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DESIGN OF AUTOMATIC STARTUP AND SHUTDOWN LOGIC FOR A BRAYTON-CYCLE 2- TO 15- KILOWATT ENGINE

James E. Vrancik and Richard C. Bainbridge

Lewis Research Center
Cleveland, Ohio 44135

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SUMMARY

The NASA Lewis Research Center is conducting a closed-Brayton-cycle power conversion system technology program in which a complete power system (engine) has been designed and demonstrated. This report discusses the design of automatic startup and shutdown logic circuits as a modification to the control system presently used in this demonstration engine. This modification was primarily intended to make starting the engine as simple and safe as possible and to allow the engine to be run unattended. In the modified configuration the engine is started by turning the control console power on and pushing the start button after preheating the gas loop. No other operator action is required to effect a complete startup. Shutdown, if one is required, is also effected by a simple stop button. The automatic startup and shutdown of the engine have been successfully and purposefully demonstrated more than 50 times at the Lewis Research Center during over 10 000 hours of unattended operation. The net effect of this modification is an engine that can be safely started and stopped by relatively untrained personnel. The approach lends itself directly to remote unattended operation.

INTRODUCTION

A closed-Brayton-cycle engine was tested at the Lewis Research Center. The Brayton engine was comprised of first-generation components for which there were very little component experimental data. In addition, no system experimental data were available, particularly with respect to startup, shutdown, and control. As a result an effort was made to incorporate redundant and alternate subsystems where a failure could interfere with the overall testing schedule. At the end of about 3800 hours of performance and endurance testing, it was determined that the engine could be improved and simplified on the basis of the data and experience gained. Reference 1 provides a complete description of the engine and components and of the initial experimental results from the testing program.

As part of the ongoing component technology improvement program the startup and shutdown of the Brayton engine were completely automated by modification of the original control system described in references 2 and 3. The control system was reduced in size by removing controls and instrumentation which proved unnecessary. Also, the redundant oil coolant loop was removed, hardware required for gas injection startup was removed and replaced by motor startup hardware (ref. 4), and four jacking gas valves were combined and replaced by two. The net effect is an operational power conversion system that is smaller, lighter, more reliable, and much easier to operate.

This report deals with logic and electronic circuit design for the automation of the startup and shutdown of the Brayton engine. The primary objectives were to make starting the engine as simple as possible and to allow unattended operation. Originally, with a manual start, extensive operator training requiring detailed knowledge of operating procedures and engine operating conditions was necessary to operate the system. In practice, several people usually assisted in startup. This approach was justified when the engine was first being tested and a large number of uncertainties existed in its response. However, through experience, the Brayton engine was found to be predictable to the point where very rigid startup and operating procedures could be imposed with no ambiguity in performance. Thus, a completely automatic startup and shutdown system was developed and implemented to simplify further testing of the Brayton engine.

STARTUP AND SHUTDOWN SEQUENCE

Brayton engine startup, modified by the automatic startup and shutdown logic, consists of turning the control system on, waiting a few minutes for thermocouple ovens to warm up, and pushing the start button. This assumes that, as part of facility control, the test support heat source has been brought up to operating temperature and there is sufficient thermal energy to allow an engine startup (ref. 1). Once the engine startup is initiated, jacking gas is used to float the Brayton rotating unit (BRU) turboalternator-compressor shaft, and the engine is motored to a speed of approximately 12 000 rpm. The engine continues to motor at this speed until the turbine inlet temperature reaches 728 K, the temperature at which turbine work exceeds compressor work and rotational losses by a safe margin. At this time the motor start inverter is turned off. The engine then bootstraps to the 36 000-rpm design speed and begins producing electrical output power. The complete startup can be performed by a single person having no knowledge of the Brayton engine.

Automatic shutdown circuits are activated during both startup and steady-state operation to monitor engine operation. If out-of-tolerance conditions are detected by the redundant monitoring circuits, a shutdown is initiated. Shutdown is accomplished by automatically applying 1.5 times rated load to the alternator and discharging the working gas in the loop. Jacking gas is also applied to protect the bearings. The BRU quickly decelerates to 5 rpm, at which time the jacking gas and parasitic load are removed and the BRU rests on the bearing. The console power is manually turned off if the engine is not to be restarted.

Design Requirements

The logic circuits needed to achieve automatic startup and shutdown were incorporated into the existing Brayton control system printed-circuit card file. The existing power supplies were sufficient to power the additional circuits. All logic elements were SN7400 series transistor-transistor logic (TTL) with a few discrete transistors to interface to higher voltage circuits.

All circuits were designed such that a single failure at any time would, at most, cause a safe orderly shutdown. No single failure would inhibit a safe shutdown. No single failure that could combine with another random single failure to cause a problem would go undetected. (A problem in this case is defined as an event that could induce the failure of a major power system component, e.g., by allowing overheating or overspeeding.) Any one printed-circuit card could be removed from the rack at any time with the only effect being a safe orderly shutdown. No attempt was made to account for the possibility of several failures at once. These are essentially the same design requirements that were followed in designing the original card file.

Startup Sequence

A normal automatic Brayton engine startup sequence is as follows: When the start button is pushed, the jacking gas valve (JGV) opens. Jacking gas pressure floats the BRU shaft and causes a slow reverse rotation. At 40 rpm, the motor start inverter contactors (K506 and K507) close. Two seconds later the inverter starts, and the engine accelerates to approximately 12 000 rpm (synchronous speed at the inverter frequency) in about 10 seconds. When the turbine inlet temperature reaches 728 K, and the speed is over 10 000 rpm, the inverter is turned off after a 2-second delay. The engine then continues to accelerate. At 26 000 rpm the alternator field power is applied. At 30 000 rpm the batteries are removed from the dc bus, after a 4-second delay, if the dc supply is producing power. At 35 000 rpm the jacking gas is turned off. At 36 000 rpm the speed control becomes active and electrical power output is available.

The startup sequence actually begins when the dc control power is turned on. The control panel is presented in figure 1. After the ±28-volt power is turned on and control panel power supplies begin operating, a monostable with a 50-millisecond delay issues a 2-second initialize pulse (I-pulse) to initialize all flip-flops and to acknowledge all panel alarms. The responses to the I-pulse are as follows:

(1) All startup sequence lights are turned off.
(2) The main jacking gas valve is closed.
(3) The backup jacking gas valve is closed.
(4) The jacking gas valves are closed.
(5) The start permissive flip-flop is set.
(6) The start flip-flop is reset.
(7) Shutdown circuits are disabled.
(8) Startup is inhibited until I-pulse is complete (2 sec).
(9) All alarms are acknowledged.
(10) Motor start inverter control power is turned off.
(11) The motor start inverter input (K507) and output (K506) breakers are opened.
(12) Cavity pressure is set to low value.

If and when the system is ready to be started, the start light will begin flashing. The following conditions are necessary before a startup:

(1) The initialize pulse is finished.
(2) All override switches are in proper position.
(3) The start permissive flip-flop is set.
(4) The coolant loop oil flow is above the minimum limit setpoint.
(5) The heat source temperature is above the minimum limit setpoint.

The override switches that are used as a start permissive condition and their proper positions are given in table I. The start permissive flip-flop is set by the I-pulse and is cleared by a completed startup. In the event of a shutdown prior to completion of the startup sequence, this flip-flop will inhibit any further action by the startup logic even though all other start permissive conditions are met. The dc power must be turned off and then back on again to generate another I-pulse. A flow chart of this turnon sequence is shown in figure 2.

The startup sequence will be initiated if the start button is pushed when it is flashing and all start permissive conditions are met. If prior to pushing the button the conditions are no longer satisfied (i.e., an override switch is placed in an improper condition), the start light will continue flashing but will go out if it is pushed. No startup will occur. If later the conditions are satisfied again, the light will flash and a startup is possible.

