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NASA Project Apollo Working Paper No. 1054

PROJECT APOLLO
PRESSURIZED GAS REACTION CONTROL SYSTEM
FOR LITTLE JOE II

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

October 26, 1962

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PRESSURIZED GAS REACTION CONTROL SYSTEM FOR LITTLE JOE II

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FOR LITTLE JOE II

SUMMARY

This paper presents the analysis and test evaluation used to establish the feasibility of a pressurized-gas reaction control system for Little Joe II. A comparison of a pressurized-gas system and a monopropellant system is also presented. The comparison includes considerations of reliability, launch operations, cost, development time, and weight. The pressurized-gas system offers decided advantages in every consideration except weight.

INTRODUCTION

A study of the control system for "Little Joe II" has established that a combination of aerodynamic and reaction controls will be needed to perform all phases of each type of mission. The lack of sufficient aerodynamic control during the first ten seconds of flight results in a requirement of about 1000 pounds of side force from the reaction control system during that flight phase. Flight beyond the atmosphere requires approximately the same control force for about 40 seconds. A total impulse of about 50,000 pound-seconds is required.

Preliminary investigation (Ref. 1) showed that either a solid or monopropellant type system could be used for this application. Also, a pressurized-gas type of system appeared feasible. However, a thorough definition of the latter system was required before it could be further considered for this application.

Approval has been given to proceed with construction of a monopropellant system because early action on this system was required if it were to be available for the proposed flight schedule. However, study of the pressurized-gas system has continued on the basis that it might be used as a substitute or backup for the monopropellant system. This paper presents the results of the study.

The paper is divided into three sections. The first section is devoted to an analysis of the thermodynamics of the system. The second section describes an experimental test program using available hardware and presents the results of the tests. The third section contains a discussion of the comparison of the pressurized-gas and monopropellant systems. Figure 1 shows the two systems schematically, and figure 2 illustrates the installation of the systems in the Little Joe II vehicle.

SYSTEM ANALYSIS

Several of the thermodynamic properties of nitrogen are shown in the temperature-entropy chart (fig. 3). Isentropic processes A, B, and C are superimposed on this chart to show the technique of locating thermodynamic state points as used in this study. Process D is shown to illustrate a realistic polytropic type process in which the gas absorbs some heat during expansion. The assumption of the isentropic expansion in the propellant tank leads to a conservative estimate of propellant availability.

Figure 4 shows the variation of the compressibility factor of nitrogen in the ranges of pressures and temperatures considered.

Data from figures 3 and 4 were used in the determination of an "Availability Factor" shown in figure 5. The "Availability Factor" is the ratio of expendable gas to the initial quantity as calculated by the ideal gas law.

The specific impulse which can be obtained from the available gas shown in figure 5 is presented in figure 6. The choice of a pressure ratio used to calculate the specific impulse may be questioned because the nozzle expansion process continues into the saturated vapor region. However, in a purely isentropic expansion from very high pressures (5,000 psi) to very low pressures (2 psi) only 20 percent of the vapor is condensed (fig. 3). Also, in a blow-down type system, the required pressure ratio (about 150/1) is available outside the saturated vapor region during most of the process and the condensation affects only a small portion of the overall process. Therefore, the selection of a nozzle pressure ratio of 150 for this study is entirely acceptable. This corresponds to a 10:1 nozzle area ratio. The under-expansion of the exhaust gases during the first portion of the process has also been neglected. This factor tends to offset the condensation effect mentioned above insofar as total impulse is concerned. The information in figure 6 is believed to be accurate within a few percent. The largest deviation from this analytical performance prediction will be caused by "non-isentropic" processes in the storage tank. In this case, the analytically predicted total impulse for a system will always be conservative. The amount by which the prediction is conservative is not determined.

Changes in storage tank initial pressures do not significantly affect the specific impulse calculation for the propellant; therefore, figure 6 can be used for any system having storage pressures between 2,000 and 5,000 psi. This is because the only variable factor affecting performance is the temperature at the isentropic "state-point" associated with each amount expended and this temperature did not change appreciably with the various initial storage pressures selected for this study.

The data presented in figures 5 and 6 are combined in figure 7. This information can be used to estimate the weight of the propellant and storage tank in a system if the total impulse and the storage tank pressure ratio are known.

