Control and Instrumentation

Edited by R. Kisner

Safety Implications of Diesel Generator Aging

By K. R. Hoopingarner[a] and F. R. Zaloudek[b]

Abstract: *The emergency diesel generators in a nuclear power plant have an important safety function—supplying emergency electrical power to maintain cooling and other vital functions. The research reviewed in this article addresses the safety implications of aging of these emergency diesel generators and the influence of aging on their reliability. Historical operational information was assembled on component and system failures and their causes. One significant research result is that the fast-starting and fast-loading test procedure mandated by Regulatory Guide 1.108 and the standard Technical Specifications has contributed to wear and degradation. Other equally important aging and degradation factors for the diesel generators are identified and reviewed. A new approach developed represents a more balanced aging management program that includes (1) slow-start testing during which operating parameters are monitored, (2) analysis of data trends, (3) training, and (4) maintenance. This approach should improve safety by identifying aging degradation that leads to future diesel generator failures. Timely maintenance could then prevent actual failures.*

Diesel generators are used in nuclear power plants to supply electrical power for emergency core cooling and related emergency needs in the event of a loss-of-offsite power. Typically, a plant has two redundant diesel generators rated at 3 000 to 10 000 hp.

Diesel generators have been identified by the U.S. Nuclear Regulatory Commission (NRC) as components with significant safety importance, and their operating history has been documented to show failures and performance degradation as a result of wear and aging. Consequently emergency diesel generators were included in the NRC's Nuclear Plant Aging Research (NPAR) Program. The overall objectives of this program were to find causes of aging-related degradation processes and to recommend methods for managing these aging processes. By detecting and correcting wear- and performance-related degradation, the reliability of the emergency diesel generators can be improved; this will reduce risks associated with offsite power loss events.

The purpose of this article is to present the principal causes of wear and aging degradation of emergency diesel generators as identified in the NPAR Program and to describe methods by which such degradation can be avoided or detected before it becomes a nuclear safety concern.

In 1975 the NRC staff noted the numerous failure-to-start problems of emergency diesel generators. An NRC Technical Report[1] documented the problem and formed a part of the basis for Regulatory Guide 1.108 (Ref. 2). This guide established a requirement that the emergency diesel generators be "fast, cold" tested (i.e., rapidly started and loaded to simulate operation during a plant emergency) with a frequency related to the number of failures during the previous 100 tests.

Failure-to-start problems declined as utility and NRC experience led to the identification of failure causes and as appropriate solutions were implemented. Other reliability problems persisted, however, and there was an increasing regulatory awareness of wear and aging problems possibly associated with the testing requirements. In 1982 the Advisory Committee on Reactor Safeguards was advised by the NRC staff that identifying unreliable emergency diesel generators and performing necessary repairs were more appropriate than promoting additional testing as required by Regulatory Guide 1.108. Subsequently NRC Generic Letter 83-41 (Ref. 3) requested

[a]Pacific Northwest Laboratory.
[b]P.O. Box 5704, Richland, WA 99352.

information on the detrimental effects of "fast, cold" testing, and Generic Letter 84-15 (Ref. 4) requested that licensees take action to change plant Technical Specifications to permit slower test starting/loading while retaining the emergency fast-starting response requirement.

It was with this background that the study of emergency diesel generator reliability was undertaken by the Pacific Northwest Laboratory (PNL) for the NRC under Contract DE-AC06-76 RLO 1830, NRC FIN B2911. Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy (DOE).

DIESEL ENGINE NPAR PROGRAM RESULTS

The NPAR Diesel Generator Study consisted of two phases. In Phase I, plant operating experience, data, expert opinion, and statistical methods were used to produce a data base related to aging failures, failure causes, and corrective actions. Phase II included the development of a more appropriate testing and aging management program that could enhance the availability and reliability of these diesel generators.

Phase I Results

The complete results of Phase I have been published in two volumes by Hoopingarner et al.,[5,6] and will only be briefly summarized in this article. The focus of Phase I was to identify and quantify the aging-related failures for the diesel generator system.

A data base of 1984 incidents of diesel generator component failures was created with statistically random selections from incidents in Licensee Event Reports (LERs) and other data bases reported occurring from 1965 to 1984. After analysis of these failures by experts, 1064 were judged to be related to some form of aging. Of these aging-related failures, 629 resulted in the loss of function of the diesel generator or an impairment of its reliability. Systems and components identified as being major contributors to this latter group are listed in Table 1. The principal causes of these failures are summarized in Table 2. Both tables may be used by utilities to indicate the systems and components that would benefit most from increased preventive maintenance attention to reduce future failures.