The startup sequence flow chart is shown in figure 3. Such logic decisions as whether the jacking gas valves are open or closed and whether K506 and K507 are open or closed are decided by monitoring auxiliary contacts on the valves and relays rather than by monitoring open or close commands.

The decision to start the motor is made only if (1) the start flip-flop is set; (2) the jacking gas valves are confirmed open; (3) the pressure switch is closed, indicating proper jacking gas pressure; and (4) the digital speed indication is greater than ±40 rpm. (Application of jacking gas applies a small torque on the shaft causing slow reverse rotation of the engine.)

After K506 and K507 are confirmed closed, the startup sequence branches. The normal sequence is to start the inverter, wait for synchronous speed and turbine inlet temperature to rise high enough, and stop the inverter. This would cause K506 and K507 to open, and the sequence would continue. However, if at any time during the normal sequence either the input (K507) or the output (K506) breaker were to open, the inverter would be safely shut down. If the conditions were such that the engine would not bootstrap, it would decelerate to zero speed, the control system would reset, and the startup would be safely aborted. The decision to stop the motor start inverter is made only if the turbine inlet temperature is higher than the setpoint (728 K) and the digital speed is greater than 10 000 rpm. A startup will be safely aborted anytime a shutdown is requested, either manually or automatically. If the motor start inverter is running at the time, it is commanded off, K506 and K507 are commanded open, and control power is removed. This procedure will isolate the inverter from the engine, protect the inverter, and allow the engine to decelerate. The start light will remain on (but will be inactive), and the startup sequence lights that have not been turned off will remain lit.

The actual circuitry for the automatic startup is shown in figures 4 to 6 (cards E18, E19, E20, E21) and figure 7 (the start button). Figure 4 shows the main part of the startup sequence logic. All inputs come from TTL (or TTL compatible) logic. All outputs except the inverter controls go to TTL logic.

Figure 5, called the rotation detector card, shows the circuitry used to decode the digital readout of speed in the control system. Only speeds greater than 40, 10 000, and 35 000 rpm are output. These are used on cards E18 and E19 (figs. 4(a) and (b)) of the startup sequence and also in the shutdown sequence.

Figure 6 (card E21) contains the light drivers for the first five lights for the startup sequence (the sixth light being driven directly from the JGV auxiliary contacts) and the primary JGV-enable flip-flop. Also, the start permissive logic and the I-pulse generator are contained on card E21. The inverter-inhibit-off I_O signal is developed on card E21 and is logically 1 when I-pulse = "1," when a shutdown is occurring, or whenever the motor start inverter startup sequence light is off. Normally, I_O is zero only between the time the start button is pushed and the motor start inverter is turned off. The I_O pulse is used to lock open K506, K507, and the motor start inverter control power in order to prevent applying the inverter to the alternator bus during normal operation.

Figure 7, the start button circuit, shows the interface between the start permissive output (low active) of card E21 (fig. 6), the start button flasher and alarm, and the start sequence on card E19 (fig. 4(b)).

A simplified drawing of the inverter inputs is shown in figure 8. The control power required is 1.3 amperes. The output of the circuit in figure 4(b) was tested at 5 amperes without the transistors coming out of saturation and overheating.

Shutdown Sequence

Shutdown of the engine can be caused by the shutdown pushbutton (fig. 1), by overspeed, or by three groups of shutdown parameters. The overspeed sensing and shutdown sequence triple-redundant logic contained in the signal conditioner unit is not modified. The shutdown pushbutton is also unmodified, except that the shutdown parameters have been added in parallel to the pushbutton and cause exactly the same response as the pushbutton. The shutdown parameters in the three groups are listed in table II.

Group 1 parameters are enabled (allowed to activate a shutdown) at 35 000 rpm and are singly monitored and signal conditioned. Any one parameter going out of limits (or any single failure of a monitoring circuit) will cause a shutdown. Group 2 parameters are enabled at 35 000 rpm and are triply monitored and signal conditioned such that at least two channels out of three must be out of limits to cause a shutdown. Group 3 parameters are enabled at the same time that the motor start inverter is turned on and are all triply monitored as in group 2.

All shutdown initiation signals are disabled when the speed drops below 40 rpm, and an automatic shutdown reset occurs at 5 rpm. A shutdown request from group 1, 2, or 3 must last for at least 0.7 second to actively cause a shutdown request in the signal conditioner shutdown circuits. Any request that lasts less than 0.7 second is ignored. If a shutdown request gets to the signal conditioner circuits, that channel is latched into the shutdown mode until manually reset. When two channels in the signal conditioner unit are latched into a shutdown mode, a shutdown occurs. A flow chart of the shutdown logic is shown in figure 9, and the circuitry for one channel of the shutdown logic is shown in figure 10. When a shutdown occurs, the shutdown request logic is latched. This protects the system against an accidental or premature reset signal, which would close the jacking gas valves and turn off field power during a shutdown. A shutdown signal overrides a reset signal if both are present at the same time. When the speed goes below 40 rpm, the shutdown signal is removed; and as the speed goes below 5 rpm, a reset pulse is generated and the engine stops.

CONCLUDING REMARKS

The modification to the Brayton automatic startup and shutdown logic proposed herein was intended to make starting the Brayton cycle power conversion system as simple and reliable as possible. This objective has been met. In the present modified configuration the system is started (after sufficiently preheating the gas loop) by turning the control power on and pushing the start button. No other operator action is required to effect a complete startup. The automatic startup and shutdown have been successfully demonstrated over 50 times at the Lewis Research Center during over 10 000 hours of unattended operation.

The net effect of this system modification is an operational power conversion system that is more reliable and can be started and stopped by personnel with no special training.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 21, 1974,
506-23.

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4. Curreri, Joseph S.; Edkin, Richard A.; and Kruchowy, Roman: Motor Starting a Brayton Cycle Power Conversion System Using a Static Inverter. NASA TM X-2738, 1973.

TABLE I. - OVERRIDE SWITCHES USED AS

START PERMISSIVE CONDITIONS

Switch	Proper position
Main jacking gas valve	Automatic
Backup jacking gas valve	Automatic
Vehicle load breaker	Off
Gas inventory makeup valve	Automatic or off
Gas inventory bleed valve	Automatic or off
Gas inventory dump pilot valve	Automatic
Speed control override	↓
Voltage regulation inhibit	
Field control	

TABLE II. - SHUTDOWN PARAMETERS

Group	Parameter
1	Alternator voltage high
	Alternator voltage low
	Alternator current high
	Primary jacking gas valve open
	Backup jacking gas valve open
2	Cavity pressure low
	Speed low
3	Compressor inlet temperature high
	Turbine inlet temperature high
	Alternator output temperature high
	Compressor discharge pressure high
	Gas bottle pressure low
	External (facility support equipment malfunction)

