|  |  |
| --- | --- |
| Legends | Description |
| Q | **Flow in M3/hr** |
| Pd | **Discharge Pressure, Kg/cm2** |
| NPSHA | **Net Positive suction head available at Pump suction, m** |
| NPSHR | **Net Positive suction head required at Pump suction, m** |
| η | **Efficiency of the Pump, (%)** |
| l | **Vibration amplitude, (mm/sec)** |
| TP | **Pump temperature, oC** |
| TB | **Bearing Temperature, oC** |
| Cntrl. Vlv | **Pump discharge control valve opening, (%)** |
| (--) | **Very low** |
| (-) | **Low** |
| (++) | **Very High** |
| (+) | **High** |
| NC | **No change** |
| dB | **Noise, decibel** |
| TM1, TM2, TM3 | **Expert 1, Expert 2, Expert 3** |
| λ | **Amplitude of Vibration, (mm/sec)** |
| gSE | **Vibration Spike energy** |

**Table 1: Identified Failure Modes of a Centrifugal Pump with probable causes & Remedies.**

| Sl. No. | Function | Function Failure | Failure Mode | Probable cause of failure | | Possible Remedies |
| --- | --- | --- | --- | --- | --- | --- |
|
|  |
| 1 | Transferring fluid at designed flowrate & discharge Pressure. | Failure to transfer fluid at designed flowrate & discharge Pressure. | Pump discharge flow low | FM19 | Starvation at Pump suction/Insufficient suction volume | Check & complete filling |
| FM16 | NPSHA < NPSHR | 1. Check NPSHA > NPSHR 2. Check losses at suction strainers/fittings |
| FM4 | Closed discharge valve or high system resistance | 1. Check discharge valve internals. 2. Check back pressure. |
| FM3 | Clogged impeller | 1.Overhaul Pump |
| FM6 | Excessive Air or Gas entrapment in fluid | 1. Check for proper purging/venting. 2. Check & ensure proper sealing of flanges & other bolted joints in suction line. |
| FM11 | Inlet strainer partially clogged | 1. Check & clean inlet strainer. |
| FM21 | Worn wearing ring | 1. Replace Wearing rings. |
| FM20 | Worn Impeller | 1. Replace Inpeller. |
| FM2 | Choking of Pump casing or pipelines | 1. Overhaul Pump. 2. De-chok Pipelines |
| FM13 | Low RPM | 1. Check motor / turbine performance. 2. Check VFD. |
| FM10 | Increase in total system head w.r.t. design | 1. Check discharge head & head losses in discharge line. 2. Check back pressure is not high. |
| FM7 | Fluid viscosity too high | Check vluid viscosity at operating temp. |
| 2 | Motor tripping | FM5 | Decrease in total system head w.r.t. design | 1. Check recirculation flow & adjust.  2. Throttle discharge valve |
| FM15 | Misalignment (Pump-driver) | 1. Check for loose foundation bolt. 2. check for soft foot. 3. Carryout alignment. |
| 3 | Increase in Motor Power (current) | FM17 | Pump operating at higher capacity. | 1. Measure flow & check with designed capacity. |
| FM1 | Bent shaft | 1. Check shaft run out is within limit. |
| FM14 | Misalignment due to Excessive Pipe strain. | 1. Check flange connection & eliminate strain. |
| FM3 | Clogged impeller | 1. Overhaul Pump |
| FM9 | Impeller installed backward (double suction only) | 1. Overhaul pump. |
| FM21 | Worn wearing ring | 1. Replace Wearing rings. |
| FM22 | Worn, rusted defective bearing | 1. Replace bearings |
| FM15 | Misalignment(Pump-driver) | 1. Check for loose foundation bolt. 2. check for soft foot. 3. Carryout alignment. |
| FM18 | Specific gravity too high | 1. Check fluid density. |
| FM8 | High RPM | 1. Check motor / turbine performance. 2. Check VFD. |
| FM5 | Decrease in total system head w.r.t. design | 1. Check recirculation flow & adjust.  2. Throttle discharge valve |
| FM7 | Fluid viscosity too high | 2. Throttle discharge valve |
| FM12 | Internal rubbing | 1. Check for signs & overhaul accordingly. |
| FM23 | Wrong Pump DOR | 1. Check & correct DOR. |
| 4 | Decrease in pump discharge Pr. | FM27 | Discharge Cavitation (recirculation) | 1. Check pump flow with design MCF. |
| FM6 | Excessive Air or Gas entrapment in fluid | 1. Check for proper purging/venting. 2. Check & ensure proper sealing of flanges & other bolted joints in suction line. |
| FM10 | Increase in total system head w.r.t. design | 1. Check discharge head & head losses in discharge line. 2. Check & ensure back pressure is not high. |
| FM3 | Clogged impeller | 1. Overhaul Pump |
| FM9 | Impeller installed backward (double suction only) | 1. Overhaul pump. |