The instrument and control system appeared to be the most vulnerable to failure. The governor was the component most frequently failing, with the control air system, wiring and terminations, and sensors showing lesser, but still significant, failure rates. Vibration and vibration-induced loosening were the most frequent causes of all failures. The fuel system was the second most vulnerable system to aging-related failure. Engine piping, injector pumps, and injectors experienced significant failures, and the most prevalent degradation mechanism was vibration loosening. The third most afflicted system was the starting system; the air admittance valves, controls, and start-

Table 1 Systems and Components Subject to Aging-Induced Failures Resulting in Loss of Function of Unit

Systems and components	Percentage of aging-related failures	
Instruments and control systems	26	
Governor		12
Control air system		3
Wiring and terminations		2
Sensors		2
Fuel system	15	
Engine piping		7
Injector pumps		5
Injectors and nozzles		2
Starting system	10	
Starting air valve		5
Controls		2
Starting motor		2
Cooling system	10	
Piping		3
Pumps		2
Heat exchangers		2
Engine structure	9	
Crankcase		3
Cylinder lines		2
Main bearings		2
Other systems	30	

Table 2 Causes of Aging-Related Failures that Result in Loss of Function or Reliability

Failure cause	Percentage of aging-related failures
Adverse conditions: vibration, shock	32
Poor manufacture or construction quality control	23
Adverse environment: dust, humidity, etc.	15
Human error—maintenance	9
Poor design: wrong application or component	7
Other	15

ing motors suffered many failures. Adverse environmental conditions and poor system design were identified as principal contributors to starting system failures, which suggests that insufficient consideration was given to combat aging mechanisms involving moisture-induced corrosion, fouling, and other damage.

An industry perspective of the cause of diesel generator failure was provided by a workshop held under the auspices of the NPAR Program.[6] Attending this workshop were representatives of U.S. utilities, vendors, contractors, consultants, and the national laboratories. Workshop attendees identified the following basic causes of the observed failures of diesel generators in nuclear service: (1) current testing procedures that overstress engine components and related systems by imposing frequent cold, fast starts to verify operational readiness; (2) operational and maintenance inattention attributed to the infrequent operation and highly formalized maintenance procedures and controls for safety-related nuclear plant components; and (3) the absence of any plant or industry-wide trending practices and standards to identify components with degraded performance before they actually fail.

On the basis of the results of the Phase I studies, it was concluded that a significant reduction of aging effects and a long-term improvement of diesel generator system reliability could be achieved. The more important safety implications are (1) the reduction of stressors imposed by current guidelines, (2) the implementation of surveillance testing and trending procedures, and (3) an improvement of certain maintenance practices.

Phase II Results

Phase II of the NPAR Diesel Generator Study was directed at developing a new approach to testing, surveillance, and maintenance that would result in achieving the goal of improving long-term diesel generator reliability by mitigating aging effects.

Testing. The Technical Specifications for a majority of the U.S. nuclear power plants still require fast, ambient-temperature starts for monthly testing of the emergency diesel generators. Although the NRC has issued recommendations permitting slow-start testing under certain circumstances,[3,4] most plants have not installed the necessary hardware modifications to permit both slow- and fast-start testing. Therefore the wear and aging effects of fast starting continues, as identified in Phase I of this research.

The actual starting and loading profile for a plant is established as part of plant licensing activities and is determined by the emergency requirements for coolant flow following an accident accompanied by the loss of offsite power. Fast-starting and -loading tests mandated by Regulatory Guide 1.108 are intended to simulate this profile and to statistically verify the ability of the diesel generators to respond adequately when needed. However, concerns over basic statistical methodology flaws for both the 20 and 100 test series developed during the study.[7,8]

