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NOTATION

FBTR : Fast breeder test reactor
PFBR : Prototype fast breeder reactor
BEP : Best efficiency point
NPSH : Net positive suction head
NPSHA : Net positive suction head available mlc
NPSHC : Required NPSH for 3% drop in head criterion mlc
NPSHV : Required NPSH for visual cavitation criterion mlc
V1 : Absolute velocity of fluid at impeller inlet m/s
K : Dynamic depression coefficient to evaluate NPSHC
W1 : Relative velocity of fluid at impeller inlet m/s
g : Acceleration due to gravity m/s/s
mlc : Metres of liquid column
x : Percentage of best efficiency flow at a given pump speed
Q : Operating flow of the pump cubic metres/hr
QD : Maximum rated capacity of the pump cubic metres/hr
N : Operating speed of the pump rpm
ND : Maximum rated pump speed rpm
QR : Suction Recirculatory flow cubic metres/hr
D1 : Impeller inlet diameter metres
DH : impeller hub diameter metres

QL : Leakage flow cubic metres/hr

B1 : Impeller vane inlet angle

VR1 : Radial component of absolute velocity of fluid at the inlet of impeller for recirculatory flow m/s

U1 : Peripheral velocity of impeller at inlet m/s

SNR : Suction specific speed (rpm, cubic metres/s, m)

1.0 INTRODUCTION

Fast Breeder Test Reactor (FBTR) which is expected to become critical shortly is a loop type reactor of 40 MW thermal capacity and has two primary and two secondary centrifugal pumps for heat removal (Fig.1). During the initial periods of reactor operation, the steam generator is bypassed and the secondary sodium pumps are required to operate at flows less than that at best efficiency point.

This paper deals with the cavitation problems associated with operation at partial flows, theoretical estimations and experimental cavitation measurements carried out on FBTR secondary sodium pumps. These investigations revealed that operation of FBTR pumps at this off-design condition is free from cavitation damage.

Cavitation experiments on a model pump for the development of large sodium pumps for a 500 MWe Prototype Fast Breeder Reactor (PFBR) are described in this paper.

2.0 OPERATION OF CENTRIFUGAL PUMPS AT OFF-DESIGN CONDITIONS

At any given speed, the performance of a centrifugal pump is at its optimum at only one capacity i.e. the capacity at which the efficiency curve reaches its maximum. At all other capacities, the geometric configuration of the impeller and casing no longer provides an ideal flow pattern. Off-design conditions are thus any conditions wherein a pump is required to deliver flows either in excess or below the capacity at the best efficiency(1).

Operation of centrifugal pumps at these off-design conditions can cause erosion damage to impellers due to incipient cavitation. Further operation at low flows can cause erosion damage due to recirculatory flows.

2.1 Cavitation regimes:

At a given speed and flow, as the available net positive suction head (NPSHA) is decreased from a high value where there is no cavitation, the following cavitation regimes are observed(2)(Fig.2a).

Acoustic inception : Noise level increases with no erosion damage.

Visual inception : Further increase in acoustic noise; vapour cavities can be visually observed; can result in damage for operation over long period.

Performance deterioration : Intense cavitation; loss of pump head; may result in damage in a short time.

The net positive suction head corresponding to incipient cavitation (acoustic/visual criteria) is reported (2) to be more at off-design conditions than at best efficiency flow (Fig.2b). Hence when a centrifugal pump is designed for cavitation free performance at best efficiency point taking into account the available NPSH, such a performance is not ensured at off-design flows.

2.2 Recirculatory flows:

At certain flows below that at best efficiency, all centrifugal pumps are subjected to internal recirculation at both suction and discharge of the impeller. This can cause hydraulic surging and damage to the impeller metal similar to that caused by classical cavitation, but in a different area of the impeller. The classical cavitation occurs on the visible side of impeller vanes i.e. at rear or trailing side of the impeller vanes (Fig.2c). But suction recirculation results in cavitation type damage on the hidden side of vanes (Fig.3a). The flow at which recirculation occurs depends very much on the design of impeller. An impeller designed for high suction specific speeds i.e. low NPSH requirements at best efficiency flow will have recirculatory flows at even slightly off-design operation(1).

Such a damage at reduced flows was earlier reported in a 0.45 cubic metres/s. pump in U.K.(4). Our experience with a small centrifugal sodium pump rated at 100 cubic metres/hr, 50 mlc and 2900 rpm used in a sodium loop at Reactor Engineering Laboratory of this centre had also shown similar damage on the impeller after running the pump at low flows. The pump was run at different flows to study the behaviour of hydrostatic bearing and evolution of vibration levels at low speeds and flows. Fig.(3b) shows the erosion damage on this sodium pump impeller at the impeller outlet due to discharge recirculation.

