CHAPTER 10

CONCLUSION

10.1 INTRODUCTION

The Chapter summarizes the entire research study. The salient findings and highlights the important results of this research study have been recapped in the first portion. The second part elucidates the interpretation of these findings, while the third unit gives definitive recommendations of this research work. The conclusion of this work-study based on the findings and interpretations of results are presented in the fourth segment.

10.2 REVIEW OF FINDINGS

In this research pertaining to reliability of metal-to-carbon relays, relay failure data from all the sixteen zones on Indian Railways were analyzed. In order to ascertain the number of operations of relays, the relay failures were simulated in laboratory using a test set-up and the metal-carbon relays’ reliability index, in terms of MTTF, was calculated. Chemical & metallurgical analysis of relay contacts was conducted to highlight the factors causing High Contact Resistance phenomenon. Subsequently, DOE was performed for assessing the effects of various relay parameters on minimizing the HCR. Finally, the validation test using relay test-up was executed and again the reliability index was estimated. Hypothesis was tested using the qualitative techniques.

The synopsis of findings of the research study were as follows:

(i) For the years 2007 – 08 to 2010 – 11, the total numbers of signal equipment failures on Indian Railways were 2,47,028. The year 2007 – 08 saw 70,661 failures, while in years 2008 – 09 & 2009 – 10, there were 60,809 and 57,483 failures respectively. In the year 2010 – 11 there was a marginal increment and the total failures pegged at 58,075. Thus, during this period, on an average, there were more than 61000 signal equipment failures per annum.
(ii) Out of the total signaling equipment failures, the failures of metal-to-carbon relays on Indian Railways during the years 2007 – 08 to 2010 – 11 amounted to approximately 7% on average. The contribution of metal-to-carbon relay failures in the overall equipment failures in year 2007 – 08 was approximately 6% while in the years 2008 – 09 and 2009 – 10 it was 7 % each. In the year 2010 – 11, the relay failures accounted for approximately 8% of the total equipment failures. Thus, the average contribution of relay failures per annum was ever increasing.

(iii) In absolute terms, for the years 2007 – 08 to 2010 – 11, the total numbers of metal-to-carbon failures were 16,976. Data from the zonal railways indicated that the failures had steadily increased over the last few years (4052 in 2007 – 08, 4108 in 2008 – 09, 4233 in 2009 – 10 and 4583 in 2010 – 11). The average failures per year during this period were more than 4000, which was quite substantial.

(iv) In absolute terms, for the years 2007 – 08 to 2010 – 11, the numbers of metal-to-carbon failures were highest on ER (14%), NR (12%) and ECR (11%). The numbers of failures on NFR were 8% while on WR and NWR they were 7 % each. On SCR & SER, the metal-to-carbon relay failures were at 6% each.

(v) From the data for the years 2007 – 08 to 2010 – 11, High Contact Resistance emerged as the major cause of failures of metal-to-carbon relays, as it contributed approximately 78 % of the total failures. The other causes were coil defects (5 %), ingress of ants (1.8 %) and sulphation (0.2 %). The numbers of cases where cause could not be established were approximately 7 % and others were about 8 %.

(vi) The year wise cause wise analysis of failures for the years 2007-08 to 2010-11 implied that the cases of High Contact Resistance were 78 % of the total metal-to-carbon relay failures during the year 2007-08. The number of cases marginally dipped to 76% in the year 2008 – 09, while in years 2009 – 10 and 2010 – 2011 it again increased to 80 % and 78 % respectively.
The railway wise cause wise analysis of High Contact Resistance cases on various zonal railways, for the years 2007 – 08 to 2010 – 11 suggested that, the numbers of failures caused by HCR were highest on ER (14%), NR (12%) and ECR (11%). The numbers of such instances on NFR were 8% while on WR and NWR they were 7% each. On SCR & SER, the HCR failures were at 6% each, while on NER, SR & SECR, they were at 5% each.

For the same time period, total 4583 relay failures in year 2010 – 11 caused the highest train detention of more than 500 hours (31387 minutes). In year 2007 – 08, 4052 failures of metal-to-carbon relays resulted in a cumulative detention time of more than 340 hours (20423 minutes), while in year 2008 – 09, more than 350 hours (21506 minutes) were lost due to 4108 number of relay failures. In the year 2009 – 10, 4233 relay failures were responsible for detaining trains for more than 400 hours (26098 minutes). This was quite high and totally unacceptable.