| FM11 | Inlet strainer partially clogged | 1. Check & clean inlet strainer. |
| FM16 | NPSHA < NPSHR | 1. Check NPSHA > NPSHR 2. Check losses at suction strainers/fittings |
| FM17 | Pump operating at higher capacity. | 1. Measure flow & check with designed capacity. |
| FM19 | Starvation at Pump suction/Insufficient suction volume | Check & complete filling |
| FM21 | Worn wearing ring | 1. Replace Wearing rings. |
| FM20 | Worn Impeller | 1. Replace Inpeller. |
| FM2 | Choking of Pump casing or pipe lines | 1. Overhaul Pump. 2. De-chok Pipelines |
| FM18 | Specific gravity too high | 1. Check fluid density. |
| FM13 | Low RPM | 1. Check motor / turbine performance. 2. Check VFD. |
| FM10 | Increase in total system head w.r.t. design | 1. Check discharge head & head losses in discharge line. 2. Check back pressure is not high. |
| FM7 | Fluid viscosity too high | 1. Check vluid viscosity at operating temp. |
| FM23 | Wrong Pump DOR | 1. Check & correct DOR. |
| 5 | High Vibration | FM1 | Bent shaft | 1. Check shaft run out is within limit. |
| FM14 | Misalignment due to Excessive Pipe strain. | 1. Check flange connection & eliminate strain. |
| FM27 | Discharge Cavitation (recirculation) | 1. Check pump flow with design MCF. |
| FM3 | Clogged impeller | 1. Overhaul Pump |
| FM24 | Driver/pump rotor imbalance | 1. Check & carruout balancing. |
| FM6 | Excessive Air or Gas entrapment in fluid | 1. Check for proper purging/venting. 2. Check & ensure proper sealing of flanges & other bolted joints in suction line. |
| FM25 | Hydraulic instability |  |
| FM11 | Inlet strainer partially clogged | 1. Check & clean inlet strainer. |
| FM16 | NPSHA < NPSHR | 1. Check NPSHA > NPSHR 2. Check losses at suction strainers/fittings |
| FM19 | Starvation at Pump suction/Insufficient suction volume | 1. Check & complete filling |
| FM21 | Worn wearing ring | 1. Replace Wearing rings. |
| FM20 | Worn Impeller | 1. Replace Inpeller. |
| FM14 | Misalignment due to Excessive Pipe strain. | 1. Check flange connection & eliminate strain. |
| FM15 | Misalignment(Pump-driver) | 1. Check for loose foundation bolt. 2. check for soft foot. 3. Carryout alignment. |
| FM2 | Choking of Pump casing or pipe lines | 1. Overhaul Pump. 2. De-chok Pipelines |
| FM5 | Decrease in total system head w.r.t. design | 1. Check recirculation flow & adjust.  2. Throttle discharge valve |
| FM26 | Pump operating at lower capacity. | 1. Measure flow & check with MCF. |
| FM17 | Pump operating at higher capacity. | 1. Measure flow & check with designed capacity. |
| FM12 | Internal rubbing | 1. Check for signs & overhaul accordingly. |
| FM22 | Worn, rusted defective bearing | 1. Replace bearings |
| FM28 | Shaft rotating off-center - worn bearing, misalignment | 1. Check alignment. If satisfactory- 2. Check bearing for excessive wear. |
| FM29 | Excessive thrust due to internal failure. | 1. Check for impeller wear, clearances & balancing holes., |
| FM30 | Excessive grease in anti-friction bearings. | 1. Check frequency & method of greasing. |
| FM31 | Lack of bearing lubrication. | 1. Check lubrication history & schedule. |
| FM32 | Improper installation of bearing. | 1. Check installation record/proceedure. |
| FM33 | Damaged bearing due to contamination. | 1. Lube oil analysis. |
| FM23 | Wrong Pump DOR | 1. Check & correct DOR. |
| 6 | Pre-mature bearing failure | FM1 | Bent shaft | 1. Check shaft run out is within limit. |
| FM14 | Misalignment due to Excessive Pipe strain. | 1. Check flange connection & eliminate strain. |
| FM24 | Driver/pump rotor imbalance | 1. Check & carruout balancing. |
| FM25 | Hydraulic instability |  |
| FM28 | Shaft rotating off-center - worn bearing, misalignment | 1. Check alignment. If satisfactory- 2. Check bearing for excessive wear. |
| FM29 | Excessive thrust due to internal failure. | 1. Check for impeller wear, clearances & balancing holes., |
| FM30 | Excessive grease in anti-friction bearings. | 1. Check frequency & method of greasing. |
| FM31 | Lack of bearing lubrication. | 1. Check lubrication history & schedule. |
| FM32 | Improper installation of bearing. | 1. Check installation record/proceedure. |
| FM33 | Damaged bearing due to contamination. | 1. Lube oil analysis. |