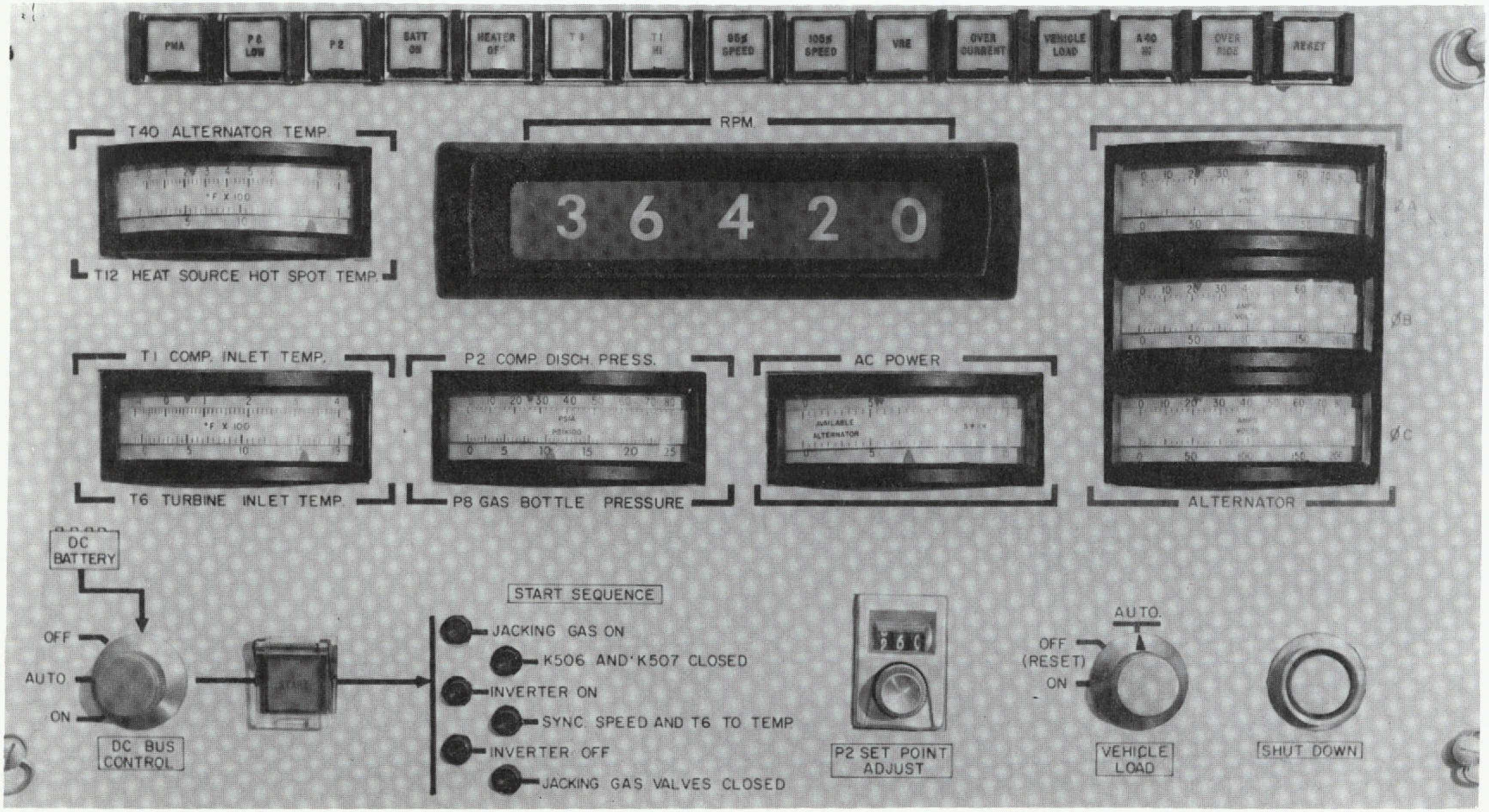


Figure 1. - Control panel.

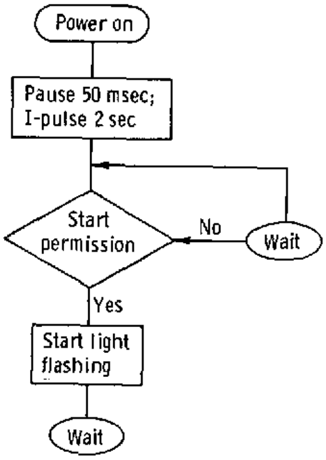


Figure 2. - Turnon sequence logic.

