area compared to that of the more conventional triangularly serrated TE wing with identical zero-serration TE lines.

TE serrations formed by primary remiges in a barn owl wing which typically contributes to noise suppression, were appended to a planar metallic delta wing, and used to reduce edge return contributions to the backscatter due to the interaction of surface traveling waves with the wing TE in an electromagnetic field. Results indicate the efficacy of barn owl type TE serration in reducing the RCS of the host delta wing especially in the crucial nose-on incidence. These serrations also become effective away from nose-on incidences with an increase in electrical size arising from decrease in the incident wavelength of incident harmonic wave. The present study indicates more optimized TE serrations inspired by that evolved for bird of prey like the barn owl for silent flight, may be able to RCS of aircraft wing in an EM field, while maintaining higher wing area for superior aerodynamic performance of the host configuration compared to more conventional serrations.

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Indigenous development of a millikelvin refrigerator at VECC, Kolkata

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Technologies related to production of millikelvin temperature have been developed and tested in the laboratory. All the critical components were assembled to make a complete dilution refrigerator. The refrigerator was successfully run and commissioned in VECC. The system involves several advanced cryogenic concepts especially the capillary impedance and heat exchanger. A temperature to the tune of 50 mK has been achieved. This is the first development of its kind in India, and likely to usher a new wave in the research arena of advanced cryogenics.

Keywords: Evaporator, mixing chamber, Millikelvin, ^{3}He–^{4}He mixture.

VARIABLE Energy Cyclotron Centre (VECC), Kolkata, has been pursuing several important cryogenic activities over the years, viz. development of superconducting magnet for cyclotron, superconducting magnetic energy storage (SMES), cryogen-free magnets, and superconducting RF cavities and technologies for very low temperature systems. Recently, the Centre has indigenously designed, developed and tested a dilution refrigerator for producing millikelvin temperature. Initially, the project was aimed at developing technologies relevant to dilution refrigerator; all components were designed, developed and tested in the laboratory and finally assembled to make a complete dilution refrigerator as shown in Figure 1.

Helium evaporation is an important cooling technique. The lowest temperature is limited by vapour pressure. Since vapour pressure decreases exponentially with falling temperature, cooling by evaporation of ^{4}He liquid can only reach about 1 K temperature. Below this temperature, the vapour is very small, and very little would evaporate. Because of the lower mass of the atom, ^{3}He has higher vapour pressure and therefore higher vaporization rate. Hence, we can reach further down to 0.3 K if we use ^{3}He instead of ^{4}He. Cooling below 0.3 K is not possible by conventional refrigeration technique; however, a dilution refrigerator can cool down to a few mK that can be maintained for several hours. It is based on the solution and separation of two isotopes of helium, ^{3}He

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*For correspondence. (e-mail: nkdas@vecc.gov.in) and ^{4}He, and can produce a stable base temperature of few millikelvin to serve as a starting point for very low temperature experiments.

Dilution refrigerator is a reliable device for continuously producing temperature in the millikelvin regime. Of the several unique features exhibited by helium, one of the most convenient for a low temperature physicist is that at sufficiently low temperatures (about 0.8 K), a mixture of ^{3}He and ^{4}He will spontaneously separate into two phases, with the lighter ^{3}He rich fraction floating on top of the heavier ^{4}He rich fraction. Since there is an interface between two phases, extra energy is required for particles (^{3}He) to go from lighter phase to heavier phase. As the still is pumped out, differences in vapour pressure between the two isotopes lead to ^{3}He being primarily removed from the dilute phase in the still. The ^{3}He that is pumped off at the still is pre-cooled through a series of heat exchangers in order to continue the cooling process. Finally, the ^{3}He rich liquid returns to the inlet side of the mixing chamber.

The dilution refrigerator comprises a cryostat that accommodates the internal vacuum chamber (IVC) and the pumping line. IVC primarily accommodates the dilution insert consisting of four major components, helium evaporator (1 K pot), ^{3}He distillation chamber (still), heat exchanger (Hex) and mixing chamber (MC) as shown in Figure 2. A thermal model of dilution refrigerator has been formulated and simulation code SIDFO. Simulation of integrated dilution refrigerator for optimization was earlier developed[1,3]. This simulation model was used for design and optimization of dilution refrigerator.

