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FULL AUTOMATION OF A BIG AIR COMPRESSOR PLANT.

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1.) GENERAL INFORMATION.

The air compression plant has 6 reciprocating, horizontal, duplex, double-acting, water-cooled compressors, driven directly by 257 Rpm synchronous motors. The "Low Pressure" compressors (# 1 to 4) are designed for 45 psig with a total capacity of 5700 cfm and require a total of 785 HP, whereas the "High Pressure" machines (#5 and 6) deliver 2210 cfm at 110 psig, requiring 450 HP together.

The full automation obviated the continuous attendance of an operator (4 men to share 21 weekly shifts), and paid for itself in less than 2 years.

The following is a condensed description of the complete system, although some features were omitted at the time of installation (e.g. the water-saving devices) for reasons too lengthy and not interesting enough to explain here.

2.) NORMAL OPERATION.

2.1.) AIR FLOW.

2.1.1.) Full Capacity Operation.

Each compressor delivers its air into an individual Receiver, whose outlet side is connected to a manifold for distribution throughout the plant (see Fig. 2.)

2.1.2.) Capacity Control.

2.1.2.1. Principle.

Constant air pressure is to be maintained in the system while the demand fluctuates. The "Dual Control" provides two operating methods: Either "Continuous Run", where the compressor is kept running all the time, but idles, wholly or partially, whenever the demand is smaller than the full capacity and the receiver pressure, therefore, begins to rise; or "start-stop", where the compressor stops every time the receiver pressure exceeds a set level, and starts again whenever the pressure drops. The first method is recommended, if and when demand equals approximately the capacity of the compressor(s), and pumping and idling periods alternate, therefore, frequently, whereas the second method is suitable, when the demand is small compared to capacity and storage volume of the system (e.g. at night and week ends). A combination of, and automatic shift be-

tween both methods was selected, whereby basically each compressor operates under constant-run control, but will automatically be stopped, when it idles longer than a given time - say 10 minutes - and will be started again only when required.

2.1.2.2.) Coordination of Several Machines.

As it is undesirable that more than one compressor should cut in or out at the same time, the control is set up so that with falling system pressure the "leading" compressor, which carries the basic load, will cut in first, and only if and when it can not cope with the demand, the second, called "trailing", compressor will start, and only if they both cannot satisfy the demand, the following machine(s) will be called up; conversely with rising system pressure the machines cut out in reversed sequence. If e.g. the demand were more than two, but less than three machines can handle, two lead machines would pump constantly, the third intermittently, while the fourth stands by. Obviously the leading machines are subject to greater wear, therefore, the lead is alternated at regular intervals (Sec. 2.4.2.2)

2.1.2.3.) Unloading.

The capacity of each compressor, even if it runs at full speed, can be held at five levels, zero, one-quarter, one-half, three-quarter, and full load, thus providing 17 capacity levels for the LP, and 9 for the HP system.

The LP compressors have a by-pass unloading valve at each end of each cylinder, which when opened, sends the air back into the suction line rather than have it compressed and pushed into the discharge, thus eliminating one quarter of the capacity. On the HP compressors the unloading valves on each cylinder end open connections to "Clearance Pockets", which are sized so that each reduces the capacity also by one quarter. All these unloading valves are held shut by air pressure, and open whenever this pressure is released.

2.1.2.4.) The Bury "MU" -Unloader.

The very heart of the control is the Mechanical-Pneumatic Regulator, Bury, Type "MU", see Fig. 2 and 8. Its main element is the Piston Valve 46, movable in cylinder 48; the pulley 62, driven constantly from the main shaft by a belt, imparts a reciprocating