3.0 OPERATING CONDITIONS OF FBTR SODIUM PUMPS DURING PHASE-I

The pumps are of centrifugal, vertical, free surface type with Francis type of impeller and a vaneless diffuser (Fig.4). The pumps are designed for a flow of 650 cubic metres/hr at a head of 57 mlc at 1390 rpm. The rated conditions of primary and secondary pumps are as below:

	Primary	Secondary
Flow	650	380 Cubic metres/hr
Head	57	36 mlc
Speed	1390	1090 rpm

The variation in flow is achieved by changing the pump speed between 200 and 1390 rpm.

During the initial periods of reactor operation, the steam generator is bypassed with a 60 mm pipeline. The flow through this pipeline is limited to 35 cubic metres/hr from flow induced vibration considerations and the flow through a parallel reheater circuit is limited to 100 cubic metres/hr from design considerations. The secondary sodium pumps of FBTR are operated at 400 rpm and at the maximum possible flow of 135 cubic metres/hr which corresponds to 70% of best efficiency flow at this speed. Operation at higher speeds is not envisaged since deviation from best efficiency flows is larger.

There was an uncertainity whether this off-design operation would cause erosion damage due to either incipient cavitation or suction recirculation.

4.0 THEORETICAL STUDIES

The required net positive suction head corresponding to 3% drop in head (NPSHC) and visual cavitation criterion (NPSHV) were estimated for FBTR pumps operating at 135 cubic metres/hr at 400 rpm from the following equations and empirical guidelines.

4.1 Calculation of NPSHC:

$$\text{NPSHC} = (V1^2/2g)+(K.W1^2/2g) \qquad (5)$$

$$\text{NPSHC} = (1.4\, V1^2/2g)+(0.5\, W1^2/2g) \qquad (6)$$

For FBTR pumps at the operating conditions, $V1 = 1.65$ m/s and $W1 = 2.91$ m/s. The value of K, the dynamic depression coefficient depends on the impeller design and deviation of operating flow from best efficiency flow. It is minimum at best efficiency flow and increases at off-design conditions. The maximum value of $K=1$ is assumed for FBTR pumps, as a conservative approach. The maximum value of NPSHC calculated from the above two equations is taken and found to be 0.53 mlc. This value is much less than the available NPSH which is atleast 10 mlc for any operating conditions.

4.2 Calculation of NPSHV:

Grist (3) suggested that NPSH requirements for avoiding erosion damage shall be 3 times NPSHC or 1.05 times NPSHV for pumps operating at 80-110% of best efficiency flows. Higher factors are suggested for operation at lower flows as shown below since the erosion damage is severe at low flows.

Percentage flow	80-110	50-79	30-49
Factor on NPSHC	3	6	9

From these guidelines, we arrived at

$$\text{NPSHV} = (140-x)(\text{NPSHC})/10$$

where $x = Q.ND.100/(QD.N)$

For FBTR pumps, substituting $Q = 135$ cubic metres/hr, $QD = 650$ cubic metres/hr, $N = 400$ rpm, $ND = 1390$ rpm, we get, NPSHV = 3.6 mlc which is much less than the available NPSH of 10 mlc. Hence it is concluded that the pump operation is free from erosion damage due to cavitation.

4.3 Recirculatory flow:

The suction recirculatory flow for FBTR pumps is evaluated from the following equation suggested by W.H. Fraser (7).

$$QR = 148.D1.(D1^{2} - DH^{2}).N.(VR1/U1) - QL \qquad \text{cubic metres/hr}$$

For FBTR pumps D1 = 0.254 m, DH = 0.104 m, N = 400 rpm, B1 = 20.5°,Q1=36 cubic metres/hr and VR1/U1 = 0.16 for B1 = 20° (7). Substituting these values in the above equation, we get the pump discharge flow corresponding to the onset of suction recirculatory flow as 93 cubic metres/hr.As the operating flow is more than the recirculatory flow, it is concluded that the pump operation is free from erosion damage due to recirculatory flows.

4.4 Safe operating zone of flows at different speeds of FBTR Pumps:

The above procedure was extended for estimating the values of NPSHC, NPSHV, and recirculatory flows (QR) for different operating conditions of flows and speeds of FBTR pumps.

From these calculations, a curve (Fig 5a) has been plotted in dimensionless numbers along axes to show the variation of NPSHC with flow at different speeds. Fig.5b shows the variation of NPSHV with operating conditions. The figure also shows the onset of recirculatory flows at any given speed. The values of NPSHV are not shown below these recirculatory flows. The figure is divided into three zones. In zone A, NPSHV is less than NPSHA. Zone B is arrived on the following basis. The pumps are normally designed to operate over some range of flow. The rated conditions of FBTR secondary pumps are 380 cubic metres/hr and 36 mlc at 1090 rpm, which correspond to 75% of best efficiency flow at this speed. In the absence of any other guideline available, it was assumed that atleast upto 75% of best efficiency flow, operation at the maximum speed of 1390 rpm should be possible for primary pumps. An abscissa is drawn passing through this point (upper limit of zone B). Operation above this line (zone C) is considered to be unsafe. Zones A and B are considered to be safe zones of operation.

