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ESTIMATING THE RELIABILITY OF SYSTEMS

A. P. Fraas

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ESTIMATING THE RELIABILITY OF SYSTEMS

A. P. Fraas

MAY 1968

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ESTIMATING THE RELIABILITY OF SYSTEMS

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Abstract

Generic data on component reliability are reviewed, a simple method of applying these data is suggested, and some resulting implications with respect to the reliability of idealized systems are pointed out. Data for a number of familiar systems such as refrigerators, automobile engines, and TV sets are examined using the same technique and found to yield results consistent with those given by the simplified application of the generic data.

The study concludes that there is an enormous amount of operating experience to indicate that the lowest failure rate one can reasonably hope to get in a piece of mechanical equipment such as a valve, pump, or motor is about one failure per million operating hours. From this it is shown that, if a system is to be designed for a 90% probability of operating 10,000 hr without a forced outage, it ought not require more than about ten thoroughly proven mechanical components (such as pumps) or one hundred thoroughly proven electronic components (such as resistors).

INTRODUCTION

Attempts to develop small nuclear power plants for terrestrial and space applications have led to some very frustrating difficulties in trying to get good system reliability (often expressed as the length of time the system can be expected to operate without repair or a forced outage). Because of the complexity of the problems many approaches have been taken in studies of system reliability. In some instances manufacturers have examined extensive operating experience to arrive at a statistical basis for estimating the reliability of equipment that they produce to provide a guide for establishing guarantees. System designers sometimes estimate reliability by obtaining data on the reliability of components that they plan to use and, where these data are available, various failure modes are envisioned and the overall system reliability is estimated. In most instances adequate data are not available, and for advanced systems such as space power plants data certainly are not available. When this is the

case, rough estimates on reliability can be based on generic data obtained for components somewhat similar to those to be used in the projected system. Still a fourth approach can be employed; this is similar to that just cited in that it employs generic data on components but differs in that the components are all grouped into one or a few groups from the reliability standpoint, and the system reliability is estimated from values for the mean time between failures for the components in each of these groups. This memorandum is concerned mainly with the latter approach.

REVIEW OF GENERIC DATA ON THE RELIABILITY OF COMPONENTS

The extremely large number of components in electronic systems has led to such severe reliability problems that an enormous amount of effort has gone into the compilation of reliability data for such items as resistors, capacitors, transistors, electrical junctions, etc., and these data are summarized in a DOD manual on the reliability of electronic components.[1] Unfortunately, similar data do not appear to be available for items such as heavy electrical switch gear, transformers, or solid state power conversion devices.[2] However, the limited data available indicate that electrical components such as switch gear, relays, circuit breakers, etc. have reliabilities more like those of mechanical components than like the much simpler components such as resistors and capacitors in electronic systems. This is to be expected in view of their much greater complexity (compare a circuit breaker to a wire wound resistor, for example). Further, electric power equipment is more likely to be subjected to thermal stresses and strains, vibration, wear, etc.

It is surprising how little statistical data can be found in the literature on the reliability of typical pieces of equipment. In an effort to obtain truly meaningful statistical data of this sort the writer has obtained summaries of over two billion hours of operating experience for electric motors and controllable valves in the gaseous diffusion plants at Oak Ridge together with over a million component operating hours on equipment in high temperature liquid metal and molten salt systems at ORNL. In addition, a summary of over a billion hours of stainless steel encapsulated

UO_2 fuel element operation give a good insight into the reliability that can be obtained in welds and tubing when first class quality control measures are exercised. These data are summarized in a set of tables appended.

The most complete summary of data on the reliability of mechanical and electrical equipment that the writer has seen is presented in a study made for the AEC by Holmes & Narver, Inc.[2] The objective of this study was to provide a basis for estimating the reliability of reactor protective systems as an aid to reactor hazards analysis. Data were obtained for a wide variety of high quality components employed in the aerospace and nuclear power fields where very high standards of quality control prevail. These data are also included in the appendix.

If one studies the data cited above and tries to use them he not only finds himself tending to get lost in a morass of detail, but also ordinarily finds that much of the data that he would like to have is missing. In attempting to fill in the blank spots one is struck by the fact that moderately complex mechanical components such as pumps and controllable valves seem to have a minimum failure rate of 10^{-6} failures per component operating hour if the component is operated unattended for long periods with no maintenance (i.e., the mean time to failure is one million component operating hours). To the writer's knowledge this degree of reliability has been achieved only under circumstances such as those that prevail in the gaseous diffusion plants, that is, after extensive operating experience and after an agressive program to correct all design, installation, and quality control deficiencies on the basis of millions of component hours of operating experience. Tabulated data appended for ORNL experience with mechanical equipment for liquid metal and molten salt systems shows that with good design and good quality control, but with only perhaps 100,000 hr of operating experience, failure rates of 10^{-5} failures per component operating hour can be achieved (see Tables 5–12). Ordinary off-the-shelf commercial mechanical components are likely to give failure rates of around 10^{-4} failures per component operating hour.