**Table 2: Assigned Individual & aggregated Occurrence values of failure modes**

| Failure Mode code | Possible cause of the failure (Failure Mode) | Occurrence (1-10) | | | Input 1 | RPN (Gupta-Ghasemian formula) {[0.6049 X (input 1)] + [0.4763 X TM3] - 0.7671} |
| --- | --- | --- | --- | --- | --- | --- |
| **TM1** | **TM2** | **TM3** | **{[0.6049 X TM1] + [0.4763 X TM2] - 0.7671}** |
| FM1 | Bent shaft | 3 | 3 | 3 | 2.48 | 2.16 |
| FM2 | Choking of Pump casing or pipe lines | 2 | 2 | 2 | 1.40 | 1.03 |
| FM3 | Clogged impeller | 3 | 3 | 3 | 2.48 | 2.16 |
| FM4 | Closed discharge valve or high system resistance | 2 | 3 | 3 | 1.87 | 1.79 |
| FM5 | Decrease in total system head w.r.t. design | 1 | 5 | 2 | 2.22 | 1.53 |
| FM6 | Excessive Air or Gas entrapment in fluid | 2 | 3 | 2 | 1.87 | 1.32 |
| FM7 | Fluid viscosity too high | 2 | 3 | 2 | 1.87 | 1.32 |
| FM8 | High RPM | 1 | 2 | 3 | 0.79 | 1.14 |
| FM9 | Impeller installed backward (double suction only) | 1 | 1 | 1 | 0.31 | -0.10 |
| FM10 | Increase in total system head w.r.t. design | 2 | 3 | 3 | 1.87 | 1.79 |
| FM11 | Inlet strainer partially clogged | 7 | 6 | 7 | 6.33 | 6.39 |
| FM12 | Internal rubbing | 4 | 3 | 4 | 3.08 | 3.00 |
| FM13 | Low RPM | 1 | 2 | 3 | 0.79 | 1.14 |
| FM14 | Misalignment due to Excessive Pipe strain. | 4 | 5 | 3 | 4.03 | 3.10 |
| FM15 | Misalignment(Pump-driver) | 9 | 6 | 4 | 7.53 | 5.70 |
| FM16 | NPSHA < NPSHR | 8 | 3 | 4 | 5.50 | 4.47 |
| FM17 | Pump operating at higher capacity. | 5 | 4 | 6 | 4.16 | 4.61 |
| FM18 | Specific gravity too high | 2 | 2 | 2 | 1.40 | 1.03 |
| FM19 | Starvation at Pump suction/Insufficient suction volume | 6 | 5 | 4 | 5.24 | 4.31 |
| FM20 | Worn Impeller | 2 | 3 | 3 | 1.87 | 1.79 |
| FM21 | Worn wearing ring | 9 | 3 | 7 | 6.11 | 6.26 |
| FM22 | Worn, rusted defective bearing | 9 | 5 | 7 | 7.06 | 6.84 |
| FM23 | Wrong Pump DOR | 2 | 3 | 3 | 1.87 | 1.79 |
| FM24 | Driver/pump rotor imbalance | 9 | 3 | 5 | 6.11 | 5.31 |
| FM25 | Hydraulic instability | 3 | 2 | 2 | 2.00 | 1.40 |
| FM26 | Pump operating at lower capacity. | 9 | 5 | 2 | 7.06 | 4.46 |
| FM27 | Discharge Cavitation (recirculation) | 7 | 6 | 4 | 6.33 | 4.96 |
| FM28 | Shaft rotating off center - worn bearing, misalignment | 2 | 3 | 2 | 2.00 | 1.40 |
| FM29 | Excessive thrust due to internal failure. | 2 | 4 | 1 | 2.61 | 1.29 |
| FM30 | Excessive grease in anti-friction bearings. | 3 | 4 | 2 | 3.08 | 2.05 |
| FM31 | Lack of bearing lubrication. | 2 | 1 | 2 | 0.79 | 0.66 |
| FM32 | Improper installation of bearing. | 1 | 2 | 2 | 0.92 | 0.74 |
| FM33 | Damaged bearing due to contamination. | 3 | 4 | 6 | 3.08 | 3.95 |