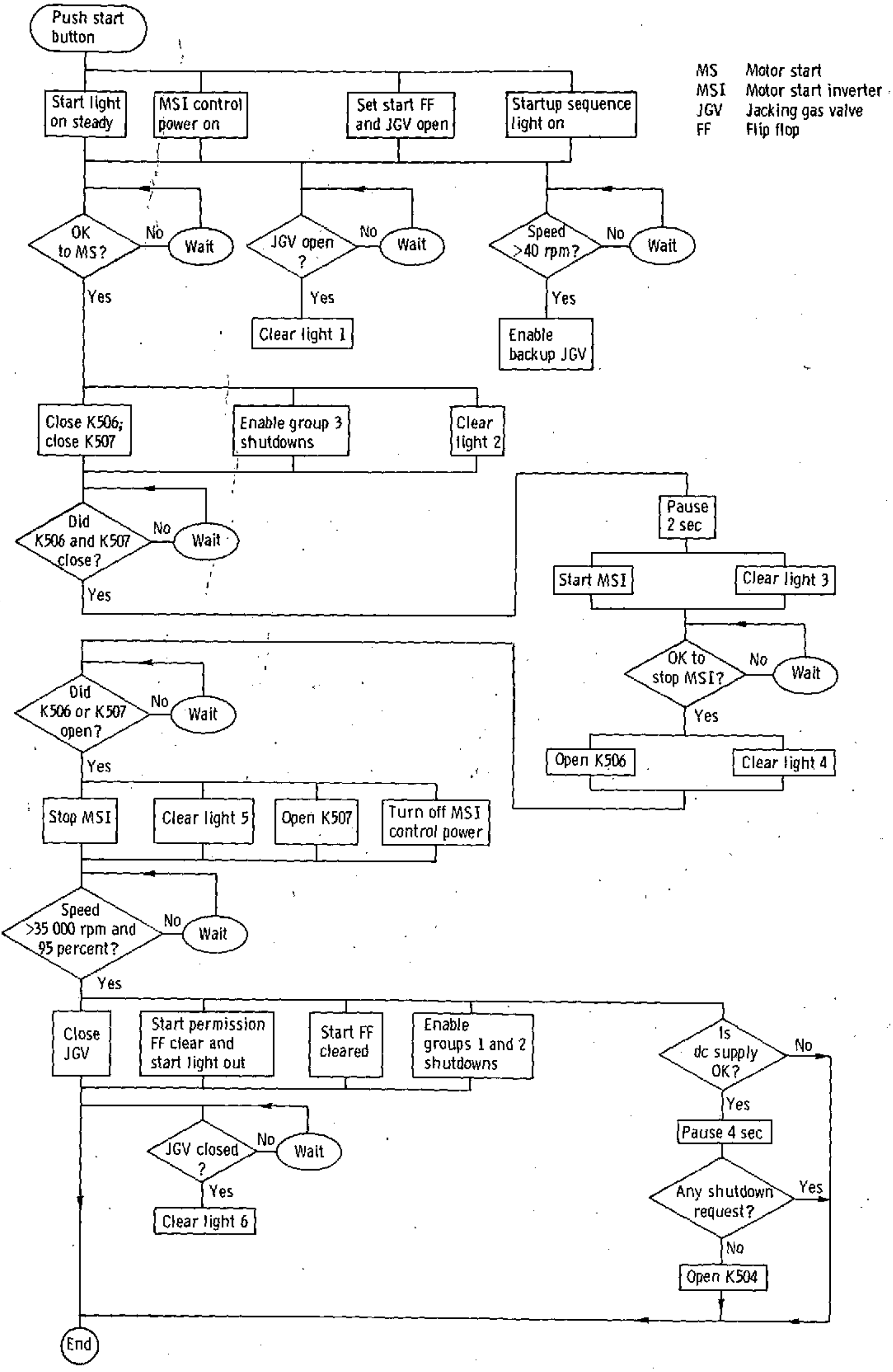
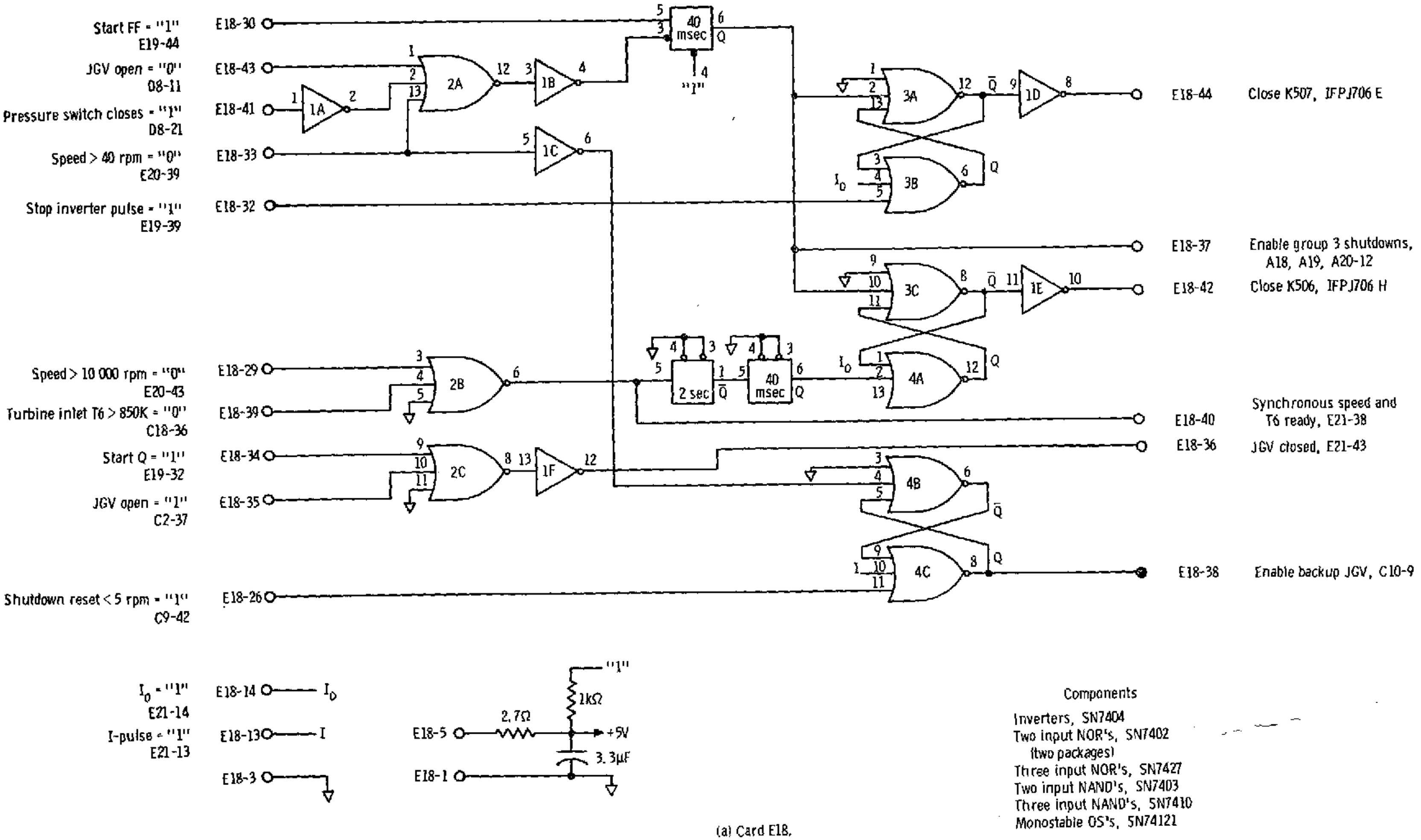
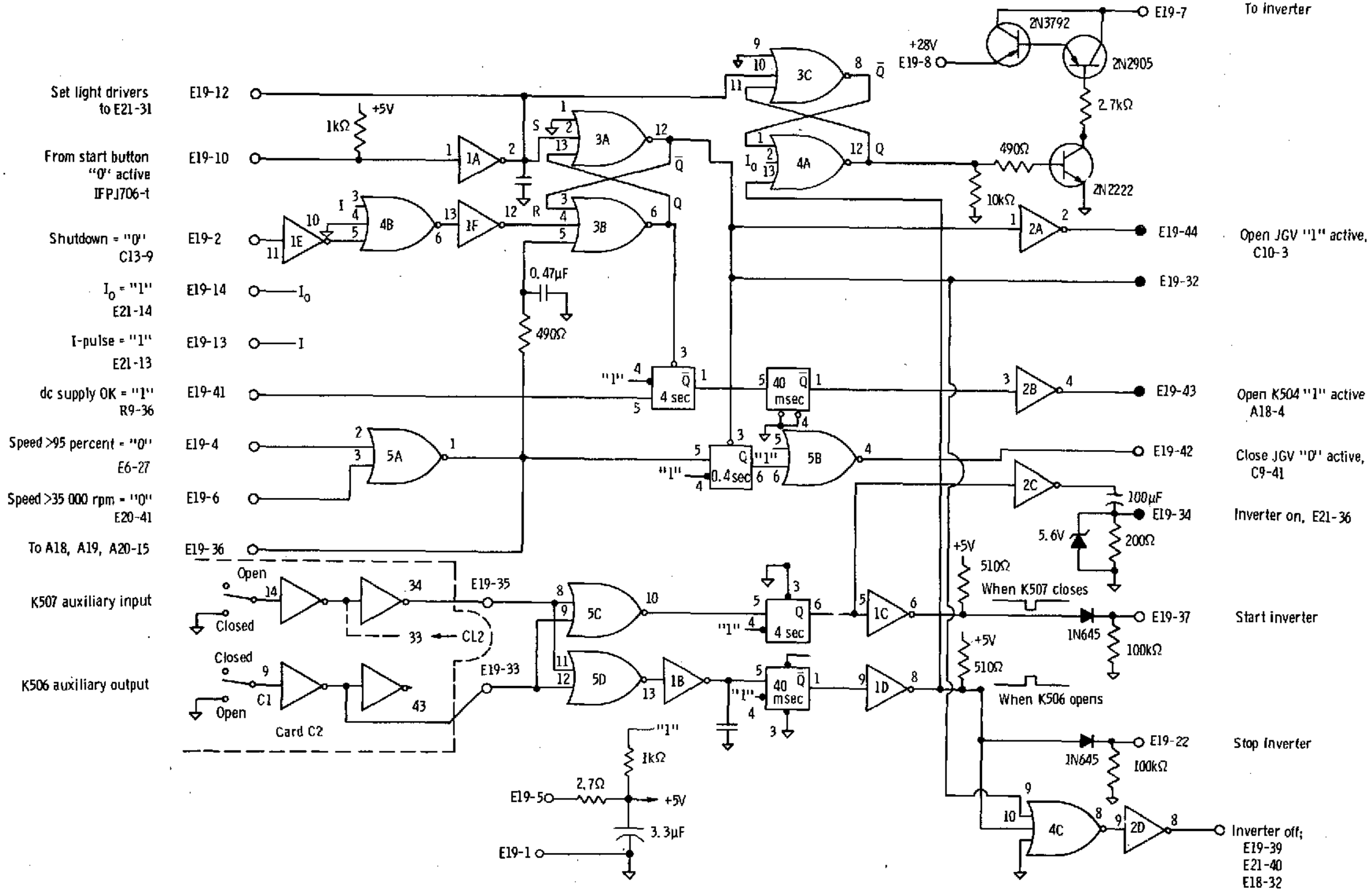


Figure 3. - Startup sequence logic.



(a) Card E18.

Figure 4. - Startup sequence logic circuit.



(b) Card E19.

Figure 4. - Concluded.