ing motion to the slide 35 through the worm gear 31, 32 and eccentric 29. The Receiver is connected by the "Sensing Line" 70 to the Bellows 50, and when the pressure rises, the Rack 45 will, via Pin 55, Lever 51, Tie Rod Rod 56, be lifted, thus engaging Pawl 38, which pushes Rack 45, Cross Head 27, and Piston 46 one step to the right with every turn of Gear 31; conversely, when the receiver pressure drops, Pawl 37 engages and the slide valve is moved to the left. With the piston in the far left position, as shown, all four Unloading Valves are connected to the receiver, that is they are held shut and the compressor pumps at its full capacity, whereas with each step to the right one unloading valve is disconnected from the pressure source and vented into the atmosphere, and thus, the compressor is gradually unloaded, until with the position on the far right it is completely idling. Spring 59 and Weight 54 allow exact setting of cut-in and cut-out pressures, and it should be emphasized that not only a very slight pressure difference suffices to move the regulator through the entire range, but that also the set points may be, and have been, identical for all machines of each group, that thus each of them is governed simultaneously by the same deviation; it is not necessary to let the trailing compressors cut in at higher pressures than the leading ones; thus only a very small differential is needed to shift the capacity through the entire range of 16 steps.

2.1.2.5.) Start, Pull-out and Sequencing.

Obviously, only when a compressor idles completely, the "Quarter Load Line" (far right in the figures) will be without pressure, and only when it is completely loaded, pressure will prevail in the "Full Load Line"; consequently, the normally open Pressure Switches Q and L can supply the necessary information to the system control.

2 three-way solenoid valves A and AV permit control air to reach the unloader, but vent it to the atmosphere, when one is de-energized. V is energized only simultaneously with the excitation of the synchronous motor (see Fig. 1); thus, during the start-up, or if the motor should fall out of step, all cylinders will be completely unloaded, regardless of the position of the slide. The AV-valves are energized through the L switches of the compressors leading in the sequence (Fig. 4); thus, no compressor will start pumping until the capacity of its leading compressor is fully utilized.

Yet another solenoid valve K in the sensing line 70 connects the Bellows 50 to the receiver, when energized, but vents it when de-energized, in which case the unloader will shift to full-load, regardless of the pressure; as the K valve is controlled by the Q-switch of the machine next in sequence, a compressor will not begin to unload, until its trailing machine is completely

idling.

On the HP machines pneumatically actuated Blow-down Valves Y, also controlled by the V-Valves, vent all cylinders and the inter-cooler at stand-still, assuring completely unloaded start from any crank position.

2.1.2.6.) Manual Override.

For starting up a completely empty system (e.g. after vacations or a strike) by-pass valves on one machine may be screwed down by hand temporarily. By manipulating the Four-Way-Cocks FWC and, thus, by-passing V and AV, the control and sequencing may be overridden, (see Note 8).

2.1.2.7.) Air Transfer.

In this plant the demand for LP air sometimes exceeds the compressor capacity, whereas most of the time the HP system has surplus capacity available for throttling down into the LP system. (see Fig. 2). Control air is taken from the HP through the Reducing Valve RV, part or all of which can escape through the nozzle of the Pressure Pilot PP, depending on the position of a flapper; dropping LP pressure tends to close the orifice via Bourden Tube, thus to raise the pressure on the diaphragm of the pneumatic valve TV, causing it to open and bleed air down into the LP system in order to maintain there the desired pressure. However the Solenoid Valve J is governed by the Auxiliary Pressure Switch AP and the 4 ZZ-switches of the LP compressors (see Fig. 4), all in series; thus, no control air can reach the diaphragm and no air be transferred, if either the HP would drop too low thereby, or before all LP compressors are fully utilized; the latter constraint can be eliminated by a jumper across the ZZ-contacts, which will waste energy, but provide a faster response; the whole control can be overridden by the Four-Way-Cock FWC (see Note 8).

2.2.) WATER FLOW.

Each of the 10 parallel streams of cooling water is regulated by a Thermostatic Valve ThV (see Fig. 3) installed near the inlet and controlled by a feeler bulb near the outlet. A small, normally open solenoid valve W opens a by-pass only when the compressor is running (see Sec. 2.4.2), assuring a prompt response, when ThV is fully closed at a stand-still; thus, rapid and extreme temperature changes on the cylinder walls are avoided and yet no water is wasted. The Room Thermostat Th will de-energize, and thus open, all W-valves, if danger of a freeze-up exists, whether the compressor is running or not.