Items of mechanical equipment such as pumps contain a number of different subcomponents such as bearings, seals, casings, shaft, impeller, etc. It might appear that the reliability of the assembly could be estimated from the reliabilities for the individual parts, but in practice this is

usually not possible because most failures in mechanical equipment stem from interactions between parts and tend to be peculiar to the particular device or machine. The situation is a bit different for electronic equipment in that an electrical failure such as a short in a condenser is likely to be a simple random failure independent of the other elements in the system. Thus in working with electronic equipment it is possible to make fairly good estimates of the reliability of the system from data on the individual components. As one would expect, simple electronic components such as resistors or capacitors give much better reliabilities than mechanical assemblies such as a pump or a motor, so that failure rates for commercial electronic components ordinarily run of the order of 10^{-6}/hr for inherently reliable items such as wire wound resistors.[1] Transistors tend to be somewhat less reliable depending on the electrical stress, operating temperature, wattage, etc. High quality aerospace electronic components show failure rates of around 10^{-7} per component operating hour. The very highest quality, specially selected components run under low electrical, thermal, and vibration stresses in some instances give failure rates as low as 10^{-8} failures per component operating hour.[3]

Table 1 was prepared to summarize information for typical mechanical, electrical, and electronic components to help give some perspective to the appraisals of system reliability in subsequent sections of this report.

In an actual system many different types of failure may be encountered. A bearing may wear out, in which case its life will depend on the quality of the lubricant, the extent to which dirt may enter the bearing, etc. or it may fail as a consequence of severe edge loading caused by thermal distortion of the casing as a consequence of thermal cycling. Electric light bulbs are subject to two types of failure — random failures influenced by quality control in manufacturing and burn-out failures stemming from gradual evaporation of material from the hot filament. Deterioration of the breaker points and spark plugs in an automobile engine are similar phenomena in that they involve gradual attrition. Sticking troubles with valves or valve lifters, on the other hand, usually stem from a gradual accretion of resins formed by polymerization of the lube oil. Cracks may develop in a part as a consequence of defects in the material because of inadequate quality control, or they may stem from excessive shock or

Table 1. Failure Rates for Typical High Quality Components Operated Under Favorable Conditions with Maintenance in the Aerospace and Nuclear Power Fields

Component	Failure Rates (Failures/10^6 hr)
Electric motors	1.0
Controllable valves	1.7
Blowers	2.4
Pumps	2.7
Generators	0.9
Circuit breakers	0.3
Fuses	0.5
Relays	0.5[a]
Switches	0.5[a]
Electrical instruments (voltmeters, etc.)	1.3
Pressure sensor	3.5
Temperature sensor	1.5
Wire wound resistors	0.5
Condensers	0.2
SCR's	1.0
Transistors	0.1

[a]Assuming 1 cycle per hour.

vibration peculiar to a particular usage. These numerous types of failure taken collectively enormously complicate reliability analyses, and make gross simplification necessary if the problems are to be made tractable.

The problem is confused somewhat by the common practice of preventive maintenance. It should be recognized that this is simply the application of extensive experience with failures, and entails repairing or replacing parts shortly before the time at which they will probably fail.

RELIABILITY OF IDEALIZED SYSTEMS

Some insight into the application of generic data of the type shown in Table 1 to system reliability appraisals can be outlined by setting up

a series of idealized systems. The simplest set of cases to consider is a series of systems having various numbers of components of essentially similar reliabilities as in Table 2. For a relatively simple system with only 10 major components, for example, the mean time to failure would be only 1000 hr if it were built of ordinary commercial components having a failure rate of 10^{-4} failures per hour. If on the other hand one assumes the highest reliability that there is reason to hope that one might obtain in mechanical components, that is, a failure rate of 10^{-6} per component operating hour, the mean time to failure for a ten component system would be 100,000 hr. Many people prefer to speak in terms of a 90% probability of satisfactory operation for some specified period. This reduces the operating period by a factor of ten, so that a ten component system with a mean time to failure of 100,000 hr would have a 90% probability of operating for 10,000 hr without a repair or a forced outage.

Table 2. Mean Time to a Forced Outage for a Series of Idealized Systems Differing in the Number of Components and Average Component Reliability

(The time given in the table should be reduced by a factor of ten to obtain the time for a 90% probability of operation without a forced outage.)

Number of Components in System	Average Failure Rate for Individual Components (Failures/10^6 hr)				
	100	10	1	0.1	0.01
1	10,000 hr	100,000 hr	1,000,000 hr	10^7 hr	10^8 hr
5	2,000	20,000	200,000	2,000,000	2×10^7
10	1,000	10,000	100,000	1,000,000	10^7
25	400	4,000	40,000	400,000	4,000,000
100	100	1,000	10,000	100,000	1,000,000
500	20	200	2,000	20,000	200,000
1000	1	100	1,000	10,000	100,000
5000	0.2	20	200	2,000	20,000

If we turn our attention from mechanical systems to electronic systems it is necessary to think in terms of much larger numbers of components, that is, at least 100 and commonly 1000 or more. Thus the mean time to failure of an electronic system such as an amplifier made up of 100 components having a reliability of 10^{-7} failures per component operating hour would have about the same mean time to failure as a mechanical system made up of ten components each having a failure rate of 10^{-6} per component operating hour.

RELIABILITY OF FAMILIAR SYSTEMS

It is interesting to compare the idealized systems of Table 2 with some actual systems for which there is extensive operating experience. Table 3 presents a simplified analysis of the reliability experience with a series of familiar systems assuming that in each case the reliability of all of the components is the same for any given system. Actually, such systems would not be built like the "one-hoss shay," but rather would have substantial differences in reliability from one component to another. Although detailed data on the reliabilities of individual components are lacking it is still informative to assume as a first approximation that the reliabilities of the various components are approximately equal in each particular system.

