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FOREWORD

This report was prepared by Southwest Research Institute, Mining Technology Section, San Antonio, Texas under USBM Contract Number J0100006. The contract was initiated under the Minerals Health and Safety Technology Program. It was administered under the technical direction of the Pittsburgh Research Center with Mr. Aldo Furno acting as Technical Project Officer. Ms. Sylvia Brown was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as part of this contract during the period November 1979 to January 1981. This report was submitted by the authors on January 29, 1981.

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1.0 INTRODUCTION/BACKGROUND

1.1 Objectives

Historical evidence has suggested that numerous air compressor accidents have and do occur in coal and metal/non-metal mining operations. This prompted the U. S. Bureau of Mines to sponsor a program to analyze air compressor hazards in underground and surface mines and, if necessary, to develop guidelines for eliminating fires, explosions, and other hazards that might result from compressor utilization in the mining industry. This report presents the results of this program with our findings offered in the form of discussions, conclusions, and recommendations.

1.2 Project Summary

The early stages of the program were designed to obtain the necessary background information to accurately define the problems associated with air compressor usage in general, and air compressor usage within the mining industry, in particular. Problems leading to actual or potential fire and explosion hazards were of major concern. For the most part, this task was accomplished through literature and field surveys, with emphasis being placed on identifying the mining industry's practices, problems, and accident experience when using air compressors. Specific attention was directed toward determining:

- Types of compressors being used and their operating characteristics and performance criteria in terms of capacity, temperatures, and pressures,
- lubricant requirements; recommended practice, fluid composition and fire resistance properties,
- frequency, type and cause of accidents,
- fire protection and safety measures, and
- special fluid or non-fluid related problems.

The literature search included both domestic and foreign sources and the field survey included contact with and/or visits to operating underground and surface mines, compressor and lubricant manufacturers, and government safety organizations.

In general, the field survey supplemented the literature survey. It provided firsthand historical data and current information on the practices and problems associated with compressor usage and it provided an opportunity to see how compressors are being used in typical mining applications. We were also able to obtain, for subsequent analysis, samples of new and used lubricants from compressors used in specific mining operations, and to review maintenance and operating procedures for the particular compressor(s) in question.

It should be noted that during our mine visits, we were not investigating specific accidents per se, but potential hazards in general. In fact, most operations at the time of our visit were "trouble free" with respect to compressors. Mines that are named and specific incidents that are referred to in this report were obtained from information contained in unclassified government documents or in the public record.

The field survey portion of the program included contact and/or visits with compressor, compressor component, and lubricant manufacturers and government safety organizations in addition to our discussions and visits with mine operators. With each contact an attempt was made to identify problems or hazards specifically related to the operation of compressors; in particular, areas of mechanical failure, overheating, material fatigue, improper maintenance and operating procedures, protection and safety device failures, and lubricant difficulties were discussed.

Results of the literature and field survey work are presented in Section 2 and in the applicable Appendices.

1.3 Conclusions

1. Current government data bases, with respect to compressor accidents, are misleading and can imply improper conclusions if the user is not aware of their composition and limitations. Without question, proper data interpretation is essential in assessing the frequency, nature and severity of compressor-related accidents and the extent to which air compressors pose a hazard when used in underground and surface mining operations.

2. Statistically, compressor hazards do not seem to pose as big a problem as originally expected. Of the numerous compressor-related accidents that have been reported, only a fraction concerned the compressor directly and only a part of these resulted in or posed a direct fire or explosion hazard. This finding, however, should not imply that concern over compressor hazards is unwarranted. Hazards do exist although, due to reporting procedures, the statistics used to determine their frequency may be misleading. Thus, while the number of compressor-related accidents reported tends to overestimate the severity of the problem, the lack of reporting of incidents which specifically involve fires and explosions* may produce the opposite effect.

3. Current data, when analyzed and coupled with comments from operators and manufacturers, suggest that compressor utilization in mining applications does not pose an unacceptable risk to the health and safety of the workers. As such, it appears that the need for new regulations governing the use of compressors in surface and underground coal and metal/non-metal mines does not exist, although the need to provide guidelines for the safe application and operation of air compressors and compressed air systems in mining applications is warranted.

4. Broadly speaking, compressor safety hazards can be classified into two basic groups: those leading to or posing a threat of fire and/or explosion, and those stemming from physical events encountered when using a compressor which will not necessarily lead to a fire or explosion, but which nevertheless present a dangerous condition for the

* Federal regulations do not require that fires must be reported if they are extinguished within 30 minutes.

operator or workers. Furthermore, if a systems safety analysis is to be conducted, the first group should be subdivided into two additional areas; one dealing with the likelihood that a fire or explosion will occur once a combustible mixture is present in the compressor or compressed air system, the other dealing with the events that produced the combustible mixture in the first place.

5. In both surface and underground mines, most compressor problems and hazards can be traced to improper utilization, operation, and maintenance; in many cases, negligence or tampering by unauthorized personnel is a primary factor. Except for centralized compressor operations (above ground for underground mines) or operations run to well defined and planned maintenance and operating procedures, control over compressor access is virtually nonexistent. Without control, compressor misuse is common.

6. Fires and explosions are due to the ignition of combustible mixtures (carbon deposits, mists and vapors), the presence of which in the compressed air system is usually a function of the mechanical condition of the compressor or certain compressor components, the selection and handling of specific lubricants, and the operating envelope imposed on the compressor (in terms of pressures, temperatures, and duty cycle).

7. The use of compressors underground is decreasing primarily because of noise standards. As a result there is a trend toward aboveground centralization of the compressor operation (for underground mines) which is expected to bring about improved maintenance practices, better operational control, and increasing attention to the compressor function.

8. In some underground mines, pneumatic equipment is being replaced by all-hydraulic equipment. If this trend continues, the demand for compressed air at the worksite will diminish and the need for and use of underground air compressors can be expected to decrease.

9. The stated trends (7 and 8) are likely to occur as a consequence of new mine development and/or the replacement of wornout equipment in existing mines. Underground compressors will be present within the mining community for some time. Their safe operation and

use will remain a concern for mining companies and the Bureau alike.

10. CFR-30 is briefer, more general and less restrictive than either the regulations of the British National Coal Board (NCB) or the West German Principle Union of the Industrial Professional Association. When provisions of the ASME Boiler and Pressure Vessel Code are included, the requirements are considerably expanded. However, the impact is more on the design and construction of pressure vessels (receivers, separators, intercoolers and aftercoolers), than on the design of the compressor or the installation, operation, and maintenance of the compressor system. Although we have stated that new regulations are not needed (see 3 above), the NCB document deserves close attention (see 2.1.3) as it may serve as a paragon for many of the guidelines which are needed.

1.4 Recommendations

As a result of the work conducted during this program, two classes of recommendations should be considered. First, there is the class of recommendations that come directly from the immediate findings which, for the most part, are directed at MSHA (data), Mine Management, and the Bureau. Secondly, there is the class of recommendations that concerns further work in the area of fluids testing to establish a common procedure for measuring and evaluating autoignition temperatures at elevated pressures such as those typical to air compressor operations.

1.4.1 General Recommendations

1.4.1.1 MSHA Data - Reporting Procedures, Data Storage, and Retrieval

Review of the MSHA accident data, with respect to air compressors, and the conclusions that have been generated from these data has shown that an inaccurate picture has evolved concerning the extent to which air compressors pose a health and safety hazard within the mining industry. In most instances, the frequency and severity of the compressor situation has been overstated and this has tended, over a period of time, to imply historical evidence that numerous air compressor accidents have occurred in coal and metal/non-metal mining operations. Our findings indicate that statistically, air compressors do not pose an unusual hazard

or pose as big a problem as originally expected.

Because conflicting meaning can easily be derived from the MSHA data, caution must be applied in use and interpretation. Therefore, these data are carefully discussed (in Section 2.1.1.1) and specific recommendations regarding the data base are given in Appendix C.

1.4.1.2 Mine Management

(1) Mine operators should review the manner in which air compressors are used in their operations or on their job sites, giving particular attention to hazards and problems that exist or could develop due to current methods of utilization, operation, and maintenance.

(2) From this review, improved operating procedures should be developed and implemented, and measures should be established for maintaining control over the compressor function.

(3) A preventive maintenance program should be established and monitored. Routine inspections should be conducted to ensure that control devices are properly set and operational.

(4) Workers should be instructed in the proper use and application of compressed air and in the hazards that can result if the compressor or compressed air system is abused. They should be able to interpret alarms and abnormal operating conditions, diagnose the problems, and respond, by habit, with safe procedures.

(5) Management must decide if and to what extent automatic shutdown controls should be incorporated into their compressor-compressed air systems, and workers must be advised of the system's automatic shutdown capabilities and instructed when they are to intervene in an automatic shutdown sequence, and in what way. When manual shutdown is required or when certain operating conditions warrant that shutdown should be initiated manually, this must be made known to the workers.

In most cases, manual shutdown can only be used if alarms provide sufficient time for workers to react. If there is no time for manual shutdown, automatic shutdown must be provided. As a means of illustration, some explosions have resulted when the operator started the compressor against a closed or "dead headed" air system. In one

instance, the operator started the compressor, then started walking toward the header valve which he intended to open. Shortly after start-up, before he could get to the valve, a violent explosion occurred. Automatic relief and shutdown would have prevented this explosion.

Whether manual or automatic shutdowns are used, particular care must be taken in their implementation, design, and use. False alarms and shutdowns must be avoided. Not only can they seriously impact production, but they can also lead to or cause more hazardous conditions in their own right, particularly when miners are performing a task in which an interruption of the air supply can pose an unsafe condition or when air is needed for control such as on a dragline or for opening and closing entry doors. In addition, and perhaps more importantly, nuisance alarms and/or shutdowns destroy the operator's faith in the protective systems. This means that when a real alarm is signaled, it may be ignored or at best, taken only casually.

1.4.1.3 Bureau Involvement

(1) The Bureau should provide improved guidelines for the safe application and operation of air compressors and compressed air systems in mining applications.

(2) Literature should be prepared and made available to the mining community discussing compressor usage in mining applications. Hazardous situations should be pointed out and guidelines for safe operations should be given.

(3) In-house or contracted reviews should be periodically and regularly conducted to determine the adequacy of reporting and documentation procedures and the accuracy of the data base.

(4) Industry trends with respect to equipment utilization and practices should be reviewed and, if warranted, a safety systems analysis performed. If safety provisions have been imposed, their effect should be evaluated.

(5) Industry intentions and their degree of implementation should be tracked. For example, our review indicates that a trend toward centralization of the compressor function above ground is developing.

Furthermore, this trend is expected to bring about improved maintenance practices, better operational control, and an increased level of interest and attention to the compressor function on the part of mine management and operators. Centralization, employing larger, more advanced units with built-in controls will reduce the potential for fire, explosion, and many other hazards by improving the quality of the compressor operation. The increased level of capital expenditure and the dependency of the mining operation on a centralized compressor function should encourage mine management to implement and enforce self-imposed regulations regarding the safe operation of the equipment.

The conversion process, however, will be an evolutionary one and as such it will not necessarily ameliorate the present concern for compressor hazards in mining applications. When considered in conjunction with our current assessment of the compressor hazard situation, this trend provides further support to the contention that new government regulations are not needed (at least until the problems of centralization evolve and industry's response to dealing with them is known). Guidelines, in the form of suggested practices and technical and safety information, however, are appropriate and should be welcomed by the industry.

1.4.2 Recommendation for Further Fluids Testing

In order to define the fluid properties that are most indicative of its fire resistance qualities during compressor usage, a procedure for determining the fluid's autoignition temperature at elevated pressures should be developed and investigated. Since this type of procedure will allow fluid evaluations under conditions that more accurately simulate the compressor's operating environment, its results should provide a more meaningful indication of the fluid's fire resistant qualities. Comparison of test results, in an experimental investigative program, with results from spray ignition, standard AIT, and carbon residue testing for a given set of fluids will provide a means for correlation among the various test methods and may show which method gives the best indication of fire resistance when compressor usage is being considered.

1.4.3 Closure

There is little doubt that air compressors perform a significant role in underground and surface mining operations and that they can be expected to do so for some time. There is also little doubt that air compressors and compressed air systems, can, if used improperly, threaten the health and safety of the workers, negatively impact production, and jeopardize the financial outcome of the project. Certainly concern over compressor and compressor-related hazards is warranted; even if the frequency of occurrence is relatively low, the consequences can be significant. In many cases, a single compressor accident can ultimately pose a hazard to a large number of workers.

It is important, therefore, that the utilization and operation of air compressors in mining applications be given proper respect and that corrective actions be taken to curb the potential hazards that can result from their use. Our findings suggest that air compressor utilization and the unsafe situations that can result from such utilization should be addressed by mine management (through better planning, preventive maintenance, and improved operating procedures) and by the Bureau (through improved guidelines and perhaps the development of new safety provisions).

No inventions were conceived during this project.

2.0 LITERATURE AND FIELD SURVEYS

In order to define the types of problems that occur when air compressors are used in mining applications, literature and field surveys were conducted to review air compressor usage in underground and/or surface coal and metal/non-metal mines. During these surveys, emphasis was placed on the industry's accident experience, with cases involving fires and explosions being of greatest concern. In general, we felt it was essential to determine the nature and extent of the compressor's involvement so that an appropriate picture could be developed regarding the severity of compressor problems and hazards. Certainly a better understanding of the compressor's involvement was needed if one was to accurately assess the problem and consider corrective measures to prevent or minimize future occurrences. This realization directed the course of our search.

Initially our work centered on making a proper qualitative and quantitative assessment of the compressor's role in reported compressor mining accidents; specifically, a proper assignment of causes was sought from MSHA data bases, published data, and from personal conversations with mine operators and compressor and lubricant manufacturers. Ultimately, our review was expanded to look at compressor problems in general since this would provide a larger data base from which to assess specific compressor problems and because many of the significant problems associated with compressors in general could be extrapolated to mining applications in particular. A review of foreign and domestic regulations regarding compressor utilization in mining applications was also conducted. The methods and procedures used in our literature and field surveys and our findings are discussed and presented below.

2.1 Literature Survey - Methods and Procedures

Two methods of assigning causes were generally pursued: (1) historical, that is causes determined or suggested by reports of air compressor accidents, and (2) analytical, that is causes indicated by design and constructional features and operating parameters considered likely to

result in fires or explosions or other hazards. The historical method was implemented through searches for reports and other publications narrating such accidents and at least suggesting probable cause. The analytical method was implemented by soliciting specific information from manufacturers (of air compressors, inter and aftercoolers, separators and filters, and lubricants) regarding design details and criteria from which engineering assessments could be drawn about the likelihood that certain compressor features (either design, installation, operating, or maintenance) might tend toward hazardous conditions or accidents. These methods were supplemented with conversations with mine operators and visits to six mines, the latter to observe some typical compressor operations first-hand. The approaches used in conducting these surveys and the results are described below.

2.1.1 Historical Method - Domestic Literature Search

In general, the historical method employed documentary search and survey of the open literature and reports held by the Bureau and MSHA; most notably the information repositories at the Health Safety Analysis Center (HSAC) and the Denver Technical Support Center. The historical method also included visits to several surface and underground mining operations.

2.1.1.1 Review of Government Reports

A visit was made to MSHA's Health and Safety Analysis Center to examine the accident data base with respect to compressor and compressor related accidents in coal and metal/non-metal mines. This visit resulted in the identification and acquisition of slightly over 200 mine operator reports of accidents, during the period of 1972 to 1979, which listed an air compressor as a primary or contributing factor. When these reports were analyzed, we found only eight accidents in which the air compressor was actually a principal or contributing cause.

In addition, copies of 18 reports of investigations of fires and explosions in coal and metal/non-metal mines between 1971 and 1980 "involving" air compressors were obtained from MSHA's Denver

Technical Support Center and from the Bureau. From this group, twelve accidents were identified in which the operation of an air compressor was a direct or contributing factor. Results from the abovementioned analyses are summarized in Tables 1 and 2.

As these tables show, statistically, compressor hazards do not seem to pose as big a problem as originally expected. Of the numerous compressor-related accidents that were entered in the data base, only a small fraction concerned the compressor directly and only a part of these resulted in or posed a direct fire or explosion hazard. The apparent discrepancy between the number of suspected and the actual number of compressor-related accidents tends to result from ambiguous reporting procedures; a failure to distinguish between those accidents in which the compressor was the principal cause and those in which the compressor or some portion of the compressed air system was present but was not a primary contributing factor. For example, the RFP stated that there were over 50 reported compressor-related accidents in 1976 alone in metal/non-metal mines; consequently, a relatively high accident frequency involving compressors should be expected. In general, these accidents were thought to be caused by equipment malfunctions, material failure or poor operating practices. As shown in Table 3, of the 56 accidents reported in 1976 for metal/non-metal mines, only one concerned the compressor directly; however, this accident did involve a fire and explosion.