**Table 3: Assigned Individual& Aggerated Severity values of failure modes**

| Failure Mode code | Possible cause of the failure (Failure Mode) | Severity (1-10) | | | Input 1 | RPN (Gupta-Ghasemian formula) {[0.6049 X (input 1)] + [0.4763 X TM3] - 0.7671} |
| --- | --- | --- | --- | --- | --- | --- |
| **TM1** | **TM2** | **TM3** | **{[0.6049 X TM1] + [0.4763 X TM2] - 0.7671}** |
| FM1 | Bent shaft | 7 | 9 | 5 | 7.75 | 6.30 |
| FM2 | Choking of Pump casing or pipe lines | 5 | 7 | 7 | 5.59 | 5.95 |
| FM3 | Clogged impeller | 8 | 7 | 5 | 7.41 | 6.09 |
| FM4 | Closed discharge valve or high system resistance | 9 | 7 | 5 | 8.01 | 6.46 |
| FM5 | Decrease in total system head w.r.t. design | 6 | 6 | 6 | 5.72 | 5.55 |
| FM6 | Excessive Air or Gas entrapment in fluid | 6 | 4 | 6 | 4.77 | 4.97 |
| FM7 | Fluid viscosity too high | 7 | 6 | 5 | 6.33 | 5.44 |
| FM8 | High RPM | 4 | 4 | 6 | 3.56 | 4.24 |
| FM9 | Impeller installed backward (double suction only) | 4 | 7 | 8 | 4.99 | 6.06 |
| FM10 | Increase in total system head w.r.t. design | 4 | 7 | 6 | 4.99 | 5.11 |
| FM11 | Inlet strainer partially clogged | 8 | 6 | 4 | 6.93 | 5.33 |
| FM12 | Internal rubbing | 8 | 8 | 5 | 7.88 | 6.38 |
| FM13 | Low RPM | 6 | 4 | 5 | 4.77 | 4.50 |
| FM14 | Misalignment due to Excessive Pipe strain. | 5 | 8 | 6 | 6.07 | 5.76 |
| FM15 | Misalignment(Pump-driver) | 6 | 6 | 5 | 5.72 | 5.07 |
| FM16 | NPSHA < NPSHR | 7 | 7 | 6 | 6.80 | 6.20 |
| FM17 | Pump operating at higher capacity. | 8 | 9 | 4 | 8.36 | 6.19 |
| FM18 | Specific gravity too high | 4 | 6 | 6 | 4.51 | 4.82 |
| FM19 | Starvation at Pump suction/Insufficient suction volume | 8 | 7 | 6 | 7.41 | 6.57 |
| FM20 | Worn Impeller | 6 | 7 | 6 | 6.20 | 5.84 |
| FM21 | Worn wearing ring | 7 | 7 | 6 | 6.80 | 6.20 |
| FM22 | Worn, rusted defective bearing | 10 | 7 | 5 | 8.62 | 6.83 |
| FM23 | Wrong Pump DOR | 5 | 4 | 4 | 4.16 | 3.66 |
| FM24 | Driver/pump rotor imbalance | 8 | 7 | 5 | 7.41 | 6.09 |
| FM25 | Hydraulic instability | 7 | 6 | 8 | 6.33 | 6.87 |
| FM26 | Pump operating at lower capacity. | 9 | 7 | 5 | 8.01 | 6.46 |
| FM27 | Discharge Cavitation (recirculation) | 8 | 7 | 6 | 7.41 | 6.57 |
| FM28 | Shaft rotating off-center - worn bearing, misalignment | 6 | 7 | 5 | 6.20 | 5.36 |
| FM29 | Excessive thrust due to internal failure. | 5 | 8 | 4 | 6.07 | 4.81 |
| FM30 | Excessive grease in anti-friction bearings. | 3 | 5 | 7 | 3.43 | 4.64 |
| FM31 | Lack of bearing lubrication. | 6 | 5 | 8 | 5.24 | 6.22 |
| FM32 | Improper installation of bearing. | 7 | 6 | 4 | 6.33 | 4.96 |
| FM33 | Damaged bearing due to contamination. | 8 | 6 | 7 | 6.93 | 6.76 |