The first example in Table 3 is a household refrigerator, a machine that has become a watchword in discussions of reliability. In this instance, in addition to each of the major items of mechanical or electrical equipment, the fluid containment system is listed as a component on the basis that a leak at any point from that system would constitute a failure. According to one of the major manufacturers of refrigerators, the mean time to failure is 15 years. Using this number coupled with a value of five for the number of components makes it possible to compute backwards to obtain an average failure rate per component, and this turns out to be approximately 1.5×10^{-6}. This happens to be essentially the same as the lowest failure rate that the large amounts of data cited above indicate can be achieved with highly developed components operated under benign conditions.

Table 3. Mean Time to Failure of Components in Typical Systems in Widespread Use

System	Number of Components		Mean Time to a Forced Outage	Average Component Failure Rate per 10^6 hr
Household refrigerator	5	(motor, compressor, thermostat, solenoid switch, vapor system)	130,000 hr (15 yr)	1.5
Automatic washing machine	15	(motor, agitator, spin dry mechanism, 2 water inlet valves, drain valve, thermostat, fill limit switch, drain limit switch, timer, cycle selector switch, cycle shift mechanism, start-stop switch, detergent dispenser, water pump)	500 hr (2 yr at 5 hr/wk)[a]	130
Automobile engine	25	(starter, starter solenoid, ignition switch, ignition wiring, spark plugs, distributor, coil, generator, voltage regulator, water pump, oil pump, oil pressure regulating valve, oil filter, radiator, thermostat, valve mechanism, pistons, crankshaft and rods, timing gears, fuel pump, fuel filter, carburetor, fuel tank, oil pressure gage, water temperature gage)	1,000 hr (30,000 miles)[a]	40
Turbo-jet engine	25	(starter, igniter, ignition switch, ignition wiring, compressor, turbine, accessory drive gear box, oil lines, oil filter, oil pump, oil pressure regulating valve, oil cooler, oil temperature regulator, 8 burners, fuel control, fuel pump, fuel lines)	4,000 hr (Extensive checks and minor maintenance at no more than 2,000 hr)[a]	10

Table 3. (continued)

System	Number of Components	Mean Time to a Forced Outage	Average Component Failure Rate per 10^6 hr
Molten salt pump test loop (500 gpm)	35	3000 hr[a]	10
Transistor radio (small)	100	5000 hr (4.5 hr/day for 3 yr)[a]	2
Household TV set (black and white)	1000	5000 hr ~~<~~ too long! (4.5 hr/day for 3 yr)[a]	0.2

[a]Estimated as typical from meager data available.

A similar procedure was carried out for another familiar household appliance, namely, an automatic washing machine. It appears that not only are there many more components in the system but the reliability of the individual components is much lower. This probably stems from the fact that the components in the refrigerator system are hermetically sealed, hence are not subject to deterioration or damage from corrosion or dirt as is the case in an automatic washing machine. It is worth noting that about half of the manufacturers that have built clothes washers and dryers in a single unit have discontinued these items — largly because of the high incidence of service troubles. Not only are such combined machines more complex but the range of temperature and humidity conditions is greater so that the stresses are more severe.

In turning to the next item in the table, that is, an automobile engine, it appears that even after enormous amounts of experience it is still not possible to get a high reliability in ordinary service. While not generally realized, there are data to show that a high price does not necessarily solve the problem — a standard Ford is likely to require less servicing than a Rolls-Royce.

ORNL experience with high temperature liquid systems gives some insight into the effects on reliability of shifting the operating temperature base from near room temperature to a red heat. Close to 200,000 hr of operating experience have been accumulated with rather simple systems designed for performance and endurance testing of liquid metal and molten salt pumps. Unfortunately, the operating schedule on these systems has ordinarily called for a shutdown every 3000 hr (approximately) to permit recalibration of the instrumentation because the sensors are subject to a drift in calibration with extended operation at high temperatures. However, the data indicate that the mean time between forced outages has been of the order of 3000 hr, and this figure was used in Table 3 as a basis for estimating the mean effective time to failure for an average component.

It should be noted that a detailed analysis of the actual failures experienced in the liquid metal and molten salt test loops indicates that roughly 90% of the forced outages were associated with the electrical equipment. At first glance, this appears surprising in that many would expect the conventional electrical components to have a much higher

reliability than the high temperature mechanical components. What is not obvious is that there are usually numerous junctions and a fair number of contact surfaces in most items of electrical equipment, and there are many places in which the electrical insulation can break down. As a consequence, there are likely to be many different failure modes in a component which, on the surface, may appear to be quite simple.

Two good examples of well developed electronic systems are given by the last two items in Table 3, that is, a small transistor radio and a black-and-white TV set. Good statistics on the reliability of typical units were not available, hence the values used in Table 3 for the mean time to failure were obtained by questioning friends on their personal experience. The resulting values are believed to be representative even if not based on a broad statistical base. Note that the value derived in Table 3 for the mean failure rate for the average component in commercial electronic equipment of this sort is not far from 10^{-6} failures per component operating hour.

