250 kg! To add to it, one of the two Basseler flights got cancelled causing panic among members to reach Bharati as this was the last flight to Bharati for the season. Now, we had the daunting task of accommodating 10 persons along with instruments such that, restricting the total weight to 1500 kg. As the official instruments could not be compromised on, the Maitri station leader came up with the plan of shifting the instruments from heavy wooden boxes to polystyrene boxes to reduce the weight. We left the spare parts of the instruments at Maitri. The personal suitcases were also done away with by transferring all our belongings to travelling bags provided at Maitri.

After reaching the Bharati station, our most important job was to unpack and install the instruments successfully. Although we had undergone training in Mumbai, we were really anxious, particularly with the installation of online instruments (Fig.7). We installed and linked two environmental radiation monitors (ERM) and started acquiring data. However, thanks to our mentors in BARC, there were no major hurdles and we soon had all the instruments operational. The field work was further made enjoyable and revitalizing, owing to the pristine environment with visibility up to a few kilometers on a sunny day, a resultant of negligible anthropogenic activities.

With very scarce flora and fauna, the place is nearly lifeless giving an eerie feeling. Strong winds and drifting snow greatly

Fig. 7: Installation of various online instruments in the Laboratory at 'Bharati' station.

Fig.8: Bharati Top having gamma radiation level of about 50 μR/h

Fig.9: Radiation survey showing hotspots with radiation levels of about 200 μR/h

affect visibility. The strong sun and the reflection from white ice causes a white-out condition wherein the objects are devoid of shadows and contrast, at times giving a sense of disorientation. There also looms the danger of getting trapped in the deep crevasses. These perils are well recognized and hence moving out alone is strictly prohibited. It was unfortunate that during our stay, one experienced helicopter pilot from the Australian station fell into a crevasse and succumbed to death as he could not be rescued on time. Therefore, all surveys for collection of radiation data, rock, soil and water samples were carried out in groups. Additionally, members always donned the UV protective glasses, applied protective cream and carried a wireless radio with communication accessibility up to 6-8 km.

Initially, we scanned the area around Bharati station and observed that the gamma radiation levels were about 20 μR/h. However, there was a surge in our excitement when we observed radiation levels of about 50 μR/h on "Bharati Top"

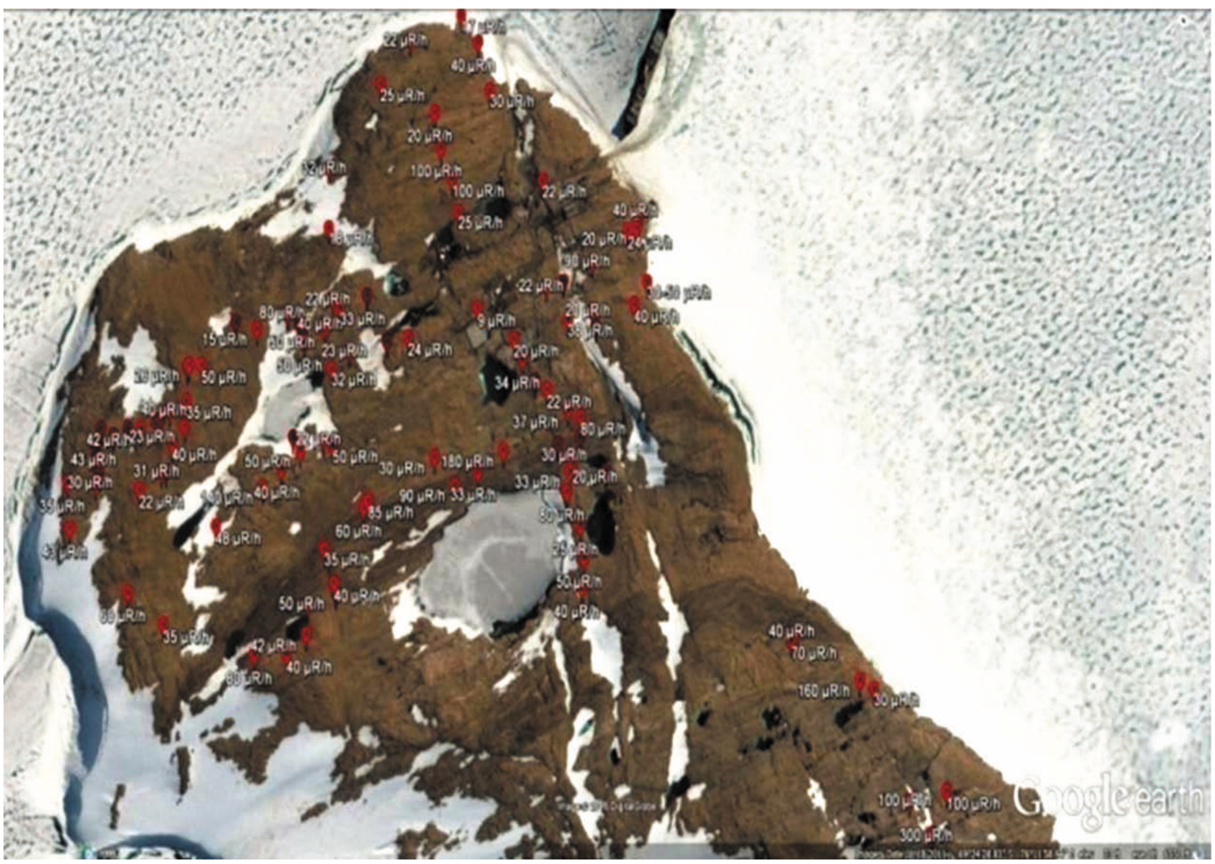

Fig. 10: Radiation survey of Bharati Island

(Fig. 8). Subsequently, as it got unfolded, there were many "hot spots" around the station with radiation levels as high as 200 μR/h (Fig.9) and the survey results were mapped on the Google map as displayed below (Fig.10). We carried instruments such as Neutron REM counter, Tissue Equivalent Proportional Counter (TEPC) for LET measurements, gamma tracer, gamma spectrometer, and indigenous Compact Ariel Radiation Monitoring System (CARMS) for measuring cosmic gamma and neutrons doses. As a part of radiation survey, we went along the frozen southern ocean on snow scooters called "skidoo" with our instruments on the sledge and generator (Fig.11). We surveyed many islands and collected rock, soil and water samples.

Fig.11: Instruments on sledge on sea ice

It was disappointing that even after a month the penguins were elusive, although skuas, snow petrels and seals were commonly spotted. It was quite a disheartening thought to return from the *Land Of Penguins* without seeing the penguins. As luck would have it, on one sunny day, near Mcleod Island, we spotted four Adelie penguins. These small penguins, were much more charming than the ones generally seen in photographs. They were equally curious but not scared, may be because there are no predators on the land of Antarctica!

In mid-December, the hard sea ice starts melting as the temperatures soar above 0°C. On a less fortunate day, as we were returning back from a survey, our skidoo got stuck in the ice which had thinned down (Fig.12). Since, it was just the beginning of the melting season, only a part of our skidoo got submerged, although our shoes and socks were wet as we vacated the vehicle. We were not very far from the station and could communicate to get help from the logistic team quickly. Thus, a major mishap was averted. From that day onwards, going to the islands along the frozen ocean on skidoo was forbidden. Now, everybody was looking forward for the ship to arrive which would bring helicopters for commuting.

During the initial few days at Bharati station, there were no fresh vegetables and fruits and the chef cooked with frozen vegetables, ready to cook food and pulses. The monotonous food made the members eagerly wait for the Russian ship "Evan Papanin", hired by NCAOR (Fig.13). The arrival of the ship brings in hope for wintering people and is celebrated with great joy. The ship is the lifeline of our Antarctic stations as it brings gallons of fuel for running the station, and it carries rations for the two stations to enable them to survive the cold months. The ship also brought in two helicopters, one of which was a large KAMOV helicopter used for transporting heavy loads such as huge containers (Fig.14). The helicopters are the means of transport in the summer months and used for providing pick up and drop for the surveying teams based on the GPS locations.

Fig.13: The Russian ship "Evan Papanin"- lifeline to our Antarctic stations.

Fig. 12: Skidoo mishap caused by onselt of melting of snow

Fig.14: KAMOV helicopter on a helipad in front of 'Bharati' station.

The two Environmental Radiation monitors (ERM), one kept inside the laboratory and the other installed outside the station, developed under Indian Environmental Radiation Monitoring Network (IERMON) was able to send data to BARC through NCAOR server with the help of networking team from NCAOR (arrived by ship) and BARC scientists stationed in Mumbai (Fig.15). It was one of the highlights of our work as the environmental radiation data could be transmitted directly to BARC without any manual intervention. For measurement of radon/thoron concentration, indigenously developed portable Radon monitor, *SMART RnDuo* was installed inside the lab.

Fig.15: IERMON installation

As the sea had melted, venturing to far-off islands was impossible. Once, we got the pick and drop support from the helicopter, we carried out field work on various islands e.g. Fisher, Broknes, Manning and Betts (Fig.16). Betts Island was by far the most beautiful island near Bharati station and the farthest island we had ventured. The southern ocean near Bharati station had by now melted and we could see penguins enjoying on small floating icebergs making loud sounds in the otherwise quiet and serene landscapes. On this very island, we came across a rock with highest gamma exposure rate of more than 700 μR/h (Fig.17). The analysis of the rock samples at BARC has shown that uranium, potassium and considerable amount of thorium got incorporated during the rock formation. According to the plate tectonic theory, over 200 million years ago, Antarctica and India were attached together as a part of the Gondwana and further a part of the supercontinent Pangaea; later the continents split and drifted away. A landmass broke away from Antarctica and joined Asia which we now call India. In that sense, Antarctica is the mother of our motherland. The eastern sea shore of India, which was connected to Antarctica, also possesses higher

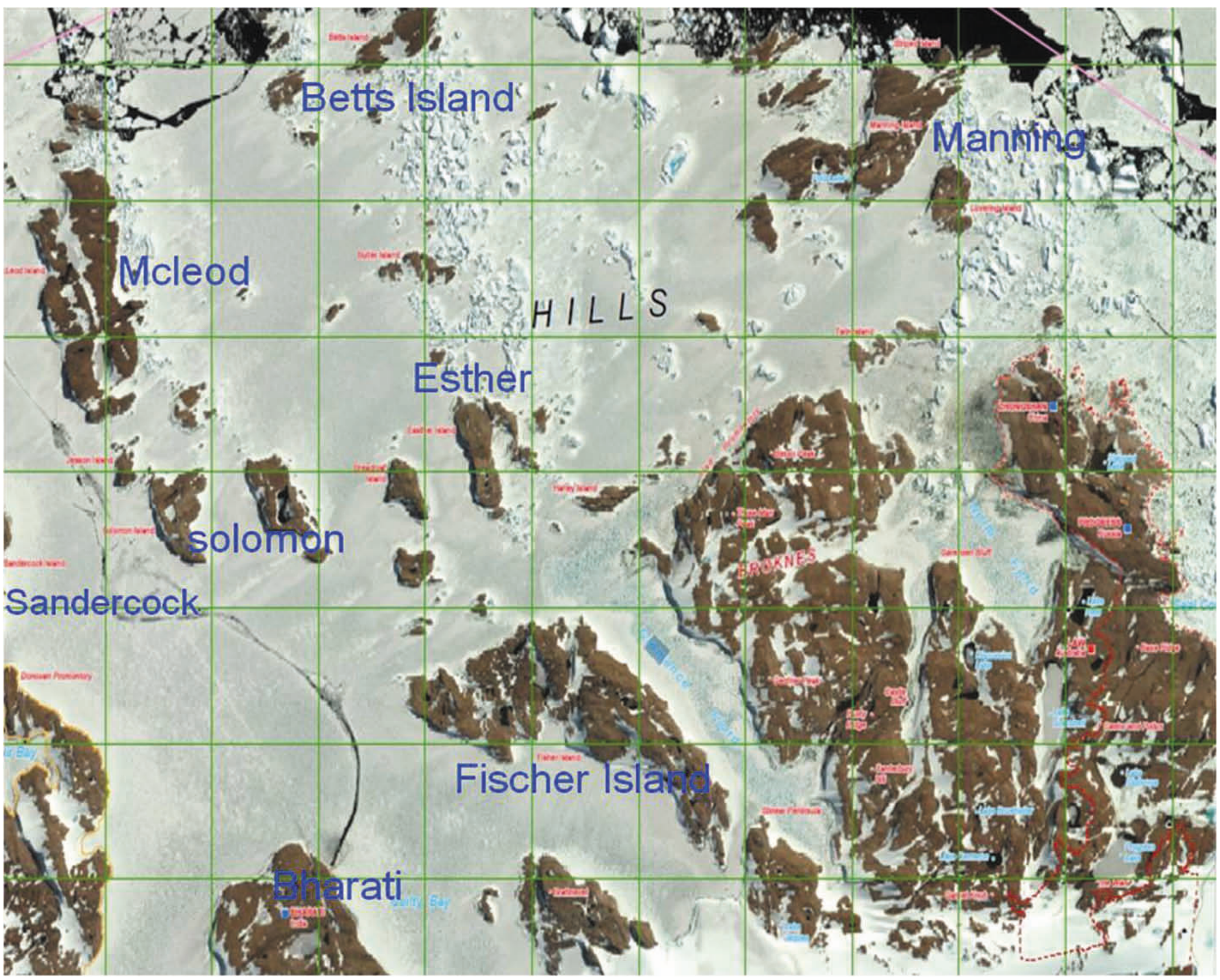

Fig 16: Various islands surveyed around the Bharati station.

Fig.17: Highest radiation dose rate on a rock in Betts Island

thorium concentration. Is it a mere coincidence that the east coast of India and the area around Bharati station has more thorium deposits or there is something more subtle hidden? Only thorough analysis of rock and soil samples using various analytical techniques will solve the mystery.

We tried to survey as many islands as possible because, with the departure of the ship, the facility of helicopter transport would also be gone. It was an amazing experience to have a breathtaking bird's eye view of the stunning landscape of Antarctica from a helicopter. We could see the big icebergs with turquoise blue water, seals lazily lying on the ice, raft of penguins drifting slowly and of course, the beautiful majestic Bharati station (Fig. 18 & 19).

Fig. 18: Pristine icebergs

Fig. 19: Delightful penguins

A harrowing incident occurred on one of the days when we were dropped to Broknes peninsula and just within 5 minutes, there was snow fall and snow drift with strong scary winds. We could barely see up to 5 m. When we contacted the station, the communication section bluntly refused to rescue us by helicopter citing the bad weather conditions and suggested us to "enjoy the Antarctica weather" in jest. Fortunately, the weather improved quickly and everybody was rescued by the helicopter. In fact, India Meteorological Department (IMD) had forewarned about the storm and snowfall but as the sun shone bright, nobody expected such a turn of weather. That day, for sure, all of us realized the importance of IMD in Antarctica and the correctness of their predictions. The weather forecast data for the two Antarctic stations is also available on their official website. Antarctica is called as the land of "Blizzards" during which speeds of the wind can be more than 300 km/h. Even today, we shudder at the thought of being stranded in the bitterly cold and windy conditions. A similar situation is a snow drift with strong winds as shown in a photograph in front of the station (Fig. 20).

Fig.20: Snow drift in front of Bharati station

Fig. 21: Aurora Australis

It was soon time for our expedition to end. In India, we are accustomed to seeing the sun rising from the east and setting in the west. But here, it revolves around us, just above the horizon! During this stay, we saw sunlight throughout the day except during blizzards and snow fall. Gradually towards mid February, it used to get dark for 2-3 hours. We would see the sunset and sunrise within a few hours, with the sky turning from orange to crimson and the sun would vanish leaving the Bharatians in the dark. On one particular night, we saw Aurora Australis! It is the flashing of colorful lights in the southern hemisphere. It was a beautiful aurora of green lights (Fig. 21). It was really a magical experience to observe this phenomenon and an apt culmination to our wonderful stay at Bharati.

BARC's quest for science

During the expedition, we set up a radiation monitoring laboratory at Bharati station. Two environmental radiation monitors (ERM), developed under Indian Environmental Radiation Monitoring Network (IERMON) were installed successfully for online gamma monitoring. The detectors are transferring data to BARC server on hourly basis all the way from Antarctica since more than a year now. A REM counter was also installed for continuous cosmic neutron monitoring. The laboratory is still well maintained and more systems were installed during the 36^{th} Antarctica Expedition. An extensive radiation survey was carried out around the Bharati station and on various islands in the 35^{th} and 36^{th} expedition. Quite high exposure rates were observed in some places. A large area of 50 m^2 in Broknes region recorded exposure rates in the range of 100-150 μR /h due to the presence of rocks called "Progress Granite" as per the geological map of the area. It represents a small high background radiation area. The rocks and soil samples were brought back and are being analyzed to figure out the reason behind the higher exposure rates. Most samples indicate higher thorium than Uranium concentration. This has also been confirmed by radon and thoron emanation studies of these samples carried out in the laboratory. On-line monitoring of radon/ thoron using Smart RnDuo has also shown atmospheric thoron gas concentration to be slightly more than the radon gas concentration though both are less than the world/Indian average. Detailed analysis of the samples is continued.

Antarctica is an out of the world experience! The ice sheets and huge icebergs give you a feeling of being in heaven. Mankind should strive towards saving the continent, its icebergs, penguins and the white landscape. We stayed in Antarctica for only about three and half months and to describe our experience in Antarctica is like, to quote from William Blake,

To see a World in a Grain of Sand
And a Heaven in a Wild Flower,
Hold Infinity in the palm of your hand
And Eternity in an hour

Acknowledgements

The Indian expedition to Antarctica is very well organized by NCAOR under the aegis of Ministry of Earth Sciences. We acknowledge the co-operation of Dr. Javed Beg, Group Director, Expeditions and Operations, NCAOR and Dr. Rahul Mohan, Group Director, Planning Co-ordination and International Affairs, NCAOR. We owe our journey to Antarctica to our organization, Bhabha Atomic Research Centre (BARC) and extend our gratitude to Director, BARC whose approval for this mission made it all possible. We are obliged to Dr. Pradeepkumar K. S., Associate Director, Health Safety & Environment Group, BARC, for motivating and providing his full support for this expedition. We are grateful to Dr. A. K. Bakshi, Head, PM&SS, RPAD who coordinated this visit with NCAOR under the cosmic ray dosimetry project. We are grateful to Dr. Palani Selvam, Dr. D. K. Koul, and Dr. D. Datta who encouraged us to participate in this expedition. We would like to thank Dr. B. K. Sapra, RPAD for encouraging us to write this article and for thoughtfully editing it. We are thankful to our seniors, friends and families for their support. We thank the leaders of both Maitri and Bharati stations, the voyage leader and all members, especially logistic team of Bharati station for their unconditional support. We thank Shri B. Sudarshan Patro, TO(B), Indian Institute of Geomagnetism (IIG), who diligently took care of our instruments installed at Bharati from March to November 2016 and enabled their smooth functioning. We wish to congratulate Shri Jis Romal Jose, RSSD, BARC for participating in the 36^{th} expedition and carrying forward the efforts by BARC in establishing a radiation monitoring laboratory at Antarctica. We are thankful to the staff at the training centre of ITBP for their holistic training on emergency rescue.