A typical startup sequence involves starting and accelerating the diesel generator to rated speed in about 10 s. This is followed by application of individual loads in order of safety priority until the diesel generators are fully loaded in approximately 45 s. This fast-start sequence is not used by utilities operating diesel generators for base- and peak-load applications. This fast-loading sequence constitutes unusually severe service. The rapid engine acceleration produces maximum piston side thrust and bearing pressures at a time when normal lubricant films are not completely established and thus promotes cylinder wall scuffing and accelerated bearing wear. Amplified torsional vibration of the crankshaft and other components can occur as the accelerating engine encounters successive harmonics of its natural frequency without time for damping from normal mechanisms. These vibrations can result in wear and fatigue of these components. The rapid acceleration and loading without the opportunity for thermal equilibrium of internal engine components can lead to distortions of the cylinder block and crankcase, which will result in metal-to-metal contact and accelerated wear. Turbocharger, engine, and generator overspeed conditions usually occur in the typical startup sequence. This overspeed condition results in increased wear, especially since bearing lubrication has not been completely established. This overspeed also leads to other accelerated mechanical stresses and wear as well as the increased risk of reaching the overspeed trip setpoint. The approximately 10-s starting time is imposed by regulatory requirements that mandate a conservative approach to mitigating a large-break loss-of-coolant accident (LOCA) with a coincident loss of offsite power (LOOP). Recently, the NRC outlined a new basis for performing LOCA analyses in SECY-83-492. Under sponsorship of the Nuclear Safety Analysis Center (NSAC), studies were performed by General Electric[9] and Westinghouse[10] to investigate the implication of this more realistic approach on the required emergency response time.

A reasonable conclusion of both studies was that a considerable relaxation of the nominal 10-s starting time requirement may be possible. The results of the General Electric study were that the starting and loading time could be delayed as much as 118 s following a combined LOCA and LOOP in a typical BWR/6 without peak fuel cladding temperatures exceeding the 2200°F limit imposed by regulatory requirements. In the Westinghouse study, the starting and loading time could be delayed for 53 s without exceeding this temperature limit. However, this study also indicated that the diesel generators should be started and loaded within approximately 45 s in Westinghouse plants to avoid containment temperatures exceeding limits for in-containment safety equipment.

Testing Recommendations. On the basis of the preceding information, the fast-starting and -loading requirement could be replaced by a modified procedure involving slower starts without compromising safety. This modified procedure could lead to higher diesel generator reliability by reducing the fast-start stressors believed to be the cause of observed degradation for certain engine components from wear and aging. Direct benefits include significantly less piston ring and cylinder wear, reduced harmful overspeeds for both the turbocharger and generator, less camshaft and bearing wear, and less threat of an engine trip as the result of the initial overspeed with the fast-start ramp.

Diesel engine expert consultants at PNL evaluated the safety assurance of slow-start testing in comparison with fast-start testing to ensure that important operational and safety questions were adequately addressed. They concluded that the slower start testing would adequately test the system and provide equal assurance of reliability. It was further concluded that, by using existing instruments and available data produced during startup and subsequent operation, the diesel generators could be monitored for deteriorating components before an actual failure occurs. In this manner, timely maintenance could be performed to avoid unexpected failures that could compromise safety.

The NRC has started to modify guide documents and Technical Specifications to support the new approach. In the modified approach, monthly tests should be preceded by a prelube step during which full lubricating oil pressure is provided. The engine should be started and accelerated to synchronous speed without load for 2 to 5 min while oil pressure and other important engine conditions are checked. If no problems are observed, full electrical load may then be applied over a 5- to 30-min period. Step loads representing actual site motor loads are useful, but not essential, for monthly testing.

About 30 parameters, which include the important temperatures and pressures in the fuel and lubricating oil, cooling water, intake air, and exhaust subsystems, should be reviewed to determine the mechanical condition of the diesel generator.[8] Three sets of data may be obtained after reasonably stable engine temperatures are achieved for each of the parameters collected on 1-h intervals.

Following testing, the engine loads should be gradually reduced and terminated at about 25% load or at the manufacturer's recommended level. Postoperational lubrication is recommended; applicable manufacturer's guidelines should be followed. Optional fast-start testing, overload tests, and additional starts and stops may be performed on a warmed and prelubricated engine with lesser aging and wear effects.