2.3.) LUBE FLOW.

All running gears have splash lubrication. One force-feed lubricator for each machine, belt-driven from the main shaft, supplies oil to the cylinders and the unloader (see Fig. 10). Lube flow and temperatures are monitored as described in Section 3.2.3.2.

2.4.) ELECTRIC CIRCUITS.

2.4.1.) Power Circuits.

The 6 synchronous motor controls differ from each other slightly, having been purchased from different suppliers at different times, but are manufacturers' standard and need not be described in full detail. The diagrams and description refer to unit 1.

2300 V, 3-phase AC is supplied to the main motors M, as well as transformers PT and CT, whereas the exciter set induction motors get 440 V AC from a separate source; 125 V DC for the motor control comes from the general plant network, but can, if needed, be taken from one of the exciters over an Emergency Switch ECS.

2.4.2. Control Circuits.

2.4.2.1.) Starting.

The starting command is given by energizing Control Contactor CC (to be described later), closing all its NO contacts; if Selector Switch SW is in "Auto" position, the starter coil XRC is energized and the Motor-Generator Set XM started; also the Auxiliary Time Relay ZA, energized (see Fig.4), closes its contact after a regulable delay, during which the DC voltage builds up, and energizes the Main Contactor C, which puts the Main Motor M on the line; the Field Contactor Frequency Relay FCFR senses when the motor has accelerated to synchronization, then causes the Field Contacts to close and energize the field, whereupon the Motor runs synchronously.

2.4.2.2. Sequencing.

Only the LP system control is shown and described here; the HP system control is essentially the same, some minor variations (only two units) are obvious.

Suppose transformers PT and CT are on line - as they normally are - and all 4 units are ready for service, thus the manual H-switches are in the shown position; # 1 has been selected as leading, thus the Sequence Selector Switch contacts 1A, 2X, 3X, 4X are closed, but 1X, 2A, 3A, 4A open, then the Secondary Control Time Relay ZZ1 will be energized, one of its contacts will close and energize Primary Control Time Relay Z1, which over one of its contacts energize CC1 (AR1 being closed) and bring about the start of M1, as described. Also AV1 is energized through ZZ1, and V1 through FC1, whereas K1 is still de-energized, thus the compressor can take on load; also through another NC contact on Z1 the Water Valve W1 will be de-energized and open.

Now, when due to high demand for air # 1 machine is fully loaded, thus its L-switch closed, ZZ2 and subsequently Z2 will be energized, but only after a delay, regulable from 10 sec to 3 min; thus, if the demand persists for that period, # 2 compressor will start. As long as # 2 is pumping, its Q-switch is closed and K1 energized, thus prevent # 1 from unloading. Conversely, when the system pressure rises, # 2 will unload, but contin-

ue running, # 1 carrying all the load. Further pressure rise will unload # 1 partially, and as soon as it runs with 3/4 load only, L1 will open and de-energize ZZ2, which in turn will instantaneously de-energize Z2 and AV2; thus, # 2 will be kept idling unless and until # 1 is fully loaded again; however, # 2 will continue running for a time regulable from 30 sec to 15 min due to the off-delay of the Z-switch; only if not called back to pumping during that time will # 2 be stopped via the NO contacts of Z2, CC2, ZA2, and Z2. By means of these built-in delays unnecessary long idling times (e.g. during nights and on week ends) are avoided, as well as too frequent starts (not permissible for the synchronous starting gears).

To keep the running times for all units approximately alike the lead is to be alternated periodically. By opening contacts 1A, 2A, 4A, 2X and closing 1X, 3X, 4X, 2A (see Note 5) # 2 will be made first and # 1 last in the sequence, whereby the open contact E2X prevents the K1 valve from being energized through Q2.

To take a compressor off the line (e.g. for repairs) turn the manual H-switch to the opposite position, the unit will then be skipped in the sequence and also shorted out of the alarm circuit (Sec.3.2.1.1.).

3.) SAFETY DEVICES.

3.1.) PNEUMATICALLY OPERATED.