Development of Helium Refrigeration and Liquefaction System at BARC

N.A. Ansari, M. Goyal, A. Chakravarty, Rajendran S. Menon, M. Jadhav, T. Rane, S.R. Nair, J. Kumar, N. Kumar, S.K. Bharti, Abhilash Chakravarty, A. Jain and V. Joemon
Cryo Technology Division,

An experimental helium refrigerator and liquefier, using ultra high speed cryogenic turboexpanders is designed and developed in BARC. The system is based on the Modified Claude Cycle consisting of process compressor with gas management system, coldbox, helium receiver Dewar, tri-axial transfer line and helium recovery system. Extended trial runs are conducted to evaluate the performance of the system. During these trials, liquefaction rate of around 32 l/hr and refrigeration capacity of around 190W@4.8K is achieved. The long term reliability of system is ensured by running the plant round the clock for a month. The article addresses design, development and commissioning aspects of the liquefier along with results of performance evaluation trial runs.

Introduction

Turboexpander based helium liquefaction system is developed in BARC to cater to cooling requirements of radio frequency (RF) cavity and superconducting magnet being developed at BARC. This system is based on Modified Claude cycle with a pre-cooler turboexpander and two process turboexpanders in series with intermediate multi-stream plate fin heat exchangers. The system consists of helium compressor with gas management system, coldbox, transfer line, helium receiver Dewar and helium recovery system. Turboexpander based helium liquefaction system is developed and demonstrated first time in India. Most of the components of the helium liquefier such as high speed turboexpanders, multi stream heat exchanger, coldbox, long stem cryogenic bellow sealed valves, helium transfer line, etc., are developed either in-house or with local vendors. During the trial runs, liquefaction rate of around 32 l/hr and refrigeration capacity of at 190W@4.8K is achieved. The design, development, commissioning and performance evaluation of the system are discussed in the following sections.

Process description

The process schematic of the system is shown in fig 1. The HP helium gas, from the exit of oil flooded helium screw compressor and fine oil removal system, enters the coldbox. This HP (High Pressure) stream is cooled in the series of plate fin heat exchangers (PFHE 1-3) and then gets purified further in the activated charcoal bed (ACB-1). The pure helium stream then bifurcates into two - One goes to a series of two process turboexpanders while the other goes to series of heat exchangers and two Joule Thompson valves (JT valves). The two streams are cooled in multi stream heat exchanger PFHE-5 by return LP (Low Pressure) cold stream coming from the liquid Helium receiver Dewar.

The stream, going to the series of turboexpanders, expands though the first turboexpander (TEX-1) before entering PFHE-5 as IP (Intermediate Pressure) stream. The IP stream exiting from PFHE-5 expands further in the second turboexpander (TEX-2) before mixing with the return LP stream at the LP inlet of PFHE-6. The stream, going to JT circuit, passes through a series of heat exchangers (PFHE 4-6)

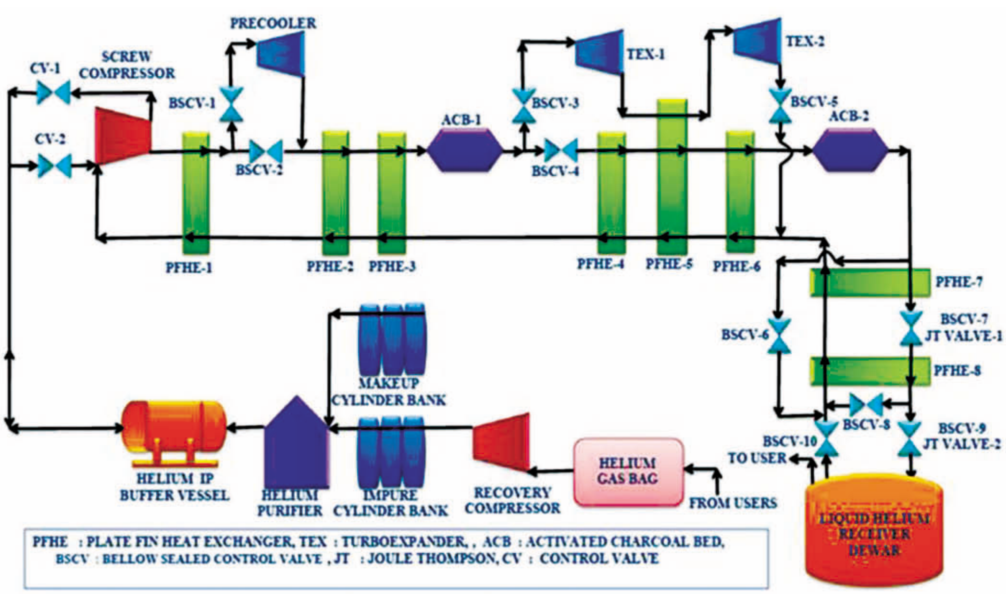

Fig 1.: Process schematic of the developed helium refrigeration/ liquefaction system

followed by activated charcoal bed ACB-2. The stream further cools down in the PFHE-7 before entering the first JT valve (BSCV-7). Subsequently, HP stream cools down in the PFHE-8 and then expands in the second JT valve (BSCV-9). In the BSCV-9, part of the HP stream liquefies. The two phase helium is transferred through a tri-axial transferline to the LHe receiver Dewar and the low pressure helium vapor returns to the compressor suction via the heat exchangers while cooling the incoming high pressure helium streams.

A by-pass valve BSCV-6 is provided to bypass the last two heat exchangers during initial cool down when the lowest temperature is above maximum inversion temperature for helium. A bypass valve BSCV-8 is provided before second JT valve (BSCV-9) to bypass the LHe receiver Dewar during initial experiments when the coldbox is not connected with the LHe receiver Dewar. A pre-cooler turboexpander is also provided to enhance the plant capacity using extra available pressure head.

Gas management system consists of three buffer vessels of 20 m^3 capacity. They are filled with helium gas upto 8 Kg/cm^2 pressures through helium quads having 56 cylinders of 10 Nm^3 capacities.

The process compressor is connected to these buffers through two control valves for closed loop control of process compressor. The used or excess gas from users, Dewar vent and safety valves is collected in two helium gas bags of 28 m^3 capacity. The gas from the bags is filled in impure helium quads through recovery compressor. The impure gas from impure quads is purified with liquid nitrogen cooled external helium purifier and subsequently stored in helium buffer vessels. Before starting the plant, gas is purified with LN_2 cooled external purifier [17]. The moisture level after purification is less than 1 ppmv and N_2 impurity (as per multi component impurity detector, MCID) is 1-2 ppmv.

Major components developed in BARC

Cryo-Technology Division (CrTD), BARC has been working on development of various cryogenic components for helium refrigeration systems. Various research papers are published by CrTD, BARC related to development of these components and systems [1-24].

Turboexpanders

Ultra high speed cryogenic turboexpanders are one of the most important components in a modern large scale cryogenic system. Turboexpanders based on aerodynamic gas bearings are developed in BARC. Various components of turboexpanders are manufactured in-house using precision machining facilities such as 5 axis milling machine for turboexpander 3-d profile. Photographs of various turboexpander wheels are shown in fig. 2. Dynamic balancing of turbo expander shaft, turbine and brake wheel assembly is done using specifically developed precision balancing facilities. Balancing in the order of mg-mm is achieved in the balancing facilities. Rotor-dynamic performance of the turboexpanders is evaluated in closed loop test facilities before installation in the helium refrigerator/ liquefier. In the helium refrigerator/ liquefier, the pre-cooler is used to augment liquefaction/refrigeration capacities by making use of higher available process compressor pressures. For normal runs, pre-cooler is excluded from the circuit.

Fig. 2. Photographs of the turboexpander wheels used in the developed system

Table 1. Comparison of turboexpanders performance with designed parameters.Parameters TEX-1 TEX-2

Parameters	TEX-1			TEX-2		
	Design	Max. Ref.	Max. Liq.	Design	Max. Ref.	Max Liq.
Inlet pressure (MPa)	1.2	1.013	1.141	0.649	0.491	0.637
Exit pressure (MPa)	0.65	0.492	0.638	0.195	0.170	0.242
Inlet temperature (K)	44.6	46.0	59.9	12.8	9.18	14.9
Exit temperature (K)	37.8	37.8	51.9	9.0	6.71	11.46
Rotational speed (rpm)	260000	266820	251040	168000	139800	156060
Turbine major diameter (mm)	16	---	---	16.5	---	---
Flow rate (g/s)	45	46.74	46.42	45	46.74	46.42
Power developed (W)	1620	2044	2005	720	376	719
Isentropic efficiency	70%	71.6%	65.6%	70%	60.8%	65.9%

During system performance evaluation, vibration of turboexpanders is continuously monitored using OROS make vibration analyzer (Model Number: OR36). The process turboexpanders are designed for refrigeration mode operation. Comparison of turboexpander performance during experimental refrigeration and liquefaction runs with their basic design specifications is shown in table 1.

Coldbox

The coldbox, which houses the cryogenic process piping and equipment for maintaining high insulating vacuum condition, is designed, developed and tested in-house. The vacuum vessel (1.5 m in diameter and 2.3 m in length) is fabricated and tested as per ASME Section VIII, Div-I [25] standard. It is properly cleaned, buffed and baked to reduce the out gassing. The process piping and equipment are supported from top through 40 mm thick top cover of coldbox. The pipes and valves which come out of the coldbox are connected to top cover through thin sleeves to reduce distortion during welding and to reduce axial conduction heat losses. The computer generated 3-d model, fabricated piping assembly and MLI wrapped assembly are shown in fig. 3. Based on piping and instrumentation diagram, coldbox dimensions and piping layout are optimized for compactness, ease of operation and maintenance, ease of fabrication, multilayer super insulation wrapping and heat in-leak mitigation, etc. The piping design and fabrication is as per process piping Code B31.3 [26]. The flexibility and stress analysis of the process piping is done using piping systems stress analysis software. The material for process piping is SS304L. The fabrication is done using TIG welding with pure argon gas purging and shielding. Individual subassemblies are fabricated and leak tested up to 10^{-9} mbar.liters/sec in vacuum mode and up to 10^{-6} mbar.liters/sec in sniffer mode. The subassemblies are set up in the top cover and welded together to form the final piping assembly, which is then subjected to

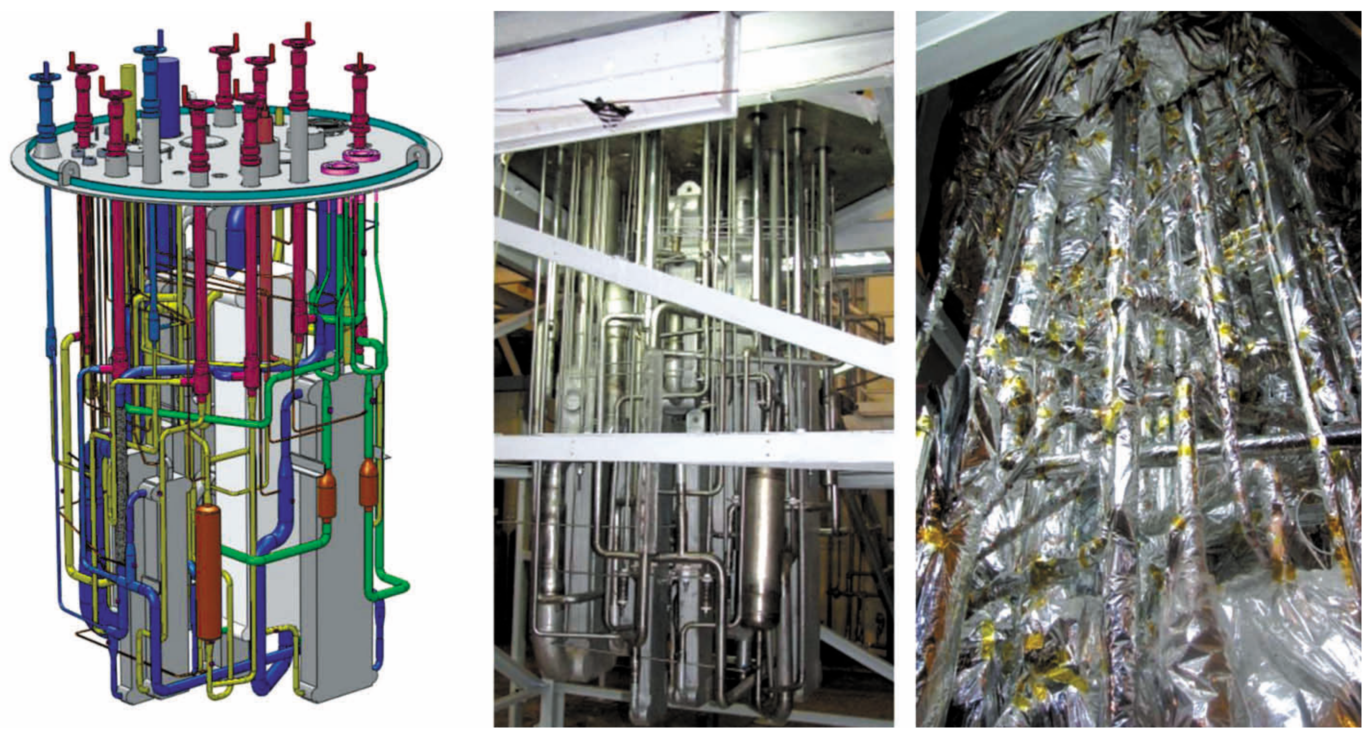

Fig. 3: Photographs of the developed coldbox piping

pressure hold and pneumatic testing as per B31.3 [26]. and tested for leak tightness using mass spectrometer leak detection (MSLD). All the heat exchangers are supported by top cover through spring type supports to allow for thermal contraction during cool down. The flow rates through the turboexpanders and JT valves are measured by orifice plates installed in the piping. The tapping for pressure transmitters and differential pressure transmitters is taken at various places through 6 mm tubing. For temperature measurement, copper blocks conforming to the outside diameter of pipes are silver brazed to the pipes and sensor elements (Silicon diode) are screwed to these blocks. The sensor leads are then taken out of the coldbox top cover through multi-pin electrical feed-throughs. Heat in-leaks are controlled by using multi-layer super insulation. Vacuum of the order of 10^{-6} mbar is maintained in the coldbox using turbo molecular pump backed with rotary vane pump (TMP system: ALCATEL make TURBOSTAND ATP-900). 20 layers of double-sided aluminised Mylar with polyester net spacer are wrapped to the inside diameter of the coldbox. The piping assembly is also wrapped with multilayer super insulation. The higher temperature heat exchangers and other piping components are wrapped with 20-30 layers while the lower temperature heat exchangers, pipings are wrapped with 10 layers.

Multistream plate fin heat exchanger

Multistream plate fin heat exchanger (PFHE-5) shown in fig. 4 is designed in-house and fabricated by M/s Apollo heat exchangers, Vasai. Construction details of the multistream PFHE-5 are described in Table 2. Performance of this heat exchanger is evaluated during performance evaluation of the system. There is a good match between experimentally measured and numerically predicted performance of multistream PFHE. Measured exit temperatures of different streams match within measurement accuracy of temperature sensors with the predicted exit temperatures.

Table 2: Construction details of the multistream PFHE.

Description	Value	Description	Value
Heat Exchanger Matrix Metal	Aluminium (3003)	Fin Height	3.6 mm
Core Length	1335 mm	Serration Length	3 mm
Core Width	300 mm	Fin Pitch	1.4 mm (As
Side Bar Width	10 mm	Total No. of Layers	39
Total Width	320 mm	No. of Layers for LP	20
Separating Plate Thickness	0.8 mm	No. of Layers for	13
End Plate Thickness	5.8 mm	No. of Layers for HP	6
Fin Type	Serrated	Fin Metal Thickness	0.2 mm

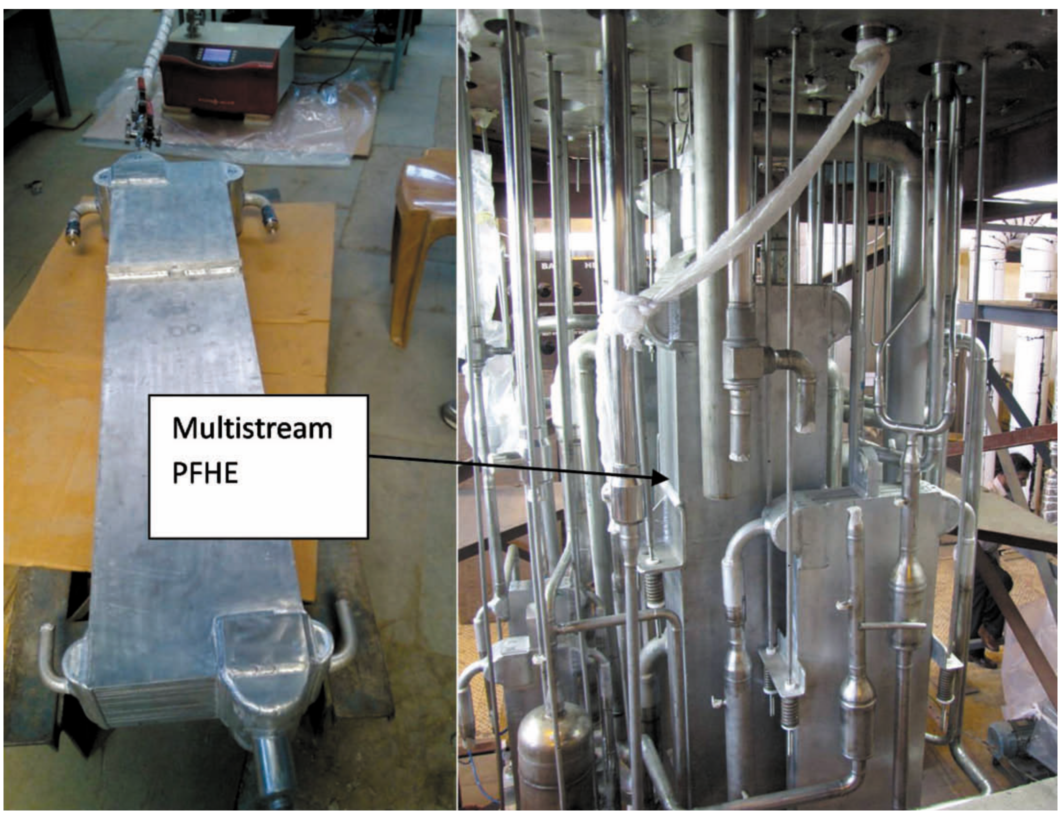

Fig. 4: The developed multistream PFHE (Left) undergoing leak detection; the PFHE mounted on the coldbox top cover (Right) along with other piping.

