LOCOMOTIVE Spring 1988 Volume 66 Number 1

Photos this issue: Alacrity Photo, HSB Staff, Darryl Peetz

Single subscriptions are available free of charge. To receive "The Locomotive", write to The Hartford Steam Boiler Inspection and Insurance Co., One State Street, Hartford, CT 06102, Attn: Locomotive

Published quarterly for owners and operators of boilers and power equipment

The country's oldest company magazine published continuously under the same name Now in its one hundred twenty-first year of publication

The Hartford Steam Boiler Inspection and Insurance Co.
One State Street, Hartford, Connecticut 06102

Editor: Fred A. Corwin, P.E., C.P.C.U. Assistant Editor: Nancy E. Bergeron
Address corrections should be sent to: Locomotive

ISSN 0741-8760

This update of a 1980 article adds credibility to our recommended accident prevention procedures. An analysis of new data reveals some improving trends, but few surprises.

REFRIGERATION AND AIR CONDITIONING EQUIPMENT FAILURES

by
David E. Stouppe and Tom Y. S. Lau
Support Engineer Senior Engineer

In the fall of 1980, *The Locomotive* published an article by Raymond F. Stevens (now enjoying his well-earned retirement) summarizing one year of failure data on refrigeration and air conditioning systems (Volume 62, Number 3, also reprinted as Engineering Bulletin 81). Company experience since 1980 adds credibility to the statistics and recommendations made in Mr. Stevens' article.

Insurance recommendations are based on experience. This hard learned knowledge is gained by insurance companies through the medium of failures experienced and claims paid. In years past, claims experience was manually recorded and used by engineers to formulate recommendations. The advent of computerized databases has introduced greater accuracy into this process.

This article utilizes eight years of data summarizing 15,760 failures that occurred from the years 1980 to 1987. Of the failures reported, 11,349 were electrical, involving motors, controls and electrical apparatus; 4,411 failures were mechanical in nature, involving compressors, system piping, or vessels. From this population, 12,518 failures with defined causes, occurring in a statistically significant quantity, were selected to be analyzed. The remaining failures were either from apparently isolated causes, or the cause was undetermined.

We have presented the information in three aspects. First, probable age at failure is analyzed as an aid to understanding our time-between-overhaul recommendations.

Next, we have analyzed the major failure causes themselves. These were selected either on the basis of high frequency of occurrence or high severity of loss.

Lastly, and most importantly, we have summarized our accident prevention recommendations. This is the whole point of the article. We believe that following these recommendations in a planned preventative maintenance program can significantly reduce the probability of failure of your refrigeration and air conditioning system.

AGE AT FAILURE

Hermetic Air Conditioning and Refrigeration Units

To those owners who will experience failure of this type of equipment, our statistics indicate that if the failure involves the windings of the hermetic motor, there is a probability that the unit will be approximately 10 years old for air conditioning units and eight years old for refrigeration units.

If the failure involves the compressor, chances are that the unit will be approximately 10 years old and would not have had a major inspection or overhaul since it was installed.

Large Hermetic Compressors and Motors

To those owners who will experience a motor failure in this type of equipment, there is the probability that the unit will be approximately 10 years old and will, in most cases, have the original windings.

For those failures which involve mechanical damage to the compressors, there is a probability that the unit will be approximately 15 years old for centrifugal compressors, 10 years old for reciprocating air conditioning compressors, and 11 years old for refrigeration units.

Large Non-hermetic Compressors and Motors

To those owners who will experience a motor failure in this type of equipment, there is the probability that the motor will be approximately 12 years old and will, in most cases, have the original windings.

For those failures which involve mechanical damage to the compressors, there is a probability that the unit will be approximately 12 years old for centrifugal compressors, 13 years old for reciprocating refrigeration compressors and 16 years old for reciprocating air conditioning compressors.

As each class of equipment analysis is presented, it will be followed by a summary of the causes of the failures since a statistical analysis would not be complete if the underlying causes were not revealed.

Since failure data is compiled by its insurance classification, a brief definition of terms is called for because most owners and users do not use insurance terminology to identify their equipment.