No data are available on the reliability of electronic control systems for space power plants, but some idea of how formidable the problem really is can be seen from consideration of a relatively simple item, a voltage regulator. To the writer's knowledge by far the least complex design recommended for this application by a major electrical equipment manufacturer includes 85 electronic components even with no provisions for redundancy, and it was estimated by the manufacturer to have a mean time to failure of only a little over 10,000 hr. On detailed questioning, the design engineer responsible stated that even with the optimum amount of redundancy and the highest quality electronic components available he doubted that better than a 90% reliability could be achieved for a 10,000 hr period. The only solution to the problem in the writer's view is to relax specifications on the power plant control system to accept voltage and frequency fluctuations of as much as ±15% under transient conditions[4] together with a voltage variation with load of as much as ±5% rather than the 1% to 3% ordinarily specified.* This approach would permit the

*Voltage and frequency variations of ±15% are ordinarily acceptable for naval shipboard diesel generator sets, and commonly occur in practice in army and air force portable field equipment.[5] Radar and other electronic equipment can be designed to tolerate such fluctuations.[6]

use of an ac generator system analogous to that of a compound wound dc generator,[4] and would reduce the number of electronic components in the control system to less than ten. Such an approach coupled with the control scheme employed in the MPRE* system would yield an overall mean time to failure of about 10^6 hr for the entire control system of the power plant, that is, about that of a typical piece of mechanical equipment such as a feed pump.

RELIABILITY OF ACTUAL POWER PLANTS

A number of efforts have been made to gather data on complete power plants including steam and hydro central stations, army package power reactor plants, and diesel generator units. Of these systems only the hydro units are sometimes operated unattended. The crew size for a central station steam turbine-generator-boiler unit commonly includes 25 to 40 men in four shifts of six or more men each. The crew size for both army package power reactor plants and nuclear submarine power plants runs 25 to 40 men. Yet even with these large crews and as much on-stream maintenance as possible the probability of operating for 10,000 hr without a forced outage just in the steam turbine-generator unit itself is only 4% in a central station (i.e., not including forced outages caused by the boiler or auxiliary equipment).[7] Hydro units give only about double the reliability of steam boiler-feed water systems (but in this case forced outages caused by auxiliaries are included). The experience with five army package power reactor plants has been comparable. In about 15 operating years (not including the time spent in shutdowns) no plant has operated without a forced shutdown for more than 3390 hr. Diesel generator units are somewhat better but still leave much to be desired. For example, of four units at the Naval South Pole Station in 1956 only one was still in operation at the end of the winter season in spite of the fact that two men were assigned full time and one man half time to operate and maintain them.

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*The MPRE is a boiling potassium reactor space power plant that was under development at ORNL from 1961 to 1967.

To offset these discouraging data it should be mentioned that a 360 kwt electrically heated mockup of the MPRE power plant with all components except the turbine-generator (none was available) was operated for 4000 hr with only two men on the day shift and only intermittent attention nights and weekends. Except for some initial shakedown troubles almost all of the forced outages that occurred stemmed from the electric heaters, and the balance were caused by either the instrumentation or operator errors.

CONCLUSIONS

In reviewing the information presented above it appears that there is an enormous amount of operating experience that places an upper limit on the reliability that one might hope to achieve in components designed to operate under even moderate temperature, electrical, and mechanical stresses. These data indicate a failure rate for mechanical and electrical equipment of roughly one per million hours of component operation, and this in turn implies that, for a 90% probability of operating for 10,000 hr without a forced outage, a system built of such equipment ought not have more than about ten components. Simple electronic components of very high quality give failure rates of 10^{-7} to as little as 10^{-8} per hour, hence an electronic system ought not have more than 100 to 1000 electronic components if it is to have a 90% probability of operating for 10,000 hr. Further, for either the mechanical or electronic systems each component should be of a type that inherently has a high reliability, and the installation of each component in the system should be such that it will operate under thermal, mechanical, and electrical stresses that are low by conventional design standards.

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APPENDIX

Table 4. Failure Rate Data on Selected Electronic, Electrical, and Mechanical Equipment Used in the Nuclear Power Plant and Aerospace Fields (Excerpted from Ref. 2)

SOURCE	FAILURE RATE, Failures/10^6 hr				
	AHSB(S) R 117	MI-60-54-(Rev 1)			Others
		High	Mean	Low	
Accumulators		19.3	7.2	.4	
Actuators		13.7	5.1	.35	
Alternators	7	2.94	.7	.033	
Baffles		1.3	1.0	.12	
Batteries	1.0				
Rechargeable		14.29	1.4	.5	
Bearings					
Ball					
Heavy Duty	2.0	3.53	1.8	.072	
Light Duty	1.0	1.72	.875	.035	
Roller	5.0	1.0	.5	.02	
Sleeve	5.0	1.0	.5	.02	
Bellows	5.0	4.38	2.237	.040	
Blowers		3.57	2.4	.89	
Buzzer		1.30	.60	.05	
Circuit Breakers	2.0	.40	.1375	.045	
Thermal		.50	.3	.25	1.0
Magnetic					.5
Coils		.088	.050	.033	
Connectors, Electrical					
General, each pin	.2	.47	.2	.03	
Contactors	3	.4/c	.25/c	.1/c	
Covers					
Dust		.01	.006	.002	
Protective		.061	.038	.015	
Cylinders	.1	.81	.007	.005	
Hydraulic		.12	.008	.005	
Pneumatic		.013	.004	.002	
Diaphragms		9.0	6.00	.10	
Metal	5				
Rubber	8				
Ducts	1	1.3	.5125	.21	
Fans					
Exhaust	90	9.0	.225	.21	
Fasteners					
Bolts	.02				
Nuts	.02				
Screws	5				
Filters		.8	.3	.045	
Blockage	1				
Leakage	1				
Fuse	5	.82	.5	.30	.1
Gaskets	.5				
D-ring	.2	.03	.02	.01	
Phenolic		.07	.05	.01	
Rubber		.03	.02	.011	
Generators		2.41	.9	.40	
d.c.	9	6.27	.9	.30	
Diesel, Battery start					89
Heaters, Electrical					
Elements		.04	.02	.01	
Heat Exchangers		18.6	15.0	2.21	
Hose		3.22	2.0	.05	
Heavily Stressed	40				
Lightly Stressed	4				