Although Unloader failure is extremely unlikely, conventional springloaded safety valves are installed at suitable locations.

3.2.) ELECTRICALLY OPERATED.

3.2.1.) Alarm Circuit.

3.2.1.1.) In-Plant Alarm.

An Alarm Relay AR for each unit is wired in series with a number of switches, any one of which, when opened, will de-energize it with the following consequences (Fig.4): a yellow lamp IL will light up, locating the cause of the trouble, one NO contact will de-energize the Alarm Master Relay AMR, which then closes its NC contacts, one of which sounds a Horn, the other connects the Silencer Relay SR to one side of the line.

An operator, present at the plant, can then quickly take the guilty compressor off the line by turning its H-switch, which will stop the machine, re-energize AMR and silence the horn; however, the lamp will remain lit, until the reason has been eliminated. Each AR has a second, time-delayed, NO contact and, if after elapse of the delay period (adjustable from 0 to 3 min) no action has been taken, this contact will cut off Control Contactor CC and stop the unit, while the alarm continues. A third, instantaneous, NC contact will energize the ZZ-relay of the compressor next in line, starting it, if not already running; this will happen regardless whether the unit was stopped by a monitor or manually, in other words, whenever a machine

is unavailable for whatever reason, it is automatically skipped in the loading sequence. An NC contact on the ZA-relays will, whenever a compressor stands still, transmit the venting command from the Q-switch of the following machine to the K-valve of the preceding one, while the open Ex-contact prevents its Q-switch from energizing its own K-valve.

3.2.1.2.) Remote Alarm.

Another NO contact on AMR de-energizes in case of an alarm two Remote Relays RR, located at distant points, closing their NC contacts and putting a siren on the local power line, this also in the unlikely case of failure of the transformer CT or an interruption of the transmission line. An operator at the remote site can acknowledge the alarm by depressing a Silencer Button SB, one of whose contacts will lock it in after release of the button, the other will re-energize the RR relays, silence the audible alarm at the remote locations, but not the horn in the compressor room, and at the same time yellow lamps will light up at the remote stations and remain lit, until the alarm is cancelled by turning the appropriate H-switch. (If it cannot be cancelled, there must be control power failure).

3.2.2.) Power Circuit Protection.

If one phase of the main power supply became grounded, the currents in the Current Protective Transformer CPT would be unbalanced and the Momentary Cut-out Relay MCR would not only de-energize AR and set up an alarm, but also (because extremely fast action is required) directly and immediately de-energize Contactor C and separate the synchronous motor from the line; it must then be re-set manually. (See Fig.1).

An objectionable overload would be sensed by the Current Transformer CUT, activate the Overload Relays OL, energize the "t" coil of the Trip Relay TRY in the DC control circuit, which will de-energize AR and also C, thus stopping the motor; TRY is mechanically held and can be re-set only by momentarily energizing its "r" coil, which takes place automatically, when the operator takes the defective unit off the line by turning its H-switch. The same shut-down sequence can also be initiated by undervoltage (which will also reduce the secondary voltage of PT) or by the Out-of-step Protector OSP, both of which cause the Undervoltage Relay UVR to close its NC contact, or by pushing the Emergency Stop Button OCB.

The exciter motors are protected by the usual thermal Overload Protectors OLX.

3.2.3.) Mechanical and Thermal Protectors.

3.2.3.1.) Temperature Monitors.

Practically every irregularity in a compressor system, that may lead to damage or danger, will manifest itself by a tempera-

ture rise; thus, a high degree of safety can be obtained by monitoring the temperatures at appropriate points. (See Fig.2 and 3)

Switches U1 and U2 are installed in the compressor discharge lines; valve failure, the most common trouble, lack of cooling water, excessive friction (broken piston rings or stuffing box trouble e.g.), all will result in high discharge temperature. Temperature switches U3 at the aftercooler outlets guard against lack of water; U4 and U5 are submerged in the crank case oil, as bearing trouble will raise the oil temperature. All these switches are normally closed and will break their contacts, whenever the temperature exceeds the pre-set value; then the corresponding B-relay (Fig.7) is de-energized, its NC contact causes a yellow trouble lamp IL to light up, one of its NO contacts sets up an alarm, as described, the other is the holding contact and will prevent the relay to get re-energized, even after the unit has stopped and the temperature returned to normal; thus, the alarm will remain in force and its cause be evident, until the Cancelling Button CB has been depressed.