Discrepancies between the apparent and actual number of compressor-related mining accidents most likely arise from procedures used to report, code, store, and retrieve the accident data--particularly when summary information is being sought. For example, when accident summary information is being sought and when accession of the accident data base is initiated by using the key word "compressor", the results produce a listing of "compressor accidents" even when the compressor was not a primary contributing factor, or in some cases, even involved in the accidents in question. It is evident that a summary generated in this manner will significantly overstate the compressor's involvement and the degree to which compressors should be expected to pose a health

Table 1

Summary of Types of Accidents Represented in the Over 200 HSAC Reports
(January 1972 to December 1979)

Fire, explosion, or other accident in which an air compressor was a primary or contributing cause.	<u>8*</u>
Contact with air compressor, bumping, etc.	37
Contact with air hose, coupling, header, etc.	33
Using air to clean, blowing of dirt, cleaning out holes, etc.	23
Lifting, moving, etc., air compressor.	11
Air leak, burst hose (effect of air blast)	32
Maintenance, working on air compressor	36
Electrical equipment, controls, etc.	8
Inflating tire with compressed air, blown tube, etc.	6
Other pressure vessel explosions or busts, such as acetylene tank, porta-power, naptha tank, airdox shell	4
Other accidents involving the words "air" or "compressor".	8
• Compressor timber guards burned, and burned compressor foreign substances inhaled (3)	
• Compressor struck roof jack	
• Tripped over air compressor hose	
• Contact with compressor hose reel holder	
• Blow pipe fell on arm	
• Untangling air compressor hose from cable	
Unrelated to air compressor, system, or compressed air	<u>21</u>
TOTAL NOT ATTRIBUTABLE TO AIR COMPRESSORS AT FAULT	219

* Air compressor accidents in which an air compressor was a primary or contributing factor are listed by HSAC document number in Appendix A, Table A1. A summary of the hazard is also given.

Table 2

Reports of Bureau of Mines/MESA/MSHA Investigations of
 Fires or Explosions Involving Air Compressors*
 (September 1970 to October 1980)

<u>LOCATION</u>	<u>DATE</u>	<u>AIR COMPRESSOR INVOLVED</u>
Valencia Pit	September 10, 1970	No
Columbia Quarry & Mill	July 27, 1971	No
Steward Mine	December 6, 1971	No
Star Mine	March 16, 1972	No
Anaconda Company	July 7, 1972	Yes
Schwartzwalder Mine	October 26, 1972	Yes
Morton Mine	November 16, 1973	Yes
Shannon Branch Mine	November 26, 1973	Yes
Ozark-Mahoning Mine #6	June 1, 1976	Yes
Henderson Mine	November 16, 1976	No
Ozark Mine & Mill	December 29, 1976	Yes
Smelting & Pelletizing Plant	February 3-8, 1977	No
Valley Road Quarry and Mill	April 15, 1977	Yes
Williams Brothers Slate Quarry	May 5, 1977	Yes
Cargill Mine	March 28, 1978	Yes
Cyprus Mill	February 15, 1979	Yes
Sugar Creek Quarry & Mill	May 29, 1979	Yes
Oro Grande Plant	October 3, 1980	Yes

* Summaries of these accidents are given in Appendix A, Table A2.

Table 3
Types of Accidents in HSAC Records
For Metal/Non-Metal Mines, Year 1976

Direct Air Compressor Involvement, cause not stated.	
Accident Occurrence Data in Report: "Compressor Exploded"	1
<u>Summary of Other Types of Accidents Reported as Air Compressor Accidents</u>	
Contact with air compressors, bumped, etc.	2
Contact with air hose, couplings, pipe, valves, headers, etc. (1)	12
Using compressed air for cleaning (2)	10
Lifting or relocating compressor	2
Blowouts, leaks in hoses, couplings, etc. (3)	7
Maintenance, working on air compressor	6
Inflating tires.	3
Miscellaneous, or not applicable to air compressors (4)	<u>13</u>
TOTAL, INCLUDING AIR COMPRESSOR ACCIDENT	56

- NOTES:
1. Usually involved person being struck by one of these.
 2. Usually involved particle being blown into eye, or cutaneous or subcutaneous injury.
 3. Usually reflected effects of an air blast, quite often due to employee negligence in not bleeding a line or system before working on a fitting, valve, etc.
 4. Neither compressor nor compressed air line involved in 9 of the total of 13. One of the 4 remaining consisted of jumping off an air compressor, two consisted of stumbling over a compressed air line, and one when untangling an air line from another line.

and safety hazard, unless by chance, the compressor actually was a primary factor in nearly all of the cases comprising the data base.

Current reporting procedures pose a further difficulty when trying to define the severity of compressor-related hazards. Although the extent is not known, compressor hazard data is certainly skewed as a result of Federal Regulations which do not require fires to be reported if they are extinguished within 30 minutes. In addition to providing for legitimate omissions from the data base, this regulation probably sets the stage for not reporting some fires even if the 30 minute limitation is exceeded. The result is that many of the more serious compressor-related accidents -- those involving fires and explosions -- may not be reported, and therefore, the data base may be inaccurate by reason of omission.

Under these conditions the extent to which compressors and compressed air systems pose a health and safety problem becomes more difficult to assess. While the overall number of "compressor-related" accidents actually in the data base tends to overestimate the severity of the problem when actual cause and effect relationships are analyzed, the lack of reporting of incidents which specifically involve fires and explosions could produce an opposite effect.

While the above discussion implies that all fires should be reported, regardless of whether they are extinguished within 30 minutes or not, this requirement is not recommended at this time. The reason is that in doing so, the government might be imposing another burden on the mining industry, in terms of additional reporting requirements, that is not needed or justified. It is our opinion, after looking at all of the available data in conjunction with the comments from operators and manufacturers, that compressor utilization in mining applications does not pose an unacceptable risk to the health and safety of the workers. As such, we do not see a need at this time for new regulations governing the use of compressors in surface and underground coal and metal/non-metal mines, although we do see a need to provide guidelines for the safe application and operation of air compressors and compressed air systems in mining applications.

2.1.1.2 Computer and Manual Literature Search

A computer search of national data bases was undertaken concurrently with a manual search for documents held by the Southwest Research Institute Technical Library or obtainable by loan or purchase. The manual search produced an extensive bibliography of articles applicable to air compressor design and utilization; only a few pertinent additions were gained from the computer search of the national data bases. Of this bibliography, however, only a small number of articles mentioned mine applications, and this was generally by reference. Nonetheless, the content of many of the articles, although not directly aimed at mining, was certainly applicable to the scope of our investigation. Many of the articles were explanatory in nature, primarily describing equipment, components, operating practices, lubricant properties and requirements, and maintenance requirements and applications. Some articles dealt with compressor safety while a limited number dealt with compressor hazards, the most common being fires and explosions caused by lubricant involvement within the compressor's operating environment.

2.1.1.3 Findings

Our review of the accident data and of the open literature indicates that broadly speaking, compressor safety hazards can be classified into two basic groups: those leading to or posing a threat of fire and/or explosions, and those stemming from physical events encountered when using a compressor which do not necessarily lead to fires and explosions, but which nevertheless present a dangerous condition for the workers. Examples of these hazards include:

- (1) The whipping of hoses accidentally broken or of couplings inadvertently separated,
- (2) the absence of guards on drives, couplings, and flywheels,
- (3) contact or exposure to heat transfer equipment,
- (4) improper suspension, anchorage or routing of pipes and lines,

- (5) hazards created by the improper use of air, for example, using high-pressure air for cleaning and inflating tires, etc.,
- (6) unsafe working practices on and around the compressor unit or air system or violation of safe working rules, such as spilled oil on steps or failure to bleed the pressurized system before disconnecting or otherwise working on a component, and
- (7) exposure to high noise levels.

While it is inappropriate to list examples from the first group because of the complex interaction among the many variables involved, it should be noted that almost all fires and most explosions are due to the ignition of combustible mixtures (carbon deposits, mists, and vapors) stemming from lubricant involvement. Therefore, the hazard analyses dealing with this group can be subdivided into two additional areas: one dealing with the likelihood that a fire or explosion will occur once a combustible mixture is present in the compressor or compressed air system, the other dealing with events that produced the combustible mixture in the first place. While both of these areas are influenced to some extent by the compressor's design, the second area, that is, the condition or chain of events that lead to the development of the potential hazard, is primarily dependent on the manner in which the compressor is employed and operated. In particular, the development or presence of combustible mixtures is usually a function of the mechanical condition of the compressor or certain compressor components (mechanical design and maintenance factors). Overall, however, our findings suggest that compressor and lubricant manufacturers have carefully studied many of the problems associated with the lubricant's interaction among varied compressor design and operating parameters and as a result, many improvements in mechanical design and lubricant properties have been introduced.

The mechanisms by which lubricants and certain lubricant properties interact with the compressor's operating environment to create conditions which are prone to fire and explosion hazards have also been extensively studied, although for many years not all of the findings have found full and general acceptance. Since fire and explosion hazards are a

major concern to this program, and since lubricant involvement is a primary factor leading to these hazards, this area is reviewed in detail in Section 3.0. In particular, lubricant properties, combustible mixtures, and ignition phenomena are presented.

2.1.2 Analytical Method

The analytical method was intended to assign probable cause with respect to accidents or problems involving air compressors by identifying design and constructional features and operating parameters considered likely to result in fires and explosions or other hazards. The method was implemented by soliciting specific information from manufacturers of air compressors, air compressor components or lubricants regarding design details and criteria upon which to make engineering assessments about the likelihood that certain design, installation, operating or maintenance features might trend toward hazardous conditions or accidents. In general, the following information was sought:

- (1) Compressor design and performance data,
- (2) Lubricant requirements, practices, and recommendations,
- (3) Specific installation, operating, and maintenance requirements,
- (4) Cooling requirements and limiting ambient temperature conditions,
- (5) Limitations or restrictions in operation,
- (6) Known failure mechanisms and design changes to improve operational safety,
- (7) Known past accidents; knowledge of any fires or explosions,
- (8) Known mines with compressor installations,
- (9) Experience with field maintenance, and
- (10) Person(s) knowledgeable of compressor field data, designs, and operations.

For the most part calls to compressor manufacturers were routed through sales and marketing people rather than to the engineering staff. The reasons for this are that marketing people are more familiar with customer requirements and field performance since they serve as liaison with the user after the sale and are, in effect, the primary feedback link to the company. In addition, almost all salesmen are graduate mechanical engineers, thoroughly familiar with the company's product lines and their application and field performance. Conversely, design and test engineers have little contact with customers, their only regular source of feedback from the field being through sales.

In general, all manufacturers contacted were helpful, although the desired design data necessary to assess, on an engineering basis, the propensity of any significant number of compressors toward fires and explosions could not be readily obtained. In most instances, the best compromise consisted of obtaining catalog sheets and operator installation, maintenance, or service manuals for representative models. Manufacturers of aftercoolers, separators, and filters furnished catalog sheets but were not in a position to do more.

Lubricant manufacturers were quite responsive; several provided lists of their lubricants formulated for or used specifically in air compressors; test data and specification sheets were also provided. A representative sampling of these data along with some compressor manufacturer specifications were presented in the Phase I report. A review of these lubricants with respect to the lubricant properties and specifications recommended by the compressor manufacturers showed that several quality lubricants, meeting known manufacturers' requirements, are available.

Since specific design data were not available, analytical methods were redirected to consider the compressor's given operating parameters, lubricant characteristics, and safety devices and the influence these factors might have on projecting a safe operating envelope for compressor utilization. Toward this end, pertinent data were extracted from manufacturer's literature or obtained from telephone conversations with manufacturers, maintenance shops, distributors, and dealers and sale

representatives. The parameters of primary interest included compressor type and capacity, pressure and temperature limits, safety devices for warning and/or automatic control or shut-down, lubrication requirements, and the chemical and physical properties of the lubricants with respect to their tendency to break down and form carbonaceous deposits or combustible mixtures under both ordinary and severe operating conditions.

As a result of this effort, a listing of compressor operating parameters and lubricant requirements was developed for numerous compressors offered by the leading manufacturers. This information, which is believed to provide a comprehensive representation of the compressor population, was presented in the Phase I report. Even though all of the compressors listed may not be used in direct mining applications, a large number are used or are at least representative of those used in such applications. This list was used to develop the maximum recommended operating envelope, in terms of discharge pressures and temperatures, for the compressor population. These envelopes are shown in Figure 1 (reciprocating), Figure 2 (rotary screw), and Figure 3 (centrifugal and rotary vane).

Nearly all modern compressors are equipped with pressure relief or safety valves to limit system pressure in event of a malfunction in the compressor or in the immediate air line components. In addition, most compressors have a set of valves or a pressure control system which cycles the compressor's operation in such a manner that system pressure remains within preset limits.

Compressors usually incorporate a temperature-controlled safety shut-down switch which shuts down the compressor drive in the event that a predetermined discharge air temperature is reached or exceeded. In some compressors, oil pressure switches are incorporated to either shut down the compressor or to prevent its starting if low or insufficient oil is present in the lubricating system.

Many centrifugal compressors employ vibration detection equipment and automatic controls to provide immediate compressor shut-down if preset vibration limits are exceeded. Through extensive research and development, it has been shown that certain vibration limits provide

FIGURE 1. MAXIMUM TEMPERATURES AND PRESSURES OF DISCHARGE AIR RECIPROCATING COMPRESSORS

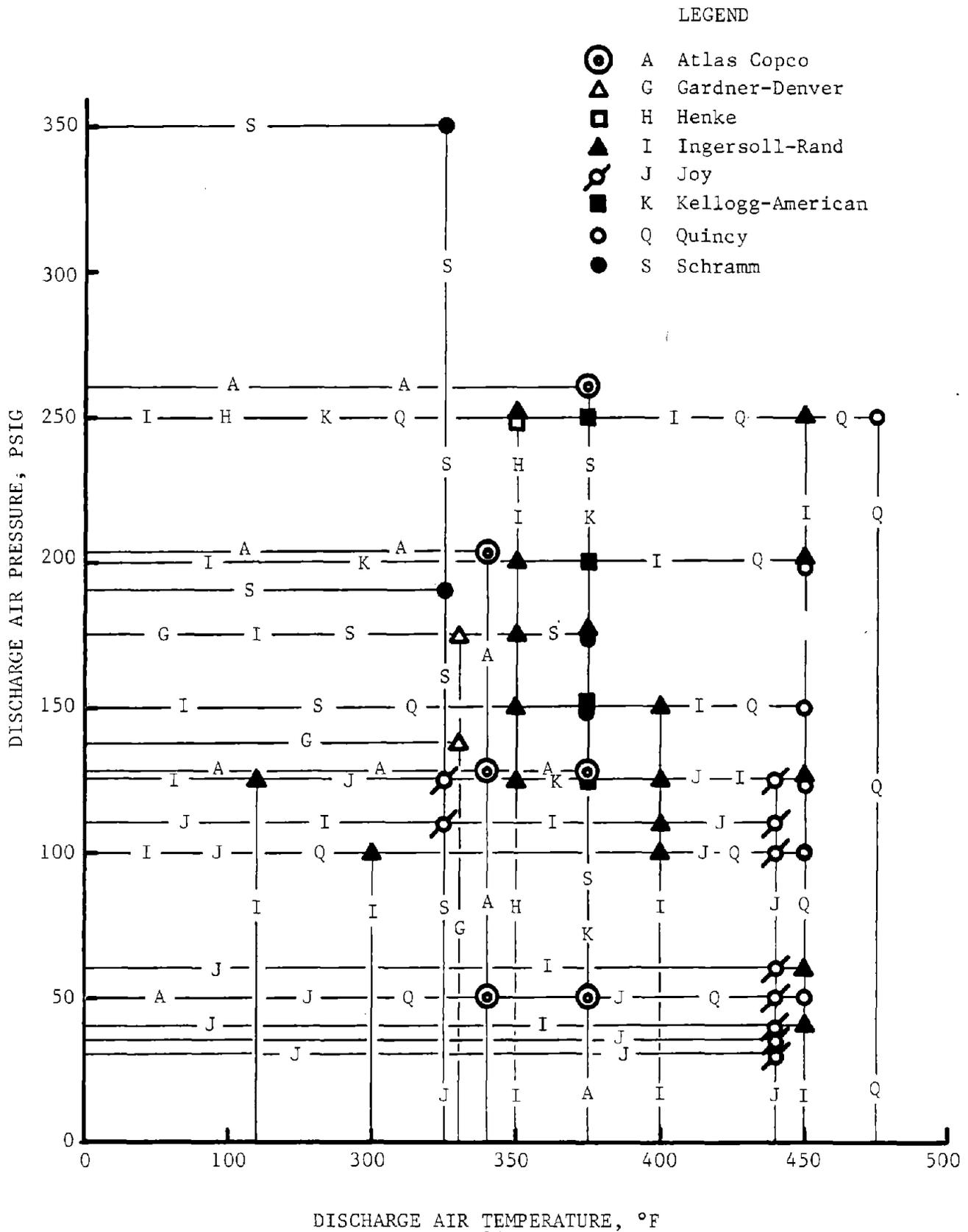


FIGURE 2. MAXIMUM TEMPERATURES AND PRESSURES
OF DISCHARGE AIR
ROTARY SCREW COMPRESSORS

LEGEND

- | | | | |
|---|--------------------|---|----------------------|
| ⊙ | A - Atlas Copco | ✕ | K - Kellogg-American |
| ◻ | D - Dunham-Bush | ◼ | L - LeRoi |
| △ | G - Gardner-Denver | ○ | Q - Quincy |
| ▲ | I - Ingersoll-Rand | ● | S - Schram |
| ⊗ | J - Joy | | |