DEFINITIONS

"Air Conditioning Unit"

According to a standard boiler and machinery policy, an air conditioning system having a rated cooling capacity of not more than 600,000 Btu/hr (50 tons) may be insured as an air conditioning unit. Such an object includes all compressors and their driving motors which form part of the unit, including refrigerant circuits and coils or vessels containing refrigerant, and any condenser or evaporator, fans, pumps, and motors used solely with the unit. Systems with a rated capacity greater than 600,000 Btu/hr (50 tons) may be insured by the principal components — compressors, drive motors, vessels, and piping containing refrigerant. A system which qualifies for rating as an air conditioning unit may, at the Insured's option, be insured on the same component basis as larger systems.

"Motors" (Rotating Electrical Machines)

Briefly stated, the insured motor definition includes motors and any nonrotating equipment used solely to start, stop, or control any such motor, but does not include any electronic computer or electronic data processing equipment.

"Centrifugal or Reciprocating Compressors" (Freon or Ammonia)

An insured compressor means a complete compressor as may be designated in the policy schedule, but does not include any air tank, or other apparatus connected to the compressor, except control apparatus mounted on the compressor; nor any electrical apparatus, any condenser or its adapter, or any piping or duct leading to or from such compressor.

TABLE I

Hermetic Air Conditioning and Refrigeration Units

Age at Failure	*Motor*	*Compressor*
Air Conditioning	10 Yrs	10 Yrs
Refrigeration	9 Yrs	8 Yrs
Type of Failure	*Total*	*% Total*
Electrical	5221	76.6
Mechanical	1288	18.9
Refrigerant Circuit	306	4.5
Electrical Parts That Failed	*Total*	*% Electrical*
Motor Windings	4522	86.6
Motor Control Equipment	271	5.2
Auxiliary Motors/Fans & Controls	428	8.2
	5221	
Mechanical Parts That Failed	*Total*	*% Mechanical*
Compressor		
Valves/Springs	370	28.7
Bearings	249	19.3
Connecting Rods	393	30.6
Pistons	120	9.3
Crankshafts	97	7.5
Lubrication System	59	4.6
	1288	
Refrigerant Circuit	*Total*	
	306	

"Refrigeration and Air Conditioning Vessels and Piping" (System)

Such a system includes all interconnecting vessels, coils and piping containing the specified refrigerant, and all valves and fittings on such vessels.

Note: These equipment definitions are generalized statements relating to classification of failure data collected and should not be interpreted as being exact policy language.

ANALYSIS OF FAILURES — MOTORS

Insulation Deterioration Due to Age and/or Service

Since most motor winding failures involve a deterioration of the insulation in one form or another, this broad category is most difficult to assign specific causes.

In general, the insulation of motor windings is selected for the temperatures for which the motor is designed to operate. However, abnormally high temperatures are considered to be the principal cause of deterioration of winding insulation. As a general rule, motor manufacturers have determined that an increase in the winding temperature of 10°C above designed limits will result in an approximate 50% decrease in the life of the windings.

Unbalanced Voltage and Single Phase Operation

In terms of its heating effect in a 3-phase motor, an approximate 3% voltage imbalance between phases results in an approximate 25% increase in the temperature of the windings.

As it applies to 3-phase motors, a single-phase condition occurs when there is an interruption of the supply of voltage to one of the three phases. Continued operation of a motor results in overheating of the windings and a breakdown of the winding insulation.

Short Cycling

This is a condition which most often occurs when a compressor's operating controls malfunction causing a repeated stopping and restarting of the motor — 168 failures occurred due to this cause. This repeated restarting occurs with locked rotor currents and results in a rapid increase in the temperature of the windings, which in the worst case results in burning. In other cases where failure does not occur, the life of the windings will have been adversely affected, and a failure may occur at some future date under what may appear to be normal conditions. Some motors may be equipped with thermal detectors imbedded within the windings and wired into the motor control circuit to prevent damage from overheating. However, in addition to thermal damage, there is also the possibility of insulation damage from the mechanical stresses imposed on the windings during repeated locked rotor starting. This mode of failure is often suspected when damage to the windings occurs at the end of the coil slots in the stator.

Large hermetic motors which drive centrifugal compressors are less susceptible to the adverse effects of short cycling since they generally have a time delay relay in the starter control circuit to limit the number of motor starts to about three an hour. Although they are not widely used in reciprocating type units, a time delay relay can be installed if circumstances warrant. However, the equipment manufacturer should be consulted about such an installation.