Contact resistance comprises of two components – constriction resistance and film resistance. The $R_{\text{constriction}}$ for a pair of silver (radius 19R) – SIG contacts, at the averagely used contact force of 0.4118 Newton was approximately $6.78 \times 10^{-7}$ Ohms, which was extremely low. Similarly, for the carbide film on SIG contact, the $R_{\text{film}}$ was in nano / microOhm range for film thicknesses up to approximately 45 Å, while for films of thicknesses 45 Å and more, it increased exponentially and was more than 50 Ohms.

Chemical analysis of silver contacts revealed that the purity of fresh (unused) silver contacts was 97.04% and of failed (used) contacts was found to be 96.89%. The other chemical elements present in negligible quantities in the samples.

Chemical analysis results of fresh (unused) & failed (used) SIG contacts were as shown in Table 7.4, reproduced in Table 10.1.

Table 10.1 SIG contact chemical analysis results

<table>
<thead>
<tr>
<th>Component (content by mass)</th>
<th>Fresh / Unused Samples</th>
<th>Failed / Used Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>57.57 %</td>
<td>52.99 %</td>
</tr>
<tr>
<td></td>
<td>Failed</td>
<td>Fresh Unused</td>
</tr>
<tr>
<td>----------------</td>
<td>--------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Carbon</td>
<td>41.54 %</td>
<td>43.23 %</td>
</tr>
<tr>
<td>Ash in graphite</td>
<td>0.72 %</td>
<td>3.38 %</td>
</tr>
<tr>
<td>Water soluble impurities</td>
<td>0.15 %</td>
<td>0.36 %</td>
</tr>
</tbody>
</table>

Ref. Compiled from study

It can be seen that the quantitative parametric values of the chemical constituents of failed and fresh unused SIG contacts were within the permissible limits, and the silver content had decreased, while carbon and ash content had increased. The water soluble impurities in failed contacts were on higher side in comparison to the fresh unused contacts.

(xi) The SEM analysis micrographs of failed SIG contacts clearly depicted depletion of silver and presence of free carbon granules on the surface. On comparison, the same was not seen in unimpregnated graphite blocks and fresh (unused) SIG contacts.

(xii) From the EDX analysis of SIG contacts, it was seen that the carbon mass in fresh SIG sample was 1.12%, while in failed samples it was 3.28 % / 3.23%. This implied that the carbon content had increased in failed samples (during usage) and clearly depicted the formation of carbide film on the failed SIG contact surface. Besides, other chemical impurities had also increased (such as silicon from 1.32 % to 2.98 %; Silicon dioxide from 2.82 % to 6.19 %; Potassium from 1.83 % to 3.10% and Potassium oxide from 2.21 % to 3.63 %), indicating the presence of impurities on the contact surface. An interesting point was that the silver content had decreased from 86.88 % in fresh samples to 83.29 % / 80.95 % in failed samples. This suggested that the silver element had eroded from the surface during operation.

(xiii) GIXRD analysis indicated broadening of silver peak and presence of new peak at a depth of 25 nanometer to 50nanometer. As the number of peaks was limited, exact phase identification could not be done. However, the results clearly showed that the new phase had formed in the failed SIG contact. Qualitatively, more severe transformation was seen at higher resistivity.
The TOF-SIMS results showed that the failed SIG contact had additional peaks corresponding to carbon molecules. The silver peak isotope ratio in the failed SIG contact also showed distortion. The good (used) SIG contact showed copper line in the depth profile analysis.

As per the ANOVA table for analysis of DOE results, obtained through Minitab 16 software, the F-value for contact pressure was 86.94 while for contact radius it was 131.85; both the values were quite substantial in comparison to the critical F-value. This indicated that the contact radius and contact pressure were the two main factors affecting the contact Resistance.

The interaction effects and main effects plots demonstrated that for minimization of high contact resistance, the best setting of contact pressure was 30gram while for the silver contact radius, it was found to be 6R.

The reliability index of metal-to-carbon relays, in terms of MTTF, before modification in parametric values of contact pressure and contact radius, was 288967 and after modification it was 824239.

In the Anderson - Darling test for normality, the correlation coefficient for pre-modification data was 0.960, while for post-modification data it was 0.988. This indicated that the test result data followed normal distribution.