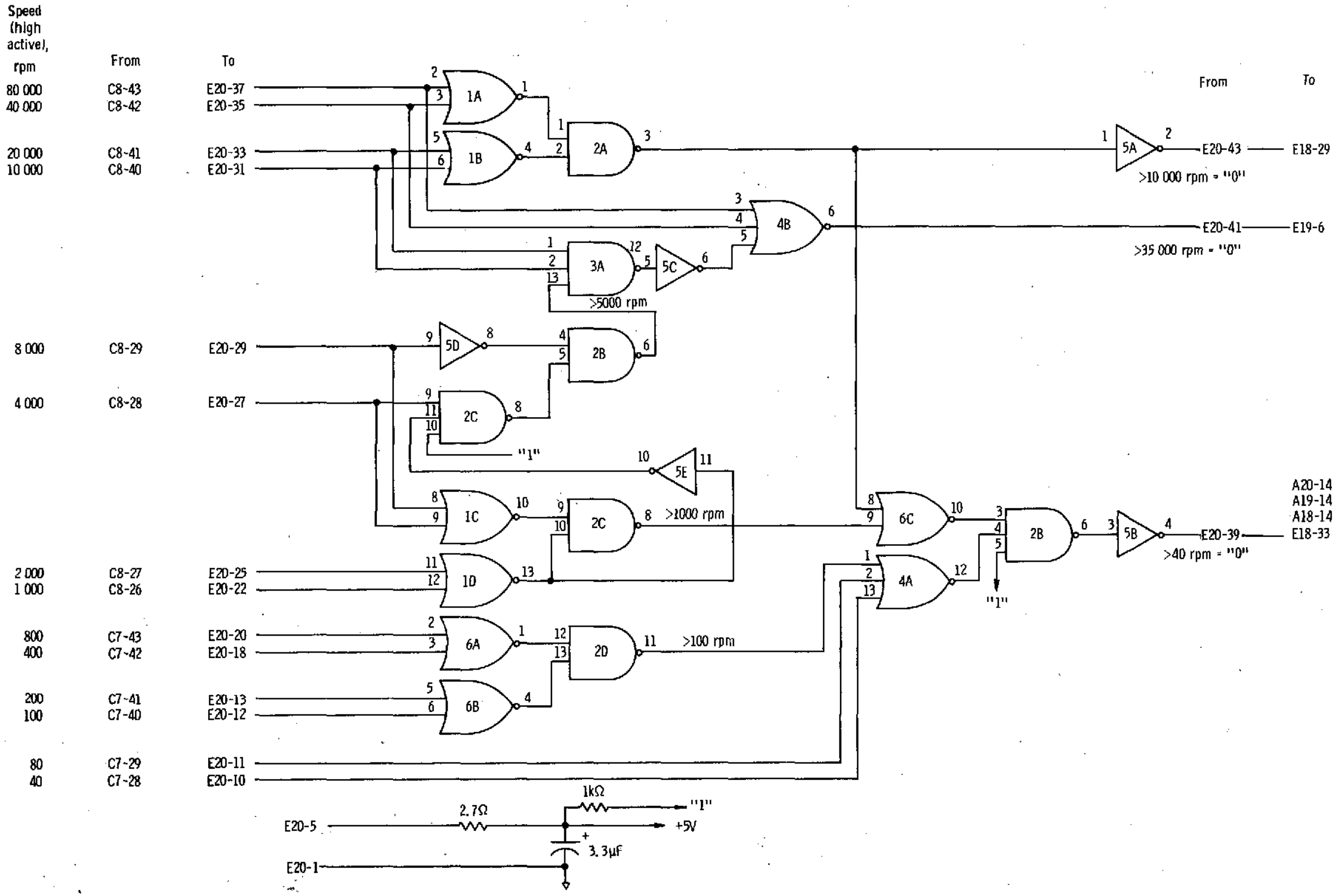


Figure 5. - Rotation detector circuit (card E20).