TABLE II

Hermetic Motors

Age at Failure	*Years*	
Air Conditioning	10	
Refrigeration	9	
Parts That Failed	*Total*	*% of Total*
Motor Stator Windings	5444	84.0
Rotor Bars	620	9.6
Bearings	90	1.4
Motor Control Equipment	326	5.0
	6480	

TABLE III

Non-Hermetic Motors

Age at Failure	*Years*	
Air Conditioning	11	
Refrigeration	12	
Parts That Failed	*Total*	*% of Total*
Motor Stator Windings	1966	73.8
Rotor Bars	278	10.4
Bearings	212	8.0
Motor Control Equipment	209	7.8
	2665	

Refrigerant Contamination

Some fluorocarbon refrigerants will react with moisture and lubricating oil to produce acid, contributing to the formation of copper plating and the corrosion of metals.

The degree that contaminated refrigerants may contribute to the deterioration of insulation and the failure of hermetic motors is, in our opinion, significant. It may warrant analytical techniques and preventive measures to minimize the possibility of deterioration of electrical and mechanical components in contact with the refrigerant.

There were 339 reports attributed to contamination of refrigerant/lubricating oil of hermetic compressors that caused winding or bearing failures.

ANALYSIS OF FAILURES– *RECIPROCATING COMPRESSORS*

Valves/Springs — Metal Fatigue

Of all the compressor accidents recorded, between 24 to 37% involved the failure of the internal suction and discharge valves and springs, down from 50%; and in about 50% of the cases, the failure of the valves was attributed to metal fatigue associated with age and wear. A total of 675 failures of this type occurred in the freon and ammonia compressors.

To better appreciate why metal fatigue occurs with compressor valves, one need only look at the number of operating cycles the valve will experience over a given period. For instance, the valves will open and close once during each revolution of the compressor crankshaft. Since most compressors operate between 1,750 and 1,770 rpm, by converting this into the number of operating cycles for compressors which operate around 4,000 hours each year in seasonal service, we see that the valves will have operated 422,400,000 times.

There have been considerably lower percentages of accidents attributed to valves and springs during this period.

Hydraulic Forces — Liquid Slugging

Compressors built for air conditioning and refrigeration application are designed to handle vapor and perhaps a small volume of liquid without sustaining damage.

Liquids, of course, are not compressible and attempting to compress them in the cylinder results in hydraulic forces which act on the valves, valve plates, pistons, and connecting rods. More often than not, valves and valve plates are broken and result in a cascading type of damage to mechanical parts of the compressor. Twenty percent of all mechanical failures were due to liquid slugging.

Generally, liquid slugging occurs when the compressor is started and is a result of an accumulation of liquid refrigerant in the crankcase of a compressor due to refrigerant migration while the compressor is stopped.

TABLE IV

Hermetic Reciprocating Freon Compressors

Age at Failure	*Years*	
Air Conditioning	10	
Refrigeration	11	
Parts That Failed	*Total*	*% of Total*
Compressor		
Valves/Springs	227	37.2
Bearings	89	14.6
Connecting Rods	183	30.0
Pistons	44	7.2
Crankshafts	19	3.0
Lubrication System	49	8.0
	611	

TABLE V

Non-Hermetic Reciprocating Freon Compressors

Age at Failure	*Years*	
Air Conditioning	16	
Refrigeration	12	
Parts That Failed	*Total*	*% of Total*
Compressor		
Valves/Springs	71	24.7
Bearings	56	19.5
Connecting Rods	84	29.3
Pistons	16	5.6
Crankshafts	25	8.7
Lubrication System	35	12.2
	287	

To minimize the possibility of damage due to liquid slugging, compressors are equipped with crankcase heaters which keep the oil at a temperature higher than other parts of the system while the compressor is idle. This maintains the refrigerant in a vapor phase and prevents migration to the crankcase.

TABLE VI

Ammonia Reciprocating Compressors

Age at Failure	*Years*	
	20	
Parts That Failed	*Total*	*% of Total*
Compressor		
Valves/Springs	34	22.8
Bearings	22	14.8
Connecting Rods	41	27.5
Pistons	12	8.1
Crankshafts	24	16.1
Lubrication System	16	10.7
	149	

Bearings — Loss of Lubrication or Insufficient Lubrication

Bearing damage due to a loss of lubrication accounted for about 7.8% of all compressor mechanical accidents, down from 32%.