Tri-axial transfer line

A helium transfer line shown in fig. 5 is developed in-house [22]. The cryogenic coupling (female) is welded on the coldbox flange to facilitate disassembly of the transfer line from coldbox. One end of the transfer line is welded to the cryogenic coupling (male) and the other end enters the Dewar through a Goddard coupling. The transfer line has three coaxial pipes, innermost one transfers two phase helium to Dewar, the vapour flows from the Dewar to coldbox through the second coaxial pipe and the third pipe is for vacuum insulation (vacuum with MLI and activated charcoal fabric wrapped on middle tube). G10 spacers (1 mm thick) are provided in the vacuum region. No spacers are required between the middle line and the innermost line since they are at the same operational temperature. The welding and subsequent MSLD of the transfer line is carried out in stages. All welds are manual TIG welds and leak tested before they are assembled. The weld joints are helium leak tested up to 10^{-8} mbar l/sec. Utmost care is taken during welding of outer tube by providing metallic barrier to protect MLI.

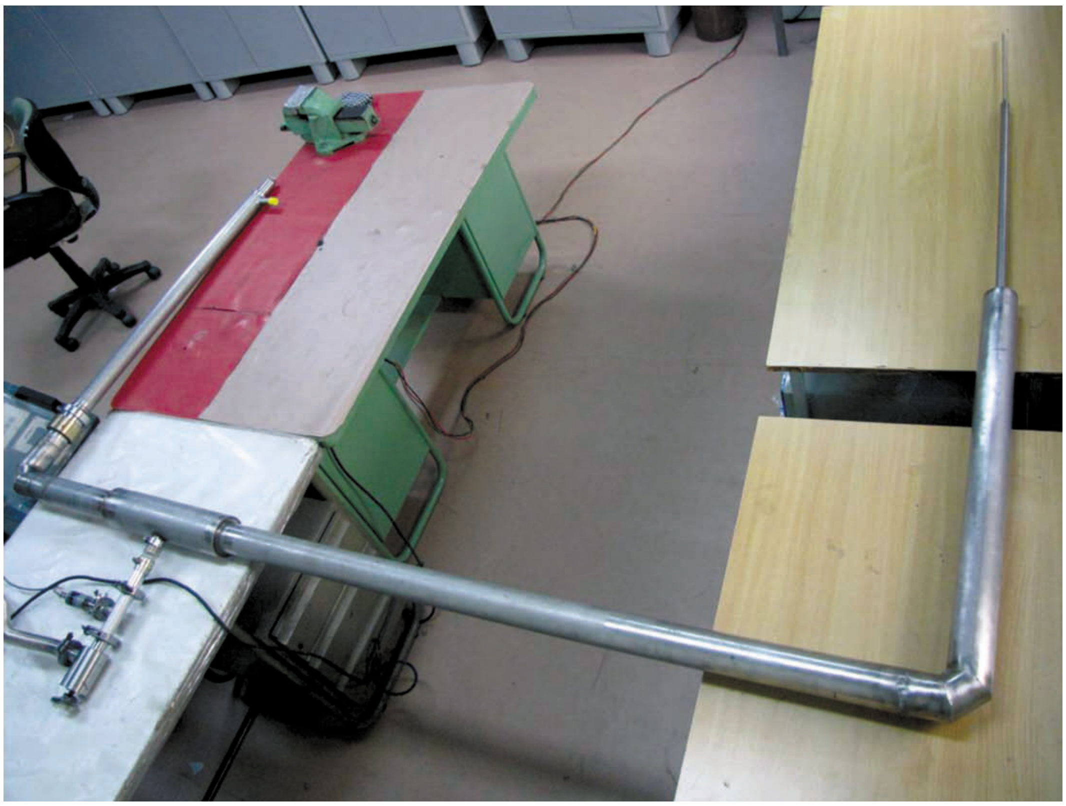

Fig. 5: Photograph of developed tri-axial transferline

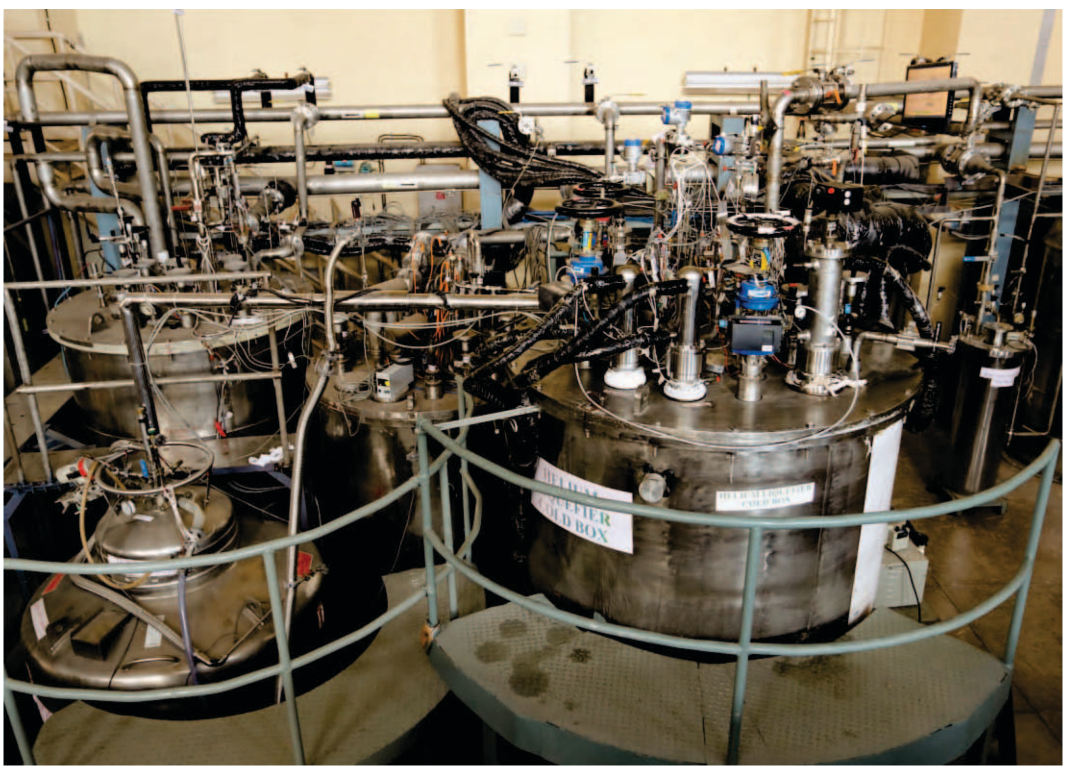

Fig.6: Developed helium refrigeration/ liquefaction system

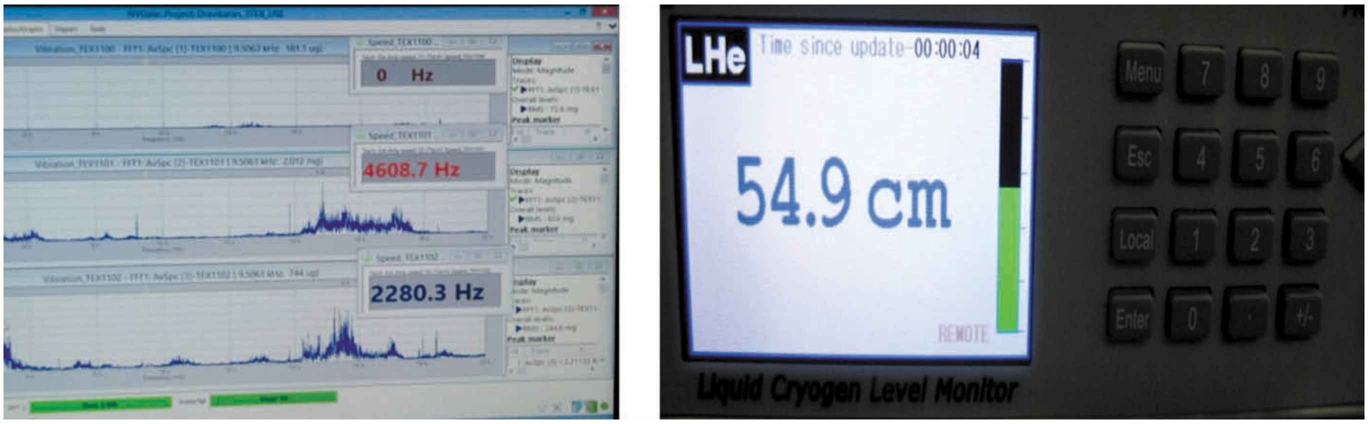

Fig. 7: Turboexpander vibration signature and speed (L) Liquid level (R)

Performance evaluation of helium refrigeration/ liquefaction system

After a series of trials, liquefaction of helium was achieved on 21st of September 2015 after about 15 hrs of operation and liquid helium first collected on 26th September, 2015. The measured liquefaction rate was around 20 l/hr. The total process compressor flow was about 38 g/s. Turbine isentropic efficiencies were 67% and 60% respectively. About 600 liters of LHe was collected and subsequently level was maintained through heater for a week. LHe level was measured using a superconducting level sensor and transmitter. In the refrigeration mode, refrigeration load is applied through a Kapton® (Polyimide film) insulated flexible heater dipped in the Lhe.

In the second trial run during the last week of October 2015, chilled water was made available and turbines could be operated at design speeds. Pre-cooler turbine was used only during cooling down. It was possible to validate the helium liquefaction process for its most standard mode of operation, i.e., with two turbines. Measured helium liquefaction rate of about 32.7 l/hr and refrigeration capacity of about 193 W@ 4.8K was achieved during this trial. Maximum isentropic efficiency of 72% was achieved for TEX-1 at speeds exceeding 4600 Hz. Both the turboexpanders exhibited efficiency in excess of 67% even during off-design conditions. Snap shot of turboexpander vibration signature and speed along with LHe level indicator is shown in fig. 7. To test the long term reliability of the system, the plant was operated round the clock from 29th Jan, 2016 to 02nd march, 2016. During this run, the measured liquefaction rate was around 32 l/hr. Around 400L of LHe was collected and subsequently the level in the LHe Dewar was maintained using process heater. In the refrigeration mode, the refrigeration capacity was around 160-180 watts. During this run, the vacuum system was isolated and good vacuum hold without active pumping was achieved by cryo-pumping in the charcoal, which is wrapped on the cold helium return piping.

Subsequently, three more trial runs are successfully conducted. Around 200 L of LHe is used for performance evaluation of the LHe Dewar. During the latest operation in the month of March 2017, 500L LHe helium is transferred online to two 250L LHe Dewars for conducting the experimental performance of superconducting magnets developed by Accelerator Control Division, BARC.

Conclusion

A helium liquefier and refrigerator, based on high speed turboexpanders and compact plate fin two stream and multistream heat exchangers, is developed by CrTD, BARC. During operational trials, liquefaction capacity of around 32 l/hr and refrigeration capacity of about 190 W @ 4.8 K without any pre-cooling is achieved. The turboexpanders and heat exchangers in the process performed reasonably well during the trials. Work is underway to convert the presently manually operated plant to a completely automated one. As we gain operational experience and with ongoing improvement efforts, we expect that the plant efficiency will further improve.

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A Study to Assess the Role of Bulk Density of Process Load in Co^{60} Based Food Irradiation Facility

Bhaskar Sanyal, V. Prakasan, S.P. Chawla and Sunil K. Ghosh

Food Technology Division

Radiation processing of foods and allied products is one of the important techniques to extend shelf-life. The success of this technology depends on the adequate dose delivery to the food products. The absorbed doses are functions of several irradiation parameters based on the design of the facility. The variable bulk density of the process load is of paramount importance in determining the dose uniformity. Bulk densities of the product in the range of 0.01 to 0.75 gm/cc were prepared and its influence on absorbed dose was studied in a Co^{60} based food package irradiator. The results established that the bulk densities of the process loads would considerably change the absorbed doses and dose uniformity. The data would be useful to the facility operators to take adequate decision in dosimetry procedures.

Introduction

Ionizing radiation can modify physical, chemical and biological properties of the irradiated materials. The principal industrial applications of radiation are irradiation of food and agriculture products for various end objectives, such as disinfestation, shelf life extension, sprout inhibition, pest control and sterilization. Global trade in food and agricultural commodities has become more liberal following the GATT Uruguay Round and subsequent establishment of the World Trade Organization (WTO) in 1995.

The success of this technology depends on adequate delivery of radiation dose to the products. Process dose is the dose needed to achieve a desired effect in the product and is determined through radiation research which involves determination of the dose-effect relationship for the product. Generally, the outcome of such research is identification of two dose limits: the lower dose limit sets the minimum dose that is required to achieve the desired effect in the product, and the upper dose limit is set to assure that radiation will not adversely affect the functional quality of the product. Usually, each product/process has a pair of these limits defining the acceptable dose window in such a way that every part of the product receives dose within that range. These dose limit values, especially for regulated products like foodstuff, are prescribed by national authorities. The ratio of the upper dose limit to the lower dose limit usually referred to as dose uniformity ratio (DUR). In order to maximize the benefit of this technology, the government of India has given blanket permission to irradiated food commodities based on the class of food. Under each class dose limits have been prescribed to achieve the desired purpose of irradiation[1]. Variation in dose in the irradiated food product is unavoidable because radiation gets attenuated during passage through the food product. In addition, there is also dose variation in the lateral direction depending on the geometry of irradiation. Both types of dose variation contribute to the non-uniformity of the dose delivered to the product.

In a commercial food irradiator the dimension of the product container and the source geometry are fixed. Therefore, the non-uniformity in absorbed dose would mainly be influenced by the variation in the bulk density of the process load. A large scale variation in bulk density of the process load has further been important after introduction of the new class based permission of food irradiation. The objective of the present study is to understand the role of bulk density of the product on absorbed doses in a Co^{60} based pilot scale panoramic commercial food irradiation setup. The variation in dose uniformity ratio has also been studied with different bulk densities of the process loads.

Materials and method

The bulk densities of the process load in the range of 0.01 to 0.75 gm/cc were prepared with different materials namely, thermocol, petry dishes, wooden dust, onion, rawa (semolina) and rice, respectively. The irradiation was carried out in a Cobalt 60 pilot scale Food Package Irradiator (FPI) of one by one two passes with source overlap geometry available in Food Technology Division, BARC. The source strength was 74 kCi. The dimension of the aluminum product boxes was 33 cm (length) X 33 cm (width) X 22.5 cm (height). Each product box was filled up to the full height of the product container and weighed. The bulk density was calculated by dividing the weight of the filled product container by the volume. The products were irradiated at ambient temperature at 27±2°C. Complete dose distribution with each of the bulk densities was measured using Fricke dosimeters keeping other plant running parameters identical. Fricke solution was prepared and calibrated following ASTM Standard E1026[2]. To determine the dose distribution in the product boxes, Fricke dosimeters were placed inside the boxes at nine positions (in duplicate) in each plane and a total of 27 positions (54 dosimeters) for three panes. After irradiation A Jasco Model 7800 spectrophotometer was used to determine the absorbance of the Fricke dosimeters at normal laboratory temperature (25±1°C) at 304 nm. The wavelength of this spectrophotometer was checked using holmium and didymium glass filters.