Choice of a storage tank pressure ratio depends on the flow capacity of the valve used to control thrust. For convenience, the thrust available from several nozzles operating at various pressures is shown in figure 8. Since the thrust variation in a blow-down type system may be reduced by successive introduction of more "sets" of thrusters. Figure 9 is provided to show the "thrust variation" factor as a function of storage tank pressure ratio for one, two, and three "sets" of nozzles. In the data of this figure the assumption was made that, with the initial functioning of each successive "set" of thrusters, the thrust will return to its original value. This illustrates the "regulation" effect which can be obtained in a "blow-down" type system.

TEST PROGRAM

In cooperation with the Flight Dynamics Branch of the Spacecraft Technology Division, a test program was initiated with the following goals:

1. Demonstrate that the analytical estimates of system performance are valid.

2. Demonstrate the vehicle flight dynamics using the available hardware and establish realistic reaction control system total impulse and thrust level requirements.

Test Apparatus

The test apparatus used is shown in figures 10 and 11. Figure 10 shows the three control valves considered for this application. Figure 11 shows a closeup of the Marotta 121E valve and the associated nozzle and plumbing used. Figure 12 shows the thrust stand with two 1,000 in^3, 3,000 psi tanks. These tanks are balanced over a pivot in order that the change in weight of propellant will not affect the thrust measurement. The thrust in the vertical direction is measured by a load cell consisting of SR4 strain gages mounted on an aluminum bar.

The Honeywell carrier amplifier and CEC recorder used to measure the thrust and response of the reaction control system is shown in figure 13. The Pace analog computer used to simulate the vehicle dynamics is shown in figure 14. The brush recorder used to record vehicle flight dynamics is shown in figure 15.

Test Valves

Three valves were tested: Two Marotta valves, MV 121E and MV 553, and one Flowdyne valve. The Marotta valves are 1-inch tube size, poppet-type valves, piloted by a 3-way solenoid valve. The MV 121E has an 0.84" equivalent diameter sharp-edge orifice characteristic. Approximately 1,000 such valves have been flown on Thor. The MV 553 is undergoing qualification tests at present for use on Titan and should be qualified in time for use on Little Joe II.

The valve submitted by Flowdyne is a 1-inch tube size ball valve actuated by a three-way solenoid pilot valve. This valve has been qualified by NASA-MSFC for use on G.S.E. and could be qualified further as a flight item in time for this application. This valve is also available in a 2-inch tube size version with similar qualification status.

All three valves have a response time of 30 to 40 milliseconds in opening or closing. All three have sufficient flow capacities to warrant consideration in the design of the proposed system. The valves have delivered up to 1,120-pounds thrust at sea level with a nozzle area ratio of 4.

Reaction System Performance

Data obtained from the test apparatus have substantiated the analytical estimate of total impulse within about ±3 percent. One test of the MV 121E valve, with initial storage tank pressure at 3,000 psi and final pressure at 350 psi, produced results that agreed very closely with the analytical prediction of total impulse for the system. The test consisted of a single "blow-down" of about one second duration. It is very unlikely that a significant quantity of heat was transferred to the gas during this period and, hence, the close agreement verifies the conservative estimate obtained by assuming isentropic expansion. An estimate of the additional performance which can be obtained by slow expenditure of the gas was not made and this factor is not included in sizing the system.

Several tests were run using the analog computer to simulate vehicle dynamics while the RCS test apparatus was used to simulate the reaction control system. These tests included the effects of the thrust delay after valve command signal and the effect of relay delay between the guidance system command and valve command signal. Results from these tests indicate that the "blow-down" type system is acceptable from the standpoint of changing thrust level and that a total impulse of about 50,000 lb-sec will be sufficient to control the vehicle for the first 10 and last 40 seconds of booster operation. These results are preliminary in nature and will be redefined by the Flight Dynamics Branch after the data have been reviewed in detail.

SYSTEM SELECTION FOR LITTLE JOE II

Pressurized-Gas System Considerations

Two types of pressurized-gas systems are considered:

1. Regulated - delivering constant thrust throughout flight.
2. Unregulated or "blow-down" - delivering thrust which decreases as pressure decreases.

Both types appear feasible for this application and are shown schematically in figure 16. The thrust delivery characteristics of the unregulated system can approach that of the regulated system if additional thrusters are made available as the propellant storage pressure decays (see figure 9). The choice of a system then becomes one of a trade-off between additional thrusters and a pressure regulator. The main consideration is the effect of thrust variation on flight dynamics. Also, the availability of hardware may influence the choice of the system.