A liquid nitrogen (LN$_2$) shielded cryostat was used to house the dilution insert within the IVC. This cryostat was shielded by an annular space filled with 80 litres of liquid nitrogen. The liquid helium capacity of the cryostat is about 40 litres with a hold time of about two days. The height of the cryostat is 1367 mm with diameter of 382 mm. The top flange at room temperature is provided with vacuum port, helium connections and electrical feedthrough. The heat load on the helium bath is estimated to be about 0.76 W at 4.2 K considering the effect of outer radiation from liquid nitrogen chamber and conduction through pumping lines, needle valves, etc. The cryostat was designed to obtain a long running time by having a sufficient volume of liquid ^{4}He and also by minimizing the heat leak by using a narrow neck.

Table 1. Parameter of tubular helical Hex

	Concentrate stream	Dilute stream
Tube size (mm)	Length: 2400 Inner diameter: 3.0 Wall thickness: 0.3	Length: 2090 Inner diameter: 5.0 Wall thickness: 0.4
Surface area (cm^{2})	181	226
Impedance (cm^{-3})	9×10^{8}	5×10^{8}

Figure 1. Dilution refrigerator set-up developed in the laboratory.

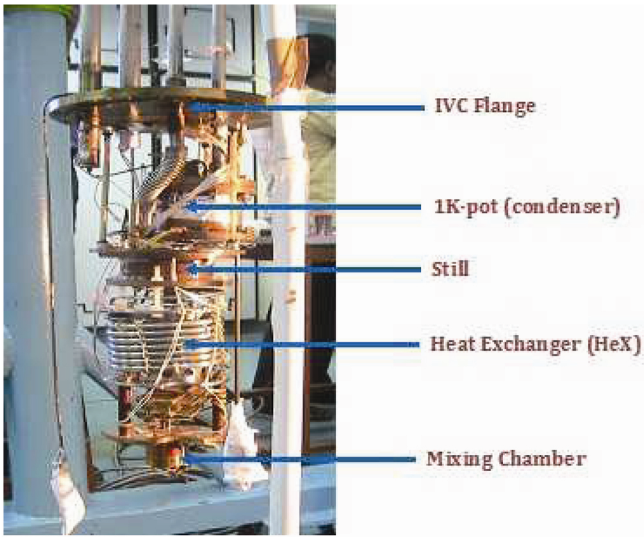

Figure 2. Dilution insert showing different components.

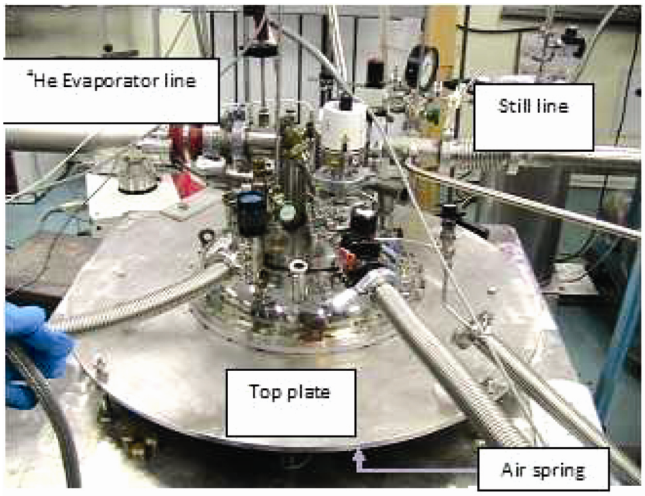

Figure 3. Mounting of cryostat top plate with air springs and pumping lines.

This IVC was housed within the helium bath of the cryostat with its top flange immersed in liquid helium. The leak tightness of this demountable flange was ensured with the help of indium o-ring corner seal. IVC is made of OFE copper with height and diameter of 350 mm and 130 mm respectively. It was evacuated to about 10^{-6} mbar of pressure using a turbo molecular drag pump. IVC was leak-checked with mass spectrometer leak detector (MSLD) by spraying helium in the liquid helium chamber, condenser line and still pumping line. It was found to hover around 10^{-8} mbar-litre/sec. In order to facilitate this evacuation activated charcoal was kept within a perforated SS-envelope. It was fitted with cartridge heater (25 W) and left at the bottom of the IVC for its regeneration. IVC plays a significant role by way of thermally isolating the sub-kelvin dilution insert from the liquid helium bath at 4.2 K. However, during initial cooling of dilution insert to 4 K, ^{4}He exchange gas is admitted inside IVC. The outer vacuum chamber (OVC) of the cryostat was maintained below 10^{-6} mbar pressure using a 400 litre/sec turbo molecular drag pump backed by dry scroll pump.