Safe and unsafe operating zones as obtained from figures 5a, 5b and based on recirculatory flow estimates is shown in figure 5c. The minimum operating speed is fixed to be 200 rpm from the considerations of hydrostatic bearing design. From the figure it can be seen that the minimum safe operating flow is dictated by recirculatory flows for speeds up to 1200 rpm and governed by NPSHV criterion for operation at higher speeds. The maximum flow at any speed is limited to 110 % of best efficiency flows, as operartion at higher flows is not envisaged. This will act as a guideline for operating personnel.

5.0 EXPERIMENTAL MEASUREMENTS

It is known that during cavitation, acoustic noise is generated due to formation and collapse of vapour bubbles and that this noise contains high frequency components upto about 100KHz. Acoustic measurement techniques are used to detect cavitation in a pump at its inception itself. Qualitative cavitation noise measurements were carried out on the FBTR secondary pump during system commissioning.

There was no penetration available through which an acoustic pressure transducer could be immersed in sodium within the pump and it was also not possible to weld a wave guide to the pump shell at impeller level. Hence for these measurements, a Piezoelectric accelerometer having a resonant frequency of 115 KHz and a sensitivity of 13 pc/g was mounted on the top flange of the removable assembly of the pump. The accelerometer signal was amplified, filtered with a high pass filter set at 5 KHz and then viewed on an oscilloscope. The signal was also recorded on an analog instrumentation tape recorder.

Noise measurements were carried out at 400 RPM and at flows of 189 cubic metres/hr (Flow at BEP), 135 cubic metres/hr (Flow during initial phase of reactor operation) and 35 cubic metres/hr. A flow of 189 cubic metres/hr could be established for a short time through a parallel path by operating the appropriate valves in the automatic dump system. Sodium temperature was 200°C and the argon cover gas pressure in pump was 30 mbar gauge.

A reference signal from pump, under positively known non-cavitating conditions, against which the signals obtained from present measurements could be compared was not available. Hence for these measurements, presence of impulsive type signal was considered to be indicative of existence of cavitation. Signal strength (Mean Square Value) was also estimated using a signal analyser, for noise signals at different flows.

Observation on oscilloscope indicated presence of impulsive signal superimposed on a steady noise at all operating conditions. Impulsive signals were slightly less at 189 cubic metres/hr when compared to other flows. There was no change in signal between flows of 135 and 35 cubic metres/hr.

Mean square value of the signals was estimated from the recorded signal using a FFT analyser. Level at 189 cubic metres/hr was only about 2.5 dB less when compared to values at other flows. There was not much difference between 135 and 35 cubic metres/hr flows.

Conclusion drawn from these qualitative measurements is that the noise pattern which suggested presence of cavitation did not change much between operation at best efficiency point and at other flows.

6.0 CAVITATION CRITERIA FOR LARGE SODIUM PUMPS OF PFBR

Design of Prototype Fast Breeder Reactor (PFBR) which is a pool type reactor of 500 MWe capacity has been initiated at this centre. This uses four primary and four secondary sodium pumps rated at 8050 cubic metres/hr and at a head of 80 mlc. The available NPSH for primary pumps in a pool type reactor depends upon cover gas pressure and submergence of impeller beneath sodium. Both are limited - the cover gas pressure from the considerations of seals and safety and the submergence from critical speed considerations. Hence it is necessary to design the primary pumps for high suction specific speeds, which enable the pump to operate at high speeds and a reduction in size.

Also, it is intended to design these pumps with minimum cavitation noise so as not to interfere with boiling noise detection system. In view of the above, it is planned to conduct model studies to understand and improve the pump design.

6.1 Model pump studies:

A small centrifugal pump of capacity 50 cubic metres/hr at a head of 22.5 mlc and a speed of 2900 rpm giving the specific speed nearly same as that of the expected specific speed of PFBR pumps was designed. The pump (Fig. 6a) is a vertical, free surface, single stage, single suction centrifugal type driven by an induction motor. The fabrication of the pump is completed and is to be tested shortly in a water loop. Cavitation measurements for conventional 3% drop in head criterion and acoustic noise criterion at various flows will be carried out using this test rig (Fig. 6b). It is also planned to study the effect of impeller inlet geometry with different number of vanes, vane inlet angles, eye diameter etc on cavitation performance.

7.0 SUMMARY AND CONCLUSIONS

1. Cavitation regimes, and problems associated with operation at partial flows are discussed.

2. Theoretical and experimental studies revealed that the operation of FBTR secondary sodium pumps at off-design condition, because of change in system characteristics during the initial periods of reactor operation, is free from erosion damage due to incipient cavitation or suction recirculatory flows.