Results and discussion

Facility processing food by ionizing radiation must be licensed and registered according to the Codex General Standard for Irradiated Foods. Additional information on dose distributions achieved under the practices of the given facility needs to be established. In a commercial food irradiation facility the bulk density of the process load may be within a range of 0.01 to 0.8 gm/cc. In view of this different bulk densities were prepared using various food and equivalent commodities as mentioned earlier. Over the years, the manufacturers and suppliers of gamma irradiators have put much effort in response to the growing needs of the industry. The main elements that have been the focus of continuous attention include cost effectiveness of the radiation process, dose uniformity in product, turn-around time and operational reliability. These elements have seen steady improvement with time. Consequently, a variety of sizes and designs of irradiators that are suitable for specific applications for pilot-scale and full commercial-scale irradiations, panoramic irradiators are more suitable, where the source consists of several cobalt-60 pencils arranged in a plane. After irradiation, the source can be brought into its safe storage filled with water (wet storage), or lead (dry storage). Because a radionuclide source emits gamma rays in all directions, it may be surrounded by product containers to increase the energy utilization efficiency. Thus, several (sometimes 100 to 200) containers are typically irradiated simultaneously. For such an arrangement, the average dose rate is significantly lower and the product needs to be irradiated for longer time periods. However, this is compensated by the fact that several large containers are irradiated simultaneously. In order to achieve better dose uniformity the food products are irradiated from both the sides by the suitable movement of the product conveying system. The both side irradiation geometry is depicted in Fig. 1. Experiments were carried out in the same irradiation facility (Food Package Irradiator, FTD, BARC) in order to simulate the actual commercial food irradiation scenario and also to minimize the uncertainties in dose measurements. During irradiation gamma radiation interacts with the product through several types of atomic interactions, such as Compton scattering, photoelectric effect and pair production. Through these and subsequent interactions, it imparts energy and thus radiation dose to the product. The dose distributions for minimum (0.0161 gm/cc) and maximum (0.7524 gm/cc) bulk densities are shown in Fig. 2a and b. As radiation proceeds through the product its intensity decreases, resulting in the decrease of dose with depth. This is referred to as depth-dose distribution. The rate of decrease depends on the composition and density of the product because the energy of the radiation and geometry of irradiation were identical in all the cases. In both the products the dose distribution profile was similar. The zone of $Dose_{max}$ and $Dose_{min}$ were observed at surface planes and middle vertical plane, respectively. Fig 2 shows that the distribution of doses on both the surface planes have $Dose_{max}$ position almost at the centre of the respective planes and attributed to the source pencil distribution geometry into the source rack. Similar trend was observed for all the products with varying bulk densities. On the other hand the distribution of dose on the middle plane was highly influenced by the bulk densities of the products and no common trend was observed amongst different products. These results suggested that the $Dose_{min}$ which is the technologically required dose to achieve the objective of the food irradiation should be measured carefully with bulk density of the actual process load. Variation in dose in the irradiated product is unavoidable. One accepted method of describing this non-uniformity of dose is the concept of dose uniformity ratio (DUR), which is the ratio of the maximum dose in a product container to the minimum dose in the container. Fig. 3 shows the behavior of DUR and absorbed doses (D_{max} and D_{min}) with increasing bulk density of the process load. Both the $Dose_{max}$ and $Dose_{min}$ shown a small increase initially with respect to the empty box. This increase was obvious because of the increased amount of scattering of interacting photons with product followed by decreasing trend with increasing bulk density due to attenuation. $Dose_{min}$ showed faster rate of reduction with increasing bulk density as it was

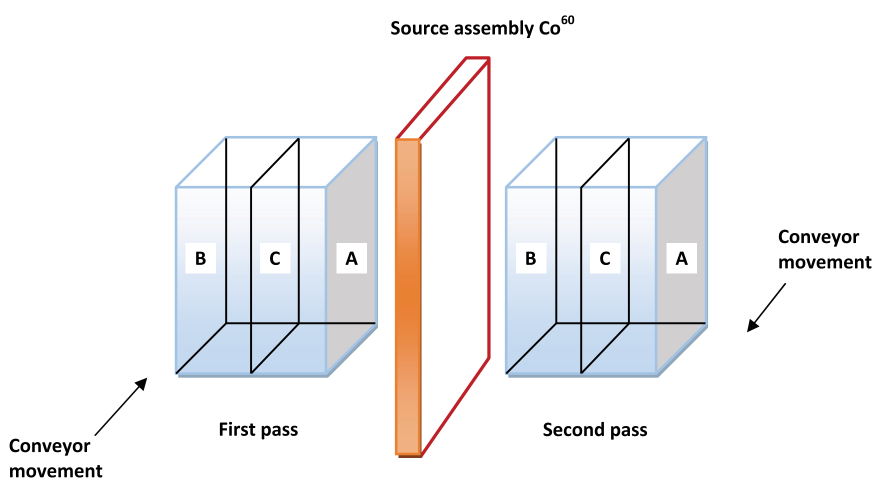

Fig. 1: Irradiation geometry of one by one two passes around the rectangular source assembly and the product boxes with three dosimetry panes (Plane A, B are surface planes, Plane C is middle plane).

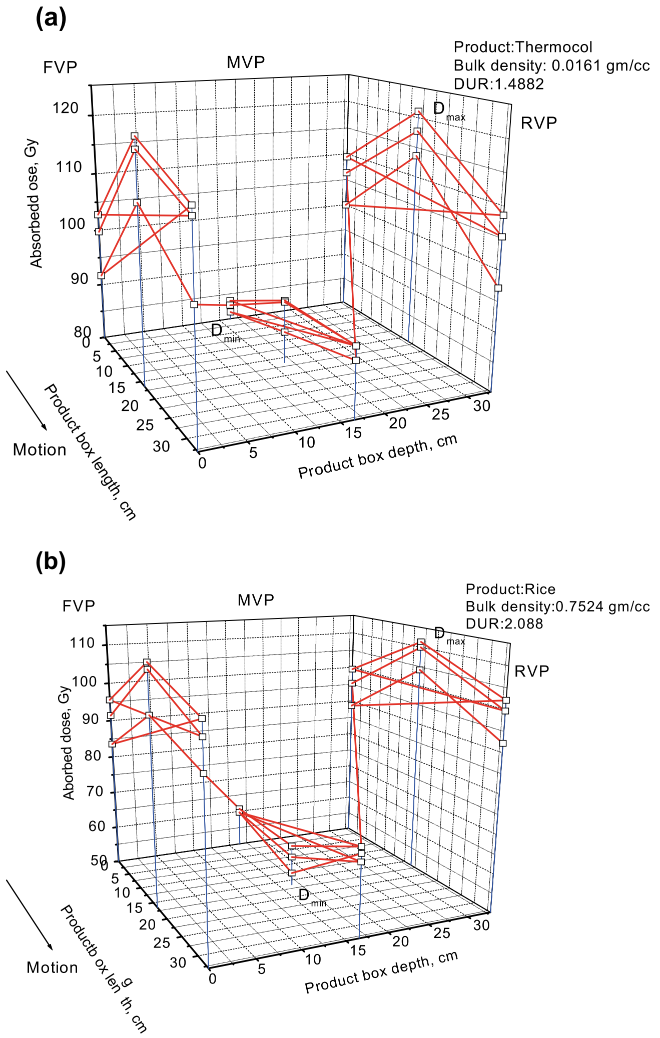

Fig. 2: The dose distribution inside the product boxes filled with bulk density a) 0.016 gm/cc and b) 0.752 gm/cc. (RVP=Rear Vertical Plane, FVP=Front Vertical Plane, MVP=Middle Vertical Plane)

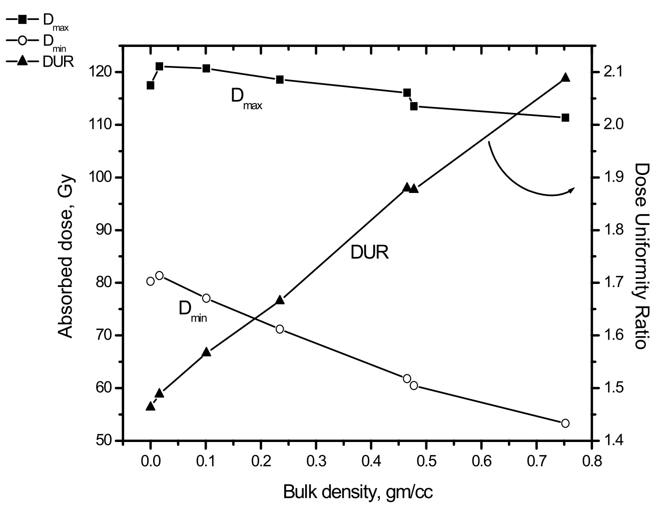

Fig. 3: Variation of Dose$_{max}$ (D_{max}), Dose$_{min}$ (D_{min}) and Dose Uniformity Ratio (DUR) with increasing bulk densitiy of process load.

highly influenced by the nature of the product. Consequently, DUR showed a monotonous increase with increasing bulk density of the process load. This ratio should be close to unity (for example, less than 1.05) for radiation research samples, where the research objective is to correlate radiation effect in the sample to the dose. This is generally achieved by reducing the size of the sample. For commercial operation, this is not possible for economic reasons. A typical product container can be 60 cm × 50 cm × 150 cm, and some irradiators are designed to irradiate entire pallets of product, 120 cm × 100 cm × 150 cm. The dose uniformity ratio would be significantly larger than unity for such large containers. However, for a large majority of applications, there is fortunately a wide window of dose that is acceptable to achieve the desired effect without detrimentally affecting product quality. However, the shape and size of the individual food products and the reference materials used to simulate the actual process load would influence the final absorbed dose in a commercial food irradiation facility. A detailed statistical analysis of all the three process qualification parameters namely D_{max}, D_{min} and DUR for different bulk densities is shown in Table 1. The D_{min} and DUR were found out as most crucial process qualification parameters with % CV of 15.78 and 13.67 %.

Conclusion

The results established the fact that the variation in bulk densities of the process loads would considerably change the absorbed doses and DUR of the facility. Therefore, dose mapping experiments for different process loads should be carried out in order to ensure the required D_{min} for successful food irradiation. The data may be of immense importance to the irradiation facility operators to take adequate decision in dosimetry procedures when different products would be targeted within the same class of foods or between different classes of food products approved for commercial radiation processing.

Acknowledgment

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Table 1: Statistical data of D_{max}, D_{min}, and DUR

	Average	σ	Min	Max	Range	Sum	%CV
D_{max}	116.97	3.6036	111.36	121.08	9.72	828.79	3.08
D_{min}	69.34	10.9462	53.32	81.36	28.04	485.43	15.78
DUR	1.718	0.2349	1.4636	2.088	0.6244	12.08	13.67

Article

AHWR Cold Start-up Simulation Using Thermal Hydraulics Analysis Code, NUTAN-th

Naveen Kumar and A.K. Nayak
Reactor Engineering Division
A. Rama Rao and P.K. Vijayan
Reactor Design and Development Group

Advanced Heavy Water Reactor (AHWR) is 300 MW_e light water cooled and heavy water moderated vertical pressure tube type boiling water reactor.The reactor uses many first-of-a-kind (FOAK) features to enhance system safety. To meet the regulatory requirements for validation of FOAK features, several in-house experimental and numerical simulation programmes have been initiated. PROMISIN (PROjectonMultiphysics and multiscale Integrated SImulation of Nuclear reactors) was one such initiative which aimed at development of advanced simulation tools. Under this programme, a multi-channel multi-physics thermal-hydraulics analysis code, NUTAN-Th (Naveen et al., 2017) has been developed in-house for simulating the thermal-hydraulic behaviour of natural circulation based nuclear reactors in time domain. The code has the capability to simulate the transient behaviour of a water cooled reactor by considering the entire main heat transport system along with pipe structures and fuel bundles. In the present study, the reactor cold start-up considering entire Main Heat Transport (MHT) system along with all the fuel bundles and associated piping structures has been simulated using the computer code, NUTAN-Th.

Introduction

AHWR is a light water cooled and heavy water moderated, vertical pressure tube type boiling water reactor (Sinha and Kakodkar, 2006). The reactor uses natural circulation for core heat removal under all operating states. It is well known that two-phase natural circulation is susceptible to different types of flow instabilities. An excellent review of these instabilities can be found in Boure et al. (1973), Yadigarogulu (1978) and D'Auria et al. (1997). These instabilities may lead to flow induced vibrations and may pose a challenge to stable reactor operation. A study of their mechanism and characteristics is must for the safe and reliable operation of these systems. It is desirable to predict the stable and unstable regions of the operating domain at design stage itself so that adequate design measures can be incorporated for their avoidance, detection and control. Nayak et al. (1998) developed a computer code for analysis of these instabilities and carried out a detailed analysis of stable and unstable operating domains which may be encountered under different operating conditions. The method of analysis was based on linear stability analysis. Based on this analysis, stable and unstable domains were identified and a rational operating procedure was devised. Fig 1 shows the AHWR stability map predicted based on twin channel linear stability analysis. Fig 1 shows a lower unstable domain and an upper unstable domain. The rational operating procedure is devised in such a manner that the reactor remains in the stable domain all the time. During the cold start-up, the low power low pressure unstable domain is avoided by using the pressurised start-up. The scheme for pressurised start-up is shown in Fig 2. As per this scheme, the pressure in the steam drum is regulated such that system remains in single-phase until the MHT system temperature reaches 285°C. The scheme to avoid instabilities during power raising is shown in Fig 3. As per this scheme, the subcooling at the core inlet is controlled through feed water temperature control. The cold start-up operation was simulated in Integral

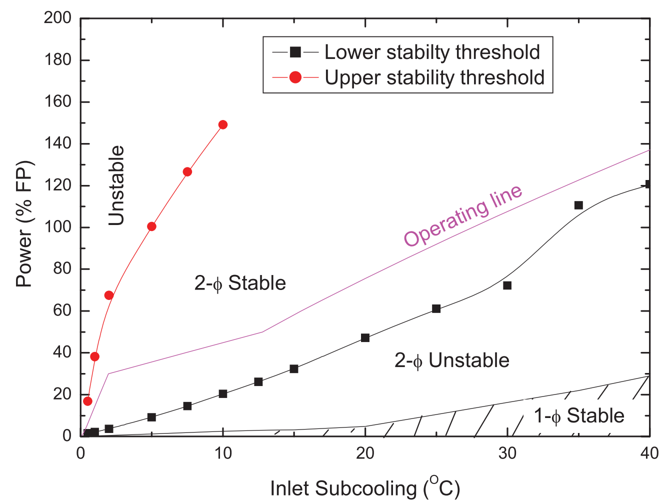


Fig. 1: AHWR stability map and operating line

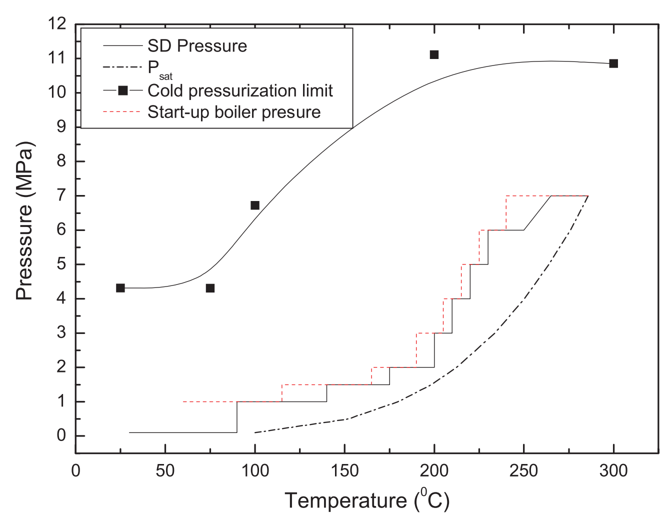


Fig 2: Pressurised start-up scheme to avoid instability during cold start-up

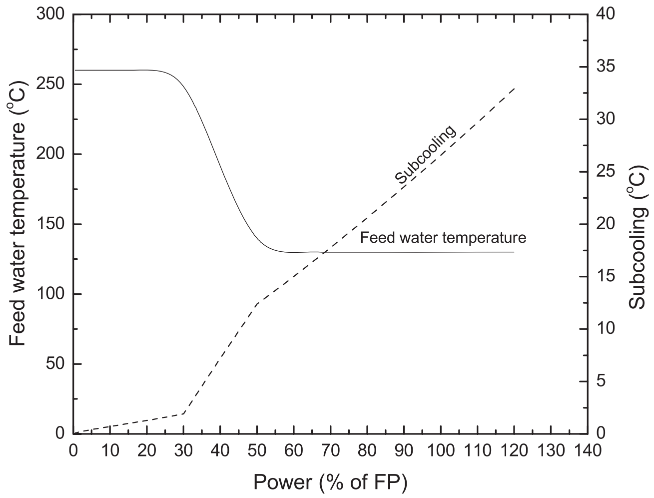


Fig. 3: Scheme to avoid instabilities during power raising

Test Loop (ITL), a test facility simulating AHWR MHT system along with all the safety systems and control. However, during the pre-licensing design and safety review of AHWR, PLDSC made the following observations:

(a) As the power of reactor is changed from one point to another, the sub-cooling at the reactor has to change, which is carried out by changing feed water temperature. However, due to change of recirculation ratio from power to power and large hold up of the down comer, feeder pipes and inlet header etc, the time constants for the two operations (power change and change of sub-cooling at the reactor inlet) are different. There is a possibility of unmatched combinations existing between power and inlet sub cooling during change over. It should be checked for all possible operating and anticipated operational transients. It was suggested that a detailed calculation be carried out to avoid significant reduction in safety margins. The calculation should also factor, instabilities so that any unsafe situation is precipitated. Consequently lumping of channels may not be advisable.

(b) Different combinations of different type of channel (power-wise and hydrodynamic-wise) may have significantly different thermal hydraulic behaviour. It was suggested that for stability and thermal margin evaluation all combinations of different types of channels should be analysed.

(c) It should be shown that if stability map is drawn for two channels then the stability map of larger number of similar parallel channels is only bigger and contains within itself the two channel map and suggested that experimental and/or analytical evidence needs to be generated.

To address the above issue, a multi-channel multi-physics thermal hydraulic analysis code, NUTAN-Th has been developed in-house.

Introduction to NUTAN-Th

The thermal-hydraulic computer code, NUTAN - Th(**NU**clear reactor **T**ransient **AN**alysis – **T**hermal**h**ydraulics)is a multi-channel multi-physics thermal-hydraulics analysis code. It has been developed in-house to simulate the thermal-hydraulic behaviour of multi-channel natural circulation systems in time domain during normal operation and operational transients. There are two main objectives of this development: first, augmentation of the existing capabilities in the field of thermal-hydraulics of natural circulation based systems and second, to assist in resolution of licensing issues raised by Atomic Energy Regulatory Board.

In NUTAN, the channel thermal-hydraulics model is based on homogeneous equilibrium approach. The homogeneous assumption implies that both the phases flow in the same direction with same velocity and are in thermal equilibrium with each other i.e. both the phases have same temperature and pressure. During normal operation and operational transients, the assumption of thermal equilibrium and flow in the same direction holds fairly well. However, during accident transients like small break LOCA and ECCS injection where counter current two-phase flow and liquid vapour separation are encountered, this assumption of thermal equilibrium between the phases and flow in the same direction may not hold. Since the objective of the present work is to analyse the system behaviour during normal operation and operational transients, the HEM is a fairly good choice.The code consists of following modules:

1. Channel thermal-hydraulics module
2. Fuel heat conduction model
3. Wall heat conduction model
4. Fluid axial heat diffusion model
5. Header model
6. Steam-drum model
7. Closures for wall friction
8. Closures for wall heat transfer

The code has the capability to simulate the natural circulation system behaviour in time domain either from a predefined steady state or from the state of rest (zero flow). In both the cases, initialization of fluid and structure properties is a pre-requisite. However, when simulations need to be started from a steady state, the code calculates the steady state based on the boundary conditions defined by the user.For the purpose of thermal-hydraulics calculations, all the piping components are divided into a number of non-overlapping control volumes. Fluid enthalpy, density and pressure are defined at cell centre and fluid mass flow rate is defined at the junction between two control volumes.