Even a slight vibration in cryostat can cause unwanted heating and can result in performance degradation of the dilution refrigerator. There are three major causes of vibration, viz. vacuum pumping lines, circulating gas lines and continuously filled 1 K pot. Vibration isolation and damping are primarily important when working in mK temperature range. In order to eliminate floor vibration coming from the surrounding environment and transmitted to the dilution insert, cryostat was mounted on a stainless steel-supported structure with air spring (1.5 bars) and kept below ground level as shown in Figure 3. All lines from the pumps were isolated by lengths of flexible convoluted stainless steel tubing followed by solid tube which were embedded firmly to the wall and ground. The pumping tubes between room temperature plate and the 4.2 K flange pass through a number of thermal baffles to which they are soft soldered to make a rigid cage to reduce the liquid ^{4}He boil-off from the cryostat. Each baffle was perforated and the positions of the perforation alternate at different sides on adjacent baffles to encourage the evolving gas to flow transversely for cooling the tubes and the leads. For mechanical stability, the three main pumping tubes of the still, 1 K pot and IVC form a tripod extending from room temperature flange to the 4.2 K flange. To accommodate the cryostat inside the existing laboratory, a 3 m deep pit had to be excavated which also made the accessibility to the top surface of the cryostat easy.

The condensation temperature of the circulating mixture is determined by the effectiveness of the condenser, the gas flow rate and the inlet pressure. The 1 K pot is a cylindrical container made of OFE copper with internal volume of 99 cm^3. For maintaining the desired circulation, condensing pressure, impedance and flow rate were decided through simulations[1]. In the given design, the condensing temperature was about 1.2 K with measured cooling power of about 18 mW (ref. 2) which provides a maximum condensing rate of about 180 μmol/sec. When the circulating flow rate becomes large the heat of condensation leads to an increase in pot temperature. If there is an increase in condensation temperature, the vapour pressure increases and the corresponding circulating pressure is computed to ensure complete condensation[1].

In order to maintain the liquid phase everywhere in the concentrated phase side of refrigerator, it is necessary to have a appropriate flow impedance. The flow impedance Z is calculated from measurement at room temperature using the relation, $Z = \Delta P / V \cdot \eta$, where ΔP is the pressure required to maintain laminar volume flow rate $\dot{V}$ of a gas having viscosity η. The volume flow rate $\dot{V}$ can be written as the product of molar volume V_m and molar flow rate. An impedance to the tune 10^{12} cm^{-3} was inserted after 1 K pot to maintain sufficient pressure (30–200 mbar) inside the 1 K pot to facilitate condensation. This ensures complete condensation of the incoming ^{3}He before entering the heat exchanger for all permissible flow rates. In fact the pressure everywhere in the concentrated phase must be greater than the vapour pressure of liquid ^{3}He at a given temperature. Another secondary flow impedance was introduced into the concentrated liquid ^{3}He line between the still and the first heat exchanger module. This secondary flow impedance ($Z \sim 10^{11}$ cm^{-3}) prevents re-evaporation of ^{3}He. The flow of liquid helium through the capillary driven by the pressure gradient is highly inhomogeneous. In general, the capillary characterization and sizing is determined experimentally. However, detailed analysis of the flow inside the capillary was performed numerically using our code, SIDFO[1,3] taking into account the fluid property variation with temperature and pressure. We measured the impedance by allowing pure helium gas at 300 K to pass through the capillary at a pressure difference of 1000 mbar. In order to make it and to mount within the limited space, we fabricated several capillary impedances with different geometrical configurations to obtain desired values.

The still is a container (40 cc) filled with ^{3}He/^{4}He solution in dynamic equilibrium with its vapour phase. The vapour phase consists of mainly ^{3}He with a small amount of ^{4}He depending on the temperature and level of superfluid film creep. The primary drive of the dilution refrigeration process is the pumping of ^{3}He vapour away from the still. This gas circulation produces cooling in the mixing chamber as it facilitates ^{3}He flow across the phase boundary to maintain the equilibrium concentration of ^{3}He in the dilute phase. The presence of excess ^{4}He in the circulating gas mixture causes phase separation at relatively higher temperature and may lead to instabilities in the system. In order to maintain the amount of circulated ^{4}He within the desired limit (1–10%), the still was provided with a heater similar to the configuration proposed