3.2.3.2.) Lube Monitors.

Liquid Level Switches LL are installed in each crank case, wired in series, each of which breaks contact at low oil level and sets up an alarm as just described.

A Flow Switch LM (U.S. Patent # 3,267,451) is provided for each lube line immediately at its connection to the compressor cylinder (Fig. 9 and 10). The bottom of the V-shaped cavity is filled with mercury, in which the auxiliary terminals 2 and 3 are immersed, as long as no pressure prevails; when oil is pushed into the switch from the left, it will push the mercury down in the vertical and up in the inclined leg; the mercury then recedes from terminal 2, but immerses the sensing terminal 1. In as much as 1 and 2 are connected to one side of the line and 3 to the other, the switch will be normally closed. When flow continues, oil will be pushed around the edge of the central vertical leg, bubble through the mercury and accumulate on top of it. After all spaces have been filled, one drop will be delivered to the cylinder for every drop coming in, and each drop, when it passes the needle of the sensing terminal 1, envelops it and breaks the contact momentarily. As long as this happens in regular intervals, all is well; but if the oil drop should fail to arrive in time, an alarm will be given.

Full voltage prevails between grid and cathode of the Electronic Timer's Tubes ET (see Fig. 5 and 6) as long as the circuit on LM is open, and a charge is built up on the grid; when, however, the LM contact is closed, then grid and cathode are laid on the same potential and the charge dissipates slowly through the resistors; as soon as the grid has become uncharged, the tube

becomes conductive and current can flow from the cathode to the plate, which energizes Relay B 1,7. Through proper selection of the electrical components the deterioration time is made just a bit longer than the permissible time between oil drops; that is, if the drop arrives in time, it will allow the grid to be recharged; however, if not, B1,7 will open its NC contact and, thus, initiate an alarm, light up a trouble lamp IL 1,7 and, through its NO contact, lock itself in; the alarm will persist, even if an oil drop should arrive belatedly, until Cancelling Button CB 1,7 is pushed.

The LM switches are sensitive to lack of oil flow for whatever reason: empty reservoir, malfunction of the lubricator, e.g. slipping belt, obstruction or leak in the feed line; in the last case the oil may be driven backwards, but then contact would be maintained between terminals 2 and 3.

One NO contact of CC is wired into the circuit to prevent alarm when the unit stands still and oil flow is not needed.

Another relay, B 1,8, will light a lamp IL 1,8, if a filament should burn out, its second contact, wired directly into the AMR line will sound an alarm, but not stop the compressor; no locking contact is needed, as a burnt-out filament will not repair itself.

3.2.4.) Manual Overrides and Emergency Stops.

In addition to the pneumatical overrides (Four-way cocks) and the Stop-Button OCB, already mentioned, several electrical overrides are provided, which need not be described here. Suffice it to say that turning the Selector SW into the "Run" position will override the thermal and lube monitors, as well as the loading sequence; these switches are, therefore, locked and can only be manipulated by an authorized person in possession of a special key. Also for repairs several manual cut-off switches are installed.

3.2.5.) Testing and Measuring.

The usual pressure gauges, thermometers, sight glasses, Volt- and Ammeters are provided, not all of which are shown here.



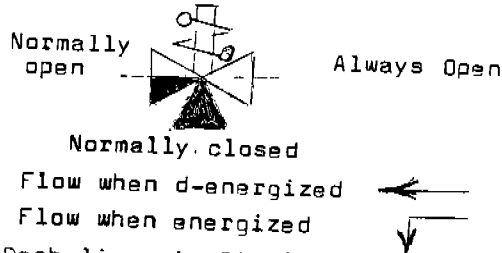
When the one Test Button TB on each monitor unit is depressed, all trouble lamps must light up except IL 9, the alarm must sound and after the preset time the compressor stopped. To check a Lube Monitor buttons LT 1 and LT 2 should be pushed, but not simultaneously, during a standstill, Lamp IL 7 must then light and an alarm initiated. After a test every single Cancelling Button CB must be pushed and the Selector SW, if used, returned to "Auto". Most tests can be made on the running machine, but details must be omitted here.