3. The safe operating zone of flows at different speeds of FBTR pumps is established from cavitation considerations.

4. Design objectives of large pumps and model studies planned are described.

8.0 REFERENCES

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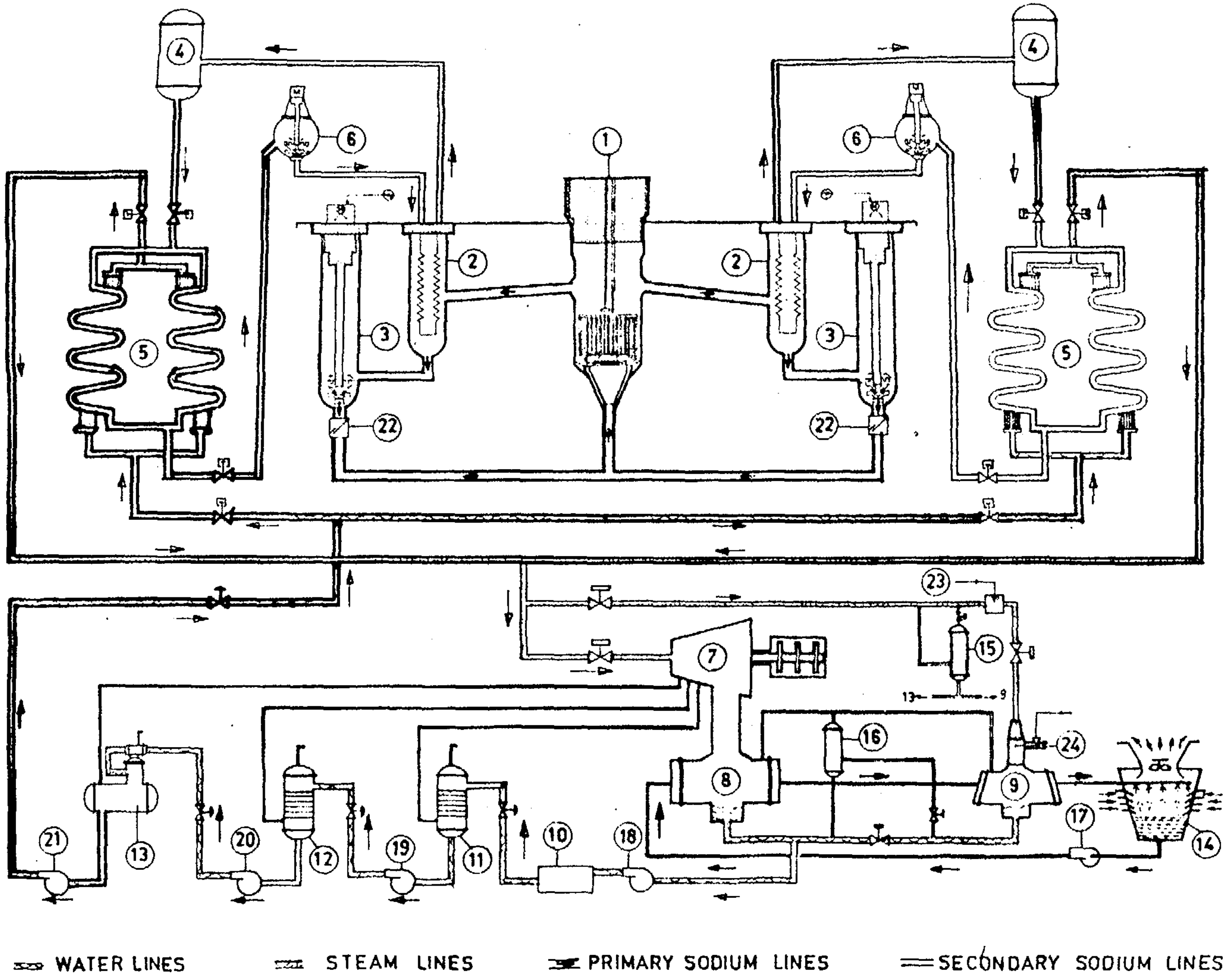

FIG.1 FBTR SCHEMATIC FLOW DIAGRAM

1. REACTOR VESSEL
2. IHX
3. PRIMARY SODIUM PUMP
4. SURGE TANK
5. STEAM GENERATOR
6. SECONDARY PUMP WITH EXPANSION TANK
7. TURBINE
8. MAIN CONDENSER
9. DUMP CONDENSER
10. CONDENSATE POLISHING UNIT
11. L.P.HEATER. 1
12. L.P.HEATER. 2
13. DEAERATOR
14. COOLING TOWER
15. H.P.FLASH TANK
16. L.P.FLASH TANK
17. CONDENSER COOLING WATER PUMPS
18. CONDENSATE EXTRACTION PUMPS
19. CONDENSATE BOOSTER PUMPS
20. DEAERATOR LIFT PUMPS
21. BOILER FEED PUMPS
22. NON RETURN VALVE
23. D.S.1.
24. D.S.2.