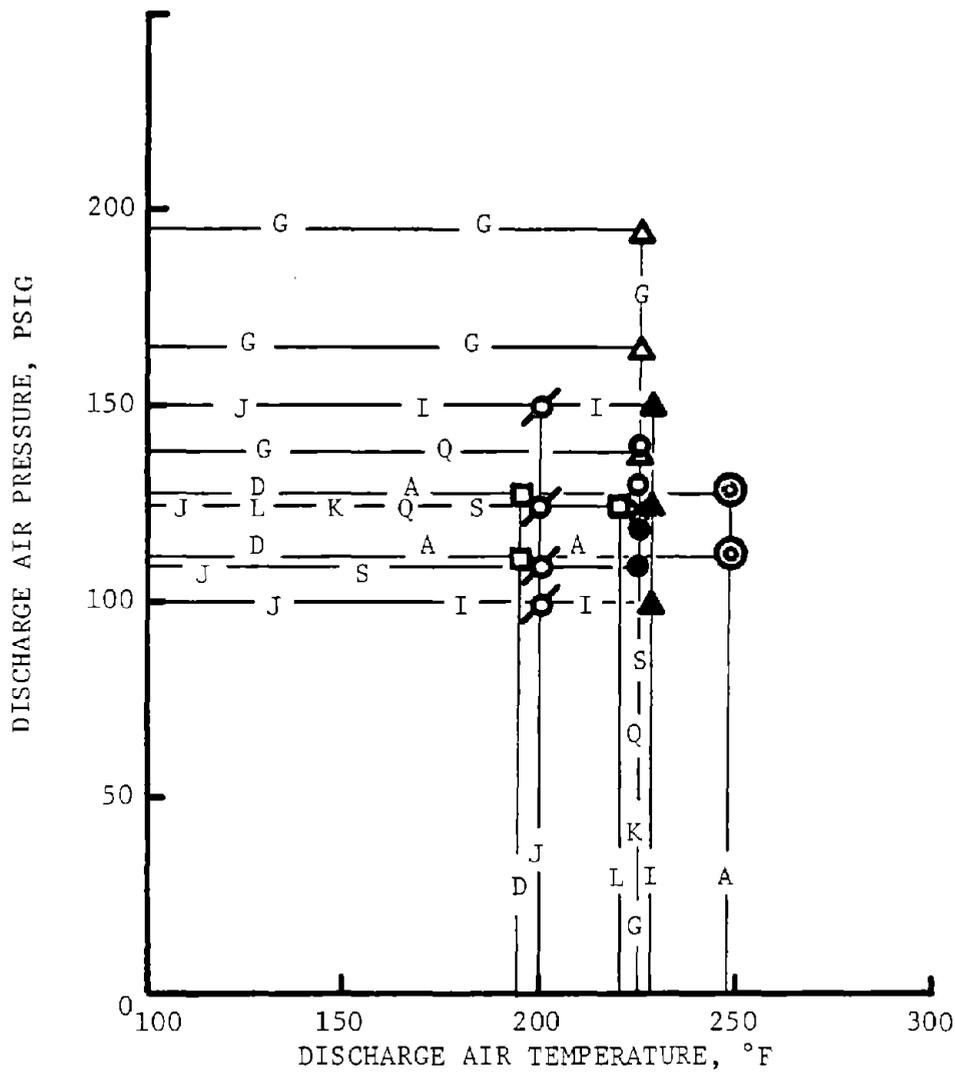
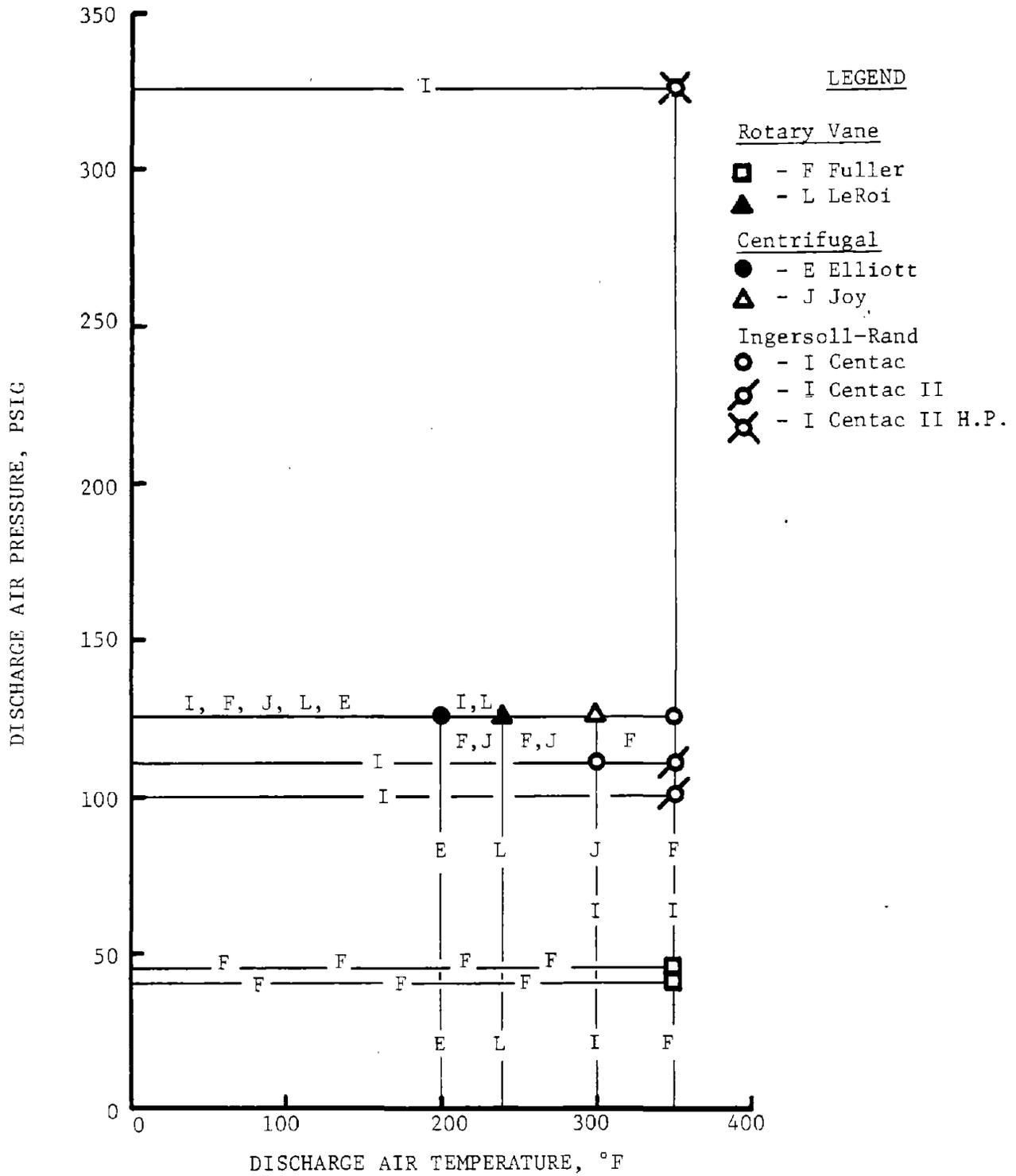


FIGURE 3. MAXIMUM TEMPERATURES AND PRESSURES
OF DISCHARGE AIR
CENTRIFUGAL AND ROTARY VANE COMPRESSORS



a good indication of impending metal-to-metal contact and that only through this warning is it possible to shut the compressor down before damage is encountered.

All of the above mentioned limiting devices are set either at the factory or during installation, according to the compressor's operating parameters and the customer's operating requirements. In most cases, however, these settings can be changed in the field and we found many instances where specific warning and control devices were reset to unsafe limits, disconnected or deactivated, or broken. Certainly malfunctioning warning and control devices were contributing factors in many of the reported compressor accidents; if these devices had worked, many compressor accidents would only have been compressor incidents; more than likely, the compressor problem or malfunction could have been corrected before a compressor accident resulted. It is important to realize, that in cases where the safety device is intended to function as an independent sensor giving "go" or "no-go" signals or providing "last resort" relief to the system (such as an oil pressure sensor or a relief valve), the safety device, whether it functions properly or not, is only responding to a prior compressor or air system malfunction. In these cases, the device acts as a protective switch and its failure to function properly, while part of the scenario, is not the cause but only a contributing factor to the accident.

On the other hand, in those cases where the compressor's operation bears a direct dependency on the safety device, that is when the safety device is at times actually involved in the compressor's operating cycle such as an unloading valve, then failure of the device can and probably will lead directly to an accident (if one of the other protection devices fails or has been disabled). Here the device itself must be considered as a primary contributing factor.

Our investigation indicates that there are two major concerns with protective or safety devices. First, they are often disabled, overridden, or improperly reset, thereby negating their function and violating the principle that at least two events should exist between a safe and unsafe situation. Secondly, for a large number of the

compressors (except for some of the newer units) no means is provided for checking the protective devices during normal operation or prior to start-up. If such checks were available, and used, not only could inoperative devices be detected and replaced, but the tendency to override or purposely reset these devices to unsafe limits would probably decrease. Since we expect that most of the protective and safety devices, if regularly maintained and checked, will offer good reliability in terms of design, system safety problems should decrease although the frequency of compressor incidents may increase. The important point is that these incidents (for example, thermal shut-down or operation of the relief valve) will direct attention toward a compressor problem which can be addressed and corrected before it leads to a serious accident.

2.1.3 Compressor Regulations - Domestic and Foreign

Compressor safety was also reviewed from the standpoint of the regulations applicable to its manufacture, installation, operation and maintenance; both domestic and foreign regulations and codes were examined:

- CFR 30/ASME Boiler and Pressure Vessel Code
- British National Coal Board
- The Principle Union of the Industrial Professional Association (West Germany)
- The Commission of the European Communities (The Luxembourg Group)

A comparison of these national regulations, standards, and codes is given in Appendix B, Table B1, where provisions of each regulation are presented in such a manner that comparisons can readily be made between similar subject areas. Pertinent sections of CFR 30 were also presented in the Phase I report along with the British Coal Board Code and English translation of the West German regulations. These documents were presented in their entirety for reference and study of details, if desired. The Luxembourg Group document contained no pertinent information; accordingly, no segments of it were reproduced for the report.

To the extent feasible, each document is arranged in the

following sequence:

SCOPE

- Compressor
 - Identification
 - Design, construction
- Aftercoolers
- Receivers
 - Identification
 - Design, construction
- Installation, general
- Piping
- Operation
 - Lubrication
 - Speed
 - Instrument readings
- Maintenance
 - Sampling of oil supplies
 - Inspection of crankcase oil
 - Pipe mains, installation, inspection, maintenance
 - Planned maintenance schedule

In comparing the various regulations, unique aspects of each should be noted. One is the intended application. The various parts of CFR 30 considered, for example, apply to air compressors for mining, without regard to the type of compressor or its intended use. The ASME Code applies to pressure vessels in general, not to compressors, and as such may be considered as governing design and construction of only compressor receivers, separators, intercoolers, and aftercoolers, insofar as air compressors are concerned. CFR 30 provides very general coverage of air compressors, covering receivers and other pressure vessels largely by reference to the ASME Code. Whereas CFR 30 is very general, the ASME Code is very specific and detailed. The British regulation considered applies only to reciprocating compressors for use underground and on the surface at coal mines and other National Coal Board undertakings. It is very

specific and quite detailed, to the extent of containing many of the instructions included in installation, operating and maintenance manuals generally furnished by U. S. compressor manufacturers. Although it covers certain aspects of receivers, it refers to appropriate British Standards for design and fabrication details and also to the Mines and Quarries Act, 1954. The West German VBG 16 applies to industrial compressors without restriction as to type, but includes individual sections on air compressors with "oil-lubricated pressure spaces", compressors for flammable, poisonous or chemically unstable gases, and compressors for reacting gas mixtures. Special sections concentrate on safety devices and instrumentation.

The 16th Report of the Safety and Health Commission for the Mining and Extractive Industries of the Commission of the European Communities, for 1978, contained no information or regulations pertaining to air compressors. The bibliography of the work of the Safety and Health Commission in this volume did not indicate any activity in the field of air compressors. The Mine Safety Commission of this organization is composed of 36 members: four each from the Federal Republic of Germany, France, Italy, the Netherlands, Belgium, Luxembourg, the United Kingdom, Ireland, and Denmark. This body is often referred to as the "Community of Nine", or the "Luxembourg Group". The function of the Commission as a whole is to compile safety statistics, investigate common problems, and prepare proposals to member governments in various safety areas. Proposal adoption by the member governments is optional.

CFR 30 contains separate regulations designated as: Part 55 -- Health and Safety Standards - Metal and Non-Metallic Underground Mines; Part 75 -- Mandatory Safety Standards - Underground Coal Mines; and Part 77 -- Mandatory Safety Standards - Surface Coal Mines and Surface Work Areas of Underground Coal Mines. Within CFR 30, consistencies and differences -- not necessarily conflicts -- are found. Four mandatory provisions are common to each of Parts 55, 57, 75, and 77. These pertain to (1) receiver construction, etc., according to ASME Code, (2) pressure relief before repairing pressurized systems, (3) prohibition against directing compressed air toward a person, and (4) use of safety chains at high pressure air connectors. Part 75

specifically incorporates the provisions and specifications established by Section VIII of the ASME Boiler and Pressure Code (1971). Parts 55 and 57 contain six recommended or suggested practices which are omitted completely from Parts 75 and 77. In addition, provisions of compressors and receivers with relief and drain valves and pressure gauges, recommended in Parts 55 and 57, is mandatory in Parts 75 and 77. A comparison of these Parts is shown in Table B2.

The British regulation is explicit in requirements for monitoring air and lubricating oil pressures, pressure drop across the inlet air filter, and temperature indicating or recording instruments. It also requires comprehensive protective devices to automatically shut down the compressor if air, water, or lubricant temperatures or pressures exceed established maximums. The West German regulation is oriented more toward pressure than temperature monitoring, but also requires protective devices to automatically shut down the compressor if certain maximum pressures are exceeded. Table 4 compares limiting temperatures as specified in the various national standards.

Only the British regulation contains mandatory provisions for assignment of responsibilities to compressor operators for starting, stopping, operating, and surveillance of operating conditions. It also includes mandatory provisions for inspection and maintenance and a suggested planned maintenance schedule with mandatory components.

2.1.3.1 Codes and Rules of the British National Coal Board, Reciprocating Air Compressors (Surface and Underground)

Since the British Code is the most explicit with respect to the design, construction, acceptance, installation, operation, inspection, and maintenance of reciprocating air compressors in mining applications, it is examined more closely below.