4.) ACKNOWLEDGEMENTS.

The equipment was furnished by the Erie Electric Mfg. Corp., for which the author was consultant, the unloaders were manufactured by the Bury Compressor Company, the main control cabinet was constructed and wired by the Lake Erie Electric Manufacturing Inc., co-inventor of the Lube Monitor Patent is Mr. Norman J. Anderson, all these of Erie, Pa.; Plumbing and wiring on the site was done by the Witham Electric Inc. at the plant of the Universal Atlas Cement Division of the United States Steel Co., both in Hudson, N.Y.

5.) DIAGRAMS.

5.1.) EXPLANATORY NOTES.

- 1.) In the Symbols the digit before the decimal point, if any, designates the unit (1 to 6).
- 2.) For emergency stop depress OCB, do not pull DS on Main Motor.
- 3.) MCR after trip must be manually re-set
- 4.) Turn SW-switch to "Hand" only to supply DC to other units, if main DC supply is out; see Sec. 3.2.4. and 2.4.1.
- 5.) Manual Selector Switch E has several double-throw poles; while one pole is making its "A" and breaking its "X" contact, the others are in the opposite position; see Sec. 2.4.2.2.
- 6.) Manual H-switches have maintained contacts.
- 7.)  signifies "On-delay"
 signifies "Off-delay"
- 8.) On the Unloader and [Transfer] Four-way-cocks (Fig. 2) the positions are used as follows:
I = Automatic
II = Unload [No transfer]
III = Load [Transfer] constantly
IV = Not to be used.
- 9.) Three-way Solenoid Valve

- 10.) Dash lines in Fig.'s 5,6, and 7 delimit the boundary of the sub-unit.

5.2.) SYMBOLS.

ACA	Ammeter	MCR	Momentary Cut-out Relay
AF	Air Filter	MW	Manual Water Valve
AHP	Auxiliary High Pressure Switch	QCB	Stop Button
AMR	Alarm Master Relay	OL	Overload Protector
AR	Alarm Relay	OLX	Exciter Overload Protector
AV	Auxiliary Solenoid Valve	OSP	Out-of-Step Protector
B	Monitor Relay	P	Pressure Gauge
C	Main Contactor	PP	Pressure Pilot
CB	Canceling Button	PT	Power Transformer
CC	Control Contactor	Q	Quarter-Load Pressure Switch
CK	Lube Check Valve	R	Resistor
Cond	Condensate Trap	Rec	Air Receiver
CPT	Current Protective Transformer	Rh	Rheostat
CS	Cut-off Switch	RR	Remote Relay
CT	Control Transformer	RV	Reducing Valve
CUT	Current Transformer	SA	Sub-Assembly Protective Device
Cyl	Compressor Cylinder	SB	Silencer Button
DCA	D C Ammeter	SG	Sight Glass
DS	Disconnect Switch	SR	Silencer Relay
DV	Drain Valve	ST	Timer Sub-Assembly
E	Sequence Selector Switch	SU	Lube Monitor Sub-Unit
ECS	Emergency Connect Switch	SV	Safety Valve
ET	Electron Tube	SW	Exciter Selector Switch (Control Override)
F	Fuse	TB	Test Button
FC	Field Contactor	Th	Room Thermostat
FCFR	Field Contactor Frequency Relay	ThV	Thermostatic Valve
FT	Filament Transformer	TRY	Trip Relay
FWC	Four-way-Cock	TV	Transfer Valve
G	D C Generator	U	Temperature Switch
H	Manual Control Switch	V	Unloading Solenoid Valve
HP	High Pressure Switch	VV	Slow Vent Valve
IL	Indicating Lamp	W	Solenoid Water Valve
IWM	Indicating Wattmeter	WHM	Watt-Hour Meter
J	Transfer Solenoid Valve	XDS	Exciter Disconnect Switch
K	Sensing Line Solenoid Valve	XM	Exciter Motor
L	Full-Load Pressure Switch	XRC	Exciter Running Contactor
LL	Lube Level Switch	Y	Blow-down Valve
LM	Lube Monitor	Z	Primary Control Time Relay
LP	Low Pressure Switch	ZA	Auxiliary Time Relay
LT	Lube Monitor Test Button	ZZ	Secondary Control Time Relay
Lub	Cylinder Lubricator		
M	Main (synchronous) Motor		