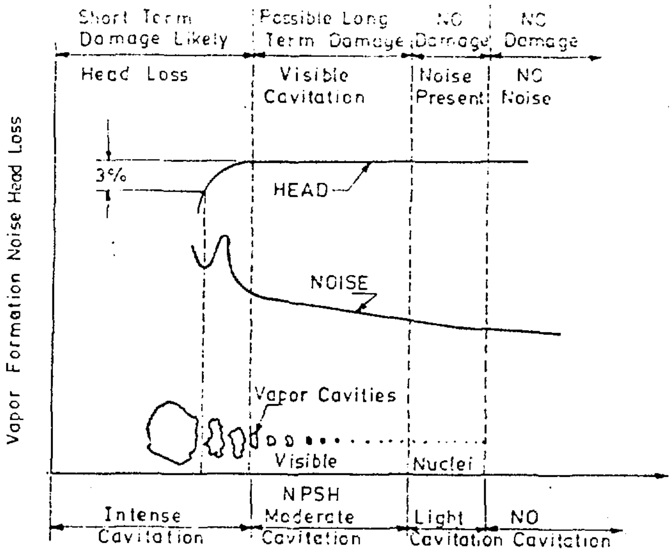

FIG.2a CAVITATION REGIMES.

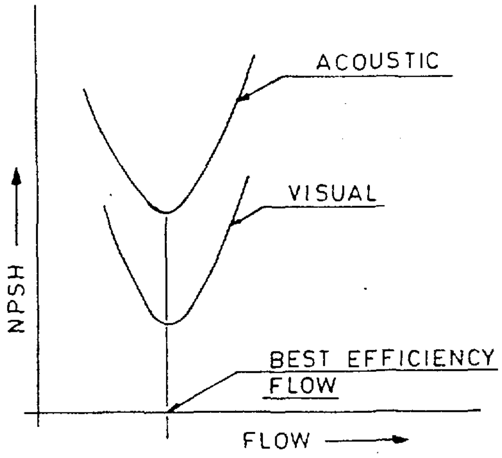

FIG 2b CAVITATION INCEPTION vs FLOW

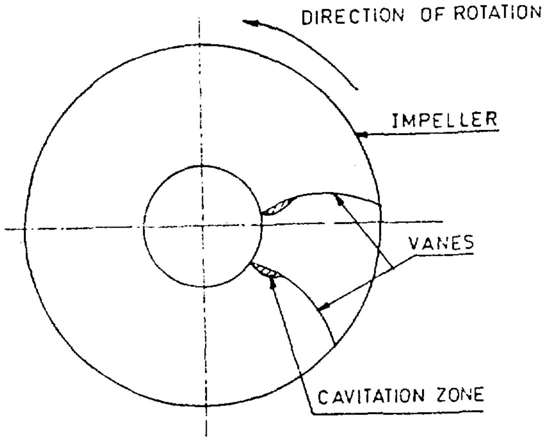

FIG.2c CLASSICAL CAVITATION ZONE

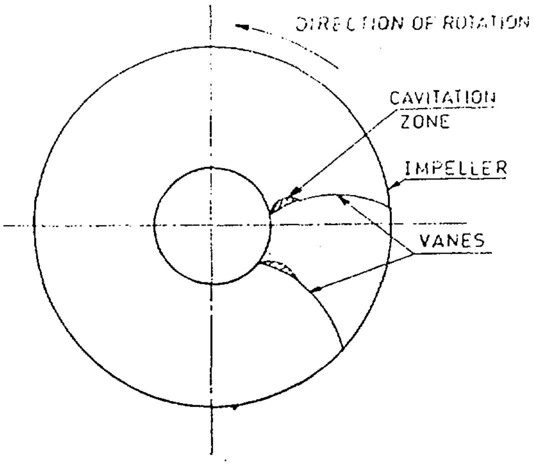