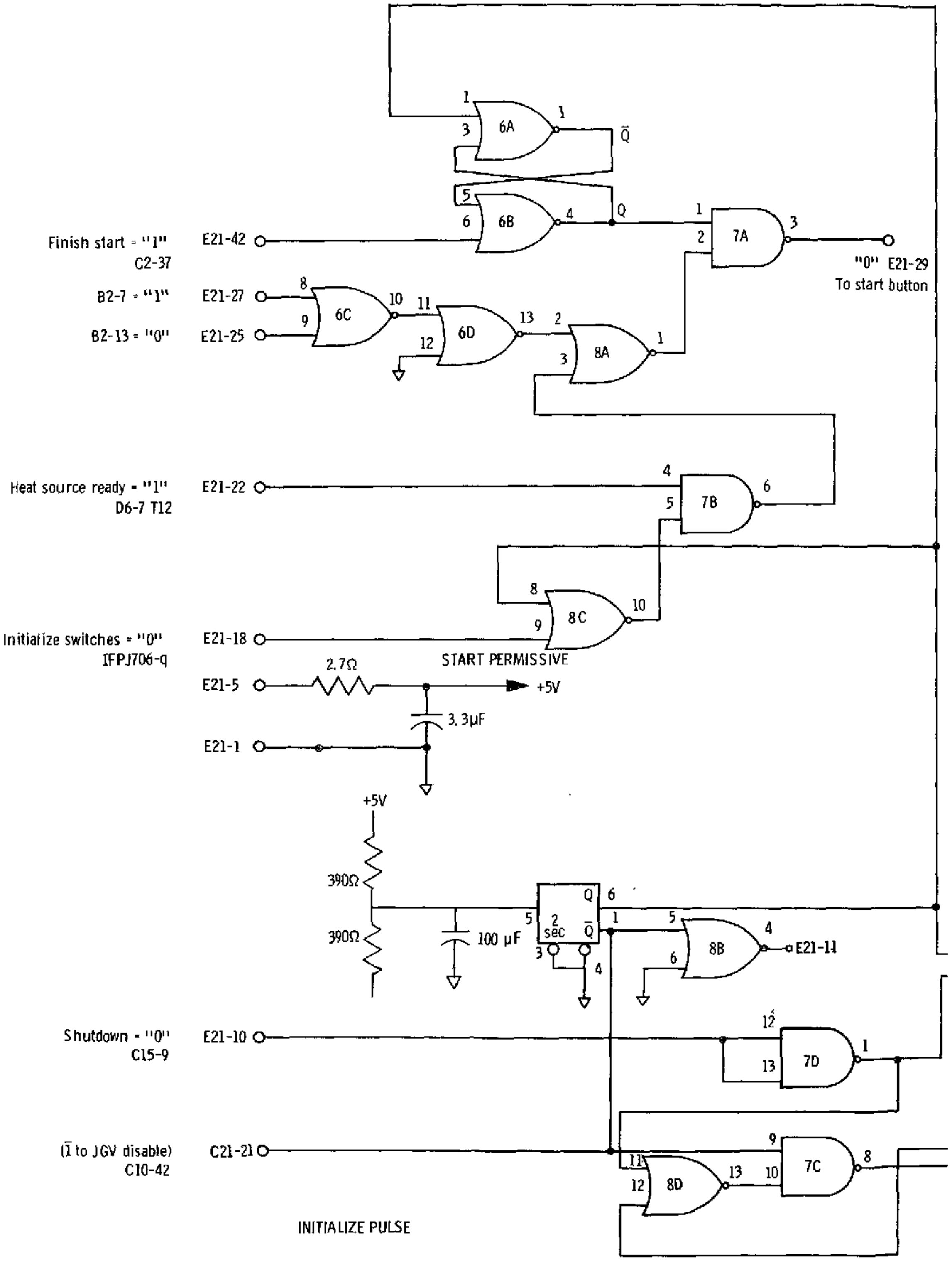
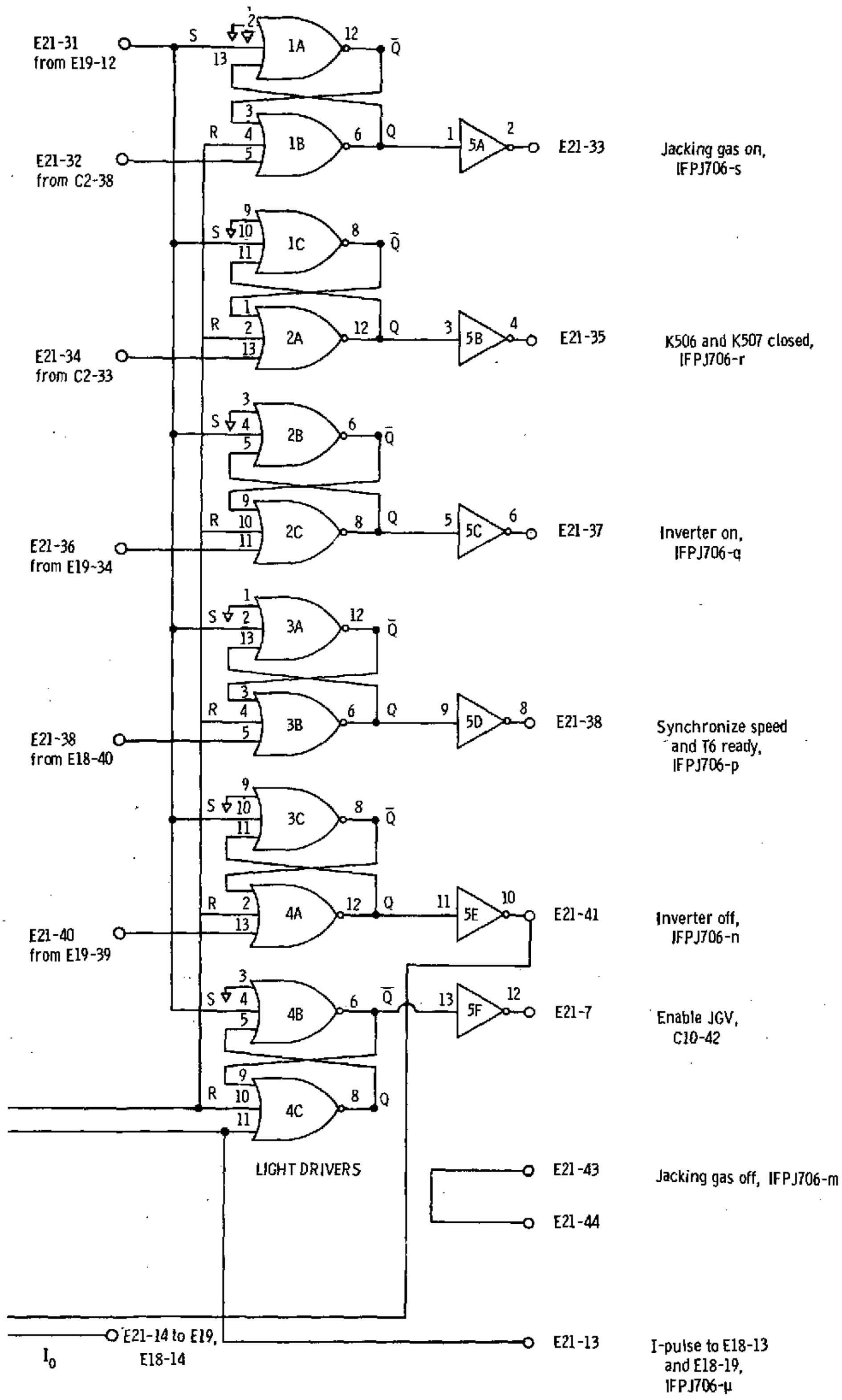
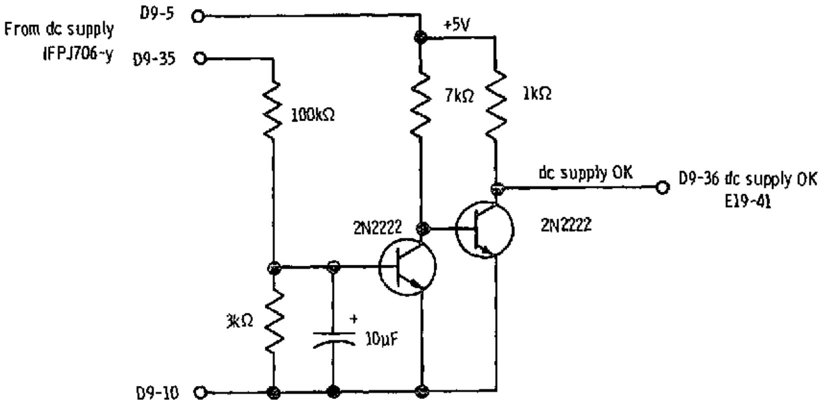


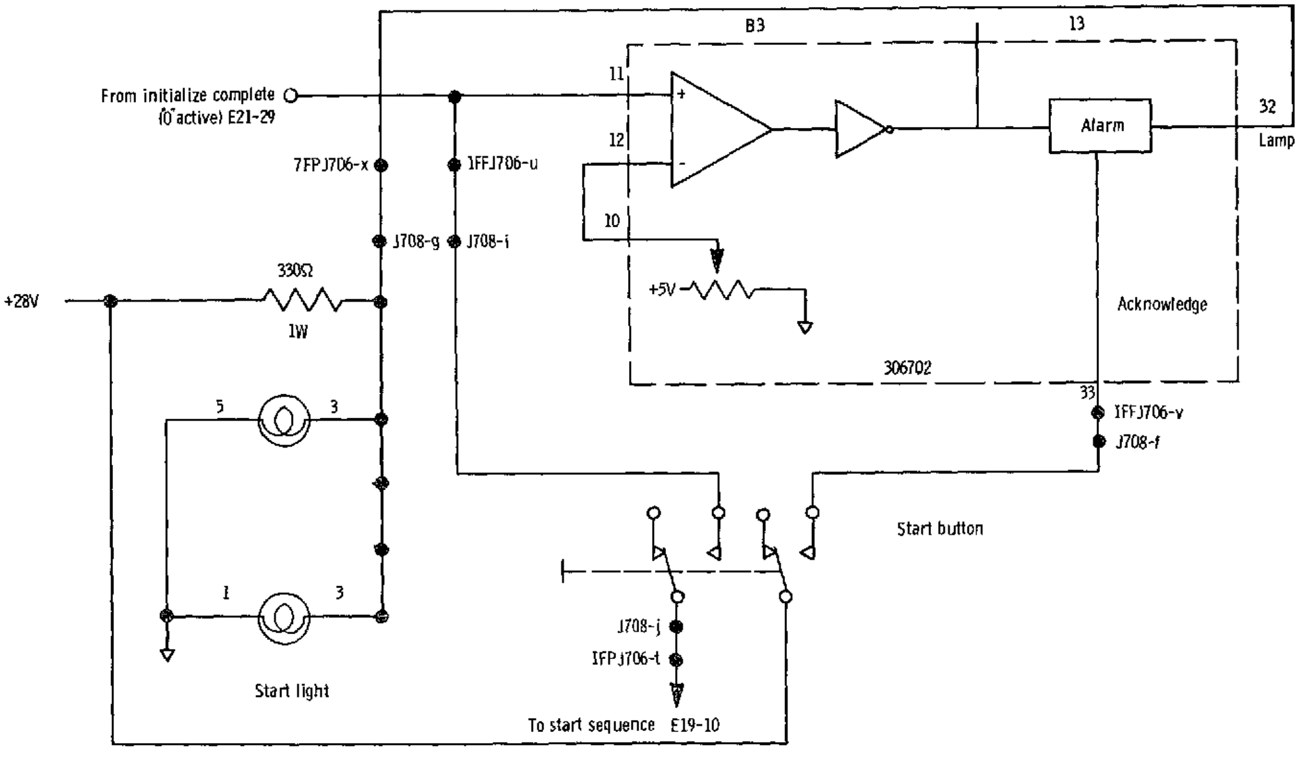
Figure 6. - Light driver, start permissive,



and initialize pulse circuit (card E21).