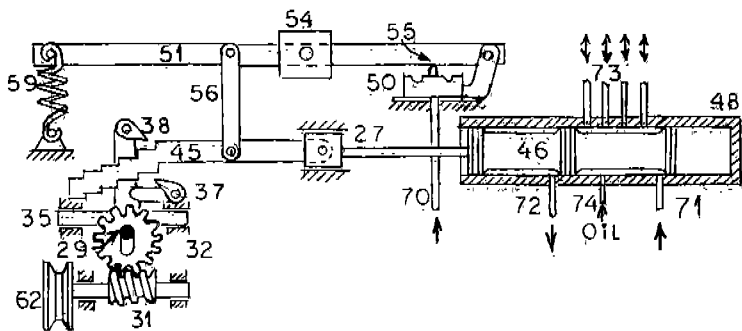


Fig. 8. Unloader Mechanism.

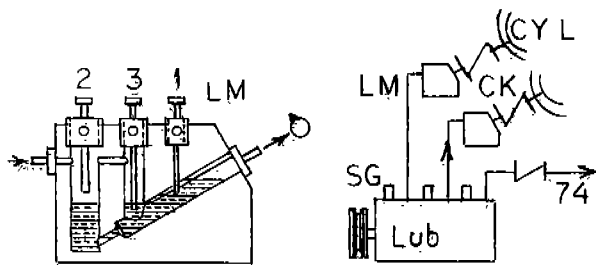


Fig. 9. Flow Switch Fig. 10. Lube Piping

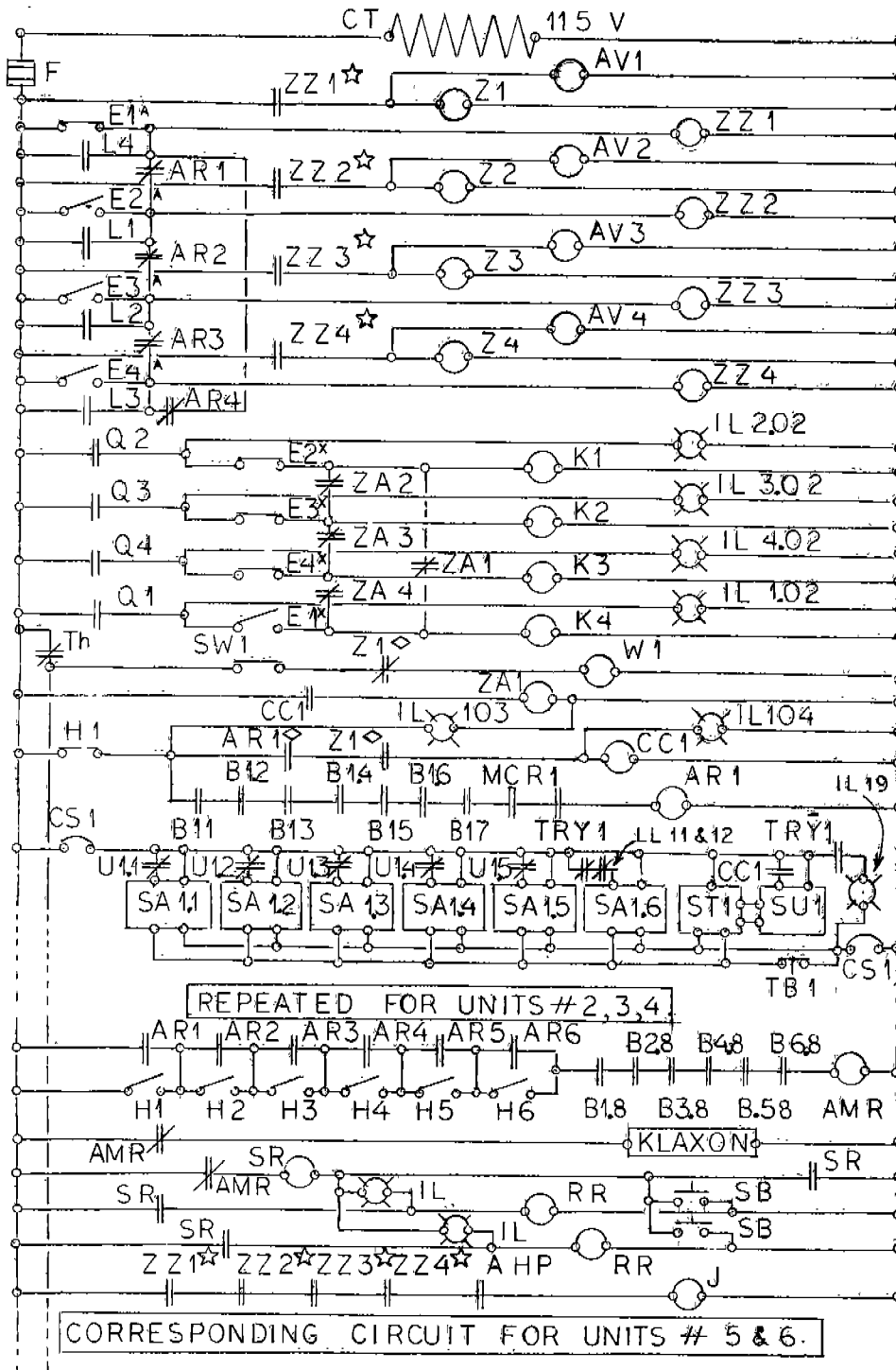