For this application, the unregulated type system could use the MV 121E valve in a dual "set" type configuration. Further evaluation of the flight dynamics data may show that three sets are required, but that is not indicated at present. The valve-thruster unit with a 10:1 area ratio nozzle would be about 7 inches long and about 3 inches in diameter. This unit would weigh about three pounds. The tankage and propellant weight would depend upon the actual thrust level required (that is, the final storage pressure), but will not exceed 80 pounds per 1,000 lb-sec for nitrogen and tankage (see System Analysis). The plumbing weight will not exceed 100 pounds. Therefore, the system weight for 50,000 lb-sec total impulse is estimated to be about 4,150 pounds.

The use of a regulated system requires thrust control valves capable of handling the total thrust at the minimum pressure. Therefore, the 2-inch tube size, ball-type valve would be required. No regulator for this application appears to be available. However, another method of pressure control is available which would use parallel solenoid valves operated by pressure switches. In order to avoid the problem of relief devices, the complete system should be designed for maximum storage pressure, thereby enhancing the reliability of the system. Design of the system for this application could be quite simple depending upon the thrust tolerance (pressure tolerance) which is used. The MV 121E valve would probably be sufficient for this application when arranged in a bank of five valves. Hence, the system would consist of eight 2-inch ball valves for thrusters and five MV 121E poppet valves for pressure regulation. This system would require further qualification of the ball valve. This system weight is estimated to be about 3,632 pounds.

Comparison of Monopropellant and Pressurized-Gas Systems

The particular system selected for comparison with the monopropellant system is the non-regulated system shown schematically in figure 1. Comparative installation of the two systems on the booster are shown in figure 2. The weight of the mounting arrangement for the tankage in the pressurized gas system has been estimated to be about 260 pounds (Ref 2).

An estimate of the reliability of the pressurized gas system has been made, using the same reliability numbers as were used by Convair Astronautics for similar parts in the monopropellant system. The results show that the pressurized gas system is more reliable even though the "modular" concept used in the case of the monopropellant system was not used on the pressurized gas system (see figure 17).

A brief review of launch operation complexity indicates that the pressurized gas system is less difficult to prepare for launch than the monopropellant system.

A brief review of the cost of the system showed that the pressurized gas system would cost about $300,000 to install on one vehicle. This cost includes 16 valves at $200 each ($3,200) and 12 titanium tanks at $13,000 each ($156,000). Some saving in cost may be possible by using glass wound tanks. This cost figure represents a significant advantage over the monopropellant system which may cost several times this amount.

The development time for the experimentally-proven concept described in this study could be essentially the same as the "lead time" for the manufacture of parts. Delivery time on such hardware can be as short as three months.

The pressurized-gas system will weigh about twice as much as the monopropellant system. However, if the 2-inch tube size ball valve mentioned above is flight qualified, the weight of the pressurized-gas system could be reduced by 500 pounds. This reduction results from increased utilization of the pressurized gas. This decision must be based upon overall design consideration including qualification costs of the valve and the effect of the extra weight on the overall mission. Present considerations indicate that an additional 2,000 pounds added to a 243,000-pound vehicle may not seriously compromise the mission.

RESULTS AND CONCLUSIONS

The results of this study of a reaction control system using pressurized nitrogen are as follows:

1. Experimental performance of the pressurized nitrogen system agrees closely with analytically predicted performance.
2. Total impulse and thrust level requirements for this application are within the capability of this system using available flight-qualified hardware.
3. The nitrogen reaction control system will fit into the space available in "Little Joe II".
4. A comparison of the pressurized-gas and monopropellant reaction control systems indicates an advantage for the first system in reliability, launch complexity, cost and development time.
5. The pressurized-gas system will weigh from 1,100 to 2,000 pounds more than the presently proposed 2,100-pound monopropellant system.

It is concluded that the use of a pressurized-gas reaction control system for this application is feasible using presently available flight qualified hardware and offers a significant advantage over the monopropellant systems in every consideration except weight.