Code Architecture

The code architecture can be divided into following groups:

(a) **Pre-processor:** The main functions of the pre-processor are: reading of input, initialization of fluid and structure properties and checking of loop continuity and closedness. The code has the capability to simulate the natural circulation system behaviour in time domain either from a predefined steady state or from the state of rest (zero flow). In both the cases, initialization of fluid and structure properties is a pre-requisite. While simulating the integral behaviour of natural circulation systems, it is necessary that loop must close because the driving force is strongly dependent on loop height. A slight mismatch in loop height can lead to commensurate and in some cases considerable error in code predictions. This becomes a necessity for multi-channel systems like AHWR where 452 number of coolant channels along with all the downcomers need to be simulated. It is worth noting here that each channel is having a different layout. The elevation of feeder coupling and take-off connection is different almost for each channel.

(b) **Steady State Solution:** As discussed earlier, this model performs the steady state initialization of all the fluid variable, viz, pressure, density, mass flow rate, wall temperature, fuel temperature etc. This module can even be used for steady state analysis of a natural circulation system. The module solves the steady state form of governing equations.

(c) **Transient Solution Module:** This module performs the time advancement calculations.

(d) **Post-processor:** The function of the post-processor is checking of convergences for the time step advancement, optimization of time step, printing of output and restart file.

A schematic of different modules and code architecture is given in Fig. 4. The details of the different modules along with solution methodology are presented in Naveen (2013a) and Naveen et al. (2014a, 2014b, 2014c, 2015). The present paper describes the code application to AHWR cold start-up simulation.

4.0 AHWR Cold start-up simulation

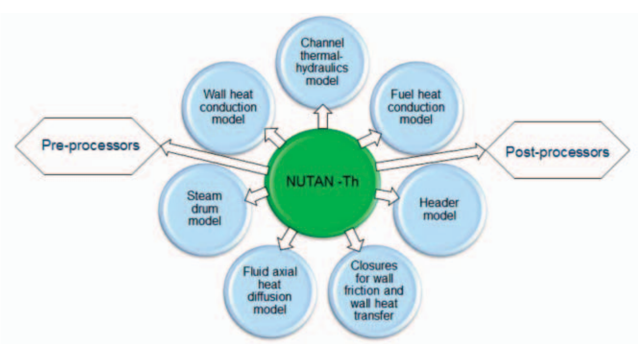


Fig.4: Overview of code architecture and calculation modules

AHWR is a light water cooled and heavy water moderated vertical pressure tube type boiling water reactor. The reactor uses natural circulation for core heat removal under all operational states. The coolant is circulated through coolant channels which house fuel assemblies by the natural circulation via downcomers, reactor inlet header, feeder pipes and tail pipes. The reactor consists of tall risers at the core exit to provide the necessary driving force for natural circulation of the coolant.The MHT system consists of a common reactor inlet header from which 452 inlet feeders branch out to an equal number of fuel channels in the core. The outlets from the fuel channels are connected to tail pipes, 113 of which are connected to each of the four steam drums. From each steam drum, four downcomer pipes are connected to the common inlet header. Fig. 5 shows the schematic of the MHT system. The geometric details of different sections are shown in Table 1 for a typical channel. Table 2 shows the inlet orificing coefficients for different channels. Table 3 show the equilibrium core channel power distribution.It is well known that two-phase natural circulation systems are susceptible to various kinds of flow instabilities under low power and low pressure conditions. Since, the reactor need to be started from zero flow conditions at 1 atmospheric pressure, a rational start-up procedure has been adopted for reactor start-up (Naveen et al., 2013b and 2015). The rational start-up procedure adopted for the reactor start-up is based on following considerations:

(a) Need to avoid low power low pressure instability by going for pressurized start-up.

(b) Need to avoid cold pressurization.

(c) Need to minimize differential thermal stresses in the steam drum.

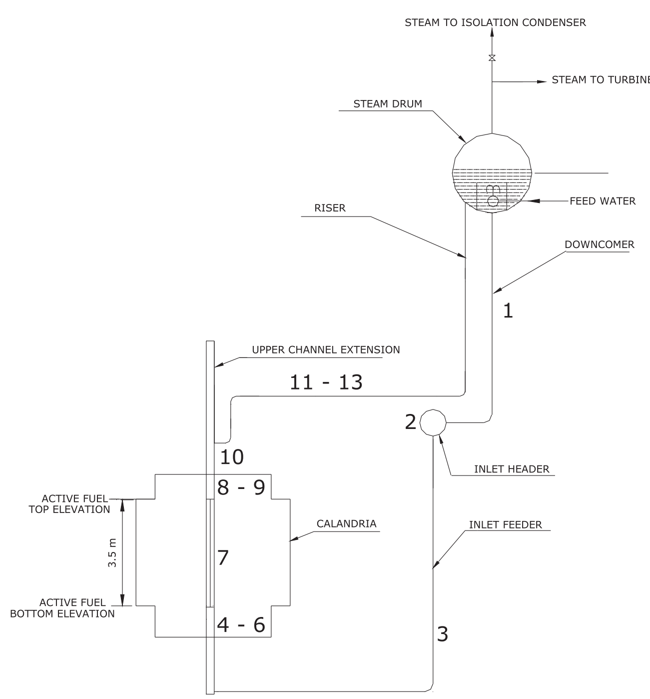


Fig 5: Schematic of AHWR Main Heat Transport System

Table 1: Main parameters of AHWR channel (V-vertical, H-Horizontal)

Part No.		Length (mm)	Hydraulic diameter (m)	Flow area (m2)
1	Downcomer	26.3(V) 5.7 (H)	0.2731	0.0586
2	Inlet Header	0.61 (H)	0.4906	0.0373
3	Feeder	8.25 (V) 9.60 (H)	0.0972	0.0074
4	Bottom	1.6 (V)	0.059	0.0027
5	End Shield	1.2 (V)	0.069	0.0038
6	Bottom Reflector	0.45 (V)	0.0083	0.005
7	Active Fuel	3.5 (V)	0.0083	0.005
8	Top Reflector	0.75 (V)	0.0083	0.005
9	End Shield	1.3 (V)	0.036	0.005
10	Riser - 1	0.9 (V)	0.036	0.005
11	Riser - 2	4.5 (H)	0.050	0.00196
12	Riser - 3	13.5 (V)	0.110	0.0095
13	Riser - 4	25.8 (V)	0.110	0.0095

Table 2: Map for the Inlet Orifice Loss Coefficient

		13	12	11	10	9	8	7	6	5	4	3	2	1
			14	15	16	17	18	19	20	21	22	23	24	25
Z	**A**	300	300	300	300	300	300							
Y	**B**	**SOR**	300	300	300	300	300	300						
X	**C**	0.0	0.0	0.0	**SOR**	0.0	0.0	0.0	0.0					
W	**D**	**AR**	0.0	0.0	0.0	0.0	0.0	**SOR**	0.0	0.0				
V	**E**	0.0	0.0	0.0	0.0	**RR**	0.0	0.0	0.0	0.0	0.0			
U	**F**	0.0	0.0	**SOR**	0.0	0.0	0.0	0.0	**SOR**	0.0	0.0	0.0		
T	**G**	**SR**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**SOR**	0.0	300	
S	**H**	0.0	0.0	0.0	0.0	0.0	**AR**	0.0	0.0	0.0	0.0	0.0	**300**	300
R	**J**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**RR**	0.0	0.0	300	300
Q	**K**	**SOR**	0.0	0.0	**SR**	0.0	0.0	0.0	0.0	0.0	0.0	**SOR**	300	300
P	**L**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**SOR**	0.0	0.0	0.0	300	300
O	**M**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	300	300
	N	**SOR**	0.0	0.0	**SOR**	0.0	0.0	**SR**	0.0	0.0	**AR**	0.0	**SOR**	300

Note :1. The symmetry lines go through the middle of channels in the N^{th} row and 13^{th} column

2. RR – Regulating Rod, SR-Shim Rod, SOR – Shutt-off Rod and AR- Adjuster Rod

Table 3: Channel Power Distribution in the AHWR Core

		13	12	11	10	9	8	7	6	5	4	3	2	1
			14	15	16	17	18	19	20	21	22	23	24	25
Z	A	1.842	1.707	1.649	1.628	1.635	1.655							
Y	B	SOR	1.842	1.75	1.908	1.732	1.658	1.859						
X	C	1.84	1.782	2.047	SOR	2.07	1.897	2.038	2.094					
W	D	AR	1.779	1.977	2.163	2.045	2.163	SOR	2.147	2.01				
V	E	1.855	1.979	2.224	2.103	RR	2.086	2.308	2.301	2.01	2.008			
U	F	2.187	2.249	SOR	2.259	2.015	1.966	2.262	SOR	2.298	2.142	2.086		
T	G	SR	2.333	2.254	2.109	1.914	1.845	1.984	2.259	2.303	SOR	2.028	1.846	
S	H	2.338	2.152	2.064	2.076	1.895	AR	1.843	1.962	2.079	2.153	1.886	1.645	1.63
R	J	2.391	2.195	2.156	2.256	2.051	1.893	1.911	2.009	RR	2.034	2.055	1.716	1.606
Q	K	SOR	2.422	2.383	SR	2.254	2.073	2.104	2.251	2.093	2.149	SOR	1.888	1.598
P	L	2.461	2.267	2.24	2.382	2.153	2.06	2.247	SOR	2.213	1.963	2.028	1.731	1.618
O	M	2.487	2.289	2.266	2.42	2.192	2.147	2.326	2.24	1.959	1.766	1.766	1.819	1.673
	N	SOR	2.487	2.461	SOR	2.391	2.338	SR	2.187	1.855	AR	1.84	SOR	1.842

Note : 1. The symmetry lines go through the middle of channels in the N^{th} row and 13^{th} column
2. Channel powers in MWth
3. RR – Regulating Rod, SR-Shim Rod, SOR – Shutt-off Rod and AR- Adjuster Rod

Table 4: Power variation during the transient simulation.

Time (s)	Power (%FP)
$0 \geq t \leq 32609.8$	2%FP
$32609.8 > t \leq 32737.4$	$2(1.02)^{t-32609.82}$
$32737.4 > t \leq 33371.9$	25
$33371.9 > t \leq 33421.9$	25(1+0.02*(t-33371.866))
$T > 33421.9$	50

From the point of view of ease of reactor operation, initial pressurisation upto 7MPa pressure using steam from external electrode boilers could have been ideal, however, this will lead to undue differential thermal stresses and steam condensation in the steam drums. During the cold start-up, the steam drums are filled, upto 0.85 m, with water at ambient temperature and pressurisation is achieved by filling steam in the space above 0.85 m. Fig 1-3 show the scheme adopted to meet the requirements specified above. The purpose of the present simulation, as discussed earlier in the paper, is to study the interactions among different channels (which are having different layout, different power distributions and different channel inlet orificing coefficients) during cold start-up and power raising. The operating line shown in Fig 1 is based on the behaviour of an average channel. The operating line ensures the reactor remains in stable operating domain all the time during cold start-up and power raising, however, the operating line was based on behaviour of an average channel. The present study demonstrates the reactor start-up behaviour by considering all the channels and seeks to address the following concerns raised by the national regulator during pre-licensing review:

(a) Interaction among different channels having different layout and different power inputs.

(b) Interaction among orificed and unorificed channels.

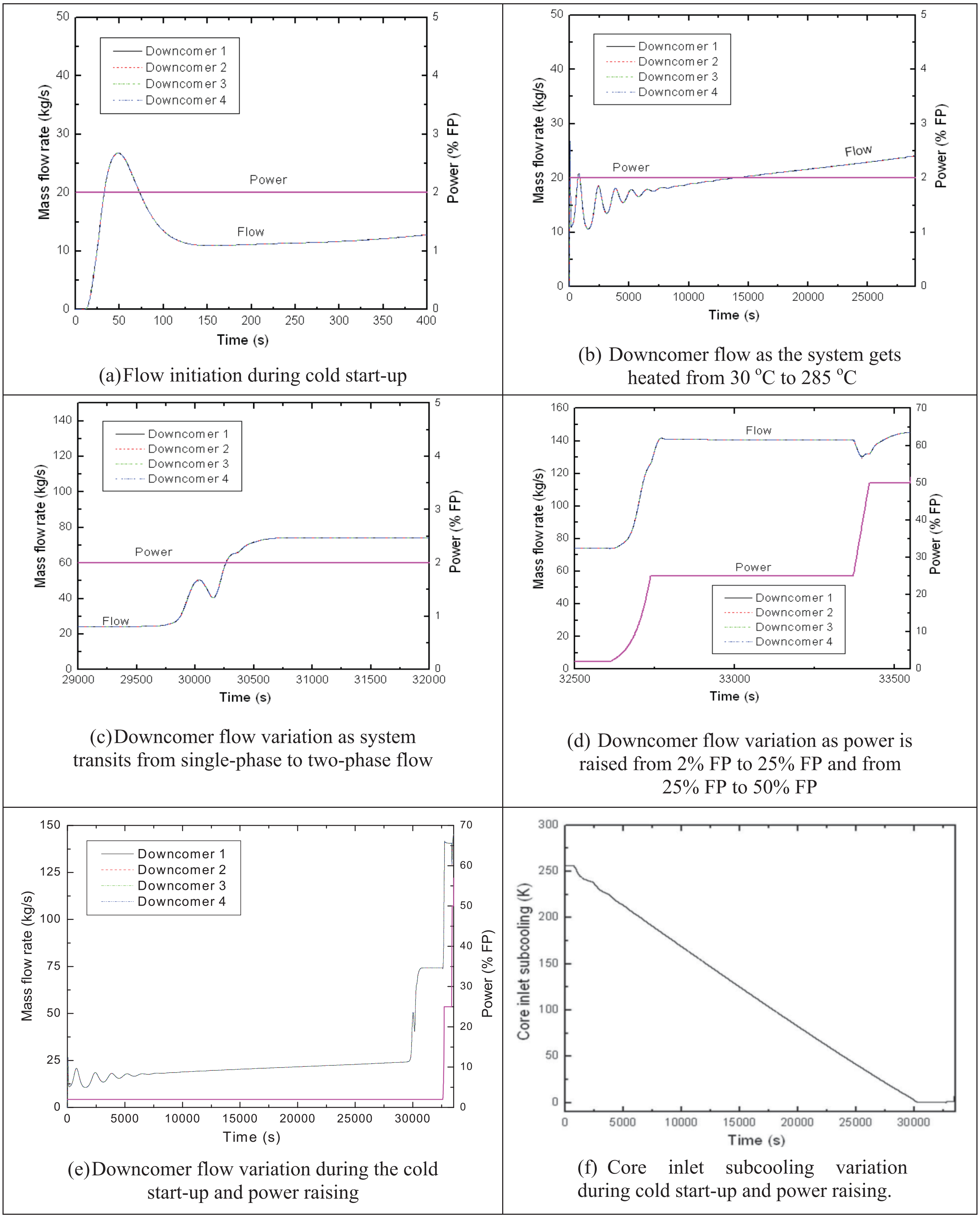
(c) Effect of change of recirculation ratio from power to power and large hold up in MHT system on core inlet subcooling

In a natural circulation system, the channel steady state and stability flow behaviour depends on the channel geometry and the operating conditions. Since all the channels have different geometry and different power, their steady state and transient thermal hydraulics behaviour is also expected to be different. Also, interaction among different channels may modify the system thermal-hydraulic behaviour because of the common boundary conditions. Linzer et al. (2003) studied the effect of power ratio on flow dynamics in a twin channel natural circulation loop having different layouts using homogeneous equilibrium model and observed that there exists a critical power ratio below which reverse flow will take place in one of the channels. Also, the channel stability behaviour is dependent on inlet orificing (Nayak et al., 1998). From Table 2, it is clear that some of the channels have orifices at inlet. MHT system has about 377 tonnes of water inventory. The operating line shown in Fig 1 is based on system steady state behaviour at different power levels. During a transient, a change in feed water temperature which is required to have the desired inlet subcooling for avoiding instability (Fig. 3) may not change immediately after change of feed water temperature because of large MHT inventory. In view of the above, it is desired that the system integral behaviour be simulated by considering all the channels with their different geometric layouts and power distributions. Since the focus of the study is to study the interactions among channels having different layouts and different power inputs, the pressure has been assumed to be 7 MPa throughout the transient. Since as per the operating rational procedure adopted, boiling takes place only at rated conditions, this will not have any significant effect on channel thermal-hydraulicsbehaviour.It is worth noting that under single-phase conditions, density which determines the buoyancy is a weak function of pressure and is mainly dependent on the fluid temperature. In view of this, the system pressure can be assumed to be 7MPa. However, this allows significant savings on computational cost because external start-up boiler system need not be simulated. In the simulation, the channel power has been assumed to be uniform throughout the heated length.Initial condition of the fluid was assumed to be 30 ^{o}C and the Steam drum was assumed to be filled upto a level of 0.85 m. Channel power was simulated as per the details given in Table 4. The feed water temperature was simulated as given below:

$$T_{Feed} = \begin{cases} 260^{o}C & t \leq 33381.9 \\ \left(260 - 3.25\left(t - 33381.9\right)\right)^{o}C & 33381.9 < t \leq 33421.9 \\ 130^{o}C & t > 33421.9 \end{cases} \quad (1)$$

The power during the cold start-up was assumed to be 2% of the power given in Table 3. The feeder and tail pipe lengths for different channels were taken based on inputs provided in manual on "Inputs for Safety Analysis and Detailed Design of AHWR-LEU Systems". Fig. 6 shows the downcomer flow variation during the cold start-up at 2% Full Power (FP) and power raising from 2%FP to 50% FP. It is seen from Fig 6(a) and 6(b) that following a power input of 2%FP, the downcomer flow rate starts increasing at around 15s and after first few oscillations, associated with flow initiation, shows a gradual increase. It increases rapidly as the system transits from single-phase flow to two-phase flow. Fig 6(c) and 6(d) show a smooth transition during power raising also. Core inlet subcooling variation during the power raisingfrom 2%FP is shown in Fig 6(f). It is seen from the figure that subcooling remains close to zero at 2%FP because of two reasons. First, the feed water temperature till 30%FP is 260 ^{o}C. Second, the steam generation rate itself is very small. As the power is raised from 2%FP to 50% FP, it is seen from Fig. 6(f) that subcooling increases gradually.