Major segments of the NCB Code concern operation, inspection, and maintenance as required by the Mines and Quarries Act of 1954 and the Coal and Other Mines (Fire and Rescue) Regulations of 1956. A pertinent factor concerning operation is supervision; each compressor and its ancillary plant shall, while it is operating, be the responsibility of a competent person instructed in writing by the manager for that purpose.

Table 4
Comparative Compressor Limiting Temperatures, °F

	<u>Discharge</u>			<u>Inlet</u>
	<u>Compressor</u>	<u>Aftercooler</u>	<u>Automatic Shutoff</u>	<u>Final Stage</u>
CFR 30 (1)	400	-	400	-
NCB, Air (2)	320	-	320	135
NCB, Lube	176 (in, out of crankcase)			
VBG 16 Oil Lub. (3)				
Single Stage	392-428	140-176	-	-
Multistage	320-356	140-176	-	-
Multistage, inter.(4)	392	176	-	-
Oil Inj. Cooling	212	-	-	-

- (1) Code of Federal Regulations, Title 30
- (2) National Coal Board, British Regulations for Reciprocating compressors in coal mines
- (3) Federal Republic of Germany General Regulations for Industrial Compressors
- (4) Intermittent operation

Requirements for supervision are broken into three levels:

CONTINUOUS SUPERVISION: Continuous supervision requires that the authorized attendant(s) shall be within audible range of the compressor during the whole time that it is running.

REGULAR SUPERVISION: Regular supervision requires that the authorized attendant(s) (who may have other main duties) start and stop (except in an emergency) the compressor and visit the compressor to check its operation at frequent intervals. Such intervals are usually once per hour.

UNSUPERVISED COMPRESSORS: A compressor is deemed to be running unsupervised when the authorized attendant(s) (who may have other main duties) start and stop (except in an emergency) the compressor and visit the compressor at least once per shift to check its operation.

These levels are applied as follows:

- Large and medium compressors, both fixed and portable, shall be operated only under regular or continuous supervision;
- Small compressors located on the surface, both fixed and portable, may be operated unsupervised or under regular or continuous supervision;
- Small compressors located underground, both fixed and portable, shall be operated only under regular or continuous supervision.

Furthermore, no compressor can be started other than by the attendant or mechanic or electrician of the mine or a person authorized to do so.

Inspection and maintenance requirements are implemented by means of a mandatory routine maintenance program and a partially mandatory, partially voluntary, planned maintenance schedule. Installation of certain instrumentation and compressor protective devices is pre-requisite to both maintenance programs; however, the provisions of each merit consideration for use in U.S. mine safety programs to minimize or

prevent air compressor fires, explosions, and other hazards. The programs are broadly as follows:

ROUTINE MAINTENANCE - MANDATORY

(a) Daily Inspection of Running Compressors

The attendant or responsible person shall during each shift:

- (1) Check that the cooling water is circulating correctly,
- (2) check the level of the oil in the crankcase,
- (3) check the oil pressure,
- (4) check the oil feed to the cylinders,
- (5) check outlet air pressure and temperature,
- (6) check the performance by listening to the standard of running, and stop the compressor and report to appropriate supervisors should there be any sudden unusually noisy running,
- (7) discharge any accumulation of oil and water from the air receiver, the intercooler, the aftercooler, and the main supply pipes, and
- (8) record all adjustments in the log book provided.

(b) Daily Inspection of Standby Plant

Standby plant shall be inspected daily by the authorized attendant to insure that it is ready for immediate duty, and the inspection shall be recorded in the log book provided.

PLANNED MAINTENANCE SCHEDULE - UNDERGROUND INSTALLATIONS (UNLESS OTHERWISE NOTED)

Because of the diversity of equipment and conditions of installation and operation underground, the schedules set out should be adopted where circumstances permit except that the mandatory requirements shall apply under all circumstances:

Weekly Maintenance

(a) At least once each week or after 100 hours running, any necessary adjustments shall be made.

(b) A responsible person who is not the regular attendant shall check the operation of safety valves, e.g., by hand easing.

Biweekly Maintenance

Air filter units should be examined and cleaned or replaced by clean units at least once every two weeks or after 200 hours.

Monthly Maintenance

(a) On underground compressors, at least once per month or after 600 hours running:

- (1) The oil in the crankcase of fixed compressors should be either changed, or inspected and sampled and changed, if necessary,
- (2) the oil in the crankcase of transportable compressors should be changed,
- (3) the air valves for each stage of compression should be inspected and cleaned, and
- (4) air filters shall be cleaned or replaced by clean units.

(b) On surface compressors, at least once per month or after 600 hours running:

- (1) The oil in the crankcase should be either changed, or inspected and sampled and, if necessary, changed,
- (2) the air filter shall be cleaned or replaced by a clean unit.

(c) Standby plant shall be inspected by a competent person.

Three Month Maintenance

At least once each three months or after 2000 hours running,

- (1) The intercooler and aftercooler sections should be cleaned or replaced by clean sections,
- (2) the radiator should be drained and washed out,

- (3) all protective devices should be cleaned and inspected and those not certified by the manufacturers to be "fail safe" shall be tested for correct operation,
- (4) the output control gear should be cleaned and inspected,
- (5) the air valves for each stage of compression in surface installations should be cleaned or replaced with reconditioned valves, and
- (6) motion bolts should be inspected and tightened if necessary.

Annual Maintenance

- (1) The air receiver(s) should be thoroughly cleaned and examined internally,
- (2) air mains should be opened up and cleaned of any carbon-oil deposits*
- (3) intercooler and aftercooler sections shall be cleaned or replaced with clean sections,
- (4) fusible pellets or complete plugs shall be replaced with new components,
- (5) safety valves shall be tested to determine that they operate at the correct pressure,
- (6) protective devices shall be examined and tested to determine that they operate correctly, and
- (7) the following shall be examined and, if necessary,

* The section of maintenance of pipe mains provides the following:

Inspection and Examination

It is recommended that the piping between the compressor(s) and the receiver(s) should be disconnected at intervals of not more than 12 months, or at such shorter intervals as may be directed by experience, for internal examination and removal of carbon deposit or rust from condensate. The first length of pipe beyond the receiver should be similarly examined, and if carbon deposit or rust is found, the pipe shall be cleaned; subsequent pipes should be removed and cleaned until a point in the main free of carbon deposit and rust is reached.

cleaned and/or adjusted:

- (a) Cylinders and ports,
- (b) piston assemblies,
- (c) crankshaft and bearings,
- (d) crosshead and piston rod assemblies
(where fitted),
- (e) oil pump,
- (f) packing glands and oil wiper rings,
- (g) alignment of driving motor, and
- (h) vee-belts and pulleys.

Records

Records shall be kept of all inspections, examinations, repairs, tests, etc., carried out on all compressors and their equipment in accordance with the planned maintenance scheme of the mine.

In a nationalized industry, such as the coal industry in England, the equipment as well as the workers are a responsibility of the government, which can, accordingly, lay down rules to safeguard both interests, including ownership and maintenance of the equipment to safeguard the investment represented by the equipment. Superficially, it might appear that the regulations contained in this document are aimed primarily at satisfying the latter objective. Important though that objective may be, when we consider the British Code with respect to the factors associated with air compressor accidents in U.S. mining operations, it is evident that provisions of the code could have prevented many of the accidents, consequently preventing many personal injuries and fatalities, as well as property and other economic loss.

Even so, introduction of a maintenance code such as this in the American mining industry would certainly meet with initial disapproval on the part of many compressor manufacturers and mine operators, who in many cases recommend their own maintenance programs. And while it is true that many others do not, imposition of a mandatory program would certainly

encounter insurmountable difficulties. However, it may be possible that a code of this type could be promoted industry-wide on a voluntary basis, supported by an education program presenting the "whys" of the program and soliciting the cooperation of manufacturers, mine operators, and union members. If issues of safety and machinery longevity are emphasized, such a program might be accepted.

2.2 Field Survey

A limited amount of field survey work was accomplished to support the literature survey. Six mines and three compressor manufacturers were visited and numerous calls were made to compressor and lubricant manufacturers, field representatives, and mine operators. Our areas of interest were applications, problems, historical accidents, current practices, and emerging trends. In addition to the mine visits, the field survey included visits to three compressor manufacturers, one of which specializes in units for underground mines. These visits, along with the mine visits and our numerous conversations with other manufacturers, were highly beneficial in helping assess the nature of compressor utilization in the mining industry, the kinds of problems which have and are being experienced, corrective measures and design improvements that have been incorporated over the years, and the trends that seem to be developing in air compressor usage in mining applications.

The mine visits were arranged to provide first-hand information on current practices and problems encountered with different types of air compressors, to observe potential hazards that could lead to accidents, and to discuss scenarios that have led to accidents (either at the mine in question or incidents at other mines with which the personnel were familiar). The group of mines visited included four western (three underground, one underground and surface; three metal/non-metal and one underground coal) mines, and two eastern surface coal mines. Since several job sites were visited at most of these mines, numerous compressors of various type, size, and function were observed. Several attitudes toward the compressor function and the mining operation in general were also noted.

For the most part, the mines were very cooperative.

Interviews with operating and maintenance personnel were made possible, and surface and underground trips to view the compressor equipment and the overall mining operation were provided. Samples of new and used compressor lubricants were provided for subsequent analyses.

In both surface and underground applications, compressed air serves many functions. For example, underground, compressed air is used to operate drills, hand tools, loading equipment, roof bolters, rock dusters, and maintenance and servicing equipment; in pumping, drainage, transport and loading; and to provide starting air for diesel engines. On the surface, air is used quite intensively in blast hole drilling. Here, air is circulated from the compressor through the drill pipe to the bits where cuttings are picked up and bailed from the hole. Since sufficient air volume and velocity are required to clear the cuttings from the hole as soon as they are formed, large reciprocating or rotary screw compressors are usually used in this application. In addition, small reciprocating compressors are used in several capacities, such as to provide pilot and control air for draglines and on service and utility trucks.

Although portable compressors are still used underground, in many cases the compressed air, or at least a large portion of it, is being supplied from a large compressor or group of compressors located on the surface. Operationally, this means that the air must be delivered through a piping network to remote locations which are often considerably removed from the source. Since the function of any compressed air system is to supply air at sufficient volume and pressure to meet operational requirements, the physical condition of the piping system becomes an important parameter of the system and can become an influential factor in contributing to a compressor fire and explosion hazard. For example, workmen have been known to adjust the compressor to unsafe conditions in order to overcome lost capacity caused by leaks or to compensate for insufficient capacity encountered when additional lines are added to the system.

Air line materials are also important, particularly in those applications where hoses are used. If the air line conveys an oil mist, it must have a tube that is resistant to oil or its ID will swell,

restricting the flow and this will lead to increases in the pressure and temperature of the air.

Fire hazards can also result at the user end of the system. Many drills develop high temperatures from the rapid compression of air and if improper lubricants are used, the exhausted air will contain oil smoke or vapor, creating a fire or explosion hazard in the mine. Excessive oil carryover from the compressor or improperly set or functioning oilers in the compressed air line can produce a similar result.

All-hydraulic equipment is replacing pneumatic equipment in some cases. Hydraulic systems result in less noise, no noxious fog, cleaner drill sites, higher penetration rates, reduced rig vibration, and lower energy requirements. If this apparent trend continues, the demand for compressed air at the work site will diminish and the need for and use of underground compressors can be expected to decrease. Additionally, even in many cases where pneumatic equipment is not being replaced by its hydraulic counterparts, the use of underground compressors seems to be decreasing, primarily because of noise standards. As a result, a trend seems to be developing toward aboveground centralization of the compressor function (for underground mines). Such a development is expected to improve the quality of the compressor function and reduce the potential for fire and explosion hazards by bringing about updated technology (more advanced units with built-in controls, reduced lubricant involvement, etc.), improved maintenance, better operational control, and increased attention to the compressor function by mine management and operators. Centralization will bring to light the importance of the compressor function in terms of production and cost. Increased capital expenditures and the new dependency of the mining operation on a centralized compressor function should encourage mine management to implement and enforce self-imposed regulations regarding the safe operation of the compressor system.

This trend, however, will not necessarily be a panacea for all compressor-related fire and explosion problems, nor will it totally ameliorate the present concern for compressor hazards in many mining applications. First, if the trend does in fact materialize, it will do so through an evolutionary process, meaning that it may take many years

before the populations of underground and aboveground compressors change sufficiently to statistically alter the accident data or to change the current state of compressor utilization and operating practices. Additionally, not all mining operations can be expected to follow this trend; thus, a certain portion of the underground population will remain intact over the years and it may prove to be the case that much of the present concern over the compressor-related fire and explosion hazards will rightfully persist. Uncertainties also exist as to the rate and extent to which air equipment might be replaced by hydraulic equipment.

On balance, therefore, we must assume that underground compressors will be present within the mining community for some time; thus, their safe operation and utilization will remain a concern for mining companies and the Bureau alike. While emerging trends suggest that the frequency of fire and explosion hazards may be fewer, the causes and means of prevention should not be ignored.

3.0 FIRE AND EXPLOSION HAZARDS

All types of oil lubricated or internally oil-cooled compressors are subject to the dangers of fire and explosion if they are not properly utilized and maintained and certainly a compressor fire can present a serious hazard in a mine. Therefore, even though compressor related fires and explosions may be rare, the consequences are usually severe enough to warrant concern and to suggest that corrective measures should be taken to prevent future occurrences. Our review of the open literature and our conversations with compressor and lubricant manufacturers indicate that the primary cause of all fires and a majority of explosions arise from the spontaneous ignition of carbonaceous deposits and oil mist or vapors which have accumulated or become trapped in a hot part of the compressed air system.

The events or scenarios leading to the development of combustible mixture and ignition sources may vary from case to case. However, once the combustible mixture is present, the potential for a hazard depends on the state of the system with respect to the threshold values that define each phase of the combustion process; ignition, flame propagation, detonation, and flame extinguishment. The dependency of these combustion phases on the system variables (temperature, pressure, mixture concentration, oxygen content, and lubricant composition) means that a system safety analysis of the compressor must be broken into two major areas, one dealing with the likelihood of a fire or explosion once the combustible mixture is present, and the other dealing with the events that have led to the development of the combustible mixture in the first place. While both of these areas are influenced to some extent by the design of the compressor itself, the second area is primarily dependent on the manner in which the compressor is employed and operated.

This section treats fire and explosion hazards associated with air compressor usage. In particular, two areas are investigated: (1) the mechanisms of fires and explosions as they relate to lubricant involvement in compressors, and (2) a summary of causes that have led to hazardous

operating conditions in mining and mine-related applications that have aggravated the lubricant problem to the extent necessary to cause a hazardous set of operating conditions.

3.1 Mechanisms of Fires and Explosions

It is well known that the occurrence of fires and explosions requires the presence of a fuel, an ignition source, and sufficient oxygen to support combustion. It is also known that the extent to which these parameters pose a fire, explosion, or detonation hazard within a system depends on the presence of threshold values for the physiochemical variables that define the combustion process. For the purposes of this report, fires and explosions can best be considered by examining each phase of the combustion process; ignition, flame propagation, detonation, and flame extinguishment, and the relationship of these phases to the design and operating parameters of air compressors and compressed air systems.

The initiation of combustion, termed ignition, is probably best defined in terms of physical criteria of events; that is, ignition can be judged to have or have not occurred only by setting the physical criteria of whether a flame or detonation has occurred. Externally, a visible flame may satisfy this judgment. Internally, the confinement of the compressed air system causes sudden increases in temperature or pressure which are often the criteria for judging whether ignition has occurred. Thus, from a hazards prevention standpoint, the initiating source is the critical link; once ignition has occurred the hazard is imminent.

The response of combustible mixtures to potential ignition sources has been studied in terms of a localization of energy within a space and time spectrum of exposure⁽¹⁾. The strength and duration of the ignition source, as well as the characteristics of the fuel-air mixture and the geometry of the vessel, influence the reaction and determine whether a fire or an explosion will take place. Electrostatic sparks are representative of one end of the spectrum; here, high local temperatures are created over short distances in a fraction of a

second. This triggers a chemical reaction and a microscopic flame kernel and makes the energy of the source a key factor in promoting ignition. If the kernel is large enough to develop a self-propagating flame, ignition is possible, whereas if the kernel is quenched below the temperature required for self-propagation, the flame will effectively be extinguished^(1, 2). The heating of gaseous mixtures in closed containers represents the other end of the time-space spectrum. Here much energy is supplied *in toto* but only the specific temperature of the system determines ignition. In this case ignition is characterized by the spontaneous ignition temperature of the mixture (which is the temperature at which the rate of exothermic chemical heating exceeds the rate of heat loss from the system) and by the phenomenon of ignition delay (which requires a finite period of exposure to a heat source before ignition can take place). An interaction involving hot surfaces, for example the movement of air containing a combustible mixture over a hot surface or the movement of a hot surface such as an incandescent particle into a combustible mixture, falls within this end of the time-space spectrum.