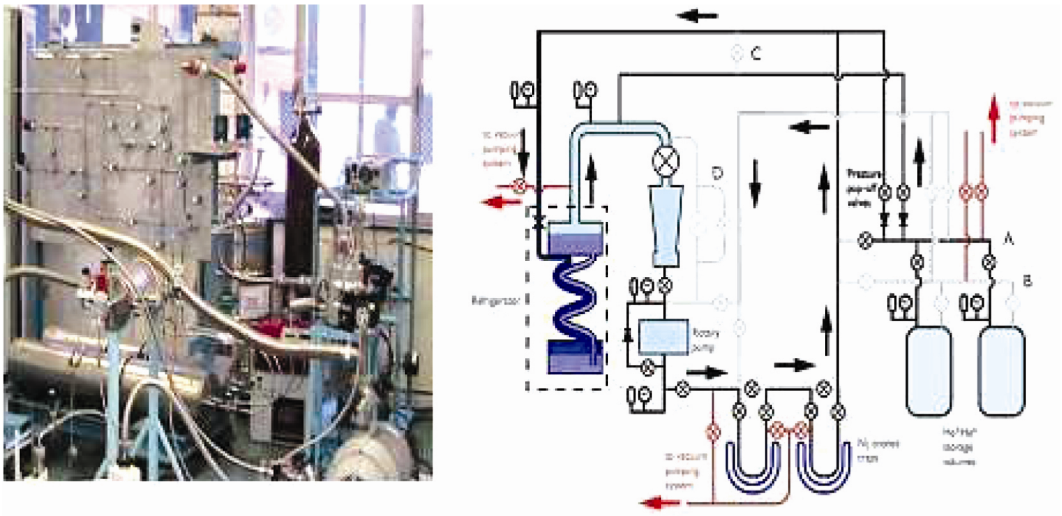

Figure 4. Gas circulation and handling system.

by Wheatley[4] and a critical heater power estimated to sustain steady-state circulation by ensuring phase separation at a reasonably low temperature. This, in turn, produces the requisite osmotic pressure difference between the mixing chamber and the still. The still power for a given flow rate yielding the minimum fraction of ^{4}He circulated was thus arrived at through simulation.

The lowest temperature which can be reached in a continuously operating dilution fridge is largely determined by the performance of heat exchanger. Operation of dilution system requires an efficient continuous tubular heat exchanger (Hex) for heat exchange primarily between the concentrated and dilute ^{3}He solution. A continuous helically coiled Hex was designed to attain a base temperature of 100 mK. The Hex comprises two thin walled cupro-nickel capillary tubing, the inner tube (id. 3 mm) is spirally wound and then inserted inside the outer tube (id. 5 mm). The assembly containing both the tubes was wound in a helical shape with a brass header. Hex was optimized for cooling the concentrated liquid below 100 mK before reaching the mixing chamber. This was analysed through a model considering tubes as a number of nodes linked by conductors.

The interface between the concentrated and dilute phases is situated inside the mixing chamber, the coldest part of the dilution refrigerator. In order to preclude the possibility of cold loss a gold plated mixing chamber (10 cc) made of OFHC copper was used. The inlet from the heat exchanger was connected on the top of the chamber while the outlet line that makes outer channel of the heat exchanger leading to still was taken from the bottom of the chamber. The ^{3}He-rich concentrated phase floats above the ^{4}He-rich dilute phase due to the weight difference between the two types of atom. Because of the finite solubility of ^{3}He in superfluid ^{4}He at very low temperature, the dilute solution always contains about 6.4% of ^{3}He.

Gas circulation and handling system at room temperature happens to be the important component of the system (Figure 4). Our gas handling system (GHS) consists of four main sections. These are ^{3}He–^{4}He storage system, ^{3}He circulation, vacuum system for outer vacuum container of the cryostat and inner vacuum container housing the dilution insert and pumping system for 1 K pot. This system involves a large collection of pumps, pipes, gauges and valves. There are two gas storage cylinders of capacity 43 litres each, filled with ^{3}He and ^{4}He mixture gas in the ratio of 1 : 3 mol. GHS was laid out such that the four operations namely gas cleaning, condensation, normal circulation and dumping are facilitated during operation.

In order for the refrigerator to operate properly it is necessary to monitor the temperature at several crucial points in the unit, such as 1 K pot, still and mixing chamber. The temperature measurements are diagnostic in nature rather than absolute. To monitor the temperature carbon resistor thermometer is installed at 1 K pot and ruthenium oxide sensors were used in still and mixing chamber. All sensors were mounted to their respective position using threaded screws and connected by 36 gauge and 38 gauge manganin wires. All wires were anchored to the immediate higher temperature posts leading to the 300 K plate of the cryostat to limit thermal conduction. Three manganin wire heaters were installed on the 1 K pot, on the still and on the mixing chamber.