Surveillance. For improved system operability and safety, PNL's diesel consultants recommended that the test data obtained during periodic testing be monitored, trended, and analyzed to detect potential component and subsystem problems during incipient states before actual failure occurs. This monitoring and trending process, often called "condition monitoring," is a forward-looking process that provides good assurance of future system operability. This is not a mathematical or statistical process but a practical method to ensure that the diesel generator system is "healthy" by checking engine parameters. In this program, data from 30 engine and generator parameters obtained during periodic testing should be compared with previous test values and with the manufacturer's recommended normal and safe operating values. If all parameters are in the normal range, near-term diesel generator operability can be anticipated, whereas values out of range indicate the need for maintenance. Longer term operability can be predicted by graphically examining trends of the data over longer time periods. Estimates of when critical data values will be out of acceptable ranges can be predicted by examination of the trends exhibited by graphs of these data, and maintenance can be scheduled before the diesel generators go out of range.

Maintenance. This research resulted in several potential improvements to current maintenance practice. First, engine disassembly for inspection purposes only should be avoided. Various studies have shown that periodic disassembly has an overall adverse influence on system failure rates.[8,11–12] The decision to overhaul or repair an engine should be based on the evaluation of the monitoring and trending data or on other positive indications of adverse conditions. A healthy engine should not be disassembled. If it is not broken or malfunctioning, it should not be disturbed.

The second potential improvement resulting from this research is that engine and governor maintenance training should be improved. At least two persons should be given training equivalent to that offered by the diesel engine and governor manufacturers. Such persons should be at the plant maintenance/engineering level, and they, in turn, should train other plant personnel. Additional training should be provided to maintenance personnel on those items which have been identified as having higher failure rates (e.g., instruments, control systems, and turbochargers). An additional potential safety improvement identified is to give specific training on manually starting the diesel generators when they fail to start automatically. The capability to manually start a diesel generator by bypassing a failed component, such as a control system component or air-start valve, could be a significant safety benefit for station blackout considerations.

The third maintenance-related potential improvement addresses vibration. Vibration was identified as the cause of the highest percentage of diesel generator failures. Preventive maintenance measures should focus on mitigating the influence of this vibration problem, with particular emphasis on engine and engine skid-mounted instrumentation. Related inspections and preventive maintenance measures were identified in the study.[7,8]

ADVANTAGES OF RECOMMENDED AGING MANAGEMENT APPROACH

Utilities should develop a program of diesel generator aging management incorporating a more balanced application of testing, inspection, monitoring, trending, training, and maintenance. The NRC's approach has been modified in recent draft guide documents to evaluate the licensees' reliability program, their application of the program, and their reported results. The implications for safety improvement of such an approach are as follows:

- The outlined reliability program is more predictive and gives more assurance of future engine operability. Rather than a single data point each month (success or failure to start and run), the recommended approach would evaluate about 30 parameters to indicate the true engine condition.[8]
- The severe fast-starting and -loading aging and wear stressor would be minimized.
- The program would be relatively easy and practical to implement by both the NRC and industry.
- The program would be capable of immediately providing significant information on the condition of the diesel generators. Further, it would provide information on either rapidly or slowly proceeding degradation processes that could eventually incapacitate a diesel generator; this information would be available in a timely manner to enable maintenance to be scheduled to avoid actual failure.
- If the program is properly managed, it will provide a significant educational benefit to the plant operators and maintenance personnel through the training, monitoring, and trending activities.
- The recommended program reduces the problems related to measuring reliability using statistical methods.

REGULATORY APPLICATION OF THE RESEARCH RESULTS

Many of the results and recommendations of the NPAR Diesel Generator Study have already been used in regulatory activities, and others are under active consideration.

Regulatory Guide 1.155, issued in June 1988, establishes a reliability program for the emergency diesel generators. A subsequent Research Information Letter distributed within the NRC was issued during 1989, which recommends a balanced program of testing, inspection, monitoring, trending, and maintenance for mitigating aging and for ensuring diesel generator operational readiness. The NRC guidelines for this reliability program follow generally the results of this research. The research letter suggests that licensees report to the NRC on the basis of deviations from acceptable levels of diesel generator program performance. Their plans to correct such program deficiencies would also be reported.

The fast-start aging stressor was found to be unique among all stressors identified in this research because it was possible to eliminate it rather than just mitigate its effects. In 1984, NRC Generic Letter 84-15[4] requested that licensees take action to change their Technical Specifications to permit slower-start tests while retaining the emergency fast-start response requirement. The Virginia Electric Power Company North Anna Station requested one of the first Technical Specification changes in response to this generic letter, and it was granted by the NRC (Ref. 13). In a 1989 research information letter for NRC use, a recommendation was made that Regulatory Guide 1.108 (Ref. 2) practices for fast-start testing should be reconsidered.