Channel A8-A13, Channel B7 – B-12, Channel C6 – C13, Channel D5 – D12, Channel E4 – E13, Channel F3 – F13, Channel G2 – G12, Channel H1 – H13, Channel J1 – J13, Channel K1 – K12, Channel L1 – L13 and Channel M1 – M13 flow and channel outlet temperature variation are shown in Fig 7 – 9 respectively. It is seen from Fig 7(a), 7(c), 7(e), 7(g), 8(a), 8(c), 8(e), 8(g),9(a), 9(c), 9(e) and 7(g) that low power orificed channel (A8-A13, B7-B12, G2, H1, H2, J1, J2, K1, K2, L1, L2 and M1, M2) show more oscillations during single-phase natural circulation phase as compared to their unorificed counterparts. Even among the orificed channels (for example channel M1 and M2), those having lower power show more oscillations. Since the pressure in the inlet header is constant, these channels experience the same driving force as the other channels. However, because of the low power as compared to other channels, these channels fail to generate adequate buoyancy force and the flow falls down. As the flow decreases, the buoyancy increases and hence flow also increases. It is seen from Fig. 7(b), 7(d), 7(f), 7(h), 8(b), 8(d), 8(f), 8(h),9(b), 9(d), 9(f) and 7(h) that core exit temperature though shows an increasing trend, it also shows oscillating behaviour in case of orificed channels. For example, it is seen from Fig 9(e) that channel L1 show much more oscillations as compared to all other channels because it is a low powerorificedchannel. Also it is seen that though Channel L2 is also orificed but it does not show as high oscillations as are observed in Channel L1. This is because of the difference in power generated in Channel L1 and L2. It is seen from Table 3 that at 100% FP, channel L1 produces 1.673 MW while Channel L2 produces 1.819 MW power. The effect of channel power on parallel channel loop behaviour was brought out by Linzer et al. (2003). Linzer et al. (2003) studied the effect of power ratio on flow dynamics in a twin channel natural circulation loop having different layouts using homogeneous equilibrium model and observed that there exists a critical power ratio below which reverse flow will take place in one of the channels.Naveen et al. (2014) studied the flow behaviour in a single-phase natural circulation loop having3 channels and single downcomer and observed flow reversal under some of the operating conditions. Both experimental and numerical simulations with NUTAN – Th showed flow reversal in the unheated channel. In the present study, it is clearly brought out that for the equilibrium channel power distribution given in Table 2, no flow reversal is observed in any of the channels. Fig 10 shows the variation of channel flow for channels M1 – M13 during the various phases of the transient. Fig. 11 shows the variation in core exit steam quality. It is noted from Table 3 that Channel M13 is the highest power channel and Channel M1 is amongst the lowest power channels. It is seen from Fig 9(g) that channel M1 shows flow oscillations; however, no flow reversal is observed. It is seen from Fig 10(b) that boiling initiation is accompanied by oscillation in channel flow. This is because of change in steam quality at channel exit (Fig 11(a)). However, the



(a) Flow initiation during cold start-up

(b) Downcomer flow as the system gets heated from 30 °C to 285 °C

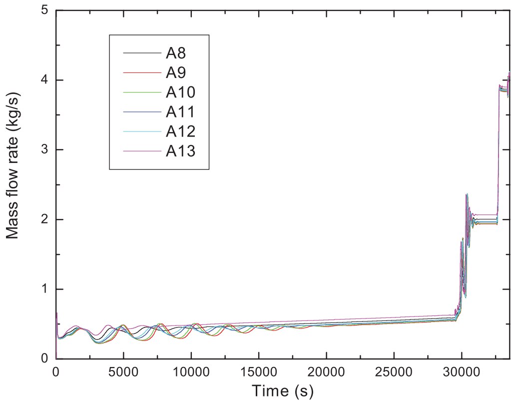
(c) Downcomer flow variation as system transits from single-phase to two-phase flow

(d) Downcomer flow variation as power is raised from 2% FP to 25% FP and from 25% FP to 50% FP

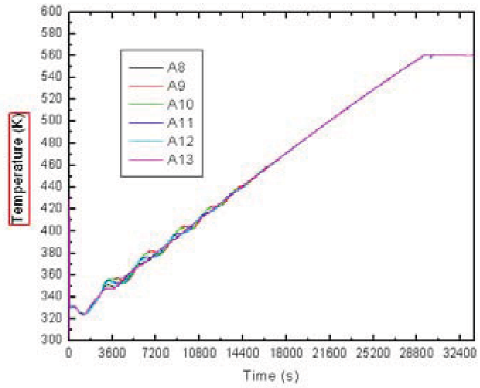
(e) Downcomer flow variation during the cold start-up and power raising

(f) Core inlet subcooling variation during cold start-up and power raising.

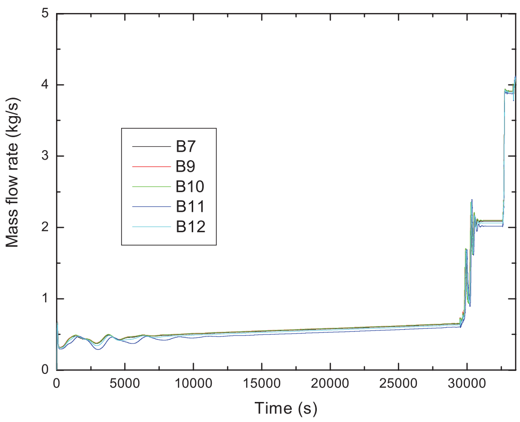
Fig 6: Downcomer flow and subcooling variation during cold start-up and power raising from 2%FP to 50% FP



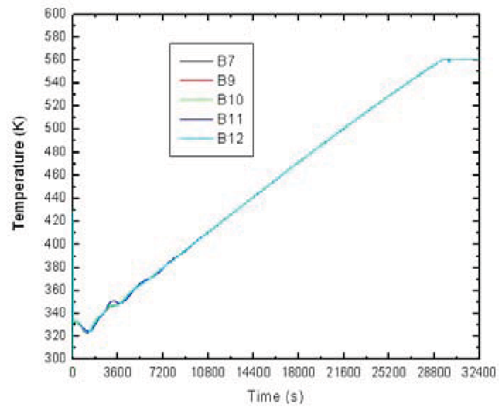
(a) Flow variation for Channel A8-A13



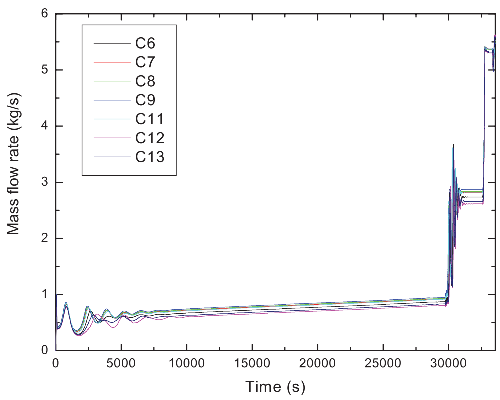
(b) Core exit temperature variation for Channel A8-A13



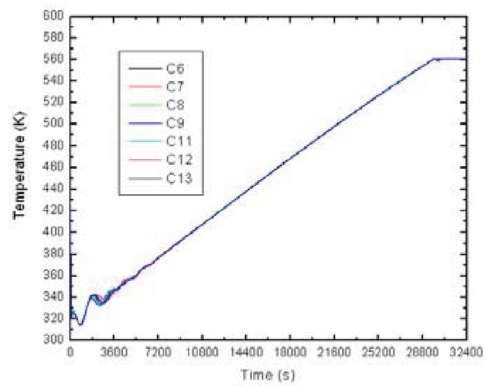
(c) Flow variation for Channel B7-B12



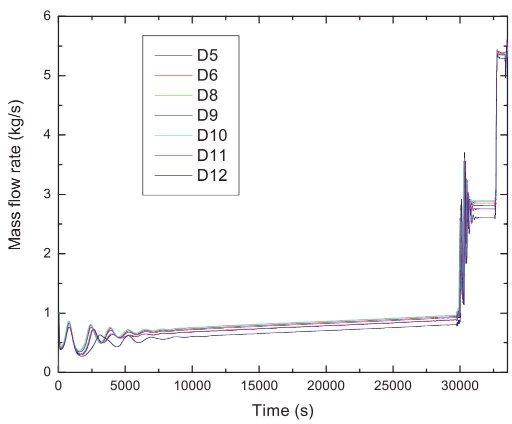
(d) Core exit temperature variation for Channel B7 – B12



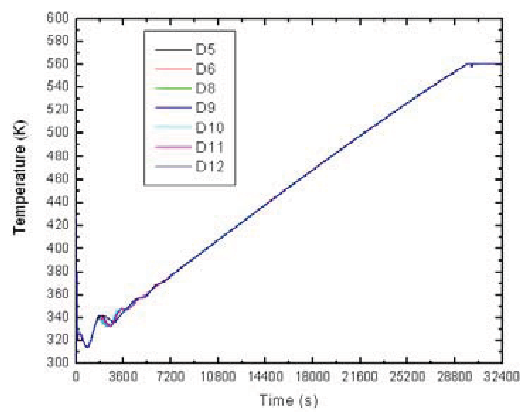
(e) Flow variation for Channel C6-C13



(f) Core exit temperature variation for Channel C6 – C13

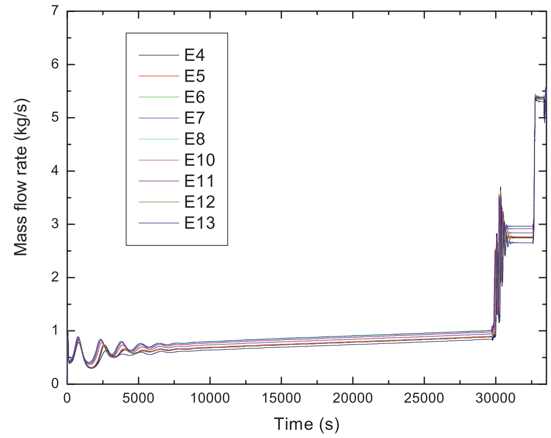


(g) Flow variation for Channel D5-D12

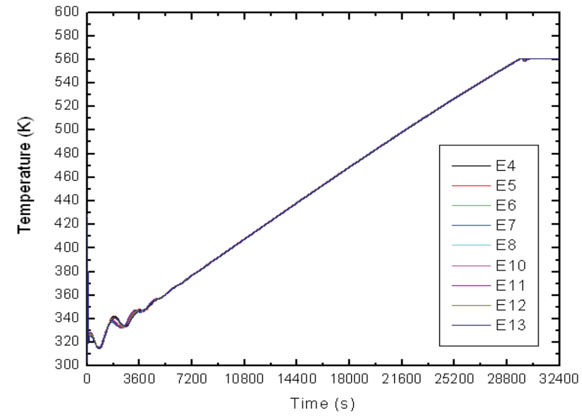


(h) Core exit temperature variation for Channel D5 – D12

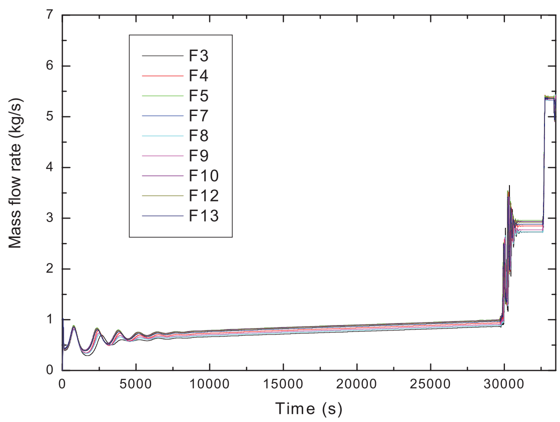
Fig. 7: Channel (A – D) flow and channel exit temperature variation during the transient



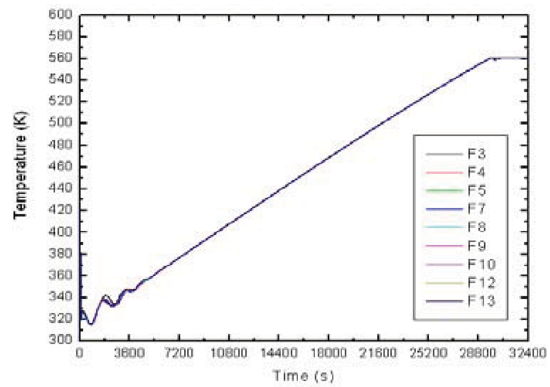
(a) Flow variation for Channel E4-E13



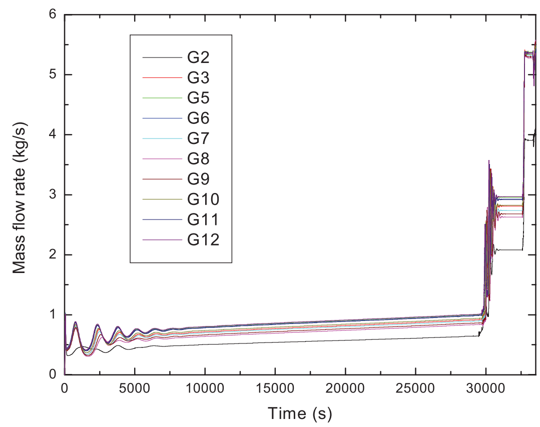
(b) Core exit temperature variation for Channel E4-E13



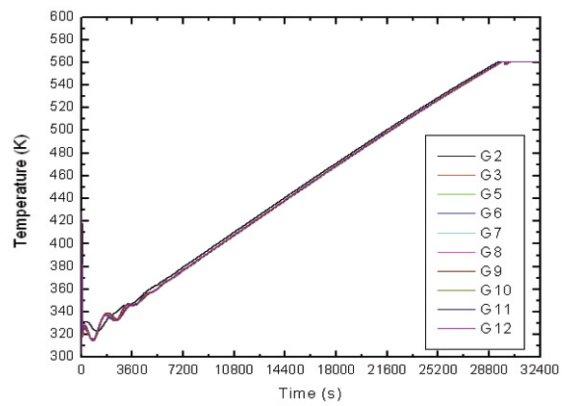
(c) Flow variation for Channel F3-F13



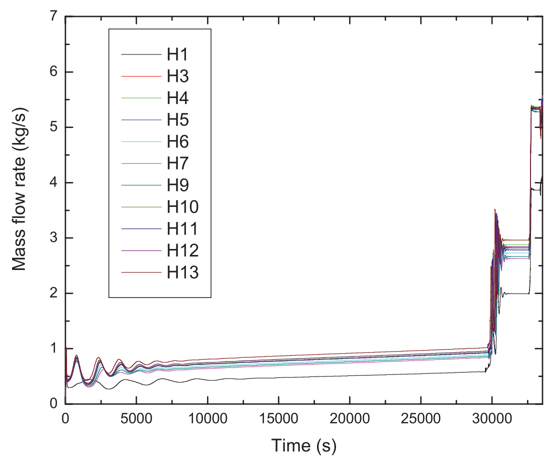
(d) Core exit temperature variation for Channel F3-F13



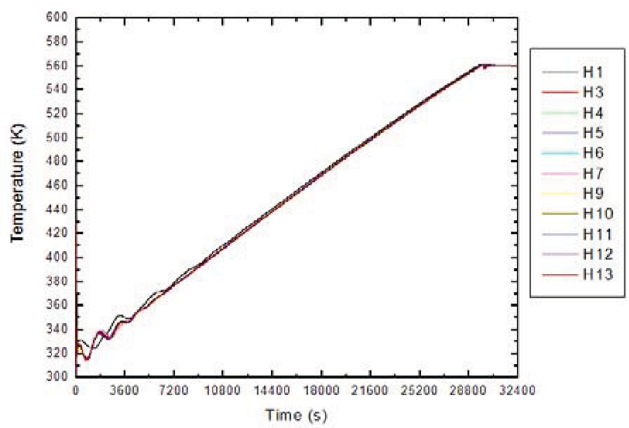
(e) Flow variation for Channel G2-G12



(f) Core exit temperature variation for Channel G2-G12

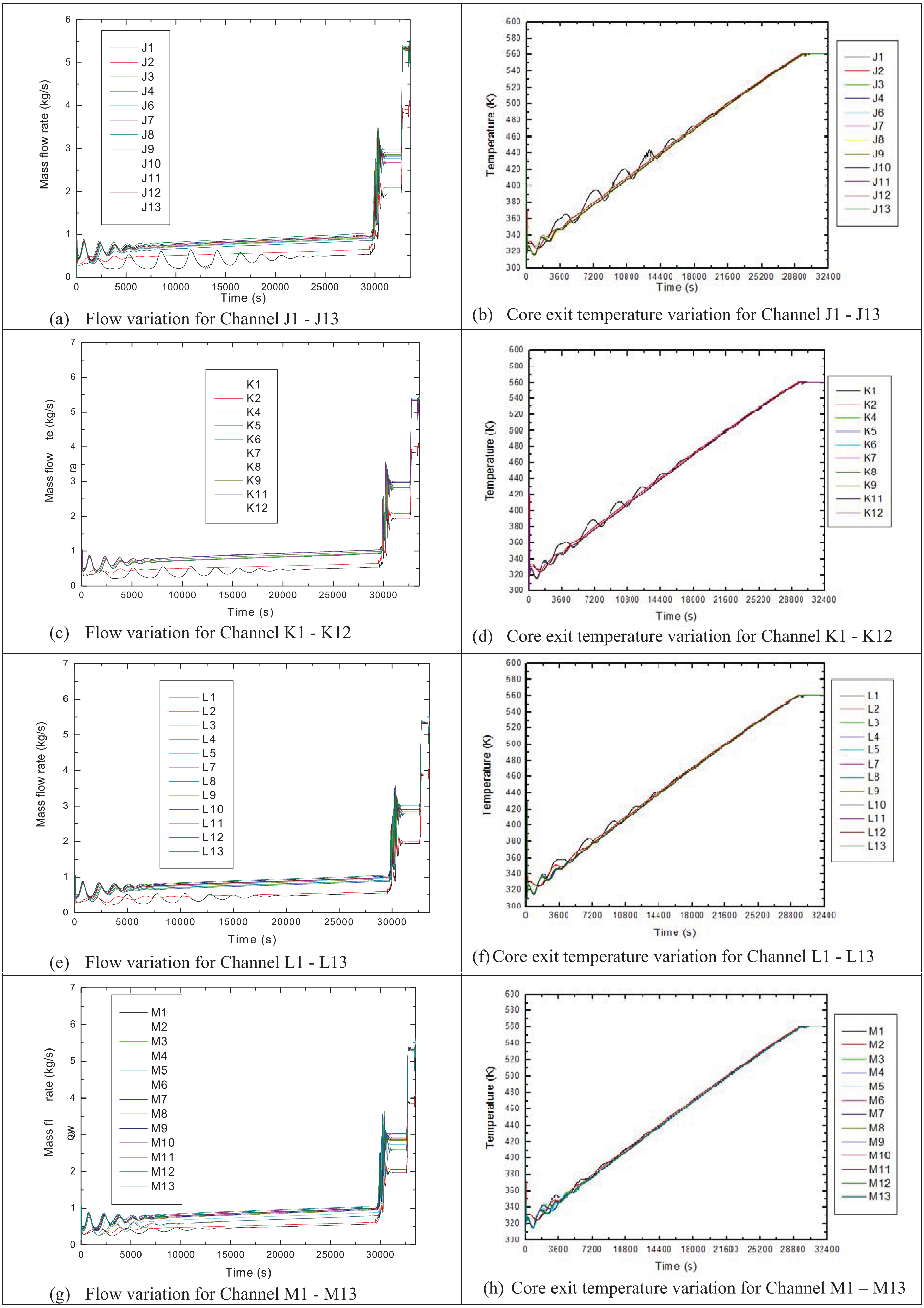


(g) Flow variation for Channel H1- H13



(h) Core exit temperature variation for Channel H1- H13

Fig. 8: Channel (E-H) flow and channel exit temperature variation during the transient