The operation of the dilution refrigerator consisted of several stages of cooling as indicated below:

- Gas mixer of helium isotopes was prepared with a molar ratio of 1 : 3 and stored in two storage tanks of 43 l each at pressure of 700 mbar. Mixer gas was cleaned by circulating through liquid nitrogen cooled charcoal trap for several times.
- The outer vacuum chamber (OVC) of the cryostat was evacuated using turbo-molecular pump backed by

scroll pump for a week. The OVC vacuum level was about 2×10^{-5} mbar. The liquid helium chamber as well as IVC were purged with pure helium gas and the cryostat filled with liquid helium. The OVC pressure stabilized to around 10^{-7} mbar.

- Because IVC is immersed in liquid helium, to cool all the components inside the IVC to 4.2 K temperature, exchange gas was introduced inside IVC at about 7 mbar pressure and left overnight for thermal equilibrium. The helium gas was pumped out of IVC and the waiting time for vacuum to reach was about 10^{-6} mbar.
- Pumping out liquid helium at 1 K pot takes it down to 1.5 K. This evaporated helium is replenished from the main cryostat through capillaries (controllable by a needle valve). This takes the system to 1.4 K from 4.2 K in ~10 min.
- The mixer gas was passed through both condenser and still pumping line. Initially gas pressure was about 500 mbar and it gradually decreased as the gas condenses (passive condensation).
- When the passive condensation ceased to extract any more gas from the storage tanks, active condensation was started by isolating the tanks. This was done by using the circulation pump (scroll pump).
- As the condensing pressure remains steady indicating no more condensation, normal circulation was started. In this condition, gas mixer circulate in closed loop, condenser-mixing chamber-still-pump and then back to condenser.
- As the normal circulation started the temperature started to decrease and took about 4 h to reach the base temperature of about 50 mK. This temperature was maintained for 6 h. During the operation liquid helium was refilled twice without any major disturbance to the temperatures.
- Different performance tests were carried out and a cooling power of 6 mW was obtained using manganin wire heater attached to mixing chamber at 50 mK.
- The refrigerator was successfully shut down dumping the helium isotopic mixture back to storage tanks.

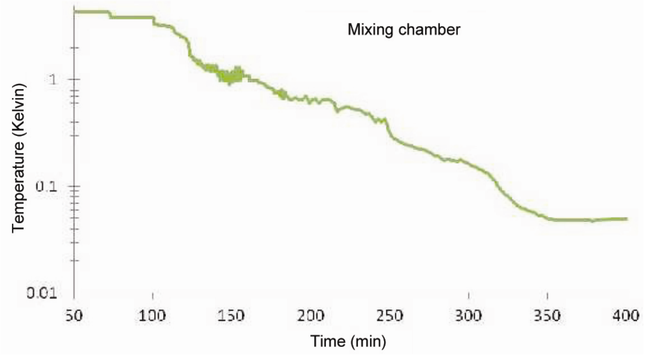

Figure 5. Temperature profile for cooling down to 43 mK temperature.

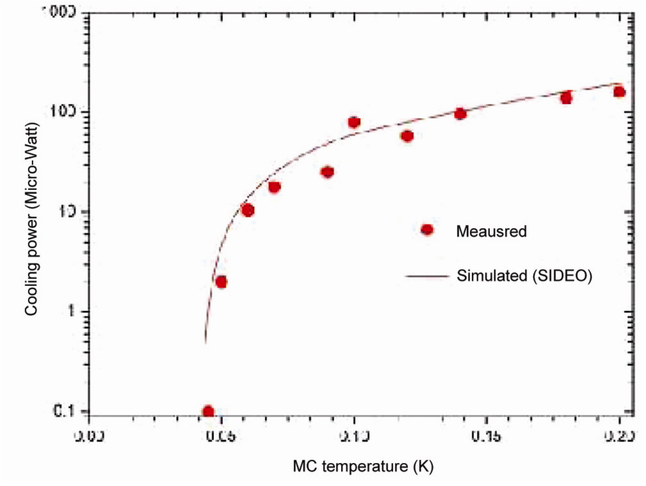

Figure 6. Comparison between simulation and measurement of cooling power under different MC temperatures for still power of 0.4 mW.