Fig. 4. Main Control Circuit.

Fig. 7. Detail "SA" Protective Device.

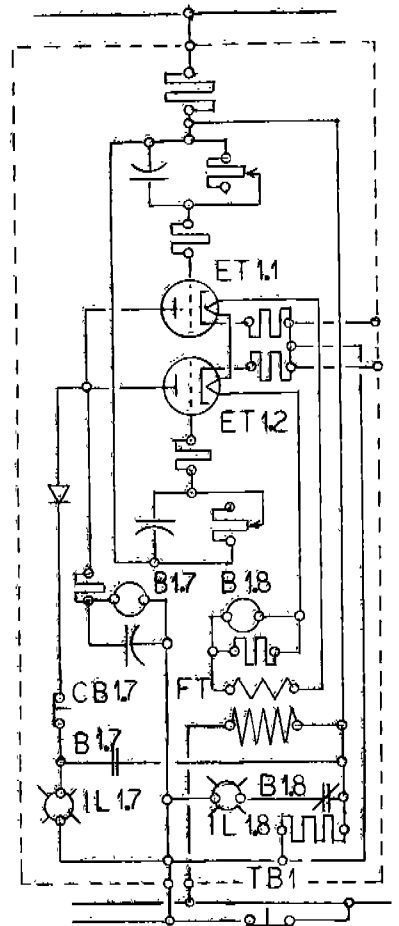


Fig. 5. "ST" Electronic Timer.

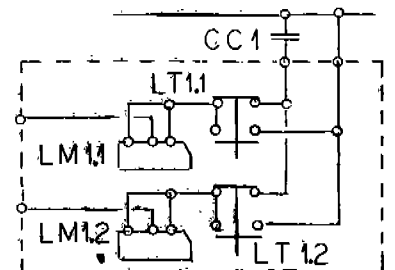


Fig. 6. "SU" Sub-Unit Lube Monitor