FIG.3a CAVITATION ZONE DUE TO RECIRCULATION

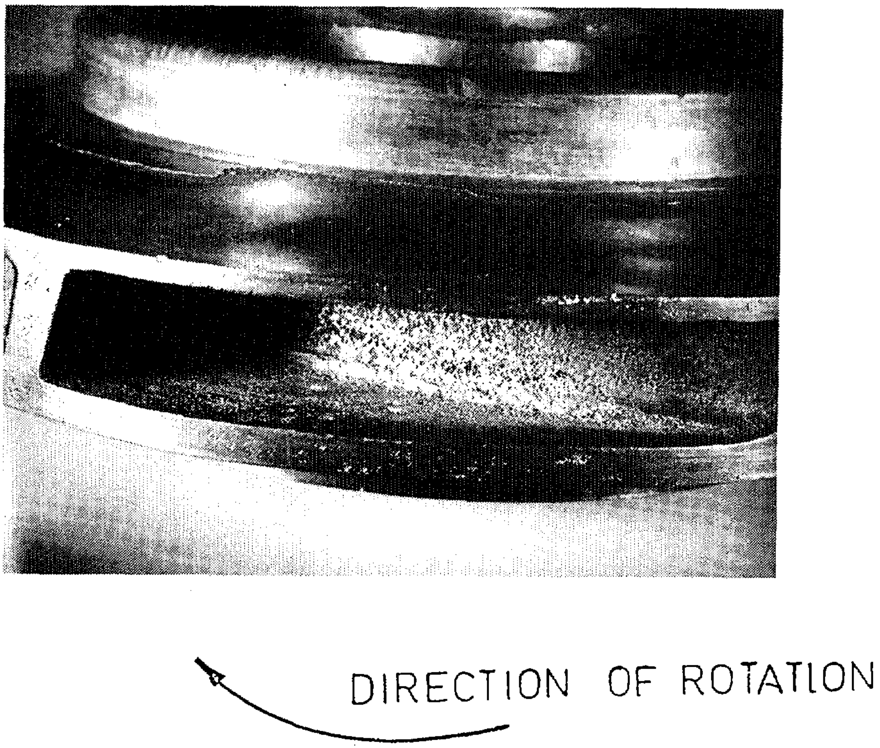

FIG.3b EROSION DAMAGE ON IMPELLER DUE TO RECIRCULATION

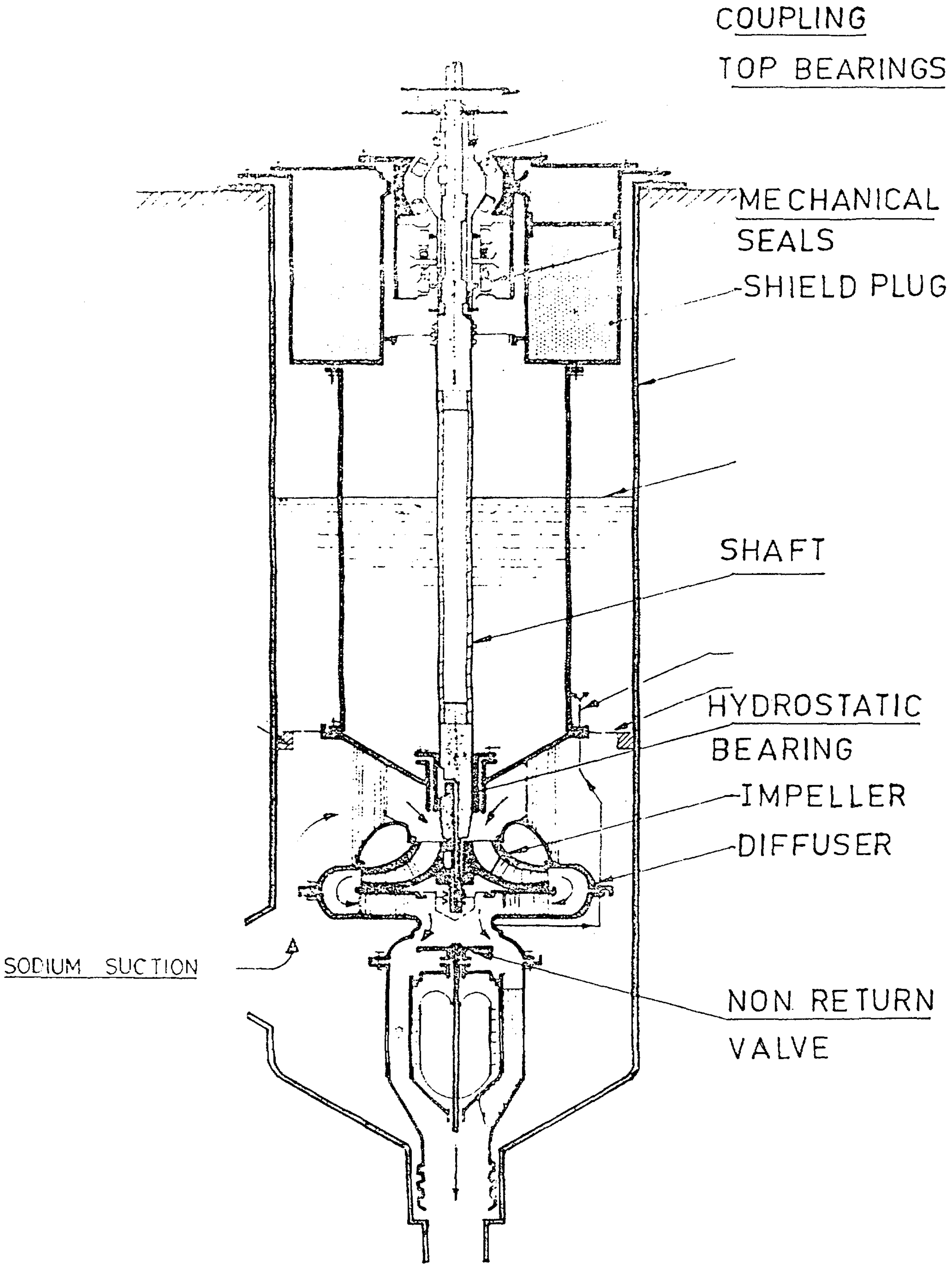

FIG.4 FBTR PRIMARY SODIUM PUMP

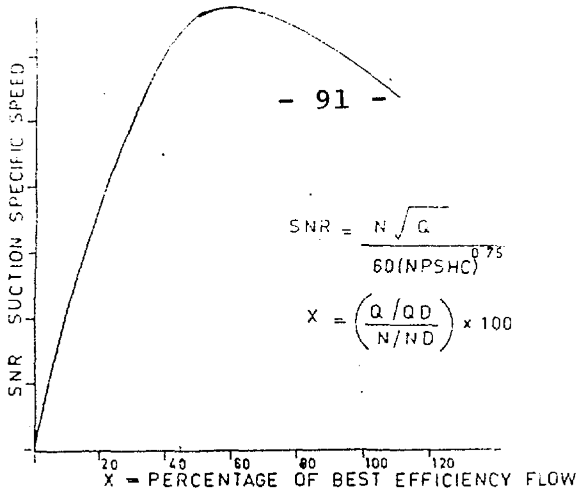