Table 4. (Continued)

SOURCE	FAILURE RATE, Failures/10^6 hr				
	AHSB(S) R 117	MI-60-54-(Rev 1)			Others
		High	Mean	Low	
Instruments					
Electrical		5.77	1.375	1.35	
Pressure					
Gage	10	7.8	4.0	0.135	
Sensor		6.6	3.5	1.7	
Temperature					
Bulb		3.30	1.0	0.05	
Sensor		6.4	3.3	1.5	
Meters (moving coil)	3				
Recorders	25				
Lamps		35.0	8.625	3.45	
Fluorescent	10				
Incandescent		32.0	8.0	5.20	1.0
Indicator	5				
Neon	2	18.8	10.25	4.50	.2
Motors	10	7.5	.625	.15	
Blower		5.5	.2	.05	
Electrical		.58	.3	.11	
Hydraulic		7.15	4.3	1.45	
Servo		.35	.23	.11	
Stepper	5	.71	.37	.22	
Mechanism, Power Transmittal					
Belts	40	15.0	3.875	.142	
Clutches		1.1	.4	.06	
Friction	3				
Magnetic	6	.93	.6	.45	
Slip		.94	.3	.07	
Coupling	5				
Flexible		1.348	.6875	.027	
Rigid		.049	.025	.001	
Gear		.20	.12	.0118	
Helical	10	.098	.05	.002	
Spur	1	4.3	2.175	.087	
Shafts		.62	.35	.15	
Heavily Stressed	.2				
Lightly Stressed	.02				
Rack and Pinion	2				
Mounts, Resilient	9	1.60	.875	.20	
Orifices					
Fixed		2.11	.15	.01	
Variable		3.71	.55	.045	
Pumps		24.3	13.5	2.7	
Electric Drive		27.4	13,5	2.9	
Piping					
Pipes	.2				
Pipe joints	.5				
Union and Junctions	.4				
Pressure Vessels					
General	3				
High Standard	0.3				
Regulators		5.54	2.14	.70	
Flow and Pressure		5.54	2.14	.70	
Pneumatic		6.21	2.40	.77	
Relays					
General		.48/c	.25/c	.10/c	
Each Coil	.3				
Each Contact Pair	.2				
High Speed	5				
Heavy Duty	5	.81/c	.5/c	.30/c	
Hermatically Sealed	.5	.19/c	.04/c	.02/c	
Miniature		.25/c	.06/c	.03/c	
High Speed		1.13/c	.7/c	.42/c	
Power		4.10/c	.3/c	.15/c	
P.O. Type					
General	2				
Fully Tropicallized	1				
Restrictors	5	.983	.59	.197	

Table 4. (Continued)

SOURCE	FAILURE RATE, Failures/10^6 hr				
	AHSB(S) R 117	MI-60-54-(Rev 1)			Others
		High	Mean	Low	
Seals					
Rotating	7	1.12	.7	.25	
Sliding	3	.92	.3	.11	
Solenoids		.55	.05	.036	
Springs		.221	.1125	.004	
Heavily stressed	1				
Lightly stressed	.2				
Hair	1				
Calibration		.42	.22	.009	
Creep	2				
Breakage	.2				
Switches		.14/c	.5/c	.009/c	
General, each contact	.2				
Micro	2	.50/c	.25/c	.09/c	
Push Button	.5	.11/c	.063/c	.043/c	
Rotary	2	.660/c	.175/c	.118/c	
Thermal		.261/c	.161/c	.114/c	
Heater	1				
Contacts	1				
Toggle		.123/c	.06/c	.015/c	
General	1				
Each Pair Contact	.2				
Synchros	8	.61	.35	.09	
Tanks		.27	.15	.083	
Pressure, small		.324	.18	.10	
High Pressure, small		.144	.08	.044	
Tachometers	5	.55	.3	.25	
Transducers		45.0	30.0	20.0	
Liquid Level		3.73	2.6	1.47	
Light		6.66	4.7	2.70	
Photoelectric Cells	15				
Pressure	15	52.2	35.0	23.2	
Radioactivity					
Beta Ray		21.3	14.00	6.70	
Ion Chamber and Leads	5				
Strain					
Gage	25	20.0	12.0	7.0	
Temperature		6.4	3.3	1.5	
Thermistors		28.00	15.0	10.0	.30
Thermocouples	10				
Transformers		2.0	.2	.07	
General, each winding	.3				
Mains					
Encapsulated	5				
Oil Filled	1				
Power		2.08	1.04	.46	
Low Voltage		.60	.3	.13	
High Voltage		1.88	.94	.407	
Pulse	1.5				
Low Voltage		.235	.15	.065	
High Voltage					
Variable	1	.31	.1	.035	
A. F.	0.3	.04	.02	.01	
I. F.	1	.31	.1	.035	
AIEE Class					
O					.21 - 10.00
A					.20 - 19.50
B					.22 - 12.00
H					.21 - 18.50
C					.20 - 1.00