Variation of temperature of the mixing chamber during experimental run with time is shown in Figure 5. During operation it was seen that as the rate of cooling decreased still power varied and the still warmed to about 0.7 K; however, mixing chamber continued to get cold. The still power was readjusted manually to maintain its temperature to about 0.6 K as the mixing chamber smoothly cools down. Thus optimum still power was obtained during operation of the machine and by observing carefully its behaviour. The Figure 5 shows that there is a noticeable change in slope of the temperature profile during the first couple of hours. This indicates that the entire Hex becomes effective and cooling occurs at a faster rate causing a sharp decrease in temperature. Finally, the cooling rate becomes very slow as the MC temperature reduces further.

The cooling power against different mixing chamber temperatures was measured and plotted in Figure 6 along with the estimated value. During measurement still power remained the same at ~0.4 mW. In addition, different performance tests were carried out and a cooling power of 6 mW was obtained at 50 mK. The estimation was performed using our code SIDFO for the given design.

The dilution refrigerator was successfully built and temperature down to 43 mK was achieved and maintained for 7–8 h. The operation of dilution refrigerator provides encouraging results in terms of base temperature and cooling power. This is the first of its kind, indigenously built in the country. As an important component of the system, a helically coiled heat exchanger was designed for very low temperature application and it was found to function satisfactorily in the system. Different performance tests were carried out and compared with the results of simulation and found to be satisfactory. We could not go below 43 mK possibly due to high residual heat load in the mixing chamber. We need to take care of possible sources of residual heat-inleak such as vibration of different components and removal of residual gas from the IVC whatever small it is to further lower the temperature. As a diagnostic tool for operation we have measured molar flow rate and temperature of still and mixing chamber under different still heater power.

Development of the dilution refrigerator happens to be an important development of technology in the field of low temperature research. However, it appears that there is scope for further improvement of the system. The cryogen-free dilution refrigerator has been formed more popular to research community for its simple operation and requires no liquid helium. We can think of making a cryogen-free system in the near future.

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Flash flood disaster threat to Indian rail bridges: a spatial simulation study of Machak River flood, Madhya Pradesh

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The recent flood in Machak River, Madhya Pradesh, India is a distinctive paradigm of flash floods that washed off rail tracks and killed a number of passengers besides incredible damage to Indian Railways and to the surrounding villages. This shows the vulnerability of bridges/culverts to flash floods in the country. Flash floods devastated the Machak River during the midnight of 4 August 2015 due to heavy rainfall in the catchment. The duration of flooding was small with less lead-time. Narrow river sections could not accommodate the peak discharge causing severe flooding in floodplains. Hydrological and hydro dynamic simulation was studied in the Machak River using space-based inputs to quantify the causes of flash floods and its impact. Satellite-based rainfall (GPM and IMD's WRF merged product) was used in hydrological modelling in the absence of field rainfall and discharge data. Flood inundation simulations were done using CARTO digital elevation model of 10 m resolution. Inundation extent, depth of inundation, and velocity of flow at different reaches were examined. As the slopes were steep in the upstream catchment area, the lag-time of the peak flood was found to be less and washed off the Machak rail culvert without any alert. The study reveals that quantitative parameters of the disaster are due to high intensity of rainfall, drainage congestion and sudden change of slopes across the catchment.

Keywords: Hydrological simulation, hydrodynamic modeling, Machak River, rail accident.

IN India, thousands of rail bridges/culverts are more than 100 years old, and many of them are prone to floods due to change in hydrological conditions and river regime. During the last decade, many bridges are affected by flash floods in the country causing damage to lives and property. A flash flood is caused by heavy or excessive rainfall in a short period of time, generally less than 6 h (ref. 1). When it rains rapidly on saturated or dry soil with very low absorption ability, the run-off that is caused gains tremendous force and becomes a gushing river which takes down almost everything in its path. It can sweep all kinds of debris downstream in just a few hours. Sometimes these run-offs could also join with other low lying water or streams causing even more devastating impact[2]. Quantitative assessment of flood hydrograph associated with flash floods is a challenging task. Anticipating the magnitude of the event and its time of occurrence is a difficult job. A given rainfall event's chances to produce a flash flood are dramatically affected by such factors as antecedent precipitation, the size of drainage basin, the topography of the basin, channel characteristics, and so on. Thus, a flash flood event is the concatenation of a meteorological event with a particular hydrological situation[3]. Development of flash flood forecast models in conjunction with flood inundation simulation models using hydrological and hydrodynamic modelling can give flood alarm in the floodplains which is an effective non-structural method of flood damage mitigation[4].

India seems to lurch from one major natural disaster to another. We experienced major earthquakes, tsunami,

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