A monthly operational readiness test indicating degraded performance may be reported to the NRC for independent evaluation, and information on aging, potential common-mode failures, and other risk-sensitive data would be available to the NRC through the licensee's trending data.

The information described in this article has been generally incorporated into a new draft of a regulatory guide that includes diesel generator testing. Revision 3 of Regulatory Guide 1.9 will define more appropriate testing requirements and is intended to replace Regulatory Guide 1.108 guidelines.

CONCLUSIONS

A new approach was outlined in this article to perform periodic "operational readiness tests" of the diesel generator system. These operational readiness tests should use a slower starting and loading profile followed by operation during which the condition of the engine is determined by the monitoring of approximately 30 operating variables. Through analysis of these data from test to test, it will be possible to detect trends that could eventually lead to component or system failures. Thus maintenance could be scheduled to avoid engine failures before they actually happen. This testing, monitoring, and trending, along with enhanced operator and maintenance personnel training, can lead to a higher state of emergency diesel generator availability and reliability and to improved reactor safety.

Periodic testing of emergency diesel generators using fast-starting and -loading procedures outlined by Regulatory Guide 1.108 (Ref. 2) was identified as a significant detractor to their reliability. Furthermore, diesel statistical probabilities based on these guidelines are very difficult to defend on a technical basis.

REFERENCES

1. Nuclear Regulatory Commission, *Diesel Generator Operating Experience at Nuclear Power Plants*, NRC Technical Report OOE-ES-002, June 1975.
2. Nuclear Regulatory Commission, *Periodic Testing of Diesel Generators Used As Onsite Electric Power Systems at Nuclear Power Plants*, Report REG/G-1.108, 1977.
3. NRC Generic Letter 83-41, *Fast Cold Starts of Diesel Generators*, December 1983.
4. NRC Generic Letter 84-15, *Proposed Staff Actions to Improve and Maintain Diesel Generator Reliability*, July 1984.
5. K. R. Hoopingarner, J. W. Vause, D. A. Dingee, and J. F. Nesbitt, *Aging of Nuclear Station Diesel Generators: Evaluation of Operating and Expert Experience: Phase I, Study*, Report NUREG/CR-4590-Vol. 1 (PNL-5832-Vol. 1), August 1987.
6. K. R. Hoopingarner and J. W. Vause, *Aging of Nuclear Station Diesel Generators: Evaluation of Operating and Expert Experience: Workshop*, Report NUREG/CR-4590-Vol. 2 (PNL-5832-Vol. 2), August 1987.
7. K. R. Hoopingarner, B. J. Kirkwood, and P. J. Louzecky, *Study Group Review of Nuclear Service Diesel Generator Testing and Aging Mitigation*, Report PNL-6287, March 1988.
8. K. R. Hoopingarner and F. R. Zaloudek, *Aging Mitigation and Improved Programs for Nuclear Service Diesel Generators*, Report NUREG/CR-5057, December 1989.
9. Electric Power Research Institute, *Effect of Diesel Start Time on BWR/6 Peak Cladding Temperature—Licensing Basis Sensitivity Calculations*, Report EPRI NSAC-96, 1986.
10. Electric Power Research Institute, *Effect of Diesel Start Time Delay on Westinghouse PWRs*, Report EPRI-NSAC-130, 1988.
11. J. W. Prichard, Equipment Age-Reliability Analysis, *Naval Engineers Journal* (September 1986).
12.. F. S. Nowlan, *Reliability-Centered Maintenance*, Report AD-A066-579, December 1987.
13. Docket No. 50-339, Amendment No. 48 to Facility Operating License No. NPF-7 for the North Anna Power Station, Unit No. 2, April 25, 1985.

Report No.	Author
No report no. (May 1987)	Tech. Integration Review Group for Aging and Life
	Extension
A-3270-12-85	Silver, Vasudevan, and Subudhi
Letter Report	Subudhi
Nuclear Safety 31: 484-489	Hoopingarner and Zaloudek
NUREG/CR-3543 (ORNL/TM 3543)	Murphy, Gallaher, Casada, and Hoy
NUREG/CR-4939 (BNL/NUREG 52031)	Subudhi, Gunther, Taylor
NUREG/CR-5643	Blahnik, Casada, Edson, Fineman