DIRECT-CURRENT SUPPLY FILTER CIRCUIT



START BUTTON

Figure 7. - Start button and filter circuits.

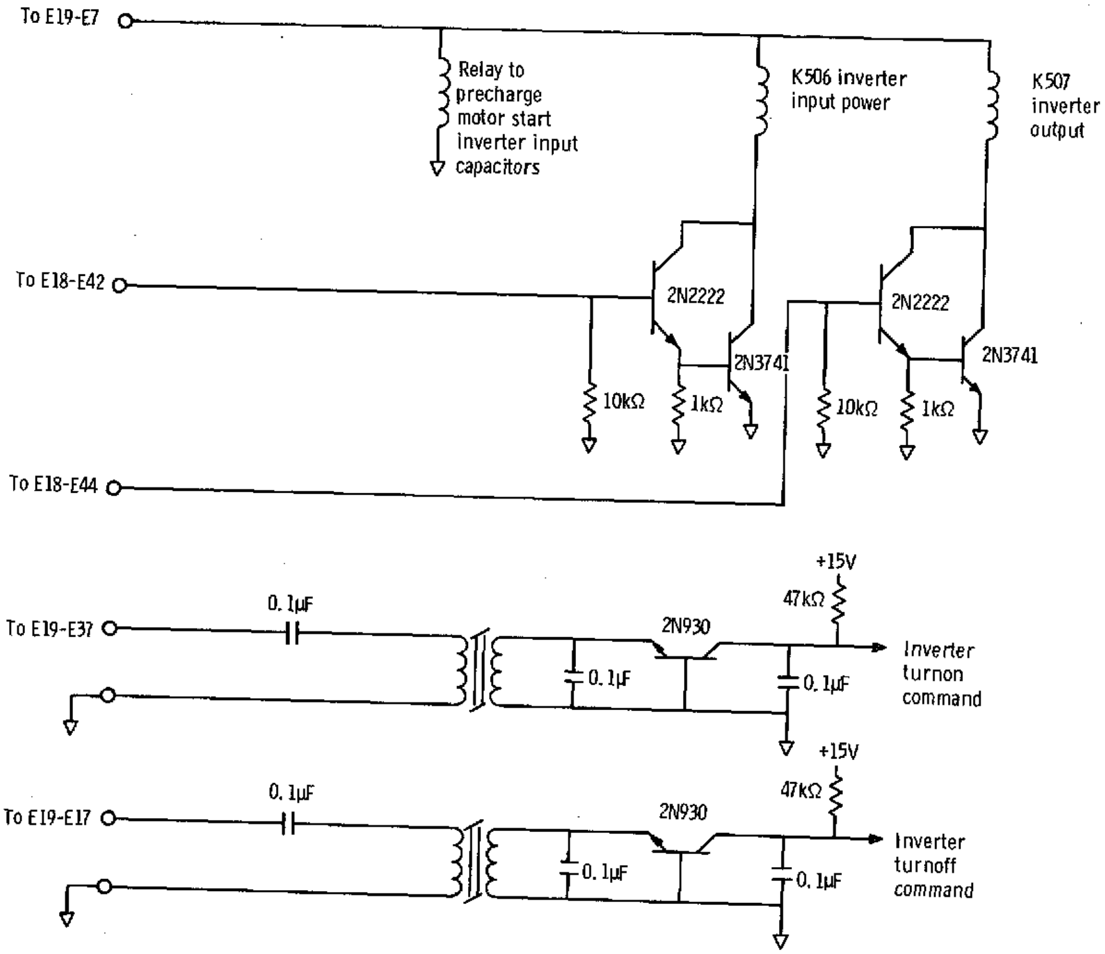


Figure 8. - Motor start control circuits (circuits internal to inverter).

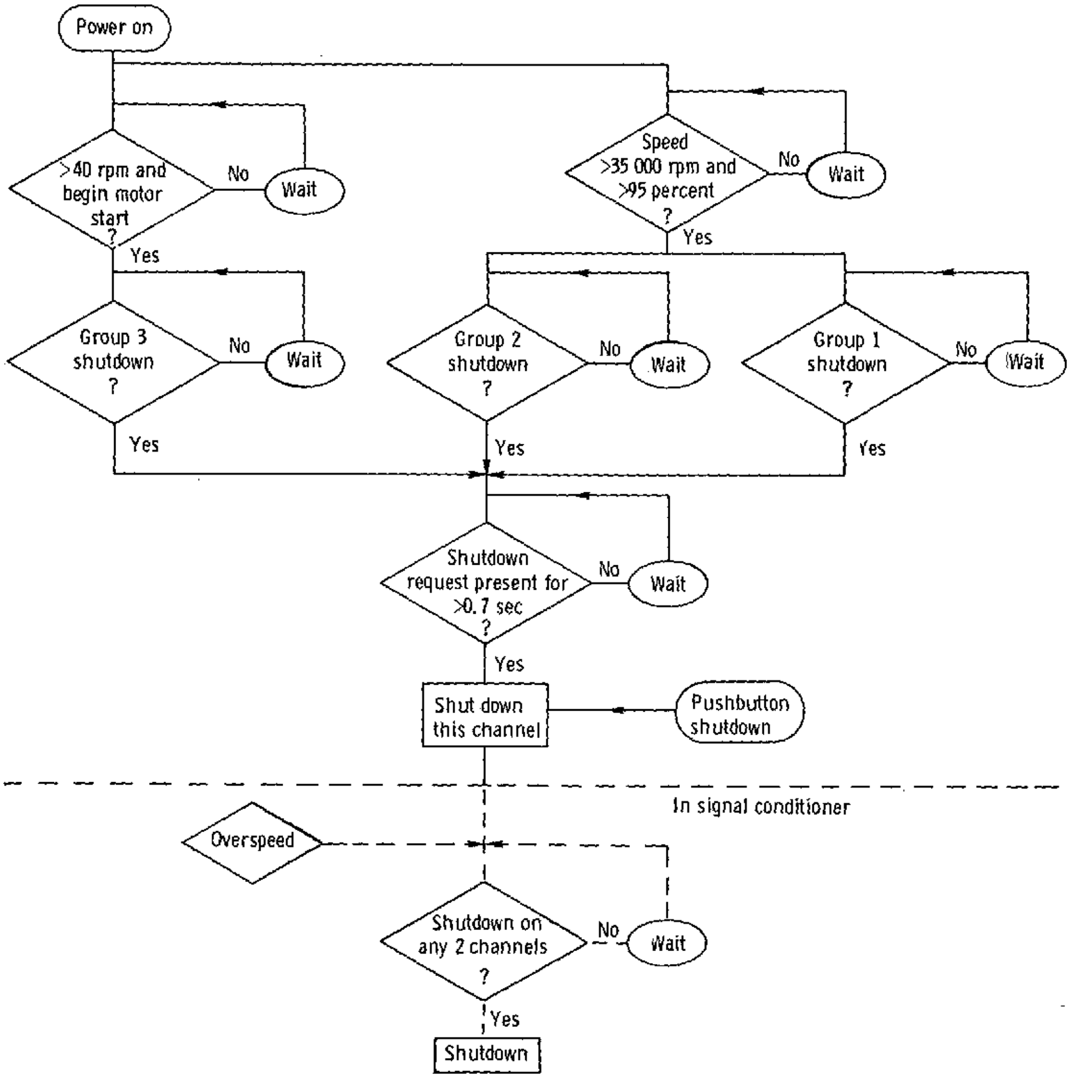


Figure 9. - Shutdown logic.