These phenomena, under suitable conditions, can readily lead to a fire or explosion within a compressed air system. Auto-ignition tendencies, reaction rates, limits of flammability, flame speeds, and extinguishment problems are all affected by hot spots and ambient pressures. In general, the flammability range widens and the auto-ignition temperature of most flammable mixtures tends to decrease with increases in total pressure; the explosion potential increases accordingly⁽¹⁾. The influence of hot spots or surfaces on compressor safety is a direct consequence of these phenomena, the compressor's lubricant characteristics, and its design and operating parameters.

Once a flammable mixture is ignited, several factors immediately begin to effect the flame which may propagate through the mixture or be extinguished. Heat lost by conduction, convection, and radiation tends to cool or quench the flame and if the rate of heat loss exceeds the rate of heat production, the flame will go out. The burning velocity or speed of propagation, which is influenced by the energetic

state and composition of the reactants, local pressure and temperature parameters, as well as by ignition source and physical environment, is of critical importance. If the propagation rate is subsonic, the flame can be considered a deflagration or a burning front; however, if the propagation is supersonic, the reaction wave is considered as a detonation in which peak pressures can easily exceed 40 times the initial pressure, causing severe destruction. Slow moving fires in compressed air systems have often been noticed by sheer accident when a section of pipe became red hot. In some compressor applications (no particular reference to mining) maintenance people have been known to consider such fires routine, indicating maintenance and cleaning are overdue⁽³⁾.

Some internal fires, even though they do not lead to an explosion, have been known to ignite wooden enclosures around piping systems or other flammable materials near the compressor and have in this manner led to serious fires. In other cases, slow burning fires have promoted the right set of circumstances to suddenly become a violent, damaging explosion. One author has observed that fires have been known to occur and to burn out without causing damage while others have caused a high pressure rise due to the increase in temperature and attempted expansion of the compressed air⁽⁴⁾. When expansion is impossible, pressure increases until relieved, usually by mechanical failure. The maximum pressures in this case may be 6 to 10 times the initial pressure.

The most serious type of hazard concerns violent explosions, more properly termed "detonations", caused by the development and propagation of very high-speed pressure waves. A simplified illustration of this mechanism has been developed by Gibbs⁽⁴⁾. As the originally ignited fuel burns, heats, and expands it sends pressure waves ahead that push into the unburned regions of the gas, compressing and heating it. As the flame follows through this hot, unburned gas, a normal explosion takes place, building an additional pressure front ahead of it and sending additional faster moving pressure waves that catch up to slower waves and build up a shock wave. Traveling at many times the

speed of sound, pressure at the extremes may reach 60 to 100 times the initial pressure, causing vessels, pipes, and fittings to rupture with great violence. The shock wave itself may move against the actual flow of air. As already mentioned, the frequency of this type of explosion is very low in air compressor systems with one exception, that being where the air system is used to furnish starting air at about 250 psi to gas and diesel engines. Here there is strong evidence that leakage from the engine through faulty starting valves can provide both fuel and ignition for a serious explosion. Under these circumstances, detonation often occurs.

3.2 Ignition Sources - Lubricant Involvement

In reciprocating compressors a combustible mass is formed on valves and piping components by the gradual accumulation of soiled residues produced by severe oxidation and decomposition of the lubricating oil. This is not overly surprising since a thin film of almost any mineral oil exposed to air at atmospheric pressures at 300°F will reduce to a coke-like mass in short order, the process being accelerated with increased air pressure, temperature, and the presence of catalytic particles such as rust^(5,6,7,8,9). Furthermore, work has been done to show that the carbon deposits formed in air compressors contain the "carbon-oxygen complex" which, because its formation is highly exothermic, can initiate and sustain combustion reactions that can lead to explosions or to the formation of carbon monoxide in compressed air systems^(7, 10). The authors conclude that "once an exothermic reaction is initiated, combustion of oil films or carbon deposits will proceed at a rapid rate under the conditions of high partial pressures of oxygen that exist in a compressed air system".

Small deposits in the compressor discharge area or compressed air system usually build in size, further reducing heat conduction from the area and increasing the surface area for the capture of further vapor, such that the enlarged deposit quickly becomes oil-soaked. In this state, the liquid film temporarily retards oxidation by reducing the amount of oxygen that can enter the deposit; however, since convective cooling is also reduced, the temperature of the deposit will gradually increase as it "dries out" by slow oxidation. As the

film continues to decompose, a critical point is reached where sufficient oxygen can enter the developing porous structure to let oxidation continue at an ever increasing rate; the process repeating until the particle reaches a critical size and temperature where more heat is produced than can be carried away. At this point, the reaction rates steadily increase: additional heat is generated, part of which is absorbed by self-heating and part of which is lost to the cooler surroundings through convection and conduction. Since the rate of heat production is an exponential function of temperature while the rate of heat dissipation is substantially linear, the oxidation process (depending on surrounding conditions) can quickly lead to temperatures which exceed the spontaneous ignition temperature of the residual carbon deposit. At this point, the particle itself may ignite or, if a combustible vapor is present, an immediate fire or explosion may result. When their temperature has reached the kindling point of dry carbon (particles), deposits have been observed to start glowing, giving off heat which causes other pieces of carbon to smolder⁽¹¹⁾.

Burning carbon deposits can seriously alter or weaken component strength, thereby reducing structural integrity to the point where mechanical failures can occur at stress levels that would normally provide an adequate margin of safety. For example, burning carbon deposits can heat the walls of cylinders, pipes, and tanks to the extent necessary to cause deformation, local melting, or rupture under high internal pressures.

In some cases, the hot carbon deposits may break loose and become ignition sources themselves as they travel through the compressed air system, thereby creating either an immediate or impending hazard. If these incandescent particles encounter a combustible mixture directly, an immediate fire or explosion may occur. Or, if the particles lodge in an oil-soaked area, their heat may form and then ignite a combustible mixture or they may experience sufficient heat transfer to be cooled below the immediate danger point. Finally, the particle may travel far enough in the airstream before deposition to cool to a point where there is no need for immediate concern.

Flaking carbon deposits, however, even if they do not cause an immediate fire or explosion hazard, can over a period of time lead to a build-up of deposits that will increase the likelihood of future hazards. For example, carbon particle impinging along with condensed oil vapor on the internal surfaces of intercoolers can lead to mechanical plugging and soaking. This will progressively reduce heat transfer from the affected surfaces, so that ultimately, as the build-up continues and the temperature continues to increase, a potential ignition source will steadily develop. If the heat transfer characteristics of the intercooler are further inhibited by rust, dust, or corrosion build-up on external heat transfer surfaces and passages or by interrupted or reduced coolant flow, temperatures in the intercooler may quickly become high enough to cause spontaneous combustion. At a minimum, higher temperature air will enter the second stage of the compressor and this will aggravate oil decomposition and carbon build-up problems*.

The formation of carbon deposits on the compressor discharge valves is particularly dangerous because it can adversely affect operation of the valve. In particular, gummy or baked deposits can keep the valve from closing fully. This reduces operating efficiency, but more importantly it can lead to serious overheating conditions since a portion of the air that has already been compressed is drawn back into the compression chamber where it mixes with the incoming charge of cooler air and is then recompressed. Since the mixed charge of air is considerably hotter than the full charge of atmospheric air that would

* The formation of dangerous carbon deposits in oil-flooded rotary compressors is also dependent on the compressor's operating condition; fires here are generally associated with a failure in the cooling system and/or rapid unloading where the airflow past the reclaimer pads drops off so as to be insufficient to prevent self-heating(5). Under normal operation, a sufficient amount of the heat evolved by oil oxidation on the reclaimer pads is removed by convection. However, if the airflow rate suddenly drops off to a value below the minimum required to maintain equilibrium for a given air discharge temperature, heat dissipation by convection would be insufficient to prevent self-heating within the reclaimer pads, possibly leading to spontaneous ignition. (Another possible cause of ignition may be the accumulation of static electrical charge on the reclaimer pad as the result of oil droplets passing through it, although the evidence here is not conclusive(5).

normally be drawn into the compression chamber, recompression will further increase the discharge temperature, thereby increasing both the danger of spontaneous ignition and the rate of deposit formation and growth. Increased frictional heating caused by the air moving through smaller passages is also a contributing factor leading to abnormally high discharge temperatures.

Compressor size was also found to influence carbon formation. Carbon deposits tended to be more common and more of a problem in large reciprocating compressors than in smaller ones, probably because the lower efficiencies of the smaller machines result in higher temperatures and air velocities which have the effect of transporting oil in the discharge air stream more quickly to cold areas of the system where formation of the carbon deposits do not readily occur^(12,13). In the larger compressors, which have better efficiency and slower air velocities, oil landing on surfaces that were not enough to cause immediate decomposition would nevertheless stay there long enough to break down into carbonaceous deposits.

3.3 Combustible Mixtures - Lubricant Properties

Lubrication problems can be further hampered by changes in the quality of the air entering the compressor. Impurities, if not removed, will more readily cling to a heavier oil and bake into carbonaceous deposits on the pistons and discharge valves. These impurities will also increase the amount of wear experienced by the compressor, ultimately allowing more oil to enter the discharge lines so that the likelihood of deposition on valves and cylinder walls is increased, which in turn increases the likelihood that a combustible mixture will be present at hot spots in the compressed air system. At the other extreme, clogged air filters will cause higher suction pressures which in turn will cause excessive oil flow past the rings, again increasing the probability of oil deposition on valves and cylinder walls. Furthermore, a reduction in the put-through of fresh, cool air and the increase in the pressure ratio will result in unusually high air discharge temperatures.

Because the rings of reciprocating compressors and the lobes of screw compressors must be lubricated to prevent wear and to facilitate sealing, lubricating oils can be passed through the discharge system as vapors, as air suspended fine droplets, or as liquid films which are driven by air along the walls of the system's components. The presence of these lubricant states under certain operating conditions (temperature, pressure, and air flow rate) can pose or lead to a fire or explosion hazard in the compressed air system. Whether a potential or real hazard exists, depends on the presence of threshold values with respect to the physiochemical variables that define each phase of the combustion process; ignition, flame propagation, detonation, and flame extinguishment. For a fire or explosion to occur, there must be a fuel, an ignition source, and sufficient oxygen to support combustion.

The relationship between specific lubricant properties and their tendency to cause fires and explosions in compressed air systems has been studied and debated. For example, laboratory flash and fire point data used to be considered indicative of the lubricant's tendency to cause compressor fires and explosions, the underlying theory being based on the fact that greater flammability was noted for low flash and low fire point oils when observed under laboratory test conditions. Presently, however, this theory has been virtually discarded; a high flash point is no longer considered a necessary requirement for reduction of fire hazards in air compressors^(14, 15). On the contrary, a high flash point oil may actually be detrimental to good lubrication because it is necessarily heavy bodied and as a result, will form more objectionable carbon deposits than a lighter bodied oil, even if both are of equal quality^(16, 17). Furthermore, low flash point oils are known to evaporate more cleanly from hot discharge valves leaving cleaner valves and dryer ports. Since no flames or sparks are expected in the compressor, flash point is not a good measure of explosion potential. Flash point may, however, provide a guide as to the base of the oil and as such, it can imply the potential carbon residue content, since oils with the highest flash points have been shown to generally develop the most carbon residue. Napthenic oils tend to have lower flash and fire points than paraffinic oils.

Testing under current laboratory standards can also be misleading when it comes to inferring the lubricant's behavior within the compressor or compressed air system. Since oils are mixtures of hydrocarbons having different boiling points, certain fractions will behave differently within the air compressor in response to local temperature, pressure and air flow conditions. The evaporation of lubricating oils in air compressors and compressed air systems is greater than that which occurs in other lubricated systems because higher temperatures, higher air speeds and a higher degree of mechanical involvement between the lubricant and air are experienced. In reciprocating compressors, piston and valve motion combine with high air speeds to cause an oil mist to form, primarily from the lower viscosity fractions of the oil, a portion of which is carried away from the hot regions by air and is not an immediate concern as far as fires and explosions are concerned. However, heavier ends having higher viscosities than the parent oil generally move more slowly through the system, often as a film on the walls and valves. Because the residence time on high temperature parts is longer for these fractions, their oxidation and decomposition proceeds more rapidly, leading to the formation of deposits which will eventually result in a hazardous operating condition. It has been noted⁽¹¹⁾ that even at moderately low discharge temperatures found in some low pressure reciprocating air compressors, any oil remaining as a thin film on a discharge valve will eventually evaporate or carbonize; a compressor using a heavy oil which does not evaporate readily will be found to have considerable carbon formation on or adjacent to the discharge valve and a heavy oil film in the discharge passages.

Of the many standard tests used to characterize lube oils, one often considered most relevant to air compressor and air line fire problems is the determination of autoignition temperature, although for a long time its principal drawback was the lack of a standardized test method. The autoignition temperature is that temperature at which the oil will ignite spontaneously in air. Since the autoignition temperature of oils tends to vary adversely with their flash and fire points, oils with lower flash and fire points usually have higher

autoignition temperatures and, therefore, may exhibit a greater resistance to burning in the compressor discharge system even at elevated temperatures. Generally, naphthenic oils, which have lower flash points, will have higher autoignition temperatures than paraffinic oils. Autoignition temperatures, however, decrease with increasing pressure and one author⁽¹¹⁾ has noted that the autoignition temperature of mineral lube oils deposited on typical pipeline scales may be below the discharge temperature of many air compressors, especially at pressures greater than 100 psig. [The autoignition temperature of higher resistant phosphate ester lubricants was shown to be above typical discharge temperatures, at least up to 700 psig, even in the presence of scale. However, even though synthetics have distinct fire resistant qualities in that they will not propagate air flame, they will burn if heated sufficiently.]

Because autoignition temperature depends on pressure and because internal ignition hazards dominate the accident area, a temperature-pressure ignition test would be more meaningful. Accordingly, testing of this type was recommended in Section 1.4.2.

The correlation between fires (and sometimes explosions) in compressed air systems and carbon deposits subsequently found in discharge lines had prompted many users to consider the tendency to form carbon residue, as determined by Conradson or Ramsbottom testing, as a measure of the formation of carbonaceous deposits in actual operation^(4, 9, 18). Testing, however, showed that the carbon forming tendency of a new oil is no measure of its quality as far as the danger of fires and explosions is concerned⁽⁹⁾. Furthermore, carbon residue (the amount of carbon left after evaporating oil under controlled conditions) is not considered a firm indication of just how much deposit might build up in a compressor, since operating care and the rate of oil feed have a much greater influence⁽⁴⁾. Carbon forming tendencies and their effect on performance are difficult to evaluate, but it is widely held that the type of carbon residue is more significant than the quantity⁽¹⁹⁾.

The problems associated with compressor lubrication have

been studied by compressor and lubricant manufacturers, and improvements in mechanical design and in lubricant properties have resulted. Presently, mineral oils are most commonly used for lubricating air compressors; however, the use of synthetic oils is increasing, primarily because of their good fire resistant qualities, excellent film strength, longer life, excellent oxidation stability, and extremely low carbon forming tendencies. Most synthetic compressor oils have diester bases, although phosphate esters and oil having a phosphate ester base and silicones are also used. Synthetics, however, also have some disadvantages: higher prices (synthetics are 3 to 5 times more expensive than petroleum-based oils); oils attack paint and some gasket and sealing materials; vulnerability to water washing and poor internal thin-film rust protection.

Mixtures of petroleum and synthetic oils are known to have been used⁽⁴⁾ resulting in a tendency to average the properties of each, many of the advantages or disadvantages being modified in the mixture. Claims of a net gain in cleanliness and safety, the principal objectives, without the drawbacks of the purer synthetics, have been made.

It appears that most compressor manufacturers recommend lubricants in one of two ways: (1) either as a prescribed proprietary lubricant obtainable only from the compressor manufacturer, or (2) as a product falling within a general specification. In most cases, compressor manufacturers list general specification or recommendations for air compressor lubricants in their instruction books, while most lubricant manufacturers and suppliers develop a list of their provisionally acceptable lubricants in collaboration with each compressor manufacturer.