At this time no discernable reason for this large drop in bearing failures is apparent. The small number of lubrication system failures probably is responsible.

We have good reason to believe that most bearing damage occurs as a result of oil diluted by liquid refrigerant in the crankcase.

The results of starting a compressor with diluted oil are widely known and understood by manufacturers and engineers within the industry. Simply stated, oil which is saturated with liquid refrigerant will, upon start-up of the compressor, result in a violent boiling and foaming of oil within the crankcase and oil pump, resulting in oil starvation at the bearings.

The same condition can also result in slugging damage to the valves and pistons.

Clearly, the use of a crankcase heater will greatly minimize the possibility of bearing damage.

Crankshafts

The breaking of crankshafts in hermetic compressors occurs infrequently, about 3.0% of the failures, and occurs in non-hermetic compressors in about 8.7% of the failures.

Examination of a broken crankshaft will often reveal the nature of the stresses which produced the break. This, in turn, can be related to operating characteristics producing these kinds of stresses.

ANALYSIS OF FAILURES – *CENTRIFUGAL COMPRESSORS*

Bearings — Lubrication

The most predominant failure of centrifugal compressors has been bearings, accounting for 55 to 70% of the total. Loss or lack of lubrication is the major cause of bearing failures. The analysis shows a small percentage of lubrication system failures. From this we conclude that the bearing failures are most likely due to the diluted oil problem mentioned previously under reciprocating compressors. Service wear accounts for the next largest rate.

TABLE VII

Hermetic Centrifugal Compressors

Age at Failure	*Years*	
	15	
Parts That Failed	*Total*	*% of Total*
Impeller	69	24.6
Guide Vanes	16	5.7
Bearings	155	55.4
Keys	8	2.9
Shafts	13	4.6
Lubrication System	19	6.8
	280	

TABLE VIII

Non-Hermetic Centrifugal Compressors

Age at Failure	*Years*	
	14	
Parts That Failed	*Total*	*% of Total*
Impeller	13	18.3
Guide Vanes	3	4.2
Bearings	49	69.1
Keys	1	1.4
Shafts	3	4.2
Lubrication System	2	2.8
	71	

Impellers

No predominant mode of failure has been found in the current analysis. Fatigue, shock loading and surge have caused a small number of failures. Damage may occur to impellers from rubbing due to a thrust bearing failure, and may also experience rubbing due to bearing wear which allows the impeller to drop and rub the casing. If rubbing is severe enough, it can result in more extensive damage from an aluminum-refrigerant reaction which is highly exothermic.

Impellers with keyways and keys for securing the impeller on the drive shaft have experienced failures by cracks originating at the root of the keyway in the bore of the impeller. Although this type of failure is rather infrequent, it is one which can be serious in terms of property damage.

SUMMARY

This analysis shows that motor windings are again the most numerous cause of failure of air conditioning and refrigerating equipment. Deterioration of the winding insulation from age and overheating, line disturbances and lightning account for about 67% of the winding failures. The use of insulation resistance testers annually, as recommended, should give advance warning of a deteriorating condition that may lead to an outage. Protection from lightning and line disturbances should be installed where feasible.

Mechanical components of the reciprocating compressors are victims of refrigerant slugging and fatigue with an increase in failures of connecting rods a partial result. Valve and valve spring failures have decreased. This may be due to the increased emphasis on routine maintenance.

The following summary of recommendations represents our judgment at this time based on the foregoing analysis.

Dave Stouppe joined Hartford Steam Boiler in 1987 as an HVAC specialist. Prior to joining the Company, Dave spent three years as the Manager of Engineering for a heat pipe manufacturer, and five years with a consulting engineering firm managing a design group for HVAC, solar and energy recovery projects. Dave is also a retired U.S. Naval Aviator. He holds a Master's degree from the Naval Postgraduate School and a Bachelor's degree from Purdue. Dave is a member of ASHRAE and RSES (Refrigeration Service Engineers Society).

Tom Lau began his Hartford Steam Boiler career at the Boiler Inspection and Insurance Company of Canada (BI&I) in 1971. Tom transferred to the Home Office Engineering Department in 1979. He has a B.S. degree in mechanical engineering from National Taiwan University, is a registered Professional Engineer and a Certified Cogeneration Professional. His present assignments include new product developments, System Performance Insurance, and Water Resource Insurance.