In the two-sample t-test, the P-value was zero at 5% significance level. As this was way below the stipulated value of 0.05, the decision was taken for non-acceptance of null hypothesis and acceptance of alternative hypothesis.

10.3 INTERPRETATIONS

Interpretations indicate what the results and findings mean within the context of objectives of research. It explains, in plain terms, how the statistical findings / results relate to the hypothesis of research. All deductions are supported by the statistics calculated while experimenting. This may also draw on the experience of previous research and integrate the findings into the results of other similar research studies.
The interpretations of the findings of this research study, enumerated in Para 10.2, were as under:

(i) The overall availability of signaling system, during the period under consideration was quite low, as the average number of failures per annum remained quite substantial. Out of the total signaling equipment failures, the failures of metal-to-carbon relays amounted to approximately 7% on average. This was pretty substantial and, considering that this was the third largest avenue of failures, implied that the reliability of metal-to-carbon relays was quite poor.

(ii) In absolute terms, the total numbers of metal-to-carbon failures on Indian Railways had steadily increased during this period. This indicated that the reliability of relays was steadily declining and needed immediate attention. The failures were widespread over all the zones of Indian Railways. This reiterated the fact that the reliability of these relays required to be worked on urgently.

(iii) As per the failure data analysis, High Contact Resistance emerged as the main cause of failures of these relays and the numbers of cases of HCR were quite substantial to warrant a detailed look into the phenomenon. The problem was quite rampant all over Indian Railways.

(iv) The reliability of metal-to-carbon relays played a substantial role in smooth & punctual train operations, as the cumulative train detentions due to their failures during the period under consideration were more than 500 hours, which was extremely high and totally unacceptable. Thus, there was a strong justification for research into the metal - carbon relays’ availability concerns.

(v) The extremely smooth surfaces of silver & SIG contacts minimized the peaks on the contact surfaces and increased the area of contact available for current flow. Adequate contact pressure also enlarged the effective contact area by elastic & plastic deformation of micro-spikes on contact surfaces. Thus, the constriction
resistance was minimized to a negligible value, and was not deemed to be substantial enough for causing HCR.

(vi) The film resistance was negligible (in nano / micro Ohms) for very thin films but it became quite substantial when the film thickness increased significantly to the order of 50 Å. Beyond this, the film resistance enhanced exponentially. This confirmed that the film resistance was the dominant component in the overall contact resistance of silver – SIG contact pair.

(vii) The silver contact didn’t seem to be a significant source of HCR, as there was negligible variation in the chemical components of failed & fresh samples. Although, SEM and EDX analysis did suggest presence of thin oxide film on the failed silver contacts, which was probably due to absorption of atmospheric oxygen by silver metal, it was not found substantial to increase the contact resistance.

(viii) The SIG contact emerged as the major contributor to HCR, as additional carbide content and residual chemical impurities were found on the surface of failed SIG contacts. The SEM micrographs and EDX analysis results clearly depicted the enhanced appearance of carbon matter on the surface of failed SIG contacts. All these facts indicated the presence of a superficial film, probably made up of loose carbon particles and other chemical impurities, on failed SIG contacts. These findings were further substantiated by GIXRD and TOF-SIMS analysis of failed SIG contacts, which undoubtedly proved the existence of a carbide film on contact surface. Hence, through the chemical and metallurgical analysis of silver and SIG contacts, it was concluded that the development of the external carbide layer on the façade of SIG contact was the sole cause of High Contact Resistance manifestation.

(ix) This film was a conglomerate of carbon particles dislodged from SIG contact during relay operation, environmental dust and chemical impurities, fused together.
The film on SIG contact surface was generated by a combination of multiple factors. Ab initio, due to constant hammering, some graphite material got worn out from the SIG contact surface. As the surface became more and more rough because of abrasion caused by this debris and environmental dust, more graphite material was dislodged during constant relay function. Thus, the silver on SIG contact got eroded and its superficial carbon volume got increased. Besides, there were already some impurities present on the surface, left behind from the manufacturing process such as soldering flux and other chemical impurities. The high current arcing during the make - break operation further metamorphosed these carbon particles / dust / debris / chemical impurities into a homogeneous film, which was spread over the effective contact area on the SIG contact surface. The presence of other chemical impurities such as potassium, silicon accelerated this activity. The film thus created, prohibited a proper consistent mating of the two contact surfaces. Eventually, the contact resistance was hiked to intolerable limits.