(a) Flow variation for Channel J1 - J13

(b) Core exit temperature variation for Channel J1 - J13

(c) Flow variation for Channel K1 - K12

(d) Core exit temperature variation for Channel K1 - K12

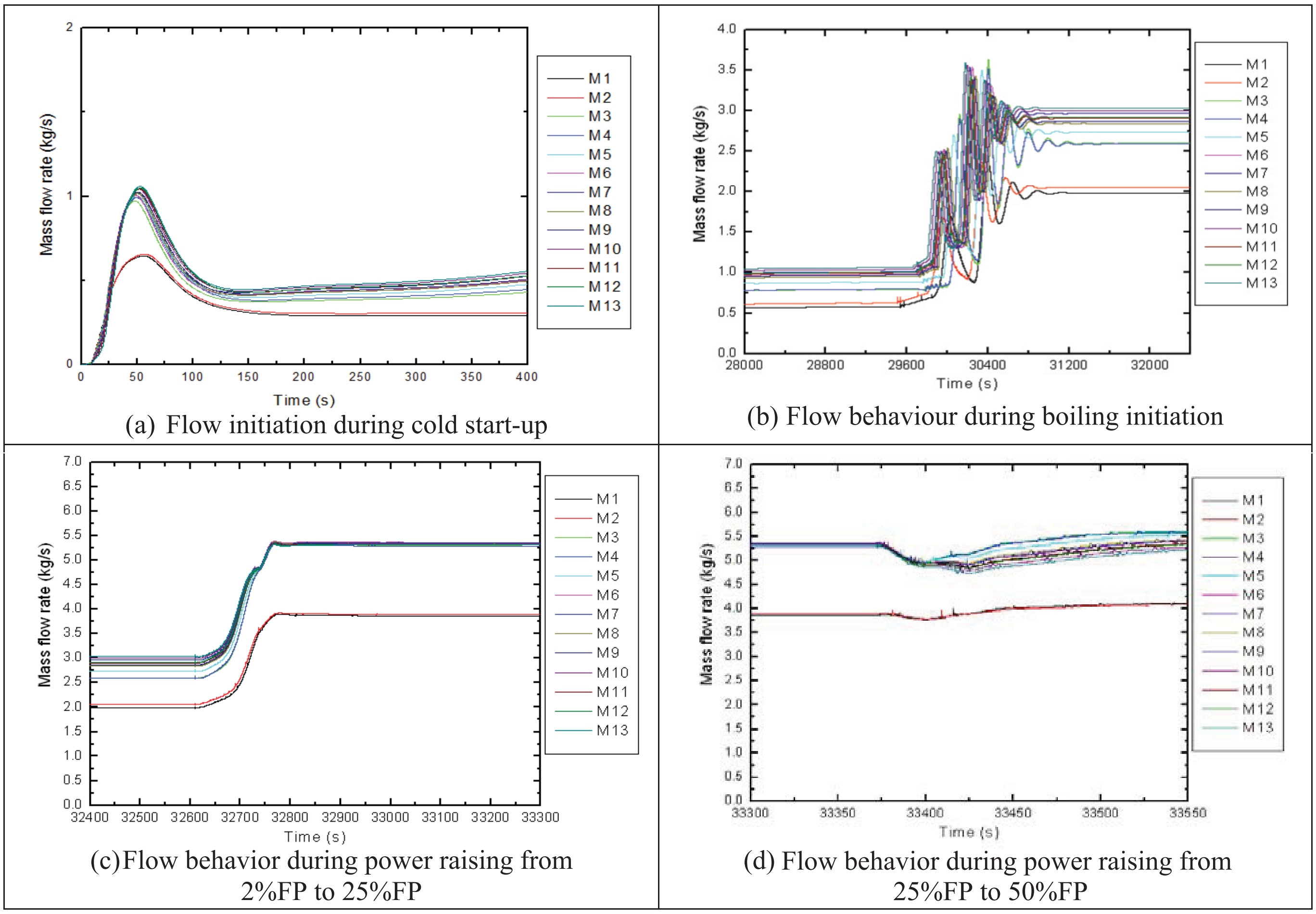
(e) Flow variation for Channel L1 - L13

(f) Core exit temperature variation for Channel L1 - L13

(g) Flow variation for Channel M1 - M13

(h) Core exit temperature variation for Channel M1 – M13

Fig. 9: Channel (J-M) flow and channel exit temperature variation during the transient



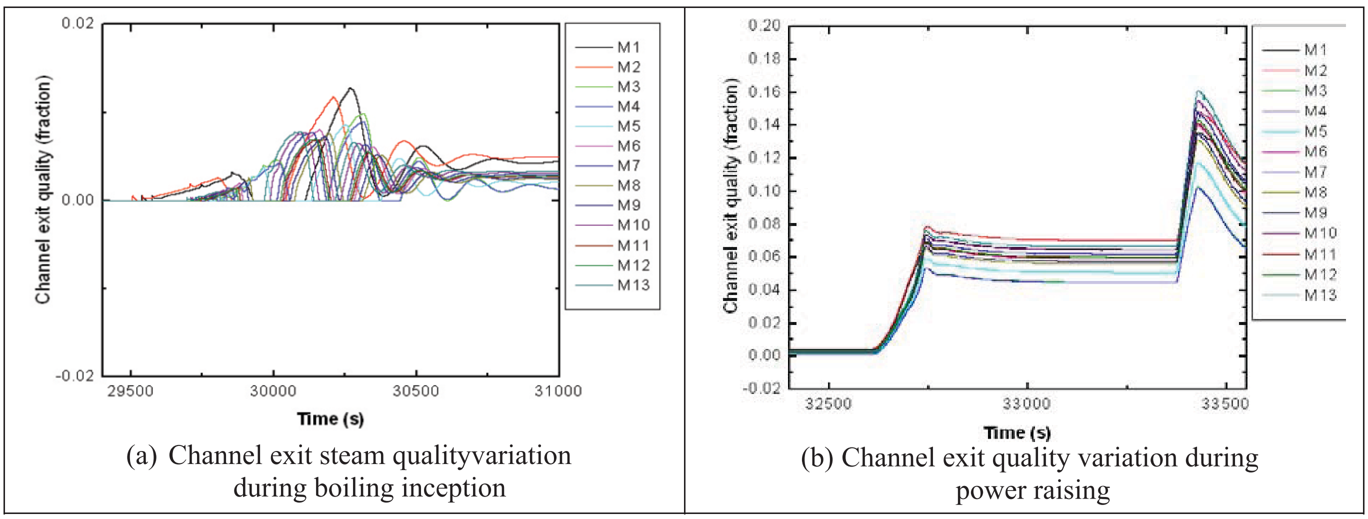
(a) Flow initiation during cold start-up

(b) Flow behaviour during boiling initiation

(c)Flow behavior during power raising from 2%FP to 25%FP

(d) Flow behavior during power raising from 25%FP to 50%FP

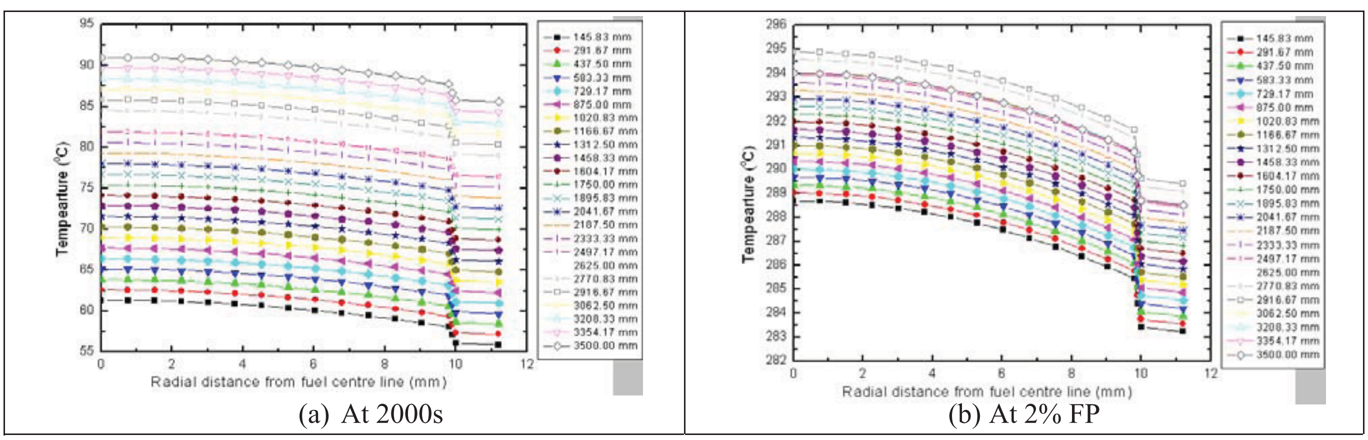
Fig. 10: Details of flow behavior for channels in Row M during various phases



(a) Channel exit steam qualityvariation during boiling inception

(b) Channel exit quality variation during power raising

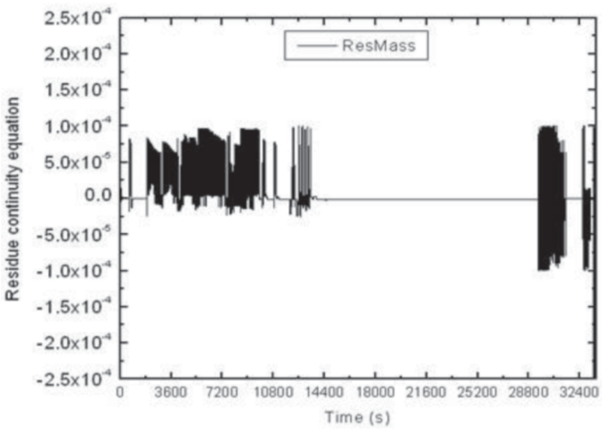
Fig. 11: Details of core exit quality variation for channels in Row M during various phases



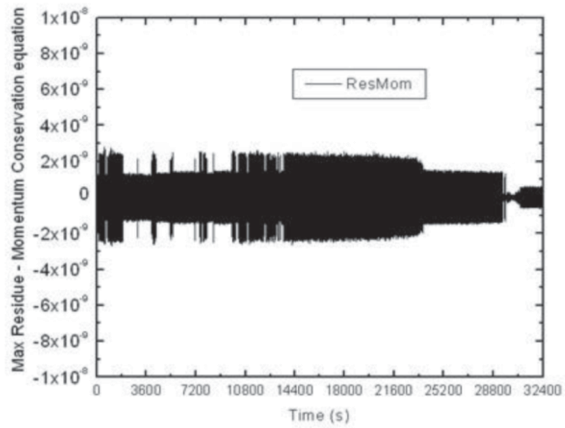
(a) At 2000s

(b) At 2% FP

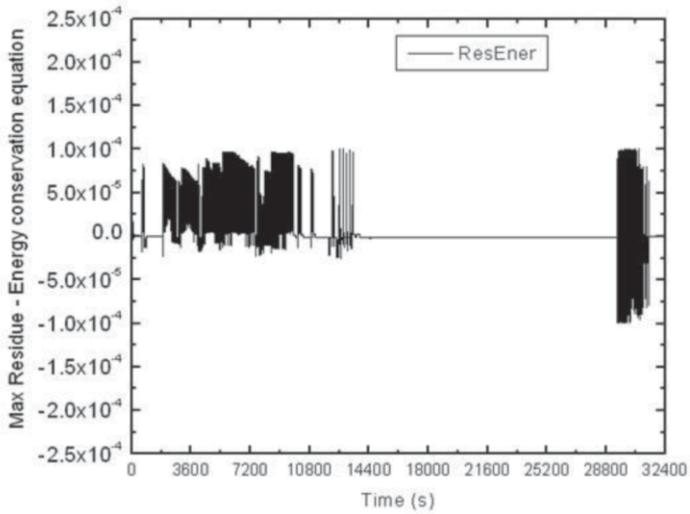
Fig. 12: Fuel temperature snap shots at different times during the transient for Channel M3



(a) Continuity equation



(b) Momentum balance equation



(c) Energy balance equation

Fig. 13: Error estimates in NUTAN-Th during the transient

variation in steam quality is very low and given the near zero void coefficient of reactivity, it should not be of any concern. Except during flow initiation at cold start-up and boiling initiation at 2%FP, no oscillations are observed during the power raising from 2%FP to 50%FP. The results presented here establish the adequacy of rational start-up procedure adopted for AHWR for cold start-up and power raising. Also, the simulation demonstrates the NUTAN-Th ability to predict the large reactor system behaviour for normal operation and operational transients. In the present simulation, each fuel pin was divided into 17 radial volumes and 24 axial volumes. The power to each fuel pin was assumed to be constant and axial peaking factor was assumed to be 1. Fig 12 shows the snapshots of fuel temperature variation for the highest power channel (M13) at different time intervals during the transient. It is seen from Fig 12(a) – 12(f) that fuel centre line temperature increases with increase in channel power.

In NUTAN, a rigorous verification and validation scheme has been incorporated to ensure the conservation of governing equations. The post-processor module of the code estimates the non-dimensional residues of the mass, momentum and energy balance equations for all the volumes at each time step. A plot of these errors for the cold start-up simulation is shown in Fig. 13. Error control is heart of any numerical scheme. Each numerical scheme must be consistent and stable. The scheme adopted was analysed for consistency and was found to be consistent. The results of consistency analysis are discussed in Naveen (2013a). Stability implies that errors are bounded. Results shown in Fig 13 show that the errors are bounded.

Conclusions

In this research, a multi-channel multi-physics thermal-hydraulics analysis code, NUTAN-Thhas been developed to predict the behaviour of natural circulation systems and nuclear reactor systems in time domain. The code has the capability to simulate the transient behaviour of a water cooled reactor by considering the entire main heat transport system along with pipe structures and fuel bundles. It is a stepping stone towards indigenous development of coupled neutronic thermal-hydraulics analysis code. Reactor start-up from zero flow and room temperature fluid condition has been simulated considering all channels along with fuel bundles and pipe structures. It included different combinations of different types of channels (power-wise and hydrodynamic wise). Different channels have been found to be having different thermal hydraulic behaviour because of differences in their layout and power. The results of numerical simulation show that the rational start-up procedure adopted for AHWR eliminates the low power instability during cold start-up and power raising upto 50%FP. The results of the simulation have successfully resolved and addressed the PLDSC concerns about cold start-up and power raising.

NUTAN-Thdevelopment was motivated by resolution of issues related to AHWR, however, the code can be applied to other reactor systems like PHWR, PWR, MSBWR, CHTR and IHTR also. This will involve addition of additional components like pumps and thermodynamic properties relevant to coolant used.

Acknowledgements

The first author takes this opportunity to express his sincere gratitude to the Department of Atomic Energy for giving him an opportunity to develop this tool. He thanks his mentors, Prof J. B. Doshi and Prof. Kannan. N. Iyer of IIT Bombay for guiding him through different phases of this work. He extends his sincere thanks to his colleagues, Dr. N. K. Maheshwari, Shri D. S. Pilkhwal, Dr. D. K. Chandraker and Dr. Deb Mukhopadhyay for their continuous support and encouragement. He expresses special thanks to ShriKapilBodkha for helping him in validating the code against single-phase natural circulation loop data. His sincere thanks to his colleagues, ShriVikas Jain, ShriMukesh Kumar, ShriSumitVishnu Prasad and ShriAnantaBorgohain for their valuable support.

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Report on DAE-BRNS 6th Interdisciplinary Symposium on Materials Chemistry (ISMC – 2016)

DAE-BRNS 6th Interdisciplinary Symposium on Materials Chemistry (ISMC-2016) was held at Multipurpose Hall, Training School Guest House, Anushaktinagar during 6-10 December, 2016. The Symposium was jointly organized by Chemistry Division, BARC and Society for Materials Chemistry and was fully supported by the Board of Research in Nuclear Sciences (BRNS). Dr. V. K. Jain, Convenor ISMC-2016, welcomed the delegates and invitees. Dr. A. K. Tyagi, co-convener, gave an overview of the Society for Materials Chemistry and BRNS. Dr. B. N. Jagatap, Director Chemistry Group and Chairman of the organizing Committee inaugurated the event. Prof. Ganapati D. Yadav, Vice-Chancellor, Institute of Chemical Technology, Mumbai delivered the inaugural lecture entitled 'Synthesis and applications of novel catalytic and allied materials for development of green processes'. In the Inaugural function, Proceedings of the 6th ISMC, Special Issue of SMC Bulletin on 'Role of Chemistry in Clean India' (Volume 7 issue No 1) and Special Issue of the Proceedings of National Academy of Sciences India on Organometallics (Volume 86, issue No 4) were released by Dr. B.N. Jagatap, Dr (Mrs) K.I. Priyadarsini and Prof. G.D. Yadav, respectively.