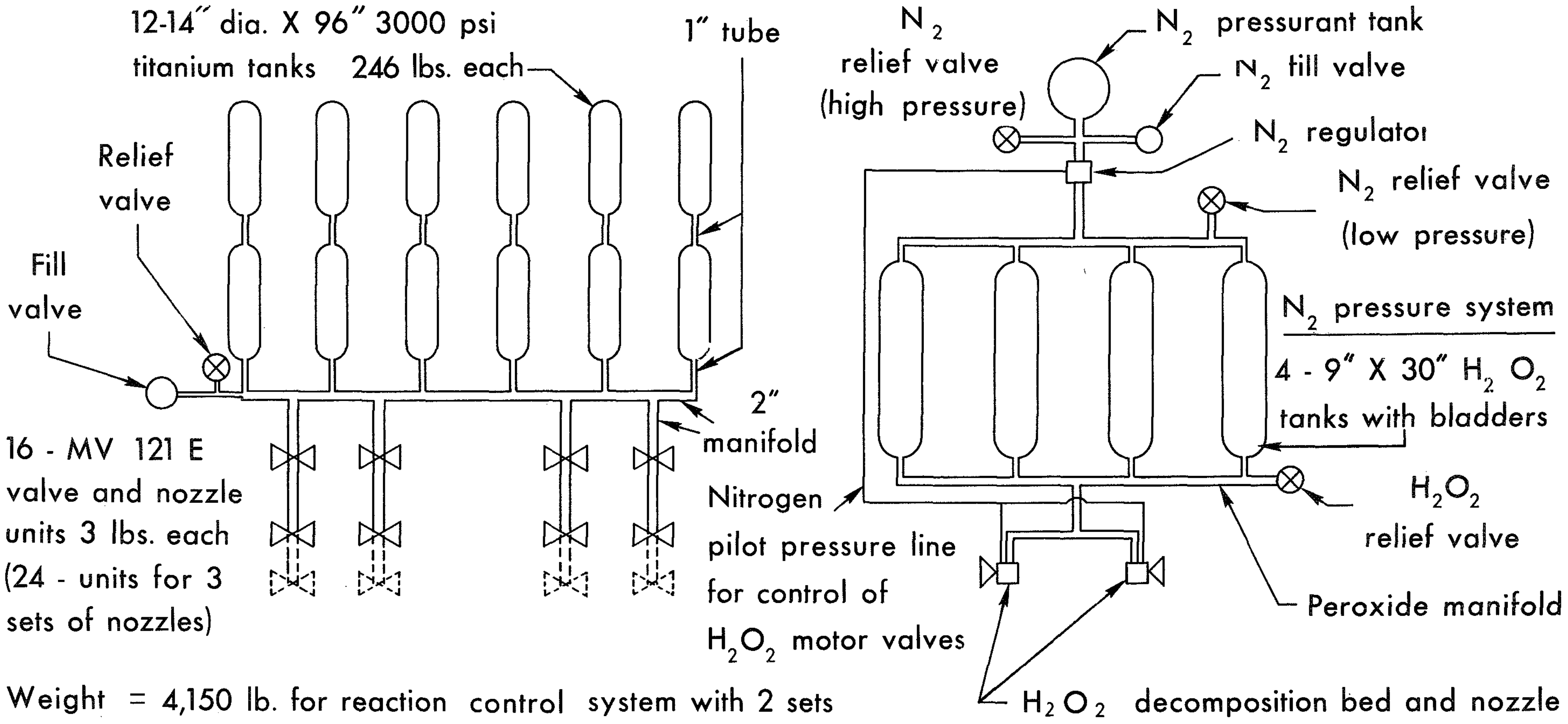
REFERENCES

1. Memorandum for Apollo Spacecraft Project Office dated August 6, 1962.
2. Letter from General Dynamics/Convair to W. W. Petynia dated August 28, 1962.
3. General Dynamics/Convair Attitude Control Systems Study Report dated July 2, 1962. (NASA Contract NAS 9-4923 - Report No. GD/C-62-190).

REQUIREMENTS - a) 540 lb. thrust at each of 8 nozzle locations b) 50,000 lb. sec. total impulse

Pressurized nitrogen reaction control system schematic for Little Joe II

Monopropellant reaction control system for Little Joe II



Weight = 4,150 lb. for reaction control system with 2 sets of thrusters (12 tanks) 3,268 lb. for reaction control system with 3 sets of thrusters (9 tanks)

NOTE: Use of 1" ball valve will reduce the weight of the '2 set' system to 3,632 lb. due to the increased flow capacity.