**Table 4: Assigned Individual & Aggregated Detection values of failure modes**

| Failure Mode code | Possible cause of the failure (Failure Mode) | Detection (1-10) | | | Input 1 | RPN (Gupta-Ghasemian formula) {[0.6049 X (input 1)] + [0.4763 X TM3] - 0.7671} |
| --- | --- | --- | --- | --- | --- | --- |
| TM1 | TM2 | TM3 | **{[0.6049 X TM1] + [0.4763 X TM2] - 0.7671}** |
| FM1 | Bent shaft | 3 | 8 | 4 | 4.86 | 4.08 |
| FM2 | Choking of Pump casing or pipe lines | 2 | 7 | 2 | 3.78 | 2.47 |
| FM3 | Clogged impeller | 6 | 7 | 3 | 6.20 | 4.41 |
| FM4 | Closed discharge valve or high system resistance | 5 | 3 | 3 | 3.69 | 2.89 |
| FM5 | Decrease in total system head w.r.t. design | 2 | 6 | 4 | 3.30 | 3.13 |
| FM6 | Excessive Air or Gas entrapment in fluid | 2 | 5 | 8 | 2.82 | 4.75 |
| FM7 | Fluid viscosity too high | 5 | 7 | 5 | 5.59 | 5.00 |
| FM8 | High RPM | 2 | 9 | 5 | 4.73 | 4.48 |
| FM9 | Impeller installed backward (double suction only) | 2 | 8 | 2 | 4.25 | 2.76 |
| FM10 | Increase in total system head w.r.t. design | 4 | 7 | 8 | 4.99 | 6.06 |
| FM11 | Inlet strainer partially clogged | 3 | 4 | 2 | 2.95 | 1.97 |
| FM12 | Internal rubbing | 6 | 5 | 9 | 5.24 | 6.69 |
| FM13 | Low RPM | 3 | 8 | 5 | 4.86 | 4.55 |
| FM14 | Misalignment due to Excessive Pipe strain. | 6 | 7 | 4 | 6.20 | 4.89 |
| FM15 | Misalignment(Pump-driver) | 7 | 3 | 4 | 4.90 | 4.10 |
| FM16 | NPSHA < NPSHR | 6 | 5 | 7 | 5.24 | 5.74 |
| FM17 | Pump operating at higher capacity. | 5 | 3 | 2 | 3.69 | 2.42 |
| FM18 | Specific gravity too high | 7 | 7 | 4 | 6.80 | 5.25 |
| FM19 | Starvation at Pump suction/Insufficient suction volume | 7 | 6 | 6 | 6.33 | 5.92 |
| FM20 | Worn Impeller | 8 | 8 | 5 | 7.88 | 6.38 |
| FM21 | Worn wearing ring | 8 | 8 | 3 | 7.88 | 5.43 |
| FM22 | Worn, rusted defective bearing | 8 | 5 | 3 | 6.45 | 4.57 |
| FM23 | Wrong Pump DOR | 1 | 5 | 4 | 2.22 | 2.48 |
| FM24 | Driver/pump rotor imbalance | 3 | 5 | 4 | 3.43 | 3.21 |
| FM25 | Hydraulic instability | 6 | 8 | 5 | 6.67 | 5.65 |
| FM26 | Pump operating at lower capacity. | 7 | 3 | 4 | 4.90 | 4.10 |
| FM27 | Discharge Cavitation (recirculation) | 4 | 3 | 6 | 3.08 | 3.95 |
| FM28 | Shaft rotating off-center - worn bearing, misalignment | 2 | 4 | 1 | 2.35 | 1.13 |
| FM29 | Excessive thrust due to internal failure. | 3 | 4 | 2 | 2.95 | 1.97 |
| FM30 | Excessive grease in anti-friction bearings. | 1 | 3 | 4 | 1.27 | 1.90 |
| FM31 | Lack of bearing lubrication. | 2 | 2 | 4 | 1.40 | 1.98 |
| FM32 | Improper installation of bearing. | 2 | 1 | 3 | 0.92 | 1.22 |
| FM33 | Damaged bearing due to contamination. | 3 | 5 | 4 | 3.43 | 3.21 |

**Table 5: Aggregation of Opinions (Occurrence, Severity, Detection) and output Risk Priority Number (Fuzzy Risk Number) for the identified failure modes.**

| Failure Cause code | Possible cause of the failure (Failure Mode) | Weightage | | | Input 1 | RPN (Gupta-Ghasemian formula) {[0.6049 X (input 1)] + [0.4763 X D] - 0.7671} |
| --- | --- | --- | --- | --- | --- | --- |
| **O  (1-10)** | **S  (1-10)** | **D  (1-10)** | **{[0.6049 X S] + [0.4763 X O] - 0.7671}** |
| FM1 | Bent shaft | 2.16 | 6.30 | 4.08 | 4.08 | 3.64 |
| FM2 | Choking of Pump casing or pipe lines | 1.03 | 5.95 | 2.47 | 3.32 | 2.42 |
| FM3 | Clogged impeller | 2.16 | 6.09 | 4.41 | 3.95 | 3.72 |
| FM4 | Closed discharge valve or high system resistance | 1.79 | 6.46 | 2.89 | 4.00 | 3.03 |
| FM5 | Decrease in total system head w.r.t. design | 1.53 | 5.55 | 3.13 | 3.32 | 2.73 |
| FM6 | Excessive Air or Gas entrapment in fluid | 1.32 | 4.97 | 4.75 | 2.87 | 3.23 |
| FM7 | Fluid viscosity too high | 1.32 | 5.44 | 5.00 | 3.15 | 3.52 |
| FM8 | High RPM | 1.14 | 4.24 | 4.48 | 2.34 | 2.78 |
| FM9 | Impeller installed backward (double suction only) | -0.10 | 6.06 | 2.76 | 2.85 | 2.27 |
| FM10 | Increase in total system head w.r.t. design | 1.79 | 5.11 | 6.06 | 3.18 | 4.04 |
| FM11 | Inlet strainer partially clogged | 6.39 | 5.33 | 1.97 | 5.50 | 3.50 |
| FM12 | Internal rubbing | 3.00 | 6.38 | 6.69 | 4.52 | 5.16 |
| FM13 | Low RPM | 1.14 | 4.50 | 4.55 | 2.50 | 2.91 |
| FM14 | Misalignment due to Excessive Pipe strain. | 3.10 | 5.76 | 4.89 | 4.20 | 4.10 |
| FM15 | Misalignment(Pump-driver) | 5.70 | 5.07 | 4.10 | 5.02 | 4.22 |
| FM16 | NPSHA < NPSHR | 4.47 | 6.20 | 5.74 | 5.11 | 5.06 |
| FM17 | Pump operating at higher capacity. | 4.61 | 6.19 | 2.42 | 5.17 | 3.51 |
| FM18 | Specific gravity too high | 1.03 | 4.82 | 5.25 | 2.64 | 3.33 |
| FM19 | Starvation at Pump suction/Insufficient suction volume | 4.31 | 6.57 | 5.92 | 5.26 | 5.23 |
| FM20 | Worn Impeller | 1.79 | 5.84 | 6.38 | 3.62 | 4.46 |
| FM21 | Worn wearing ring | 6.26 | 6.20 | 5.43 | 5.97 | 5.43 |
| FM22 | Worn, rusted defective bearing | 6.84 | 6.83 | 4.57 | 6.62 | 5.41 |
| FM23 | Wrong Pump DOR | 1.79 | 3.66 | 2.48 | 2.30 | 1.80 |
| FM24 | Driver/pump rotor imbalance | 5.31 | 6.09 | 3.21 | 5.45 | 4.06 |
| FM25 | Hydraulic instability | 1.40 | 6.87 | 5.65 | 4.05 | 4.38 |
| FM26 | Pump operating at lower capacity. | 4.46 | 6.46 | 4.10 | 5.26 | 4.37 |
| FM27 | Discharge Cavitation (recirculation) | 4.96 | 6.57 | 3.95 | 5.57 | 4.49 |
| FM28 | Shaft rotating off-centre - worn bearing, misalignment | 1.40 | 5.36 | 1.13 | 3.14 | 1.67 |
| FM29 | Excessive thrust due to internal failure. | 1.29 | 4.81 | 1.97 | 2.75 | 1.84 |
| FM30 | Excessive grease in anti-friction bearings. | 2.05 | 4.64 | 1.90 | 3.02 | 1.96 |
| FM31 | Lack of bearing lubrication. | 0.66 | 6.22 | 1.98 | 3.31 | 2.18 |
| FM32 | Improper installation of bearing. | 0.74 | 4.96 | 1.22 | 2.59 | 1.38 |
| FM33 | Damaged bearing due to contamination. | 3.95 | 6.76 | 3.21 | 5.20 | 3.91 |