FIG.5a VARIATION OF NPSHC WITH OPERATING CONDITIONS IN DIMENSIONLESS FORM

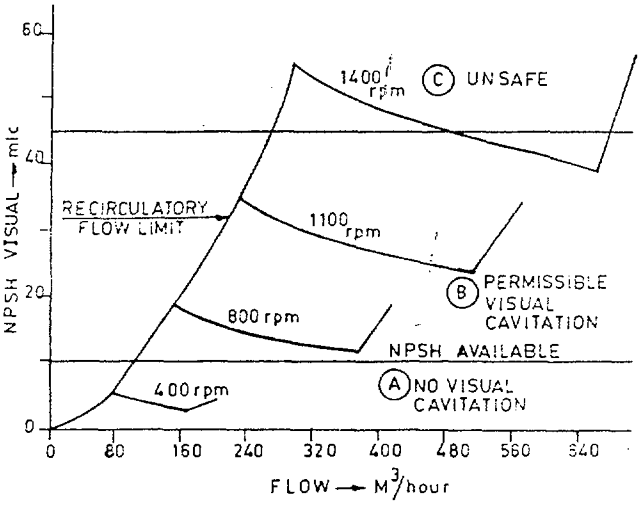

FIG. 5b NPSHV vs FLOW AND SPEED

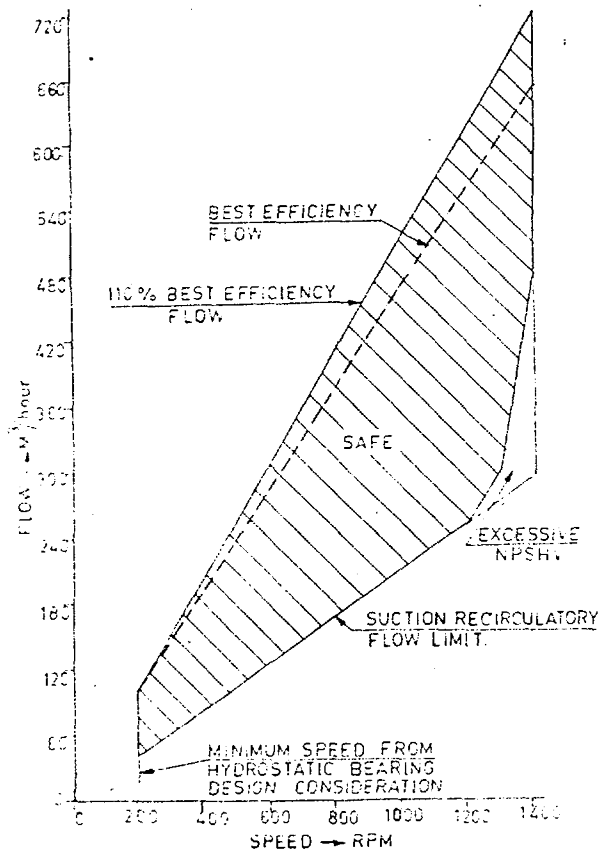

FIG. 5c SAFE OPERATING ZONE (FBTR PUMPS)