Table 4. (Continued)

SOURCE	FAILURE RATE, Failures/10^6 hr				
	AHSB(S) R 117	MI-60-54-(Rev 1)			Others
		High	Mean	Low	
Valves		8.0	5.1	2.00	
Ball	.5	7.7	4.6	1.11	
Butterfly		5.33	3.4	1.33	
Check		8.10	5.0	2.02	
Control	30	19.8	8.5	1.68	
Relief		14.1	5.7	3.27	
Leakage	2				
Blockage	0.5				
Shutoff	15	10.2	6.5	1.98	
Solenoid	30	19.7	11.0	2.27	
Selector		19.7	16.0	3.70	
3-Way		7.41	4.6	1.87	
4-Way		7.22	4.6	1.81	
Vibrators	5	.80	.5	.4	
Wiring					
Joints					
Soldered	.02	.005	.004	.0002	
Wrapped	.01				
Terminals	.5	.27	.05	.041	
Wires	.1	.12	.015	.008	

Table 5. Summary of Malfunctions in ORNL Centrifugal Pumps Having Capacities of 150 gpm to 1500 gpm Endurance Tested at Temperatures from 1100°F to 1300°F Total Running Time – 168,000 hr

Malfunction	Number of Incidents	Average Operating Time Between Failures-Hour
Pumps		
Excessive seal oil leakage	1*	> 160,000**
Seizure journal bearing	2*	> 160,000**
Seizure in close clearance region between shaft and casing	1*	> 160,000**
Drives, Controls, and Instrumentation		
Electronic drive system controls	3	56,000
Break in resistance grid	1	150,000
Drive motor		
Replace brushes	~20	7,000
Seized rotor	1	150,000
Hydraulic drives (used only on a few pumps)	4	~ 2,000
Liquid level indication		
Shorted probes	~15	11,000
Pump tank overfill	2	84,000
Gas system		
Frozen metal plug	6	28,000
Frozen salt plug	5	33,000

*Failure took place during first few thousand hours of testing of a new model.

**Excluding failures that occurred during the first few thousand hours of testing a new model.

Table 6. Summary of Malfunctions in ORNL Centrifugal Pumps having Capacities of About 5 gpm Endurance Tested at Temperatures from 1000 to 1300°F Total Running Time – 290,000 hr

(Capacity 5 gpm)

Malfunction	Number of Incidents	Average Operating Time Between Failures-Hour
Pump		
Pump bearing failure	2	145,000
Impeller rubbing (mass transfer)	4*	42,000
Drives, Controls, and Instrumentation		
Oil rotary union	5*	33,600
Vee belt (drive)	8*	21,000
Motor bearing failure (3600 rpm)	17*	9,900
Eddy current coupling**	30*	5,600

*Detailed records available for only 168,000 hr of operation.

**Involved replacement of brushes and pilot bearings.

Table 7. Summary of Failure Experience with Electric Motors in the Oak Ridge Gaseous Diffusion Plant

Motor Hp	No. of Operating Units	Motor Failure Probability per Year	No. of Years of Operation	Motor Failures (by Calendar Year)																
				1964	1963	1962	1961	1960	1959	1958	1957	1956	1955	1954	1953	1952	1951	1950	1949	1948
2000	320	0.0121	8	1	1		2	1	6	2	2	6	6	6						
1750 [1]	320	0.0270	8	9	4		10	8	31	16	0	2	1	1						
950	13						2					1			1	2				
700	287	0.0118	8					2	7	4		3	1		1	5	4			
600	200			1											1	3				
500 [2]	100	0.0411	9			4	14	11	25	5	2	4	1	8	44	34	1			
560	200	0.0379	12	4	3	1	3	12	8	4										
400 [3]									10	33	2		6	5						
300	100	0.0564	14	3	8	7	16	9	5	3	3	4	5	6	4	3		3		
200	100	0.0775	5										1	13	13	4		0		
200	360	0.0125	14	1	3	3	9	1	9	3	3	3	1	13	6	5	3	0	1	
150	600	0.0345	17	1	12	4	27	32	38	27	30	32	24	21	33	24	9	6	14	18
100	1014	0.0102	17	2	4	5	15	18	20	10	19	8	13	14	8	12	5	9	7	7
75	450	0.0189	16	6	20	12	20	11	12	7	5	15	17	0	5	2	3	0	1	
60	967	0.0128	17	12	15	12	9	13	16	24	10	18	15	8	3	10	4	20	15	7
50	491	0.0123	17	5	2	8	4	4	2	5	2	5	5	5	8	7	4	15	10	11
30	834	0.0047	16		2	1	1	3	4	2	5	2	4	5	4	2	3	13	10	1
25	10	0.040	10		1					0	0	0	0	0	0	1	1	1		
20	726	0.0065	17	1	6	3	2	3	3	3	3	1	3	4	1	5	6	24	7	5
15	300	0.0269	14		5	1		1		0	3	25	37	12	1	4	3	15	4	2
10	120	0.0396	12						1	1	3	6	11	2	4	1	1	18	6	3
7-1/2	576	0.0233	10								1	17	24	30	6	9	12	14	10	11
5	576	0.0186	10								0	4	8	23	15	6	6	10	20	15

(1) Most 1750 hp motors fail because of a lead to stator winding break – a manufacturing deficiency – no program for correction.