**Table 6: Failure Mode Effect & Criticality Analysis**

| Sl. No. | Function | Function Failure | Failure Mode | Probable causes of Failure | | Possible Remedies | Weightage | | | Input 1 | RPN (Gupta-Ghasemian formula) {[0.6049 X (input 1)] + [0.4763 X D] - 0.7671} |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **O  (1-10)** | **S  (1-10)** | **D  (1-10)** | **{[0.6049 X S] + [0.4763 X O] - 0.7671}** |
| 1 | Transferring fluid at designed flowrate & discharge Pressure. | Failure to transfer fluid at designed flowrate & discharge Pressure. | Pump discharge flow low | FM19 | Starvation at Pump suction/Insufficient suction volume | Check & complete filling | 4.31 | 6.57 | 5.92 | 5.26 | **5.23** |
| FM16 | NPSHA < NPSHR | 1. Check NPSHA > NPSHR 2. Check losses at suction strainers/fittings | 4.47 | 6.20 | 5.74 | 5.11 | **5.06** |
| FM4 | Closed discharge valve or high system resistance | 1. Check discharge valve internals. 2. Check back pressure. | 1.79 | 6.46 | 2.89 | 4.00 | **3.03** |
| FM3 | Clogged impeller | 1.Overhaul Pump | 2.16 | 6.09 | 4.41 | 3.95 | **3.72** |
| FM6 | Excessive Air or Gas entrapment in fluid | 1. Check for proper purging/venting. 2. Check & ensure proper sealing of flanges & other bolted joints in suction line. | 1.32 | 4.97 | 4.75 | 2.87 | **3.23** |
| FM11 | Inlet strainer partially clogged | 1. Check & clean inlet strainer. | 6.39 | 5.33 | 1.97 | 5.50 | **3.50** |
| FM21 | Worn wearing ring | 1. Replace Wearing rings. | 6.26 | 6.20 | 5.43 | 5.97 | **5.43** |
| FM20 | Worn Impeller | 1. Replace Inpeller. | 1.79 | 5.84 | 6.38 | 3.62 | **4.46** |
| FM2 | Choking of Pump casing or pipe lines | 1. Overhaul Pump. 2. De-chok Pipelines | 1.03 | 5.95 | 2.47 | 3.32 | **2.42** |
| FM13 | Low RPM | 1. Check motor / turbine performance. 2. Check VFD. | 1.14 | 4.50 | 4.55 | 2.50 | **2.91** |
| FM10 | Increase in total system head w.r.t. design | 1. Check discharge head & head losses in discharge line. 2. Check back pressure is not high. | 1.79 | 5.11 | 6.06 | 3.18 | **4.04** |
| FM7 | Fluid viscosity too high | Check vluid viscosity at operating temp. | 1.32 | 5.44 | 5.00 | 3.15 | **3.52** |
| 2 | Motor tripping | FM5 | Decrease in total system head w.r.t. design | 1. Check recirculation flow & adjust.  2. Throttle discharge valve | 1.53 | 5.55 | 3.13 | 3.32 | **2.73** |
| FM15 | Misalignment(Pump-driver) | 1. Check for loose foundation bolt. 2. check for soft foot. 3. Carryout alignment. | 5.70 | 5.07 | 4.10 | 5.02 | **4.22** |
| 3 | Increase in Motor Power (current) | FM17 | Pump operating at higher capacity. | 1. Measure flow & check with designed capacity. | 4.61 | 6.19 | 2.42 | 5.17 | **3.51** |
| FM1 | Bent shaft | 1. Check shaft run out is within limit. | 2.16 | 6.30 | 4.08 | 4.08 | **3.64** |
| FM14 | Misalignment due to Excessive Pipe strain. | 1. Check flange connection & eliminate strain. | 3.10 | 5.76 | 4.89 | 4.20 | **4.10** |
| FM3 | Clogged impeller | 1. Overhaul Pump | 2.16 | 6.09 | 4.41 | 3.95 | **3.72** |
| FM9 | Impeller installed backward (double suction only) | 1. Overhaul pump. | -0.10 | 6.06 | 2.76 | 2.85 | **2.27** |
| FM21 | Worn wearing ring | 1. Replace Wearing rings. | 6.26 | 6.20 | 5.43 | 5.97 | **5.43** |
| FM22 | Worn, rusted defective bearing | 1. Replace bearings | 6.84 | 6.83 | 4.57 | 6.62 | **5.41** |
| FM15 | Misalignment(Pump-driver) | 1. Check for loose foundation bolt. 2. check for soft foot. 3. Carryout alignment. | 5.70 | 5.07 | 4.10 | 5.02 | **4.22** |
| FM18 | Specific gravity too high | 1. Check fluid density. | 1.03 | 4.82 | 5.25 | 2.64 | **3.33** |
| FM8 | High RPM | 1. Check motor / turbine performance. 2. Check VFD. | 1.14 | 4.24 | 4.48 | 2.34 | **2.78** |
| FM5 | Decrease in total system head w.r.t. design | 1. Check recirculation flow & adjust.  2. Throttle discharge valve | 1.53 | 5.55 | 3.13 | 3.32 | **2.73** |
| FM7 | Fluid viscosity too high | 2. Throttle discharge valve | 1.32 | 5.44 | 5.00 | 3.15 | **3.52** |
| FM12 | Internal rubbing | 1. Check for signs & overhaul accordingly. | 3.00 | 6.38 | 6.69 | 4.52 | **5.16** |
| FM23 | Wrong Pump DOR | 1. Check & correct DOR. | 1.79 | 3.66 | 2.48 | 2.30 | **1.80** |
| 4 | Decrease in pump discharge Pr. | FM27 | Discharge Cavitation (recirculation) | 1. Check pump flow with design MCF. | 4.96 | 6.57 | 3.95 | 5.57 | **4.49** |
| FM6 | Excessive Air or Gas entrapment in fluid | 1. Check for proper purging/venting. 2. Check & ensure proper sealing of flanges & other bolted joints in suction line. | 1.32 | 4.97 | 4.75 | 2.87 | **3.23** |
| FM10 | Increase in total system head w.r.t. design | 1. Check discharge head & head losses in discharge line. 2. Check & ensure back pressure is not high. | 1.79 | 5.11 | 6.06 | 3.18 | **4.04** |
| FM3 | Clogged impeller | 1. Overhaul Pump | 2.16 | 6.09 | 4.41 | 3.95 | **3.72** |
| FM9 | Impeller installed backward (double suction only) | 1. Overhaul pump. | -0.10 | 6.06 | 2.76 | 2.85 | **2.27** |
| FM11 | Inlet strainer partially clogged | 1. Check & clean inlet strainer. | 6.39 | 5.33 | 1.97 | 5.50 | **3.50** |
| FM16 | NPSHA < NPSHR | 1. Check NPSHA > NPSHR 2. Check losses at suction strainers/fittings | 4.47 | 6.20 | 5.74 | 5.11 | **5.06** |
| FM17 | Pump operating at higher capacity. | 1. Measure flow & check with designed capacity. | 4.61 | 6.19 | 2.42 | 5.17 | **3.51** |
| FM19 | Starvation at Pump suction/Insufficient suction volume | Check & complete filling | 4.31 | 6.57 | 5.92 | 5.26 | **5.23** |
| FM21 | Worn wearing ring | 1. Replace Wearing rings. | 6.26 | 6.20 | 5.43 | 5.97 | **5.43** |