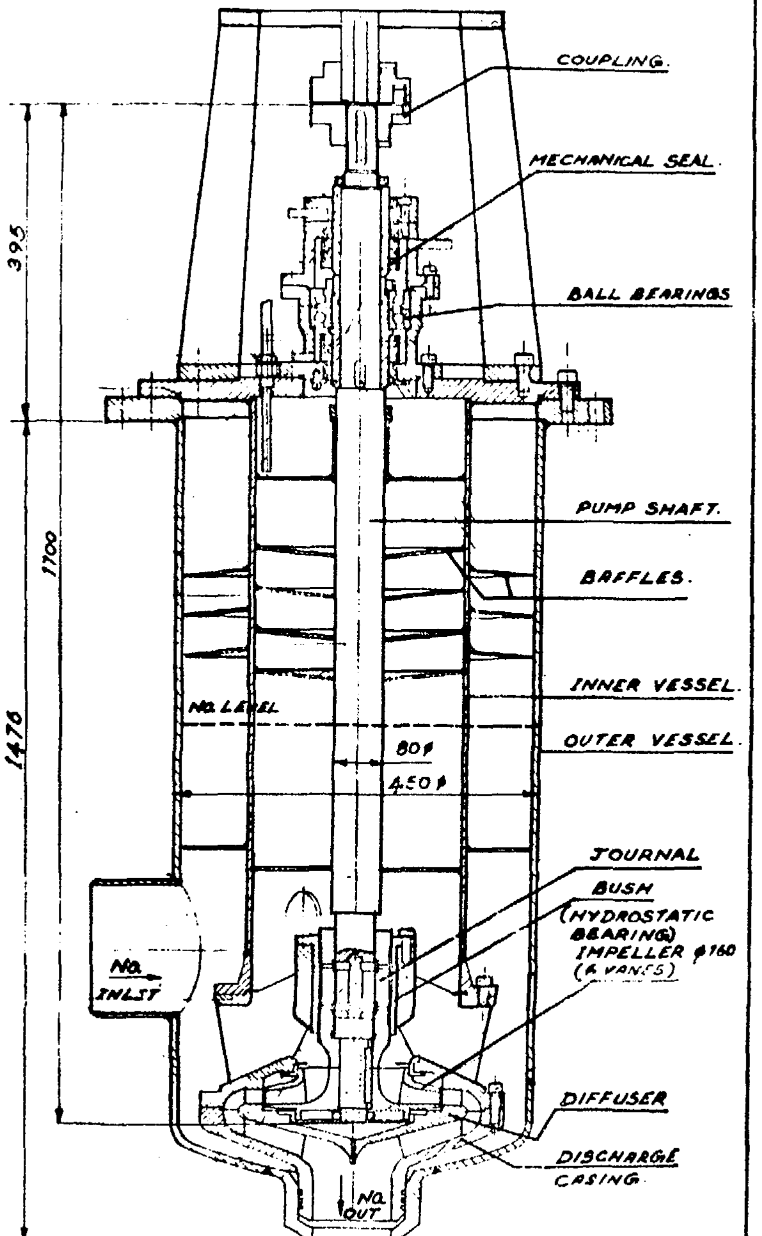

FIG.6a. 50 M^3/hr CENTRIFUGAL SODIUM PUMP

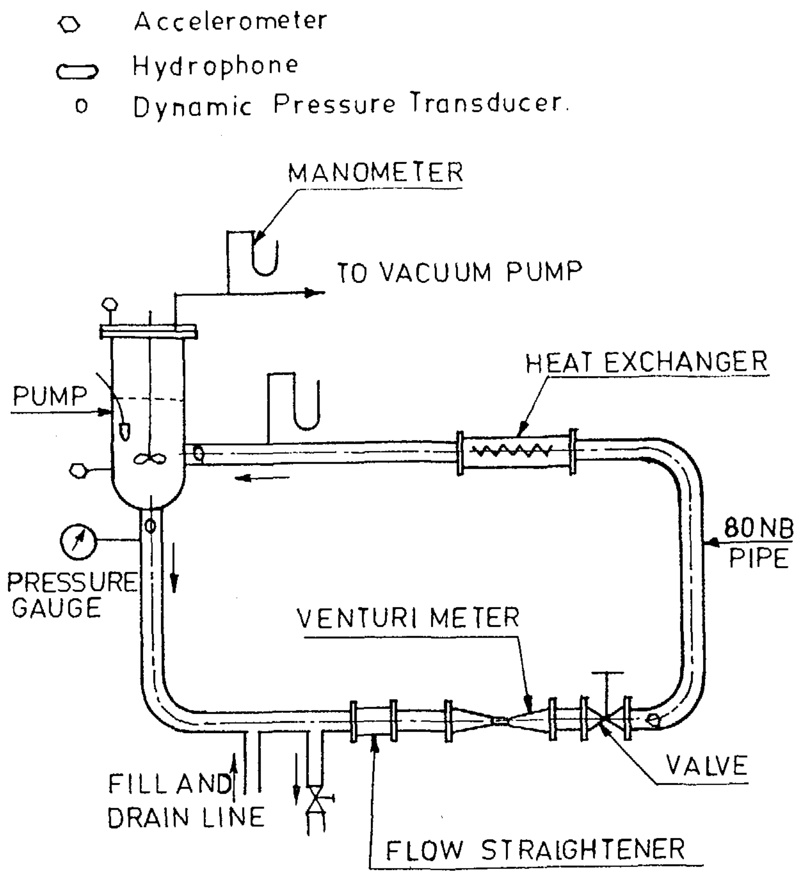

FIG. 6b WATER TEST RIG FOR MODEL PUMP