(2) Most 500 hp motors failed because of deficiency in design (1952 & 1953) – rotors were rebuilt on program basis by manufacturer.

(3) Motors operated overloaded – subsequently rewound to 560 rating because of high failure rate.

(4) Operation of most 3600 rpm equipment phased out in 1964.

Table 8. Summary of ORNL Operating Experience with Electromagnetic Pumps

Alternating Current Conduction (Linear) Type

System	Operating Time (hr)
ANP heat exchanger tests	6,700
Corrosion loops	73,850
SNAP-50 loop	5,000
SNAP-8 loops	30,000
Total	115,550

No failures that caused leaks in the liquid metal system occurred after the pump cell was redesigned as a consequence of two failures during the first thousand hours of operation. Some loss in performance occurred as a consequence of oxidation of the leads at temperatures above 1000°F.

Electrodynamic Pumps (Rotating Magnet)

System	Operating Time (hr)
Forced convection boiling potassium system	16,000
Small potassium system	7,700
Total	23,700

No failures caused leaks in the liquid metal system after the pump cell was redesigned following an early failure. The longest period without serious trouble with the rotor bearings was 2,300 hr.

Helical Induction Pumps

System	Operating Time (hr)
Forced convection boiling potassium system (one pump)	9,000

No pump failures, per se, but repeated difficulty was experienced with a mechanical voltage controller.

Table 9. Summary of Operating Experience with Bellows Seal Valves

(a) ORNL Experience with Valves in Alkali Metal in the Period 1961 Through 1965

System	Number of Leaks to Atmosphere Through Bellows	Number of Failures[a] in Stem Mechanism	Type of Valve that Failed	Number of Valves per System	Hours of System Operation	Valve Operating Hours	Remarks
IPS (Boiling K)	0	2	Hoke, except for 2 Mason-Neilan	35	~3,000	105,000	All valves are operable at this date. At least two valves have leakage across seat when closed.
SPS-1 (Boiling K)	0	5[b]	Hoke 4 – HV473 and 1 – TY445	6 primary valves sizes 3/8 – 1/2	~4,000. Average life of valves that failed – 2500 to 3000 hr	24,000	One valve presently in system leaks across seat.
SPS-2 (Boiling K)	0	1	Hoke	47[c]	~1,500	70,000	Two valves in system presently are leaking across seat.
SNAP-8 (NaK)	4[d]	4	1402 Series Hoke which were bought for ANP	7[e]	25,000[f]	175,000	
SNAP-50 Loop (NaK)	0	0	Hoke HV-473 and one TY-445	10	~5,000	50,000	

[a]Failures where valve had to be repaired or replaced.

[b]Four bonnets repaired. One valve removed because of leakage across seat. All five valves removed from system.

[c]Including sample system valves.

[d]Valves that failed operated for 480, 1300, 1600, and 5880, respectively.

[e]Thirteen loops were operated, each having seven valves. One loop operated for 5880 hr before one of the valves failed.

[f]Total operating time for all loops.

(b) Oak Ridge Gaseous Diffusion Plant Experience with 930 Valves

Year	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	Total
Number of bellows failures	55	22	16	7	7	10	14	41	23	37	19	251
Number of failures of stem mechanism	6	0	22	8	14	1	0	4	3	3	6	67

Table 10. Summary of ORNL Operating Experience with Firerod Electric Heaters Run in Boiling Potassium

Hours of Operation	Number of Heaters		Heater Power					
			Less Than 4 kw		4 to 5 kw		5 to 7 kw	
	Total	Failed	Total	Failures	Total	Failures	Total	Failures
Over 8000	1	1			1	1		
6000 to 7000	1	1			1	1		
5000 to 6000	1	1			1	1		
4000 to 5000	2	1					2	1
3000 to 4000	2	2					2	2
2000 to 3000	77	28	71	27	1		5	1
1000 to 2000	26	15	10	3	7	4	9	8
500 to 1000	18	6	1	1	9	1	8	4
Less than 500	159	39	134	32	5	1	20	6
Total	254	94	216	63	25	9	46	22

Table 11. Summary of Instrument Operating Experience in Some Typical High Temperature Liquid Systems

Test	Hours of Operation[a]	Level Elements			Pressure Transmitters			Magnetic Flowmeters		
		No.	Failures	Total Inst. Hrs.	No.	Failures	Total Inst. Hrs.	No.	Failures	Total Inst. Hrs.
Boiling Potassium Forced Convection Loops										
Loop No. 1	3,000	1	0	3,000	3	0	9,000	1	0	3,000
Loop No. 2	750	1	0	750	3	0	2,250	1	0	750
Loop No. 3	2,611	1	0	2,611	3	0	7,833	1	0	2,611
Loop No. 4	1,895	1	0	1,895	3	0	5,685	1	0	1,895
Loop No. 5	4,500	1	0	4,500	3	0	4,500	1	0	4,500
Loop No. 7	3,300	1	0	3,300	3	0	9,900	1	0	3,300
Large Molten Salt Pump Test Loops										
Test No. 1	12,000	–	–		3	–	36,000	–[e]		
Test No. 2	20,000	–	–		3	1[c]	60,000	–[e]		
Test No. 3	10,000	1[b]	–		3	–	30,000	–[e]		
Test No. 4	25,000	–	–		3	–	75,000	–[e]		
Small Potassium Systems										
No. 1	6,000	4	0	24,000	5	0[d]	30,000	2	0	12,000
No. 2	1,200	6	0	7,200	2	0	2,400	1	0	1,200
Intermediate Potassium System	2,800	7	0	19,600	4	1[c]	11,200	4	0	11,200
SNAP-50 Radiator Loop	5,000	3	0	15,000				3	0	15,000
SNAP-8 NaK Loops	25,000	7	0	42,000				10	1	60,000
EM Pump Test Rig	3,500	1	0	3,500				1	0	3,500
Total	93,056	35	0	127,356	39	2	283,768	27	1	118,956

[a]Loop at temperature but not necessarily full operation, e.g. boiling.