3.4 Contributing Factors - Operational Involvement

The foregoing discussion is pertinent because it helps to explain the mechanisms which are present during almost all fires and explosions in compressed air systems. In particular, it explains how the physical and chemical properties of the lubricants can interact with the mechanical properties of the system to form a hazardous

situation even under normal operating conditions. The situation, of course, becomes much worse under abnormal operation conditions such as may result from improper maintenance or mechanical failure of key components or safety devices.

As noted, petroleum oils decompose and form carbon deposits that collect on valves, heads, discharge ports, and piping. Furthermore, it has been shown that, in time, these deposits absorb oxygen from the air and under favorable conditions, will themselves start to decompose, generating large quantities of heat, often to the point where a mass of deposits glows and becomes a trigger for more violent burning. This action is speeded by high temperatures in a compressed air system. Normal operating temperatures are aggravated by compressor malfunction or improper maintenance procedures which allow unusually high temperatures or introduce excessive amounts of lubricating oils in high temperature areas such as might occur from intentional or accidental overlubrication, or during excessive periods of low load or no-load running while oil is still being supplied to the cylinders with insufficient air flow to speedily carry it away.

Our investigation of mining accidents in which a compressor contributed to or caused a fire or explosion has indicated that, for the most part, fires and explosions can be traced to maintenance related phenomena, most notably:

- Improper maintenance or lack of maintenance;
- improper temperature and pressure control settings, with settings often increased above the recommended limits to compensate for insufficient capacity;
- inoperative safety devices such as relief valves, automatic temperature shutdowns and the like. In many cases these devices were deliberately disconnected so as not to interfere with production;
- use of improper lubricants or improper handling of prescribed lubricants;
- inadequate ventilation or dirty and blocked heat transfer surfaces or coolant and coolant system degradation;

- improper or lack of internal maintenance;
- faulty equipment such as valves;
- improper grounding of new components which allows static charge to develop.

4.0 ILLUSTRATING SCENARIO - COMPRESSOR FIRE OR EXPLOSION

The most serious hazard presented by a compressor is its potential for causing or contributing to fires and explosions. As we have noted earlier, in almost all cases this hazard is due to the ignition of combustible mixtures stemming from lubricant involvement in the compressor, receivers or some other part of the compressed air system. Therefore, when looking at this particular hazard, it is necessary to consider the events leading to the formation or development of the combustible mixture as well as the events that cause the combustible mixture to ignite.

Our investigation has shown that the chain of events, or scenarios leading to the development of this particular hazard is primarily dependent on the manner in which the compressor is used, maintained, and operated. In particular, the development of the combustible mixtures and their ignition is usually a function of the mechanical condition of the compressor or certain compressor components, the selection and handling of the lubricants, and the operating envelope imposed on the compressor in terms of pressure, temperature and duty cycle. For the most part, it is the interaction of these design, maintenance, and operating factors that eventually produce the fire or explosion.

For example, the long term buildup of carbon deposits within the compressor or compressed air system is a mechanical design or maintenance factor; however, this in itself does not cause the fire or explosion. It only sets the stage. It is not until this compressor state is coupled with an operating condition that promotes sufficient heating to initiate spontaneous combustion of the deposits that an actual hazard becomes imminent. To illustrate this relationship, consider the recent explosion of an air compressor that had been in operation for 20 years*. In this case, a new operator started the compressor against a dead head (closed valve) resulting in rapid

* Oro Grande Cement Plant compressor explosion October 3, 1980; reference Tables 2 and A2.

compressive heating of the air. This condition (caused by an operating factor) in conjunction with the absence of thermal shut-down or pressure relief devices (in this case a maintenance factor) led to the rapid spontaneous combustion of deposits followed by a violent explosion. Here, the creation of the ignition source became the critical link.

As this example illustrates, a fire or explosion hazard is the consequence of several primary and secondary events, some of which are mutually exclusive serving only to set the stage, while others are mutually inclusive, requiring simultaneity for the actual hazard to occur. It is the order of these events which form the scenarios that typify many of the fires and explosions experienced by compressors in underground and surface mines.

The mechanisms governing carbon deposit formation and their ignition were discussed in Section 3. Here it was shown that once these deposits start to form, the problem becomes self-aggravating with the likelihood of a future accident steadily increasing, primarily because early deposits enhance the buildup of further deposits by encouraging abnormal operating conditions. The eventual breakdown and deposit of lubricant products on internal mechanical surfaces as a result of the compressor's harsh internal environment must be considered as a primary event in most fire and explosion accident scenarios, even though this is a long term process, often spanning many years before the actual fire or explosion occurs. Naturally, during this time period, the process is aggravated by many secondary events such as the operator's failure to use air or oil filters, his use of improper lubricants, operating with clogged air filters and dirty heat transfer surfaces and fluids, the failure of a low oil level detector to prohibit starting or to provide an appropriate warning, the failure of an unloading valve to properly control the compressor's working cycle, and many others.

In the early life of the compressor, the major effect of these secondary events is to quicken the rate of deposit formation. As a result, however, the compressor's tolerance to secondary events is

steadily lowered. As more and more deposits are formed, the physio-chemical properties of the altered lubricants become increasingly more sensitive to heat and temperature, so that an event that was once considered secondary is now set to become a primary or critical event. For example, in our previous illustration, when the operator started the compressor against a dead head (closed valve), rapid compressive heating resulted because there was no pressure relief valve or thermal shutdown switch in the system. In turn, the rapid compressive heating ignited deposits resulting in a violent explosion. Here, the absence of these safety devices, which up to this point had only been considered as a secondary factor, now became a primary factor in leading to the explosion. In effect, the absence of both of these devices coupled an improper operation (starting against the closed valve) with a dangerous level of deposits to cause an explosion.

A scenario typifying this type of incident can be diagrammed as shown in Figure 4. This figure reinforces the fact that most compressor fire and explosion hazards are the result of long term factors that produce a marginally stable environment which then allows a (previously considered) secondary factor to become a triggering mechanism for the hazard. While the specific secondary events or combination of secondary events may differ from incident to incident, the general scenario shown in this figure tends to typify the fire and explosion accidents which were investigated during this program.

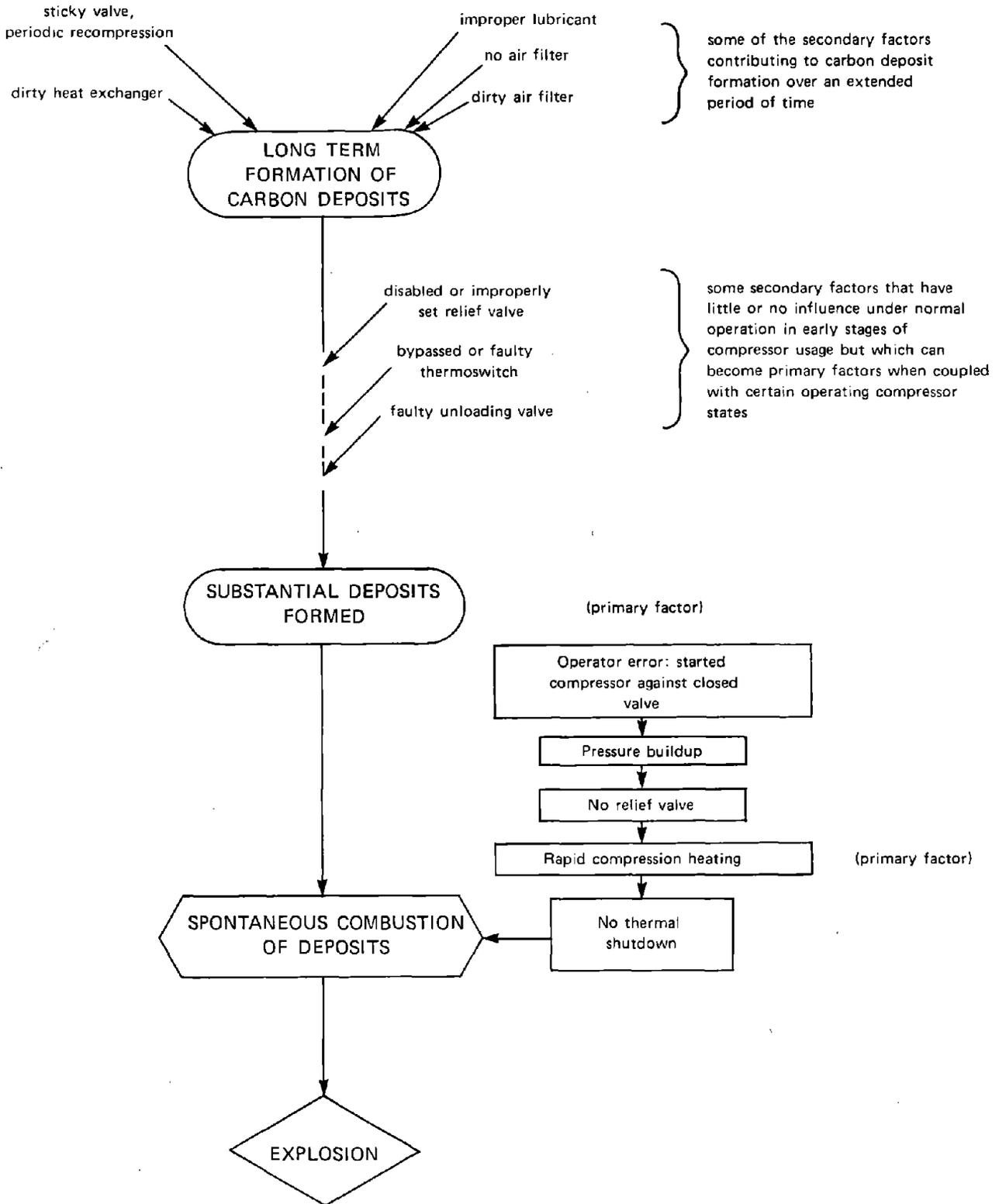


FIGURE 4. SCHEMATIC OF TYPICAL FIRE-EXPLOSION SCENARIO SHOWING THE INTERACTION OF PRIMARY AND SECONDARY FACTORS

5.0 LABORATORY FIRE RESISTANCE TEST

Laboratory fire resistance and chemical tests were conducted in an attempt to measure the ignition resistance of air compressor lubrication fluids and establish a ranking order with respect to hazard potential. As called for under the contract terms of this project, the spray-ignition test^(a) was performed along with a carbon residue test^(b). Three representative air compressor fluids suspected of having low, moderate and high fire resistance characteristics were selected and compared against a hydraulic fluid base. Each of the three fluids tested is currently used to lubricate compressors used in field mining operations and was recommended by manufacturers. We felt it was important to select test fluids that would not favor one over the other in physical specifications such as viscosity.

Two of the lubricating fluids tested have a petroleum base while the third, the one expected to exhibit the highest resistance to flammability, is synthetic. Exxon Esstic grade 68 and Exxon Teresstic grade 68 are fully-formulated fluids with a petroleum base and have been effectively used in low and high temperature applications. The synthetic lubricant evaluated was Exxon Synesstic grade 68, a diester fluid which has shown improved operating efficiency. Skydrol 500B, a phosphate ester, synthetic hydraulic fluid was the reference or base fluid used in the spray-ignition test because its flammability characteristics are well known among hydraulic fluid users.

Test results are summarized in Table 5. Nothing unusual was noted and, in fact, the results were expected since the Schedule 30 test procedure specifies quite severe parameters. One exception may be the synthetic fluid which we expected to perform better than the others. However, according to this test, the petroleum base lubricants responded on par with the synthetic fluid. Of course, in the misting mode almost

a) CFR 30, Section 35.21

b) ASTM D 524

Table 5

Test Results:
 Flammability by Federal Schedule 30
 Spray-Ignition Test Procedures (18" - 24")*,
 and Carbon Residue Test

<u>Test Fluid</u>	<u>Propane Torch</u>	<u>Trough with Ignited Waste</u>	<u>Electric Arc</u>	<u>Carbon Residue**</u>
Skydrol 500B	Fail	Fail	Pass	--
Esstic 68	Fail	Fail	Pass	0.1%
Teresstic 68	Fail	Fail	Pass	0.1%
Synesstic 68	Fail	Fail	Pass	0.1%

* Distance from nozzle tip to ignition source

** ASTM D 524 test procedure (Ramsbottom)

any fluid will ignite with halocarbons and water containing emulsions (typically used as hydraulic fluids) being possible exceptions. The carbon residue test results favored no specific lubricant either. It may be possible that the formation of carbon residue may be more dependent upon the equipment than the fluid. This, and more specific measurement of the ignition resistance of air compressor fluids, can only be determined by greatly expanded experimentation beyond the scope of this project.

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APPENDIX A

TABLE A1 - Supporting Data for Table 1

TABLE A2 - Supporting Data for Table 2

Table A1 - Supporting Data for Table 1, Section 2.1.1.1

<u>HSAC DOCUMENT NUMBER</u>	<u>ACCIDENT OCCURRENCE DATA</u>
651 9529	Opening valve on compressor tank, valve blew off.
150 8196	Employee was making a final check of controls on compressor when the relief valve blew apart, a portion of it hit him in the stomach area.
160 1024	A compressor exploded after being started, causing a sheet of flame to shoot out of the compressor and envelop man.
170 3019	* was in the process of turning the air on and the valve popped out, striking his right forearm.
280 940 001	(Report of accident almost indecipherable. Details taken from other sources.) Fire in oil separator, fuel tank explosion. Accident attributed to failure of thermal shutdown switch.
290 590 056	Employee was using respirator while welding, compressor for respirator broke and pumped oil into the air that the employee was breathing, causing a type of intoxication (NOTE: Not a fire or explosion but a type of compressor malfunction having potential hazard aspects).
291 080 080	An air compressor located on Section #5, vented with return air, was found by * about 4:45 P.M. The compressor was guarded with * which caught fire. The compressor and * were extinguished with a (indcipherable) fire extinguisher and rock dust. The fire endured for about 25 to 35 minutes.
291 580 123	Two employees were repairing valves on an air compressor. After replacing an intake valve and putting the others back in place, one employee opened the gate valve at the compressor supply tank and the other employee turned on the unloader switch, putting all compressors on manual unload. One employee started compressor, other turned off unload switch. They observed the belt slipping and starting to smoke and then the compressor exploded; they believe relief valve on compressor was defective.

* Deleted from report that was provided to us.

Table A2 - Supporting Data for Table 2, Section 2.1.1,
Summaries of Compressor Accident Investigations
By Bureau of Mines, MESA, or MSHA .

1. Valencia Pit, Tuscon, Pima County, Arizona, September 10, 1970

(Not a fire or explosion) caused by faulty installation of discharge line from compressor to receiver.
2. Columbia Quarry and Mill, Columbia, Richland County, South Carolina, July 27, 1971

Fatal accident (not a fire or explosion) caused by leak in recently installed quick-lock coupling. Contributing cause: failure to test completed air line before subjecting it to full pressure.
3. Steward Mine, Butte, Silver Bow County, Montana, December 6, 1971

(Not a compressor fire or explosion) caused by reaction of blowpipe when struck by falling rock.
4. Star Mine, Burke, Shoshone County, Idaho, March 16, 1972

Fatal accident (not a fire or explosion) caused by failure of improperly installed coupling between valve and pipe of 6" air line and absence of safety chains.
5. Anaconda Company, Butte, Montana, July 7, 1972

Fire and explosion, attributed to overheating of oily carbon deposits in discharge piping, oily vapor in wood-lined tunnel, ignition from static discharge resulting from air escaping from leak in pipe.
6. Schwartzwalder Mine, Golden, Colorado, October 26, 1972

Explosion and fire, attributed to hole in piston, caused by broken valve penetrating piston crown, allowing crankcase to be pressurized, igniting lubricant.

7. Morton Mine, Winifriede, West Virginia, November 16, 1973

Fire attributed to heat generated within the compressor and failure of mine management to maintain the designed over-temperature controls in operating condition.

8. Shannon Branch Mine, McDowell County, West Virginia, November 26, 1973

Fire attributed to failure of electrical starting system, brought on by improper preceding shutdown. Safety devices rendered inoperative, no current record of compressor examination, testing, or maintenance. Probable ignition source: arcing contact in one phase of the main starter. Oil-soaked ballast material on floor.

9. Ozark-Mahoning MM Mine #6, Illinois, June 1, 1976

Compressor house wood framing ignited because of proximity to air compressor discharge piping, attributed to ignition of carbon deposits inside pipe, overheated by malfunctioning discharge valve.