There were 15 scientific sessions and 4 poster sessions. The scientific sessions comprised of 26 invited lectures from the leading scientists from India and abroad, 13 short lectures and two evening talks; one by Prof J. B. Joshi on 'large scale manufacture of nano-materials: Computational fluid dynamics and design' and the other by Dr. B. N. Jagatap on 'Did Indian civil services examination of 1895 influence chemistry Nobel Prize in 1908?'. Poster sessions were held on first four days and a total 272 posters were presented. On each day five best posters were selected by the expert committee for the best-poster awards given by Society for Materials Chemistry (5 numbers); Royal Society of Chemistry (RSC, UK) (5 numbers); and Springer India (10 Numbers).

The deliberations of the symposium covered frontline research in diverse areas of material science such as nuclear materials, nano-materials, thin films, devices and sensors, materials for energy conversion and storage, biomaterials, magnetic materials, catalysts, soft matter, carbon based materials, high purity materials, organic materials, computational materials chemistry.

Speakers from India and abroad delivered invited talks on a variety of topics. These presentations, besides fundamental aspects, covered nano-materials for clean energy, hydrogen energy (both by photo- and thermo-chemical cycles), nano-materials for light harvesting, nano-porous materials, metallic glasses, functional materials, metal clusters and elcetro-catalysis by them, catalysts design for high activity, functional materials, oxide materials for luminescent and electrochemical applications, homeopathic medicines, chitosan polymer for therapeutic applications, polyolefin based hybrid materials, shape memory alloys, biosensors and cancer biomarkers, separation of fission products from high level nuclear waste, etc. In a five-day long deliberations, 5 scientists from countries like Germany, USA, Russia, and Japan, and 24 scientists from our national research centres like BARC, IITs, IISc and Universities delivered lectures on their recent work.

Valedictory session on 10th December, 2016 was presided over by Dr. B.N. Jagatap, Director, Chemistry Group. Many students, invited speakers and other delegates gave their feedback onthe symposium. The event has been described by the delegates as a high standard, well organized and highly successful scientific symposium. Best poster awards were presented in the session.

Brief Report on "Theme Meeting on Regulatory Inspection Practices in BARC Facilities", Organised by BSCS and BRNS

BARC Safety Council Secretariat (BSCS), in collaboration with Board of Research in Nuclear Sciences (BRNS) organised a Theme Meeting on "Regulatory Inspection Practices in BARC Facilities" on January 21, 2017 (Saturday) at Multi-purpose Hall, Training School Hostel, Anushaktinagar, Mumbai.

BARC Safety Council (BSC) is the Apex Body responsible for safety regulation in BARC Facilities. BSC Secretariat supports the Council in safety regulation, as well as in improving safety awareness among the personnel in BARC facilities. BSCS, in past, has conducted many such training courses and theme meetings. The theme of the current meeting was Regulatory Inspection, which is one of the most important tools used by regulatory bodies for verifying the safety compliance of the facilities and projects in conformance with the regulatory requirements. As of now, BSC and its committees have about fifty Regulatory Inspection Teams (RITs).

The Theme Meeting had four sessions, viz. inaugural session, two technical sessions and panel discussion. Dr. Srikumar Banerjee, Former Chairman, Atomic Energy Commission; DAE Homi Bhabha Chair Professor and Chancellor, HBNI inaugurated the theme meeting. In his speech, he shared his experience as a regulator and emphasised the importance of regulatory inspection in ensuring safety of BARC facilities. Shri Y. K. Taly, Chairman, BSC; Dr. G. Gouthaman, Raja Ramanna Fellow (RRF) and Former Chairman, BSC; Shri D. K. Shukla, Executive Director, AERB; and Shri K. Jayarajan, Head BSCS shared their experience in the meeting.

The Meeting comprised of six technical lectures, encompassing different aspects of regulatory inspections. Regulatory Inspection Practices related to Industrial Safety, Construction safety, Civil Safety, Chemical safety, Fire Safety, Radiological safety, Emergency Preparedness; Waste Management; Regulatory Aspects and Documentation were covered by eminent speakers, namely, Shri K. Agarwal, AD, NRG; Shri L. R. Bishnoi, Director, SSED, AERB; Dr. (Smt.) S. B. Roy, RRF & Former Director, ChEG; Dr. K. S. Pradeepkumar, AD, HS&EG; Shri Amitava Roy, CE, NRB and Shri K. Jayarajan, Head, BSCS. The sessions were chaired by Shri R. J. Patel, RRF and Chairman, CFSRC and Shri S. Sarkar, Former Director, ChTG.

Last session of the Theme Meeting was panel discussion. The panelists were Shri Y. K. Taly; Shri R. J. Patel; Dr. (Smt.) S. B. Roy; Dr. B. S. Tomar (Director, RC&IG and Chairman, CRRASDRW); Dr. Pradeepkumar and Shri Kailash Agrawal. The lively panel discussion improved clarity of the subject to all participants.

The Theme Meeting was attended by about 250 members of RIT and Safety Committees from Kalpakkam, Mysore, Tarapur, Trombay and Vizag.

61st DAE-BRNS Solid State Physics Symposium 2016

The annual DAE - Solid State Physics Symposium (DAE SSPS 2016) was held at the KIIT University, Bhubaneswar, Odisha, during December 26-30, 2016. This symposium is fully sponsored by Board of Research in Nuclear Sciences (BRNS), Department of Atomic Energy (DAE) and is held annually at different venues with a broad aim to bring together researchers working in various aspects of Condensed Matter Physics. About 1000 scientists, mostly from India and a few from abroad, participated in the symposium last year which was 61st in the series. Prof. S. Basu, Head, Solid State Physics Division, BARC, and Convener, DAE-SSPS 2016, welcomed the delegates of the symposium and gave an introduction to the symposium, in the inaugural session. Prof. P. P. Mathur, Vice chancellor KIIT University, Bhubaneswar welcomed the delegates of the symposium to KIIT University. The symposium was inaugurated by Prof. N. K. Sahoo, Assoc. Director, Physics Group, BARC. Prof. Srikumar Banerjee, Chancellor, HBNI & Ex-Chairman, AEC, in his address as chief guest of the symposium highlighted the importance of solid state physics research. Dr. S. K. Sahoo, Convener, Local Organising Committee addressed the delegates and highlighted the condensed matter research activity at KIIT University, Bhubaneswar. Dr. Shovit Bhattacharya and Dr. Surendra Singh, Scientific Secretary, 61st DAE-SSPS 2016, proposed the vote of thanks in the inaugural and in the concluding sessions of the symposium, respectively.

The technical session of this symposium was divided into invited talks, contributory papers in the form of oral and poster presentations, presentations by Ph.D. thesis candidates and Young Achiever Award (YAA) nominees. Last year, there had been very enthusiastic responses in terms of the number of papers submitted. We had received 1283 contributory papers from which 836 papers were chosen for presentation after a due review process by experts. In this symposium, 2 plenary talks, 50 invited talks, 24 oral presentations, and 800 posters were presented. The topics covered in the symposium were (a) Phase transitions (b) Soft Condensed Matter including Biological Systems (c) Nano-materials (d) Experimental Techniques and Devices (e) Glasses and Amorphous Systems (f) Surfaces, Interfaces and Thin Films (g) Electronic Structures and Phonons (h) Single Crystals (I) Transport Properties (J) Semionductor Physics (K) Superconductivity, Magnetism and Spintronics (l) Novel Materials. There were 8 thematic seminars on (i) Energy Materials (ii) Soft Condensed Matter (iii) Theoretical Condensed Matter (iv) Science using Neutron and Synchrotron facilities (v) Single crystal studies and application (vi) Physics of Low dimensional systems (vii) Functional materials (viii) In-situ studies with synchrotron radiation.

Two outstanding plenary talks were delivered: One entitled "Advance Functional Materials and Clean Energy" by Satish Ogale, IISER, Pune and another entitled "Active Matter: Bacterial Heat Engine, Flocking and Sorting" by Prof. A.K. Sood, IISc., Bangalore. The evening talks were delivered by Prof. S. Banerjee, Chancellor, HBNI & Ex-Chairman, AEC, on Order and Chaos in assemblies of Atoms and in Human Societies and by Prof. A.K. Samanta, KIIT & KISS, Bhubaneswar.

A panel of judges selected 3 Young achiever awards out of 10 participants. Another Panel of judges selected 3 best Ph.D. thesis awards out of 35 participants. Another panel of judges selected 24 best poster awards out of 800 posters. In the concluding session, YAA awards, Ph. D. thesis award and best poster awards were given away by Prof. Sasmita Samanta (Registrar, KIIT University Bhubaneswar), Prof. Saibal Basu (Convener, DAE SSPS 2016) and Prof. Amitabh Das (Co-Convener, DAE SSPS 2016), respectively. The first best thesis award presented by Mr. S. Gupta titled "Co-based nanocatalysts for efficient hydrogen production by electrolysis of water and hydrolysis of chemical hydrides" was sponsored by the Indian Physics Association (IPA) as IPA's Anil K. and Bharati Bhatnagar Best Ph.D. Thesis Award in Solid State Physics.

National Science Day 2017

National Science Day is celebrated in India on February 28 to commemorate the Nobel Prize winning discovery of photon scattering by Prof. C.V. Raman. BARC has been celebrating this day every year with a different theme in order to showcase the different areas of work being carried out in the centre. This year, the topic "Computer Science and Technology – Empowering the Nation" was chosen as the theme for NSD-2017. The celebration was held during the period February 28 to March 3, 2017.

The event was kept open to school and college students in the age group of 14-18 years or from 9^{th} standard to First year B.Sc/B.Tech/Polytechnic classes. The total participation was approximately 800 students and teachers from 33 different schools and colleges in the Mumbai area.

Each day's session included a technical session in the first half followed by visits to different facilities in BARC in the second half. The technical session comprised of a short explanation about Raman Effect, a technical lecture by eminent speakers, a skit expounding the advantages of atomic energy and a quiz. As part of the facility visits, the guests were taken to Dhruva reactor, Supercomputing Facility, DRHR and a poster exhibition at CC auditorium.

Shri A.G. Apte, Ex-Chairman, NTRO and former Head, Computer Division, BARC officiated as the Chief Guest on the day of the inauguration (February 28). He delivered a keynote address describing how different technologies have converged into a single smartphone, thus making it one of the most versatile and useful devices ever developed. The welcome address was delivered by Shri R.S. Mundada, AD (C), E&I Group. Shri K.N. Vyas, Director, BARC introduced the theme of the event and the presidential address was delivered by Dr. Sekhar Basu, Chairman, AEC.

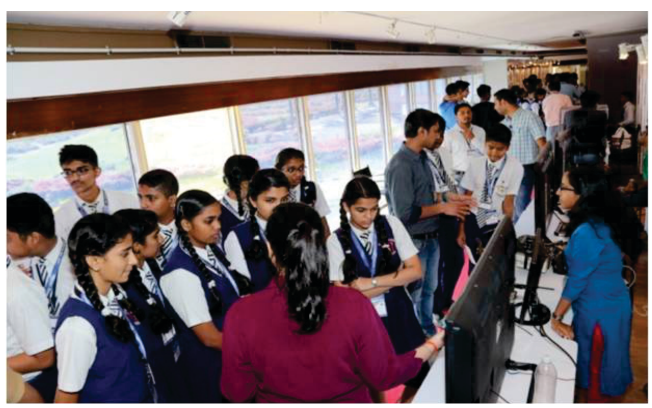
The Chief Guest also inaugurated a poster exhibition setup at CC auditorium which consisted of about 60 posters and exhibits of technologies and systems being developed by various divisions of BARC.

The technical talks were delivered by Shri A.G. Apte (Feb 28), Dr. Shashank Chaturvedi, Director, Institute of Plasma Research (March 1), Dr. A.K. Bhattacharjee, Head, SRS, RCnD (March 2) and Shri Gigi Joseph, SO/H, Computer Division (March 3). It is gratifying to report that the event was well received by students and the faculty members alike, as evinced by the hugely positive feedback received.

Shri A.G. Apte delivering the keynote address

Inauguration of the exhibition

The Chief Guest at the exhibition



Students visiting the exhibition

Technology Transfer to Industries

During the period from November 2016 to February 2017, BARC has transferred nine technologies to various industries, four AKARUTI Tech pack signed and established DAE Technologies Dissemination & Display Facilities (DTDDF) in two states. Technology Transfer & Collaboration Division, (TT&CD) co-ordinated these activities. The details are given below:

A. **"Capacitor Charging Power Supply"** technology developed by Technical Physics Division was transferred to ECIL, Hyderabad. It can be used with Triode Sputter Ion Pumps with pumping speeds up to 140 lps and for Thin film deposition by DC magnetron sputtering.

The compact switched mode triode sputter ion pump power supply made in BARC is based on a half bridge dc to dc converter operating at 20kHz resulting in a drastic size reduction of around 75% over conventional power supplies. Our compact SMPS triode sputter ion pump power supply is rated for an open circuit voltage in the range of 6-7kV with a short circuit current rating of 200mA.

B. **"Laser Vibrometer"** technology developed by Laser & Plasma Technology Division was transferred to M/s Theta Controls, Pune on Nov 23, 2016. The high-resolution, non-contact optical triangulation based instrument, ***Kampan*** measures vibration in the frequency range 0.1 Hz - 1 kHz with accuracy of 1% and amplitude range in the 2 µm - 5 mm with a micron resolution. from a stand-off distance of 200 mm In contact dependent techniques, the sensor is kept in touch with the vibrating object which may load the object and cause error in measurements.

C. **"On-line domestic water purifier based on ultrafiltration polysulfone membrane"** technology developed by Membrane Development Section, Chemical Engineering Group, BARC was transferred to M/s Laxmi Engineering Works, Mumbai, on December 5th 2016.

The purifier eliminates microorganisms, colour, odour, suspended solids and organics from tap water. It is effective in removing bacteria to the extent of 99.99%. The purifier does not need electricity and purifiers about 40 liters of water per day at about 5 psig head.

D. Technical Physics Division, BARC developed **"Data Acquisition system for Quadrupole Mass Spectrometer (QMS)".** It was transferred to M/s. Theta Controls, Pune on 19.1. 2017. QMS is a versatile analytical instrument for gas analysis, advanced surface science, plasma characterization, etc.

The data acquisition system through 16bit DAC and ADC, supports acquisition in pulse counting mode whereby for pulses in the range -10mv to -4V and width greater than 8ns. This module also can be used as a general purpose data acquisition module.

E. Food Technology Division developed technology of **"Biodegradable Films for Food Packaging Applications".** It was transferred to M/s. Veena Industries, Nagpur on February 2, 2017. Packaging constitutes the largest market for plastics, amounting to over 12 million tons per year. Synthetic packaging materials are made of petroleum products which are non-biodegradable and non-renewable. One of the alternatives is the development of packaging material from biopolymers which are biodegradable, non-toxic and derived from completely renewable resources. The films have mechanical and barrier properties comparable to that of commercially packaging.

F. **"Foldable Solar Dryer" and "Vibro-Thermal Disinfestor"** technologies developed by Food Technology Division were transferred to M/s Symec Engineers (India) Pvt. Ltd., Navi Mumbai on February 3, 2017. The Solar dryer is a rectangular box with triangular top. The solar radiation is following on the black mat metallic outer surface of the dryer is absorbed by the air inside. Geometry of the solar dryer ensures that the hot air moves up and heats and dries products evenly. The dryer is of modular type and easy to transport.

Vibro-thermal disinfestor is useful for insect disinfestation of food grains, which cause enormous losses in the quality and the quantity of food grains.

G. **"140J, 225kV, 6kA Flash X-ray generator"** technology developed by Accelerator & Pulse Power Division was transferred to ECIL, Hyderabad on February 9, 2017.

This system based on FPFL Marx generator, is an import substitute. Flash X-Ray radiography is one of the most important methods used to effectively diagnose high speed events. The nanosecond exposure time will effectively prevent motion blur. A small focal spot size gives radiographs. The system can be operated with an output voltage 125kV - 225kV under matched load conditions. It is also useful for radiography of different metallic samples, transient chemical reactions of various materials, sub-microseconds photo chemistry and flash radiography, study of material properties such as iron, cobalt, nickel, zirconium and molybdenum exposed to different radiation doses.

H. **"Nisargruna Biogas Technology based on biodegradable waste"** was developed by NA&BTD. The plant processes biodegradable waste into biogas and weed free manure. This technology was transferred to the following two parties :-

- M/s. S K & Co., Tamilnadu on 05.12. 2016
- M/s. VA Energy Technologies India Pvt. Ltd., Chennai on 13.1. 2017

I. **MoU for Setting up DTDDF** was signed with Manipur Science & Technology Council Complex, Manipur on 15.12.2016 and Hemavati Nandan Bahuguna Garhwal University, Srinagar (Garhwal), Uttarakhand on 20.12.2016.

J. **MoUs for AKRUTI Tech-Pack signed with four parties**

- MKCL Knowledge Foundation, Pune
- Dilip Kasat, Mumbai
- Seema Gulai & Shri. Amit Gupta, Kutail, Haryana
- Shri Jagdishprasad Jhabarmal Tibrewala University, Rajasthan

K. **BARC through its Centre for Incubation of Technology has signed the MoU with M/s IDRS Labs Pvt. Ltd., Bangalore for "Development of Radioprotector Drug" on February 23rd, 2017**

BARC Scientist Honoured

Dr. S. M. Yusuf, SO/H+, Solid State Physics Division has been elected a Fellow of the Indian Academy of Sciences in the year 2017. He is also a Fellow of The National Academy of Sciences, India and the Maharashtra Academy of Sciences.

Central Complex at BARC

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