The ANOVA results and main & interaction effects plots of Design Of Experiments, conducted for relay contacts, established that for minimization of HCR, the best setting of contact pressure was 30 gram while the silver contact radius should be 6R.

During hypothesis testing, the P-value suggested the same thing, that there was substantial improvement with the design parameter modifications. With these parametric settings of contact pressure and silver contact radius, the film formed on SIG contacts was broken up every time the relay operated, thus preventing the contact resistance to increase to abnormal values.

10.4 RECOMMENDATIONS

Recommendations are derived from the research study outcomes. They urge specific actions in respect to policy, practice, theory, or subsequent research. They require broad knowledge of the topic being addressed, combining facts & values, and also take into
consideration the bounds on the questions of the study, the contexts studied, and the interventions that occurred or were administered.

The recommendations from this research study on the metal-to-carbon relays’ reliability issues, based on the discoveries and results of the research enquiry were as follows:

(i) In order to inhibit abnormal increment of contact resistance during relay operation, the contact pressure should be set at 30 gram while manufacturing the relays, and silver contacts having radius of 6R should be utilized.

(ii) The cleaning procedure of SIG contacts, during its manufacturing process and also while the relay is being manufactured, should be impeccable. It should be constantly monitored, so that the chances of any impurities (chemicals / dust) being left behind on the contact surface are obviated.

(iii) Electrical zapping of metal-to-carbon relay contacts, by passing a high value current, should be done after the relay has completed at least half of its prescribed codal life cycle. The same should also invariably be done, before using the relays in signaling circuits, in cases where the relays have been kept idly stored for more than six months.

10.5 CONCLUSIONS

The conclusion is the summation of the entire research study and its findings. Conclusions consolidate together the various results of the study, consider what they mean, and suggest their importance. It is a synthesis of key points, reinforces the strengths of the main arguments and reiterates the most important evidence supporting those arguments.

The research study demonstrated that the failures of metal-to-carbon relays were quite substantial on Indian Railways and the major reason of poor reliability was development of High Contact Resistance between the silver and Silver Impregnated Graphite contacts. With the help of chemical and metallurgical analysis of contacts, presence of loose
carbon / dust particles & chemical impurities on the SIG contact surface was established. The carbon particles were generated from wear of the contact material and the unclean environs during relay manufacturing / usage contributed to the impurities such as dust / chemicals. These ingredients formed a superficial carbide film; this forbade appropriate harmonized contact touching. The superficial dilapidation of SIG contact was accelerated by the substantial softness & high porosity of graphite material.

The relay failures were simulated in laboratory through an experimental test setup and the MTTF (in terms of number of relay operations, till first time failure) pre-modification was recorded. The Cause & Effect analysis of contacts revealed contact pressure and radius of silver contact as the two major factors greatly affecting the contact conductivity. Design Of Experiments was conducted to establish that for prevention of increment in contact resistance, contact pressure was to be set at 30 gram and the silver contacts of radius 6R to be used. Sample relays with modified contact pressure and contact radius settings were manufactured; Validation test was conducted through the same test setup and the post-modification MTTF was recorded. Through the hypothesis testing tools, it was proven that with the modified settings of these two factors, there was indeed an improvement in the metal - carbon relays’ trustworthiness.

Enhancement in the availability of metal - carbon relays used for signaling purpose on railways is quite essential and shall go a long way in bringing all round improvement, not only in the train operations, but also in the safety and punctuality of trains, besides giving a boost to the customer relationship management of Indian Railways by enhancing the customer satisfaction and addressing their expectations substantially. This research study shall also prove to be a boon to the relay manufacturers, as they shall be able to increase their product reliability many fold, thus improving their business prospects with Indian Railways and also significantly saving on the repair / replacements costs of these relays.

Relays are the building blocks of signaling interlocking circuits and hence, improvement in their reliability shall consequently, boost the overall availability of signaling systems. No substantial research work has been done on the railway signaling relays till date.
Thus, it is hoped that this pioneering research work would also prove to be the springboard for more innovative research studies in future, which shall further augment the performance of metal-to-carbon relays.

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