10. Henderson Mine, Empire, Clear Creek County, Colorado, November 15, 1976

Non-fatal injury (not a compressor fire or explosion) caused by worker failure to bleed off pressure from air line before removing header.

11. Ozark Mine and Mill, Sweetwater, Reynolds County, Mississippi December 29, 1976

(Not a fire or explosion) caused by failure of air line connection and absence of safety chains.

12. Smelting and Pelletizing Plant, Copperhill, Polk County, Tennessee, February 3-8, 1977

Steam pipe rupture (not air compressor involvement) due to steam erosion thinning of pipe, not detected by scheduled examinations.

13. Valley Road Quarry and Mill, New Jersey, April 15, 1977

Explosion within "compressor receiver separator tank". Rotary screw compressor. Cause not determined, although inadequate maintenance considered a contributing factor.

14. Williams Brothers Slate Quarry, Middle Granville, Washington County, New York, May 5, 1977

Fire in diesel engine generator/compressor house, attributed to spark from diesel exhaust.

15. Cargill Mine, South Lansing, New York, March 28, 1978

Fire in oil separator, fuel tank explosion, attributed to failure of thermal shutdown switch allowing discharge air temperature to become excessive and ignite oil in separator.

16. Cyprus Mill, Fernley, Nevada, February 15, 1979

Fire in compressor oil sump, attributed to overheating of oil due to excessively dusty and dirty operating environment and failure of discharge air high temperature switch.

17. Sugar Creek Quarry and Mill, Missouri, May 29, 1979

Fire hypothesized as due to rotary compressor end bearing failure generating sufficient heat to ignite lubricant.

18. Oro Grande Plant, Riverside Cement Company, Oro Grande, California, October 3, 1980

Explosion (fatal) in compressed air line attributed to exothermic reaction of carbon deposits brought on by rapid compressive heating when compressor was started against closed valve. Failure of shear pins to shear when designated operating pressure was substantially exceeded and the lack of other pressure relief or thermal shutdown devices were contributing factors.

APPENDIX B

STANDARDS, REGULATIONS, AND CODES

Table B1 - Comparison of National Standards, Regulations,
and Codes

Table B2 - CFR 30; Comparison of Parts 55, 57, 75, and 77

TABLE B1. COMPARATIVE NATIONAL COMPRESSOR REGULATIONS

Item	UNITED STATES				Germany	Luxembourg Group
	CODE OF FEDERAL REGULATIONS		TITLE 30			
	METAL AND NON-METAL MINES	COAL MINES	ASME Boiler and Pressure Vessel Code Section VIII	Britain, National Coal Board (NCB) Reciprocating Compressors		
Scope	Part 55, Open-Pit Underground Air compressors and compressed air receivers, receiver construction and inspection, system safety features and practices.	Part 75, Underground Air compressors and compressed air receivers, receiver construction, safety features and practices.	Part 77, Surface Pressure vessels, excluding those less than 6" I.D., less than 15 psi pressure. Design, fabrication, safety features.	Reciprocating compressors, ancillary equipment. Design construction, acceptance, installation, operation, inspection, and maintenance.	Compressors VBC 16 Industrial compressors, temperature and pressure instrumentation pertaining to safety.	The 16th report (for the year 1978) contains no information pertaining to air compressors.
Compressor Identification		Applies only to receiver, not compressor.			Name plate shall identify make, type, model, year mfg., air capacity, discharge pressure max. RPM, in-stalled power.	
Control Gear				Control gear to regulate air delivered, air inlet valve, and surging.		
Compressor Liquid Cooling				Adequate cooling water supply (M) with no more than 32°F temp. rise(S).	No shut-off devices on discharge side in open systems. Design pressure not to be exceeded in closed liquid systems.	
Compressor Air Pressure Gauges	Suggested, not mandatory.	Required, mandatory.		Suggested, not mandatory.	Required if discharge pressure greater than 1 bar	
Compressor Oil Pressure Gauges				Required in force-feed systems.		
Air Filter Manometer				Large compressors - Required; small, medium-suggested.		
Compressor Temperature Measurements				Discharge air, cooling water out, lube oil.		

TABLE B1. COMPARATIVE NATIONAL COMPRESSOR REGULATIONS (cont'd)

CODE OF FEDERAL REGULATIONS		UNITED STATES		ASME Boiler and Pressure Vessel Code Section VIII	Germany	Luxembourg Group
		METAL AND NON-METAL MINES	COAL MINES			
Item	Part 55, Open-Pit	Part 57, Underground	Part 75, Underground	Part 77, Surface	Compressors VBG 16	
Compressor Safety Valves	Automatic pressure-release valves - suggested.	Automatic pressure-release valves - suggested.	Automatic pressure release valves - mandatory.	At compressor outlet before stop or non-return valve in line to receiver. (see receiver requirements) Between stages of multistage compressor (mandatory)	Safety device to assure that design pressure is not exceeded (mandatory).	
Compressor Protective Devices	Automatic temperature-activated shutoff mechanisms set for 400°F, or fusible plugs in discharge lines as near compressor as possible - melting point 50°F below lube oil flash point. (suggested).			Thermal protective device as near as possible to last stage discharge valve, operative if outlet air temperature exceeds 320°F. Cooling water protective device which will operate when water temperature exceeds 160° or flow rate falls below manufacturer's recommendation. Protective devices to operate if lubricant temperature exceeds 176°F, pressure falls below manufacturer's recommendation, or level falls below manufacturer's recommendation. Fusible plugs shall not be used. For air-cooled compressors, similar devices to monitor overheating. Operation of any of the devices stops compressor automatically. (mandatory). Devices shall be "Fail Safe", offer minimum opportunity for unauthorized interference.	Each stage must incorporate a safety device to assure that design pressures are not exceeded (mandatory). If liquid shock is a potential hazard, suction side of each stage must be equipped with suitable provisions for draining the liquid (mandatory).	

TABLE B1. COMPARATIVE NATIONAL COMPRESSOR REGULATIONS (cont'd)

UNITED STATES		TITLE 30		ASME Boiler and Pressure Vessel Code Section VIII	Britain, National Coal Board (NCB) Reciprocating Compressors	Germany Compressors VBG 16	Luxembourg Group
CODE OF FEDERAL REGULATIONS	METAL AND NON-METAL MINES	COAL MINES					
Item	Part 55, Open-Pit	Part 57, Underground	Part 75 Underground	Part 77 Surface			
Aftercoolers				When a single pressure relieving device is used, it shall be set to operate at a pressure not exceeding the maximum allowable working pressure of the vessel.	Strongly recommended on the discharge side of each compressor.		
Receiver Identification				Nameplates bearing the markings called for...shall be used on vessels constructed of steel plates less than 1/4" thick.....	Shall have marked upon it the safe working pressure and shall bear a distinguishing mark.		
Receiver Construction and Installation	All boilers and pressure vessels shall be constructed, installed, and maintained in accordance with ASME boiler and pressure vessel code.	All pressure vessels shall be constructed, installed, and maintained in accordance with Section VIII "Unfired pressure vessels" of the ASME boiler and pressure vessel code.	All boilers and pressure vessels shall be constructed, installed, and maintained in accordance with the ASME boiler and pressure vessel code.	Design temperature shall not be less than mean metal temperature expected under operating conditions for the part. Shall be designed for at least the most severe temperature of coincident pressure and temperature expected in normal operation.	...pressure vessel purchased as an air receiver shall conform to the requirements of the appropriate British standard, i.e.,.....		
Receiver Pressure Gauges	Receivers should be equipped with pressure gauges (recommended).	Receivers shall be equipped with pressure gauges (mandatory).	Receivers shall be equipped with pressure gauges (mandatory).		Shall be fitted with a correct reading pressure gauge.		
Receiver Drains	Air receivers should be equipped with...drain valves (recommended)	Air receivers shall be equipped with....drain valves (mandatory).			Shall be provided with an opening through which it can be effectively drained.	...air...containers must have at their lowest point provision for draining.	
Receiver Fusible Plugs					Where possible plugs are fitted directly to an air receiver.. (permissible).		

TABLE B1. COMPARATIVE NATIONAL COMPRESSOR REGULATIONS (cont'd)

		UNITED STATES		TITLE 30						
		CODE OF FEDERAL REGULATIONS		COAL MINES		ASME Boiler and Pressure Vessel Code Section VIII		Britain, National Coal Board (NCB) Reciprocating Compressors		
		METAL AND NON-METAL MINES		Underground		Part 75 Underground		Part 77 Surface		
Item		Part 55, Open-Pit	Part 57, Underground	Part 75 Underground	Part 77 Surface					
Receiver Access		Receivers should have inspection openings which should be manholes when the tanks are over 36 inches in diameter (recommended).						Air receiver shall be provided with a suitable manhole, handhole, or other means to allow the interior to be thoroughly cleaned and inspected.	Germany Compressors VBC 16	Luxembourg Group
Location								For fixed plant - in coolest place practical, preferably outside the compressor, as near the compressor as practicable.		
Receiver Safety Valve		Automatic pressure release valves suggested.		Automatic pressure release valves mandatory.		Shall be protected by a pressure-relieving device that shall prevent pressure from rising more than 10% above the maximum allowable working pressure... shall be constructed, located and installed so that they cannot be readily rendered inoperative.		The safety valve... shall be mounted on the receiver, and should be protected from atmospheric corrosion and mechanical damage. Shall be provided with a shutoff valve at the outlet and a suitable safety valve.		
Installation		Air intakes should be installed to insure that only clean, uncontaminated air enters the compressor. (Suggested)						Shall not be installed unless air entering the plant and delivered is as dry, cool, and clean as practicable. Underground: located in intake airway. Temperature rise of ventilating air should not exceed 15°F. Transportable compressors shall be sited on level ground with particular attention to obtaining efficient cooling. Underground houses shall		

TABLE B1. COMPARATIVE NATIONAL COMPRESSOR REGULATIONS (cont'd)

UNITED STATES		TITLE 30		GERMANY		LUXEMBOURG GROUP	
CODE OF FEDERAL REGULATIONS		COAL MINES		Compressors VRG 16		Compressors VRG 16	
Item	Metal and Non-Metal Mines	Part 75 Underground	Part 77 Surface	Britain, National Coal Board (NCB) Reciprocating Compressors	Germany Compressors VRG 16	Luxembourg Group	
Operation	<p>Part 55, Open-Pit</p> <p>Part 57, Underground</p> <p>Compressed air receivers should be drained of moisture and oil at least once each day. Should be operated and lubricated in accordance with manufacturer's recommendations. Safety devices on compressed air systems should be checked daily.</p>	Part 75 Underground	Part 77 Surface	<p>While it is operating, each compressor shall be the responsibility of a competent person instructed by the manager for that purpose. Shall not be started by other than the attendant or mechanic or electrician of the mine or a person authorized in writing to do so. As soon as the attendant or responsible person observes that any of the following conditions have arisen, he shall shut down the compressor (Conditions listed.)</p> <p>If protective devices have not already done so, shall immediately inform the mine official under whom he works that the compressor has been shut down. (Several conditions of temperature and pressure listed.)</p> <p>If stopped because of defect or by automatic device, shall not be restarted except on authority of...engineer, manager, or some competent person. Upon initial starting direction of rotation shall be checked.</p>	<p>The operator must establish written operating instructions for servicing and maintenance, safe operation, start-up, shut down. The operator is responsible for the compressor being operated only by trained personnel and maintained only by experienced personnel.</p>		

TABLE B1. COMPARATIVE NATIONAL COMPRESSOR REGULATIONS (cont'd)

UNITED STATES		TITLE 30		ASME Boiler and Pressure Vessel Code Section VIII	Britain, National Coal Board (NCB) Reciprocating Compressors	Germany Compressors VBC 16	Luxembourg Group
CODE OF FEDERAL REGULATIONS	METAL AND NON-METAL MINES	COAL MINES	Pressure Vessel Code Section VIII				
Item	Part 55, Open-Pit	Part 57, Underground	Part 75 Underground	Part 77 Surface	Only oil of a grade authorized by.... and approved by the compressor manufacturer shall be used except where exceptions have been granted NCB oil No. 11 shall be used for....and NCB No. 10 oil for.... Any other oil shall be a high quality mineral oil having a closed flash point not less than 380°F.		
Lubrication					The operating speed of the compressor shall not exceed the manufacturer's recommendation. Wherever possible underground compressors should be direct driven.		
Speed					For continuous supervision, attendant shall read and record all instruments twice per shift. Otherwise once per shift.		
Instrument Readings					The compressor shall be kept as clean and free from oil and dust deposits as possible. (Valve and filter cleaning agents closely controlled.) Inlet air filters shall be thoroughly cleaned or replaced at not more than one month or 600 running hours.		
Inspection and Maintenance					Repairs involving the pressure system of compressors, receivers, or compressed air-powered equipment shall not be attempted until the pressure has been bled off.		

TABLE B1. COMPARATIVE NATIONAL COMPRESSOR REGULATIONS (cont'd)

Item	UNITED STATES				Germany Compressors VBC 16	Luxembourg Group
	CODE OF FEDERAL REGULATIONS		TITLE 30			
	METAL AND NON-METAL MINES	COAL MINES	ASME Boiler and Pressure Vessel Code	Section VIII		
Sampling of Oil Supplies	Part 55, Open-Pit	Part 57, Underground	Part 75, Underground	Part 77, Surface	Britain, National Coal Board (NCB) Reciprocating Compressors	Oil supplies shall be sampled and analyzed at intervals.
Inspection of Crankcase Oil						Crankcase oil of fixed compressors shall be either changed or inspected and samples analyzed at intervals not to exceed 3 months.
Pipe Mains						Use of clamps and jointing to seal air leaks in damaged pipes should be avoided if possible. Compressed air mains underground should not be buried but should be slung from roof supports or supported above the floor. Pipe mains shall be inspected routinely according to maintenance schedules.
Pipe Internal Inspection and Cleaning						Recommended that piping between compressor and receiver be disconnected at intervals of 12 months or less for internal examination and removal of carbon deposit and rust. Similarly for first length of pipe beyond receiver. Similarly for subsequent lengths until clean interior is reached.

TABLE B1. COMPARATIVE NATIONAL COMPRESSOR REGULATIONS (cont'd)

Item	UNITED STATES		Germany	Luxembourg Group
	CODE OF FEDERAL REGULATIONS METAL AND NON-METAL MINES	TITLE 30 COAL MINES		
Planned Maintenance Schedule	Part 55, Open-Pit Part 57, Underground	Part 75, Underground Part 77, Surface	Compressors VBG 16	
General			Britain, National Coal Board (NCB) Reciprocating Compressors	Daily inspection of running compressors and standby plant. Weekly, bi-weekly, monthly, three-monthly, annual maintenance. At three-month, remove and clean or replace inter- and after-coolers. Annually - open and clean air mains. Maintenance schedule is suggested and is very comprehensive.
			ASME Boiler and Pressure Vessel Code Section VIII	
				At no time shall compressed air be directed toward a person. When compressed air is used, all necessary precautions shall be taken to protect persons from injury.