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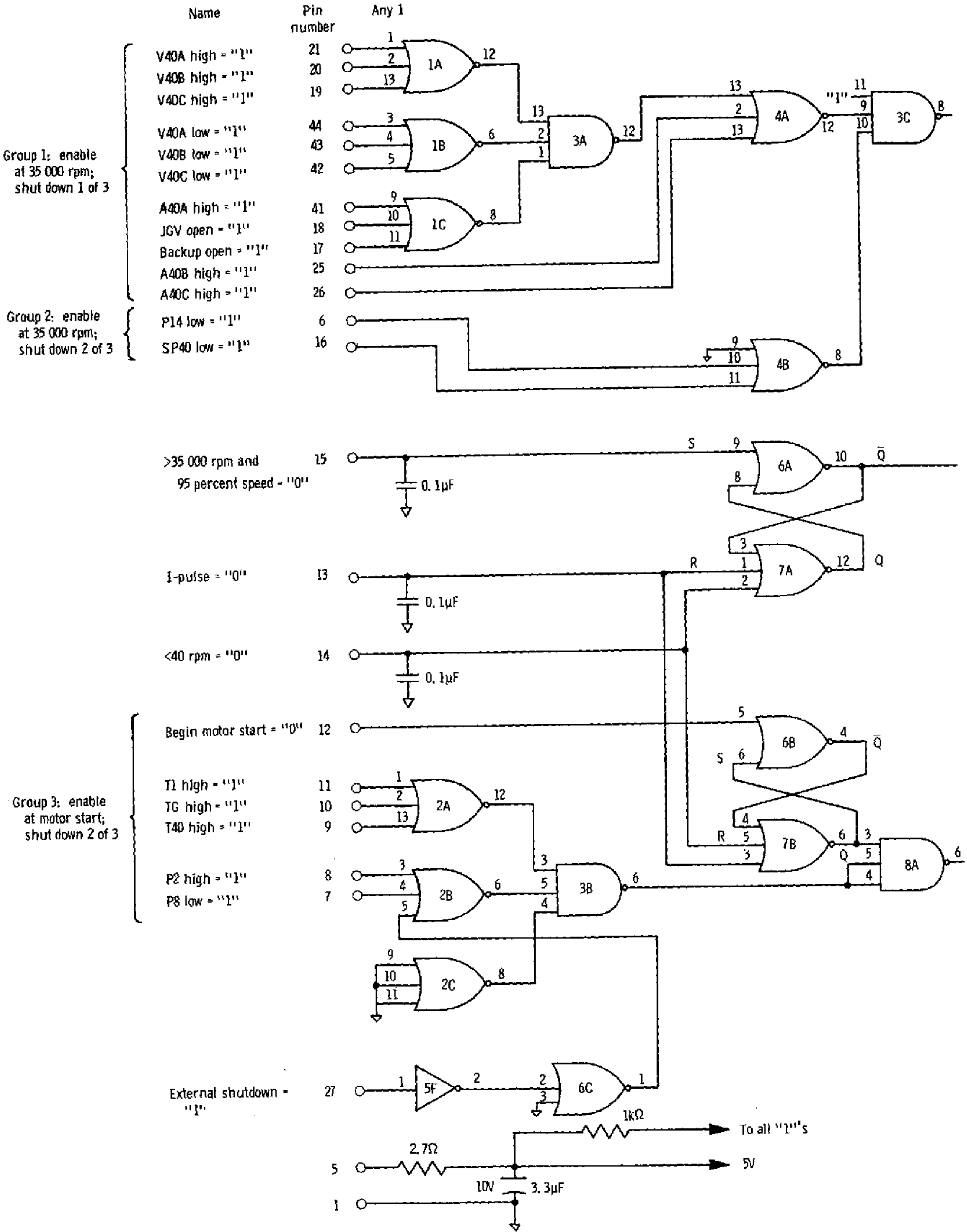
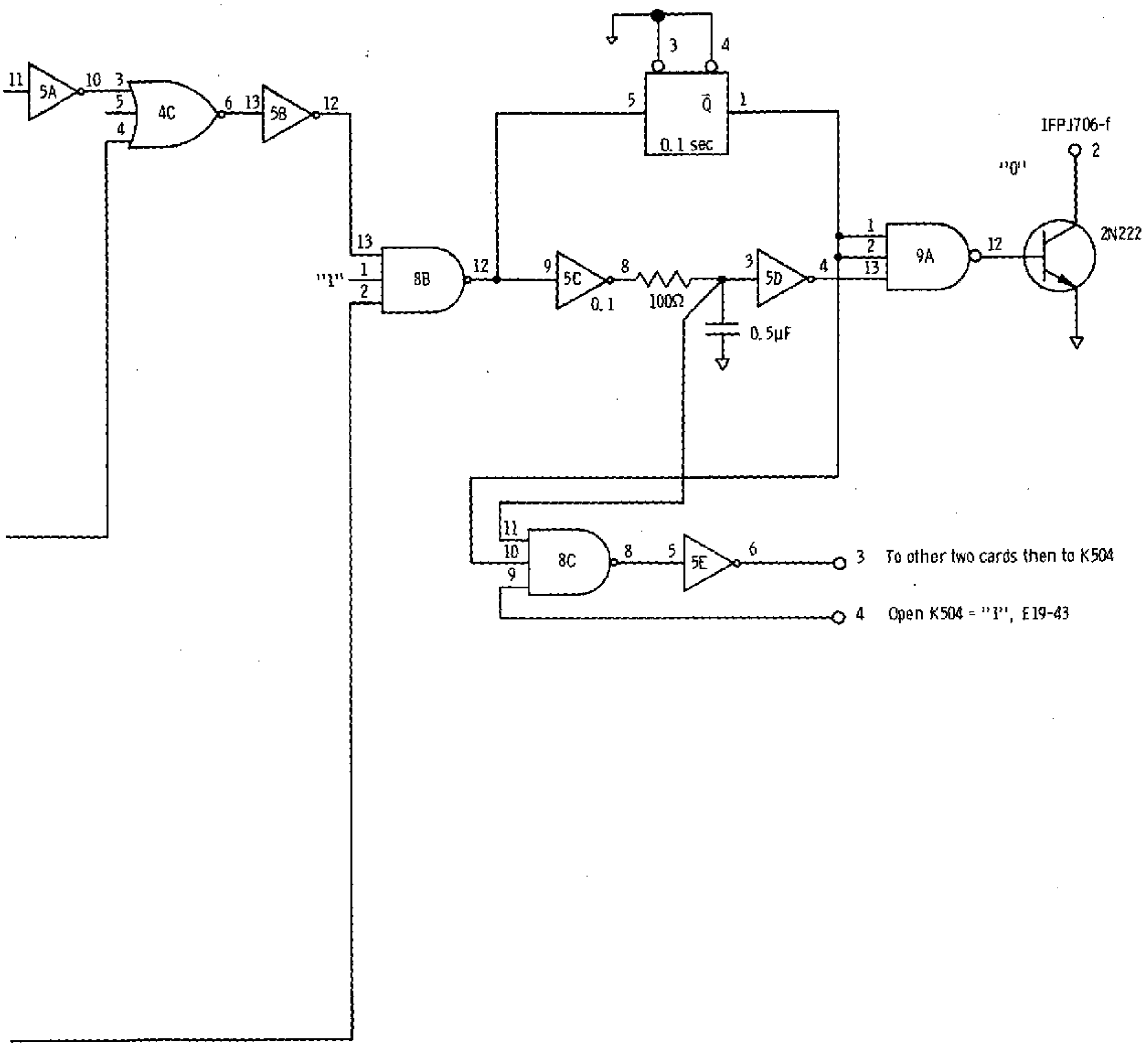


Figure 10. - Shutdown logic



circuit (cards A18, A19, A20).

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