| FM20 | Worn Impeller | 1. Replace Inpeller. | 1.79 | 5.84 | 6.38 | 3.62 | **4.46** |
| FM2 | Choking of Pump casing or pipe lines | 1. Overhaul Pump. 2. De-chok Pipelines | 1.03 | 5.95 | 2.47 | 3.32 | **2.42** |
| FM18 | Specific gravity too high | 1. Check fluid density. | 1.03 | 4.82 | 5.25 | 2.64 | **3.33** |
| FM13 | Low RPM | 1. Check motor / turbine performance. 2. Check VFD. | 1.14 | 4.50 | 4.55 | 2.50 | **2.91** |
| FM10 | Increase in total system head w.r.t. design | 1. Check discharge head & head losses in discharge line. 2. Check back pressure is not high. | 1.79 | 5.11 | 6.06 | 3.18 | **4.04** |
| FM7 | Fluid viscosity too high | 1. Check vluid viscosity at operating temp. | 1.32 | 5.44 | 5.00 | 3.15 | **3.52** |
| FM23 | Wrong Pump DOR | 1. Check & correct DOR. | 1.79 | 3.66 | 2.48 | 2.30 | **1.80** |
| 5 | High Vibration | FM1 | Bent shaft | 1. Check shaft run out is within limit. | 2.16 | 6.30 | 4.08 | 4.08 | **3.64** |
| FM14 | Misalignment due to Excessive Pipe strain. | 1. Check flange connection & eliminate strain. | 3.10 | 5.76 | 4.89 | 4.20 | **4.10** |
| FM27 | Discharge Cavitation (recirculation) | 1. Check pump flow with design MCF. | 4.96 | 6.57 | 3.95 | 5.57 | **4.49** |
| FM3 | Clogged impeller | 1. Overhaul Pump | 2.16 | 6.09 | 4.41 | 3.95 | **3.72** |
| FM24 | Driver/pump rotor imbalance | 1. Check & carruout balancing. | 5.31 | 6.09 | 3.21 | 5.45 | **4.06** |
| FM6 | Excessive Air or Gas entrapment in fluid | 1. Check for proper purging/venting. 2. Check & ensure proper sealing of flanges & other bolted joints in suction line. | 1.32 | 4.97 | 4.75 | 2.87 | **3.23** |
| FM25 | Hydraulic instability |  | 1.40 | 6.87 | 5.65 | 4.05 | **4.38** |
| FM11 | Inlet strainer partially clogged | 1. Check & clean inlet strainer. | 6.39 | 5.33 | 1.97 | 5.50 | **3.50** |
| FM16 | NPSHA < NPSHR | 1. Check NPSHA > NPSHR 2. Check losses at suction strainers/fittings | 4.47 | 6.20 | 5.74 | 5.11 | **5.06** |
| FM19 | Starvation at Pump suction/Insufficient suction volume | 1. Check & complete filling | 4.31 | 6.57 | 5.92 | 5.26 | **5.23** |
| FM21 | Worn wearing ring | 1. Replace Wearing rings. | 6.26 | 6.20 | 5.43 | 5.97 | **5.43** |
| FM20 | Worn Impeller | 1. Replace Inpeller. | 1.79 | 5.84 | 6.38 | 3.62 | **4.46** |
| FM14 | Misalignment due to Excessive Pipe strain. | 1. Check flange connection & eliminate strain. | 3.10 | 5.76 | 4.89 | 4.20 | **4.10** |
| FM15 | Misalignment(Pump-driver) | 1. Check for loose foundation bolt. 2. check for soft foot. 3. Carryout alignment. | 5.70 | 5.07 | 4.10 | 5.02 | **4.22** |
| FM2 | Choking of Pump casing or pipe lines | 1. Overhaul Pump. 2. De-chok Pipelines | 1.03 | 5.95 | 2.47 | 3.32 | **2.42** |
| FM5 | Decrease in total system head w.r.t. design | 1. Check recirculation flow & adjust.  2. Throttle discharge valve | 1.53 | 5.55 | 3.13 | 3.32 | **2.73** |
| FM26 | Pump operating at lower capacity. | 1. Measure flow & check with MCF. | 2.15983 | 6.3047 | 4.0767 | 4.08 | **3.64** |
| FM17 | Pump operating at higher capacity. | 1. Measure flow & check with designed capacity. | 4.61 | 6.19 | 2.42 | 5.17 | **3.51** |
| FM12 | Internal rubbing | 1. Check for signs & overhaul accordingly. | 3.00 | 6.38 | 6.69 | 4.52 | **5.16** |
| FM22 | Worn, rusted defective bearing | 1. Replace bearings | 6.84 | 6.83 | 4.57 | 6.62 | **5.41** |
| FM28 | Shaft rotating off-center - worn bearing, misalignment | 1. Check alignment. If satisfactory- 2. Check bearing for excessive wear. | 1.40 | 5.36 | 1.13 | 3.14 | **1.67** |
| FM29 | Excessive thrust due to internal failure. | 1. Check for impeller wear, clearances & balancing holes., | 1.29 | 4.81 | 1.97 | 2.75 | **1.84** |
| FM30 | Excessive grease in anti-friction bearings. | 1. Check frequency & method of greasing. | 2.05 | 4.64 | 1.90 | 3.02 | **1.96** |
| FM31 | Lack of bearing lubrication. | 1. Check lubrication history & schedule. | 0.66 | 6.22 | 1.98 | 3.31 | **2.18** |
| FM32 | Improper installation of bearing. | 1. Check installation record/proceedure. | 0.74 | 4.96 | 1.22 | 2.59 | **1.38** |
| FM33 | Damaged bearing due to contamination. | 1. Lube oil analysis. | 3.95 | 6.76 | 3.21 | 5.20 | **3.91** |
| FM23 | Wrong Pump DOR | 1. Check & correct DOR. | 1.79 | 3.66 | 2.48 | 2.30 | **1.80** |
| 6 | Pre-mature bearing failure | FM1 | Bent shaft | 1. Check shaft run out is within limit. | 2.16 | 6.30 | 4.08 | 4.08 | **3.64** |
| FM14 | Misalignment due to Excessive Pipe strain. | 1. Check flange connection & eliminate strain. | 3.10 | 5.76 | 4.89 | 4.20 | **4.10** |
| FM24 | Driver/pump rotor imbalance | 1. Check & carruout balancing. | 5.31 | 6.09 | 3.21 | 5.45 | **4.06** |
| FM25 | Hydraulic instability |  | 1.40 | 6.87 | 5.65 | 4.05 | **4.38** |
| FM28 | Shaft rotating off-center - worn bearing, misalignment | 1. Check alignment. If satisfactory- 2. Check bearing for excessive wear. | 1.40 | 5.36 | 1.13 | 3.14 | **1.67** |
| FM29 | Excessive thrust due to internal failure. | 1. Check for impeller wear, clearances & balancing holes., | 1.29 | 4.81 | 1.97 | 2.75 | **1.84** |
| FM30 | Excessive grease in anti-friction bearings. | 1. Check frequency & method of greasing. | 2.05 | 4.64 | 1.90 | 3.02 | **1.96** |
| FM31 | Lack of bearing lubrication. | 1. Check lubrication history & schedule. | 0.66 | 6.22 | 1.98 | 3.31 | **2.18** |
| FM32 | Improper installation of bearing. | 1. Check installation record/proceedure. | 0.74 | 4.96 | 1.22 | 2.59 | **1.38** |
| FM33 | Damaged bearing due to contamination. | 1. Lube oil analysis. | 3.95 | 6.76 | 3.21 | 5.20 | **3.91** |