TABLE B2. COMPARISON OF PARTS 55, 57, 75 and 77, CFR 30

§ 55.13 Compressed air and boilers.	§ 57.13 Compressed air.	§ 75.1730 Compressed air.	§ 77.411 Compressed air and boilers.
<p>GENERAL</p> <p>55.13-1 <i>Mandatory.</i> All boilers and pressure vessels shall be constructed, installed, and maintained in accordance with the standards and specifications of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code.</p> <p>55.13-2 through 55.13-9 (Reserved)</p>	<p>GENERAL—SURFACE AND UNDERGROUND</p> <p>57.13-1 <i>Mandatory.</i> All boilers and pressure vessels shall be constructed, installed, and maintained in accordance with the standards and specifications of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code.</p> <p>57.13-2 through 57.13-9 (Reserved)</p>	<p>(a) All pressure vessels shall be constructed, installed, and maintained in accordance with the standards and specifications of Section VIII—Unfired Pressure Vessels, of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (1971), which is hereby incorporated by reference and made a part hereof. This document may be purchased for \$25 from the American Society of Mechanical Engineers, 345 East 47th Street, New York, NY 10017; and it is available for examination in every Coal Mine Health and Safety District and Subdistrict Office.</p>	<p>All boilers and pressure vessels shall be constructed, installed, and maintained in accordance with the standards and specifications of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code.</p>
<p>COMPRESSED AIR</p> <p>55.13-10 Air compressors should be equipped with automatic temperature-actuated shutoff mechanisms set for 400° F. or higher, and fusible plugs installed in the compressor discharge lines as near the compressors as possible. Fusible plugs should melt at temperatures 50° less than the flash points of the lubricating oils.</p> <p>55.13-11 Compressors and compressed-air receivers should be equipped with automatic pressure-release valves, pressure gauges, and drain valves.</p> <p>55.13-12 Compressor air intakes should be installed to insure that only clean, uncondensed air enters the compressors.</p> <p>55.13-13 Compressed-air receivers should be drained of moisture and oil at least once each day.</p> <p>55.13-14 Compressed-air receivers should have inspection openings which should be manholes when the tanks are over 36 inches in diameter.</p> <p>55.13-15 Compressed-air receivers and other pressure vessels should be inspected internally at least once a year by qualified inspectors; records of such inspection should be kept.</p> <p>55.13-16 Compressors should be operated and lubricated in accordance with the manufacturer's recommendations.</p> <p>55.13-17 Compressor discharge pipes should be cleaned periodically.</p> <p>55.13-18 Safety devices on compressed-air systems should be checked daily.</p>	<p>COMPRESSED AIR</p> <p>57.13-10 Air compressors should be equipped with automatic temperature-actuated shutoff mechanisms set for 400° F. or higher, and fusible plugs installed in the compressor discharge lines as near the compressors as possible. Fusible plugs should melt at temperatures 50° less than the flash points of the lubricating oils.</p> <p>57.13-11 Compressors and compressed-air receivers should be equipped with automatic pressure-release valves, pressure gauges, and drain valves.</p> <p>57.13-12 Compressor air intakes should be installed to insure that only clean, uncondensed air enters the compressors.</p> <p>57.13-13 Compressed-air receivers should be drained of moisture and oil at least once each day.</p> <p>57.13-14 Compressed-air receivers should have inspection openings which should be manholes when the tanks are over 36 inches in diameter.</p> <p>57.13-15 Compressed-air receivers and other pressure vessels should be inspected internally at least once a year by qualified inspectors; records of such inspection should be kept.</p> <p>57.13-16 Compressors should be operated and lubricated in accordance with the manufacturer's recommendations.</p> <p>57.13-17 Compressor discharge pipes should be cleaned periodically.</p> <p>57.13-18 Safety devices on compressed-air systems should be checked daily.</p>	<p>(a) Compressors and compressed-air receivers shall be equipped with automatic pressure-relief valves, pressure gauges, and drain valves.</p>	<p>(a) Compressors and compressed-air receivers shall be equipped with automatic pressure-relief valves, pressure gauges, and drain valves.</p>
<p>55.13-19 <i>Mandatory.</i> Repairs involving the pressure system of compressors, receivers, or compressed-air-powered equipment shall not be attempted until the pressure has been bled off.</p> <p>55.13-20 <i>Mandatory.</i> At no time shall compressed air be directed toward a person. When compressed air is used, all necessary precautions shall be taken to protect persons from injury.</p> <p>55.13-21 <i>Mandatory.</i> Except where automatic shutoff valves are used, safety chains or other suitable locking devices shall be used at connections to machines of high-pressure hose lines of 1-inch inside diameter or larger, and between high-pressure hose lines of 3/4-inch inside diameter or larger, where a connection failure would create a hazard.</p>	<p>(c) Repairs involving the pressure system of compressors, receivers, or compressed-air-powered equipment shall not be attempted until the pressure has been relieved from that part of the system to be repaired.</p> <p>(d) At no time shall compressed air be directed toward a person. When compressed air is used, all necessary precautions shall be taken to protect persons from injury.</p> <p>(e) Safety chains, suitable locking devices, or automatic cut-off valves shall be used at connections to machines of high-pressure hose lines of three-fourths of an inch inside diameter or larger, and between high-pressure hose lines of three-fourths of an inch inside diameter or larger, where a connection failure would create a hazard. For purposes of this paragraph, high-pressure means pressure of 100 p.s.i. or more.</p>	<p>(b) Repairs involving the pressure system of compressors, receivers, or compressed-air-powered equipment shall not be attempted until the pressure has been relieved from that part of the system to be repaired.</p> <p>(c) At no time shall compressed air be directed toward a person. When compressed air is used, all necessary precautions shall be taken to protect persons from injury.</p> <p>(d) Safety chains or suitable locking devices shall be used at connections to machines of high-pressure hose lines of 1-inch inside diameter or larger, and between high-pressure hose lines of 3/4-inch inside diameter or larger, where a connection failure would create a hazard.</p>	<p>(b) Repairs involving the pressure system of compressors, receivers, or compressed-air-powered equipment shall not be attempted until the pressure has been relieved from that part of the system to be repaired.</p> <p>(c) At no time shall compressed air be directed toward a person. When compressed air is used, all necessary precautions shall be taken to protect persons from injury.</p> <p>(d) Safety chains or suitable locking devices shall be used at connections to machines of high-pressure hose lines of 1-inch inside diameter or larger, and between high-pressure hose lines of 3/4-inch inside diameter or larger, where a connection failure would create a hazard.</p>

(38 FR 4976, Feb 23, 1973)

57.13-22 through 57.13-29 (Reserved)

55.13-22 through 55.13-29 (Reserved)

APPENDIX C

RECOMMENDATIONS REGARDING MSHA DATA

C-1.1 MSHA Compressor Accident Data Base - A Need for Improvement

Review of the MSHA (compressor-related) accident data during the course of this project has shown a need for improvements in data handling if proper assessments are to be easily made in the future regarding the extent to which air compressors pose a hazard when used in mining operations. As noted in Section 2.1.1.1, the current data are misleading and the extent of the problem in terms of frequency and severity seems to be significantly misstated. To a large extent this problem is believed to stem from inherent difficulties with procedures used to report, code, store, retrieve and interpret these data. Certainly, if improper information is reported, or if correct information is recorded improperly, wrong information will enter and become part of the data base. Furthermore, if stored information cannot be properly recalled, the record, even if accurate, will be of little value. In our opinion, the current compressor data base is of this nature; from the standpoint of assessing compressor hazards, the data and the reports they generate have proven to be inaccurate, unreliable, and misleading.

Accordingly, we have considered several approaches for correcting the current data base and these are discussed in Section C-1.2. Before looking at these approaches, however, it is important to look at data bases in general and to consider their function in terms of what is wanted, what is available, and what is needed. In this light, the following comments and guidelines are offered:

(1) It should be remembered that what is needed and wanted is a timely, accurate picture showing the extent to which air compressors (or other components) pose a health and safety hazard within the mining industry. Specifically, it is necessary to determine if compressor problems present an unacceptable level of risk when compared to the levels of risk posed by other kinds of equipment used within the industry and if so, what actions should be taken to reduce these risks. This implies the direct need for a reporting system that specifically considers cause and effect relationships so that incidents, accidents, and personal injuries can be directly linked to the equipment involved. This can be

accomplished through a classification system and a severity index.

(2) A classification system should be developed so that the proper assignment of causes can be made. These assignments, followed by the proper coding and storage of the data are necessary to define the frequency and severity of air compressor (and other components) involvement with respect to specific hazards (for example, fires and explosions, whipping hoses, etc.). While the current accident reporting form (reference Appendix D) reflects MSHA's primary mission, it generally ignores the pertinent characteristics of the equipment involved.

Since accurate cause and effect relationships must be determined and since personal injuries must be accurately linked to the equipment involved, the current Mine Accident, Injury and Illness Report, Form No. 7000-1 (September 1978), should be reviewed and appropriately revised. We realize that this form is used for many purposes and that to revise it just to treat "compressor incidents" would probably not be justified. At the same time, however, we suspect that the type of revision suggested will also enhance the usefulness of the other data bases. Furthermore, if the revision is carefully thought out and implemented the additional information can be obtained without imposing any additional reporting burdens on the industry.

(3) In conjunction with the classification system, a severity index should be established to better define the extent of the hazard with respect to kind, the degree of risk posed, and the number of miners put at risk. For example, a hazard that results in a slight injury to a single miner, such as dust in the eyes as a result of using air for cleaning purposes, is less severe than a compressor fire or explosion in an underground mine that directly injures several miners and exposes many others to serious injury or risk.

(4) A method of accessing the data base in an unambiguous manner with respect to specific component involvement and hazards should be developed, particularly when summary information is being sought. Formats should be developed for treating and reporting different aspects of the problem. For example if one wishes a summary of accidents resulting from compressor operations, the system should be capable of

extracting from the data base sufficient information to count accidents such as the Bell Compressor Plant Explosion and Fire⁽¹⁾, the accident caused by the parting of a grooved coupling during compressor start-up at the Hecla Star Mine⁽²⁾, or the compressor fire at the Morton Mine⁽³⁾, while at the same time rejecting an accident such as the compressor fire at Powhatan No. 6⁽⁴⁾ in which the compressor was only involved as it was being transported from one position to another.

(5) A policy should be established for conducting periodic in-house or contracted reviews to determine the adequacy of reporting and documentation procedures and the accuracy of the data base.

While the above guidelines apply to data base requirements in general, they are for the most part only useful when a new data base is being considered or when an accurate data base is available for modification. Since this is not the situation with the present "compressor hazard" data base, it is necessary, before proceeding further, to establish a common point of departure by looking at some of the options that are available for restructuring or correcting the present data base. In doing so it is important to anticipate the potential impact of the options on the mining industry.

C-1.2 MSHA Options for Dealing with the Current Data Base

To be useful, accident data must present an accurate picture of the extent to which air compressors pose a health and safety hazard within the mining industry. In particular, the data base must be suitable for determining if compressor problems present an unacceptable level of risk when compared to the levels of risk posed by other kinds of equipment used within the industry and if so, what actions should be taken to reduce

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- (1) Bureau of Mines Special Investigative Report, Bell Compressor Plant Explosion and Fire (Surface), The Anaconda Company, Butte, Montana, July 1962
 - (2) Bureau ID No. 17006-00-10-040, Report of Nonfatal (Compressed Air) Accident, Star Mine, Hecla Mining Company, Burke, Idaho, March 1972
 - (3) Bureau ID No. 46-01329, Report of Coal-Mine (Air Compressor) Fire, Morton Mine, Carbon Fuel Company, Winifrede, West Virginia, November 1973
 - (4) Bureau ID No. 33-01159, Report of Coal Mine (Machinery) Fire, Powhatan No. 6 Mine, the Nacco Mining Company, Belmont County, Ohio, July 1973

these risks.

Given the state of the current data base, this picture can be developed in three ways: (1) new reporting procedures could be implemented that would, over a period of time, lead to accurate data bases from which the necessary information for risk assessment could be extracted; (2) survey techniques could be used to obtain, within a much shorter time frame, the information required for the comparative risk analyses. This input could also be used to update the data bases and provide the necessary information to assess the compressor situation; its severity, the extent to which it should be monitored, and the revisions needed to do so; and (3) the information reported herein could be used to establish the new data base, which would then be maintained and accessed through improved methods of analysis, coding, storage, and retrieval.

The last two approaches (survey and supplemental data bases) are advantageous because they avoid imposing more regulations and reporting procedures on the industry just to find out if compressors do, in fact, pose a problem within the mining industry or if they do not.

A fourth alternative, of course, is to do nothing with respect to the data base. This approach is based on the philosophy of "wait and see" and if one feels that the current data, even though inconclusive, is adequate to infer that compressor operations do not pose an unnecessarily unacceptable risk or hazard to miners, then this type of approach may be preferred.

Based on our study, our order of preference for treating the "data base problem" can be listed as follows:

- (1) Development of supplemental data base using the data given in Section 2.1.1.1.
- (2) Adopt a "wait and see" philosophy.
- (3) Develop and implement a survey to obtain the necessary data to update the data base and

to perform the risk analyses^(a, b).

- (4) Promulgate regulations imposing revised reporting procedures, for example, requiring all fires and explosions to be reported even if extinguished within 30 minutes.

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- (a) An industry-wide data survey was not within the scope of this project; the nature and extent of our own field survey requirements are given in Section 2.2.
 - (b) A survey approach could be implemented under the following guidelines:
 - (1) A detailed survey would be prepared and sent to mine operators, mining companies, and manufacturers to obtain the necessary inputs for a risk assessment;
 - (2) from this survey, specific mines and manufacturers would be identified for direct contact (by phone and in some cases, visits) where more exacting information is needed or warranted;
 - (3) since risk must be assessed with respect to other equipment, similar data must be obtained for all other components expected to pose high but seemingly acceptable levels of risk. While government and broad industry records may be acceptable for determining these data, it is possible that a similar situation as experienced with the compressor data may surface in which case, additional survey work would be necessary. For this reason, the first task would be to analyze the current data bases for specific pieces of equipment and if the data is unacceptable for its intended application, then the compressor survey would be expanded to ask for the necessary information.

APPENDIX D

MSHA MINE ACCIDENT, INJURY, AND ILLNESS REPORT,
FORM NO. 7000-1
SEPTEMBER 1978



DO NOT WRITE IN THIS SPACE

MINE ACCIDENT, INJURY, AND ILLNESS REPORT

SECTION A - IDENTIFICATION DATA

Report category: Metal/nonmetal mining Coal mining
Check here if this report pertains to a lessee or contractor

MSHA ID Number _____ Mine name _____
Company name _____

SECTION B - COMPLETE FOR EACH ACCIDENT IMMEDIATELY REPORTED TO MSHA

- Accident code (circle applicable code—see instructions) 01 - Death 02 - Serious injury 03 - Entrapment 04 - Inundation 05 - Gas or dust ignition 06 - Mine fire 07 - Explosives 08 - Roof fall 09 - Outburst 10 - Impounding dam 11 - Hoisting 12 - Off site injury
- Name of investigator _____
- Date investigation started (mo) _____ (da) _____ (yr) _____
- Steps taken to prevent recurrence of accident _____

SECTION C - COMPLETE FOR EACH REPORTABLE ACCIDENT, INJURY OR ILLNESS

Accident information

- Circle the codes which best describe where the accident occurred (see instructions).

(a.) Surface location	(b.) Underground location	(c.) Underground mining method
01 Surface at underground mine	01 Vertical shaft	01 Longwall
02 Mill, preparation plant, etc.	02 Slope/inclined shaft	02 Shortwall
03 Strip/open pit mine	03 Face	03 Conventional/stopping
04 Surface auger operation	04 Intersection	05 Continuous miner
05 Quim bank/refuse pile	05 Underground shop/office	06 Hand
06 Dredge mining	06 Other	07 Caving
12 Other surface mining		08 Other
17 Independent shops (with own MSHA ID)		
99 Office facilities		
- Date of accident (mo) _____ (da) _____ (yr) _____
- Time of accident _____ a.m. p.m.
- Time shift started _____ a.m. p.m.
- Describe fully the conditions contributing to the accident and quantify the damage or impairment _____

- Equipment involved: Type _____ Manufacturer _____ Model number _____
- Name of witness to accident _____

Injury and illness information

- Number of reportable injuries or illnesses resulting from this accident _____
- Name of injured/ill employee _____ 14. Sex _____
- Date of birth (mo) _____ (da) _____ (yr) _____ 16. Last 4 digits of social security number _____
- Regular job title _____ 18. Check if this injury/illness resulted in death
- Check box if injury / illness resulted in permanent disability (include amputation, loss of use, and permanent total disability)
- What directly inflicted injury or illness _____
- Nature of injury or illness _____ 22. Part of body injured or affected _____
- Occupational illness (circle applicable code—see instructions) 21 - Occupational skin diseases 22 - Dust diseases of the lungs 23 - Respiratory conditions (toxic agents) 24 - Poisoning (toxic materials) 25 - Disorders (physical agents) 26 - Disorders (repeated trauma) 29 - Other
- Employee's work activity when injury or illness occurred _____
- Experience in this job title (yrs) _____ (wks) _____
- Experience at this mine (yrs) _____ (wks) _____
- Total mining experience (yrs) _____ (wks) _____

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Degree _____
 Accident type _____
 Accident class _____
 Scheduled charge _____

SECTION D - RETURN TO DUTY INFORMATION

- Permanently transferred or terminated (if checked, complete items 29, 30, and 31)
- Date returned to regular job at full capacity (or item 28 above) (mo) _____ (da) _____ (yr) _____
- Number of days away from work _____ 31. Number of days restricted work activity _____
(Items 30 and 31 must be answered when case is closed; if none enter 0)

Person completing form: (name) _____
Date this report prepared (mo) _____ (da) _____ (yr) _____ (area code and phone number) _____