[b]Float type level element as used on MSRE.

[c]Elements failed to respond. In both cases, the process connection was plugged.

[d]Two PMD's failed in this loop when they were overheated with the loop evacuated.

[e]Two of the PMD's are used in conjunction with a venturi to measure flow.

[f]The pump test loops circulate molten salt.

Table 12. Operating Experience with Metal-Clad UO_2 Fuel Elements

Operating Organization	Reactor	Cladding Material	Number of Rods Tested	Rod Diameter (in.)	Cladding Thickness (in.)	Cladding Surface Temperature (max/av) (°F)	Coolant Pressure (psia)	Heat Flux (peak or range) (Btu/hr·ft²)	Fuel Center Temperature (max/av) (°F)	Burnup (average or range) (Mwd/MT of U)	Fission Gas Release (%)	Number of Failures	Cause of Failure	References[a]
ORNL	Experimental[b]	Inconel	32	0.425[c]	0.050	1300/1200	20-30	54-287,000	3130/1620	3,600-26,000	0.01-61	0		1, 2
ORNL	SGCR	Type 304 stainless steel	46	0.750[d]	0.020	1500/1300	315	135-175,000	2800/2200	1,000-10,000	0.1-14.0	8	Cladding collapse, defective braze joints, nitrides in UO_2, overpower	1, 3, 4, 5
AGN	ML-1	Hastelloy X	12	0.241	0.030	1650/1200	300	170,000	?/?	23,000	1-5	0		6
GE	Fast reactor[e]	Stainless steel	22	0.190	0.020	1150/950	~20	500-1,500,000	~5000/4000	4,700-99,000	10-60	0		7
Chalk River	NPD	Zircaloy-2	21	1.00	0.023-0.048	545/?	1000-1200	120-225,000	~3800/2800	222-9,120	1.2-26.8	1	High rating on brittle cladding	8
GE	Dresden	Zircaloy-2	15,500	0.570	0.030	588/555	1017	346,000	3500/1200	9,000	0.3-15	<6	Rod bowing	9, 10
GE	Dresden	Zircaloy-2	192	0.470	0.025	588/555	1017	346,000	3500/1200	7,000				
GE	JPDR	Zircaloy-2	3,460	0.564	0.033	564/540	905	296,000	3450/1820	1,000		0		9, 10
GE	KAHL	Zircaloy-2	3,200	0.571	0.033	570/565	1000	338,000	4430/1142	5,500		0		9, 10
Bettis	PWR Core 1	Zircaloy-2	16,400	0.411	0.023	550/500	1800	100-343,000	3675/955	10,000	0.16-0.57	Few	Pin holes in cladding	9, 10, 11
WAPD	Carolinas-Virginia	Zircaloy-4	1,230	0.490	0.022	600/565	1500	469,000	4500/2850	1,000		0		9, 10, 12
GE	Dresden	Type 304 stainless steel	4,900	0.440	0.019	585/555	1017	276,000	3500/1200	4,000		"Some"	Intergranular stress-corrosion	9, 10
GE	Humboldt Bay	Type 304 stainless steel	8,428	0.463	0.019	560/555	1035	365,000	3500/1300	3,000		?		9, 10
GE	Big Rock Point	Type 304 stainless steel	7,392	0.388	0.019	585/555	1050	350,000	3300/1500	3,000		?		9, 10
WAPD	Yankee	Type 348 stainless steel	23,142	0.340	0.021	645/535	2015	446,000	3450/1275	8,000	1-11	0		9, 10, 12
WAPD	Saxton	Type 304 stainless steel	1,512	0.391	0.015	642/585	2000	444,000	?/?	3,000		0		9, 10, 12
WAPD	Indian Point	Type 304 stainless steel	23,400	0.304	0.021	605/517	1500	540,000	3400/900	3,000		0		9, 10, 12
B&W	NS Savannah	Type 304 stainless steel	5,248	0.500	0.035	~550	1750	277,000		1,500		0		9
GE	VBWR	Zircaloy-2, Zircaloy-4	1,342	0.424-0.569	0.022-0.030	625/555	1000	300-460,000	3500/1200	2,500-10,000	0.3-15	2	Faulty materials	9, 10
GE	VBWR	Type 304 stainless steel	1,539	0.360-1.375	0.011-0.046	625/555	1000	300-550,000	3500/1200	5,800-10,000	0.3-15	"Some"	Intergranular stress-corrosion	9, 10

[a]See list on following page.

[b]Fuel length 1.0 in.

[c]Fuel pellets were annular, 0.078 in. ID and 0.156 in. OD. They were insulated with depleted UO_2 bushings.

[d]The pellets were annular, 0.706 in. OD and 0.323 in. ID.

[e]20% PuO_2-80% UO_2; active fuel length only 1.6 in.

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