**Table 7: Effect on hydraulic, mechanical & operating parameters of each failure cause.**

Failure causes are ranked is descending order of their RPN obtained in Table 5 above from criticality ranking FC1 to FC33

| Criticality ranking | Failure Cause code | Possible cause of the failure (Failure Mode) | Probable Remedies | Effects on hydraulic & Mechanical operating parameters | | | | | | | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Q (M3/hr)** | **No liquid delivery** | **Pd (kg/cm2)** | **NPSHR (m)** | **Pm (kw)** | **η (%)** | **Change in Vibration** | **Vib. Signature, λ (mm/s)** | **Spike energy, gSE** | **Noise, dB** | **Mech. Seal leakage** | **TP (0C)** | **TB(oC)** | **TMoC** | **Disc. Cntrl. Vlv.( Opening)** |
| FC1 | FM21 | Worn wearing ring | 1. Replace Wearing rings. | (-) |  | (--) | NC | (++) | (--) | yes | 1. Peak at Vane pass freq. |  | NC |  | NC | NC |  | (++) |
| FC2 | FM22 | Worn, rusted defective bearing | 1. Replace bearings | NC | NC | NC | NC | (++) | NC | yes | 1. Dominant peak at Bearing defect freq. | (++) | (++) |  | NC | (++) | NC | NC |
| FC3 | FM19 | Starvation at Pump suction/Insufficient suction volume | Check & complete filling | (--) |  | (-) | NC | NC | NC | yes | 1. Peak at Vane pass freq. | (++) | (++) |  | (+) | (++) |  | NC |
| FC4 | FM12 | Internal rubbing | 1. Check for signs & overhaul accordingly. | NC |  | NC | NC | (++) | NC | yes | 1. Multiple harmonics at 1X. 2. 0.5X, 0.33X harmonics. | (++) | (+) |  | (++) | NC | NC |  |
| FC5 | FM16 | NPSHA < NPSHR | 1. Check NPSHA > NPSHR 2. Check losses at suction strainers/fittings | (-) |  | (-) | NC | (--) | (--) | yes | 1. Peak at Vane pass freq. | (++) | (++) |  | (+) | (+) |  | (-) |
| FC6 | FM27 | Discharge Cavitation (recirculation) | 1. Check pump flow with design MCF. | (---) | NC | (++) | (--) | (--) | (--) | yes | 1. Peak at Vane pass freq. | (++) | (++) |  | (++) | (+) |  | (-) |
| FC7 | FM20 | Worn Impeller | 1. Replace Inpeller. | (--) |  | (--) | NC | (-) | (--) | yes | 1. Peak at Vane Pass Freq. |  | (++) |  | NC | NC | NC | (++) |
| FC8 | FM25 | Hydraulic instability | 1. Check process conditions | NC |  | NC | NC | NC | NC | yes | 1. Peak at Vane pass freq. |  | (++) |  |  | (++) |  |  |
| FC9 | FM26 | Pump operating at lower capacity. | 1. Measure flow & check with MCF. | (--) |  | (+) | (-) | (-) | (++/--) | yes |  |  | (++) |  | (++) |  |  |  |
| FC10 | FM15 | Misalignment(Pump-driver) | 1. Check for loose foundation bolt. 2. check for soft foot. 3. Carryout alignment. | NC | NC | NC | NC | (++) | NC | yes | 1. Dominant peak at 2X. |  | NC |  | (++) | (++) | NC |  |
| FC11 | FM14 | Misalignment due to Excessive Pipe strain. | 1. Check flange connection & eliminate strain. | NC | NC | NC | NC | (++) | NC | yes | 1. Generally excites 1X.  2. 2X / 3X if strain is excessive causing misalignment |  | NC |  | NC | (++) | NC | NC |
| FC12 | FM24 | Driver/pump rotor imbalance | 1. Check & carryout balancing. | NC |  | NC | NC | NC | NC | yes | 1. Dominant 1X peak |  |  |  |  |  |  |  |
| FC13 | FM10 | Increase in total system head w.r.t. design | 1. Check discharge head & head losses in discharge line. 2. Check back pressure is not high. | (--) | X | (--) | NC | NC | NC | NC |  |  | NC |  | (++) | (++) | (++) |  |
| FC14 | FM33 | Damaged bearing due to contamination. | 1. Lube oil analysis. | NC |  | NC | NC | NC | NC | yes | (++) | (++) | (++) |  |  | (++) |  |  |
| FC15 | FM3 | Clogged impeller | 1.Overhaul Pump | (--) | NC | (--) | NC | (++) | (--) | yes | 1. Peak at Vane pass freq. |  | (+) |  | NC | NC |  | (++) |
| FC16 | FM1 | Bent shaft | 1. Check shaft run out is within limit. | NC | NC | NC | NC | (++) | NC | yes | 1X in axial direction |  | NC |  | NC | (++) | NC | NC |
| FC17 | FM7 | Fluid viscosity too high | Check vluid viscosity at operating temp. | (-) |  | (--) | NC | (++) | NC | NC |  |  | NC |  | NC | NC | (++) |  |
| FC18 | FM17 | Pump operating at higher capacity. | 1. Measure flow & check with designed capacity. | (++) |  | (--) | (++) | (++) | (++/--) | yes |  |  | (+) |  | (+) |  |  |  |
| FC19 | FM11 | Inlet strainer partially clogged | 1. Check & clean inlet strainer. | (-) |  | (--) | NC | NC | (--) | yes | 1. Peak at Vane pass freq. | (++) | (++) |  | (++) | NC |  |  |
| FC20 | FM18 | Specific gravity too high | 1. Check fluid density. | NC | NC | (--) | NC | (++) | NC | NC |  |  | NC |  | NC | NC | (++) |  |
| FC21 | FM6 | Excessive Air or Gas entrapment in fluid | 1. Check for proper purging/venting. 2. Check & ensure proper sealing of flanges & other bolted joints in suction line. | (-) |  | (--) | NC | NC | (--) | yes | 1. Peak at Vane pass freq. |  | (++) |  | NC | NC | (++) | NC |
| FC22 | FM4 | Closed discharge valve or high system resistance | 1. Check discharge valve internals. 2. Check back pressure. | (--) | X | (+) | NC | (--) | (--) | yes |  |  |  |  | (+) | (+) |  | (++) |
| FC23 | FM13 | Low RPM | 1. Check motor / turbine performance. 2. Check VFD. | (-) | X | (--) | (-) | (---) | NC | NC |  |  | NC |  | NC | NC |  |  |
| FC24 | FM8 | High RPM | 1. Check motor / turbine performance. 2. Check VFD. | (+) | NC | (++) | (+) | (++) | NC | NC |  |  | NC |  | NC | NC |  |  |
| FC25 | FM5 | Decrease in total system head w.r.t. design | 1. Check recirculation flow & adjust.  2. Throttle discharge valve | (++) |  | (--) | (++) | (++) | (++/--) | yes |  |  | NC |  | (++) | (++) |  | (++) |
| FC26 | FM2 | Choking of Pump casing or pipe lines | 1. Overhaul Pump. 2. De-chok Pipelines | (-) | X | (--) | NC | NC | NC | yes | 1. Peak at vane pass freq. |  | NC |  | (++) | NC |  |  |
| FC27 | FM9 | Impeller installed backward (double suction only) | 1. Overhaul pump. | (--) | NC | (--) | NC | (++) | NC | NC |  |  | NC |  | NC | NC | NC | NC |
| FC28 | FM31 | Lack of bearing lubrication. | 1. Check lubrication history & schedule. | NC |  | NC | NC | NC | NC | NC | NC | (++) | (++) |  |  | (++) |  |  |
| FC29 | FM30 | Excessive grease in anti-friction bearings. | 1. Check frequency & method of greasing. | NC |  | NC | NC | NC | NC | NC | NC | (++) |  |  |  | (++) |  |  |
| FC30 | FM29 | Excessive thrust due to internal failure. | 1. Check for impeller wear, clearances & balancing holes., | NC |  | NC | NC | NC | NC | yes | 1. Increase in axial vibration. |  |  |  |  | (++) |  |  |
| FC31 | FM23 | Wrong Pump DOR | 1. Check & correct DOR. | (-) | X | (--) | NC | (++) | (--) | NC |  |  | NC |  | NC | NC | (++) |  |
| FC32 | FM28 | Shaft rotating off-center - worn bearing, misalignment | 1. Check alignment. If satisfactory- 2. Check bearing for excessive wear. | NC | NC | NC | NC | NC | NC | yes | 1. Generally excites 1X.  2. 2X / 3X if strain is excessive causing misalignment |  | (+) | yes |  | (++) |  |  |
| FC33 | FM32 | Improper installation of bearing. | 1. Check installation record/procedure. | NC |  | NC | NC | NC | NC | yes | (++) | (++) | (++) |  |  | (++) |  |  |