Weight = 2,100 lbs. total (as quoted by Convair)

NOTE: 4 units required @ 520 lbs. ea.

FIGURE 1.- SCHEMATIC DIAGRAM OF PRESSURIZED-GAS AND MONOPROPELLANT REACTION CONTROL SYSTEM.

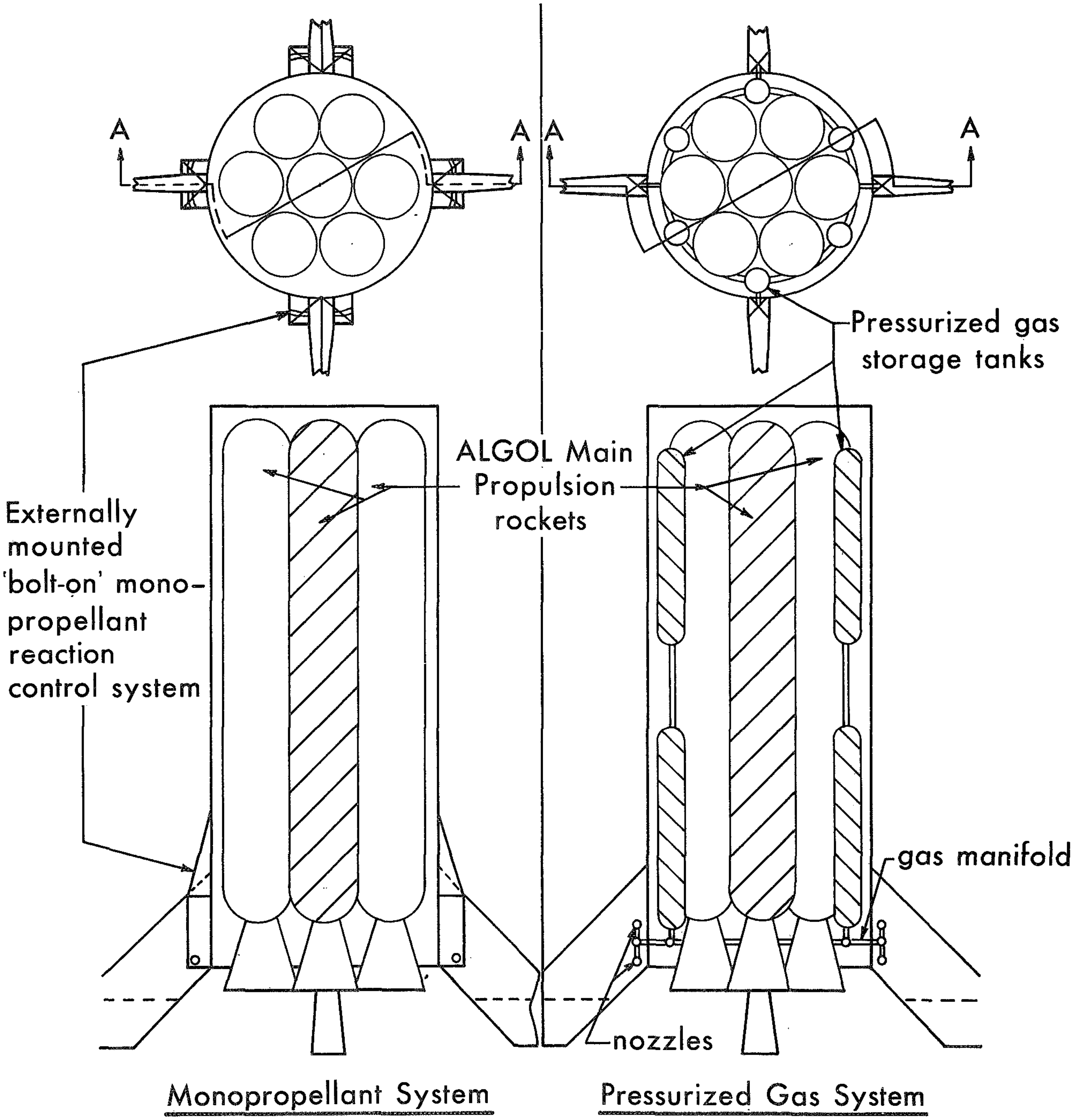
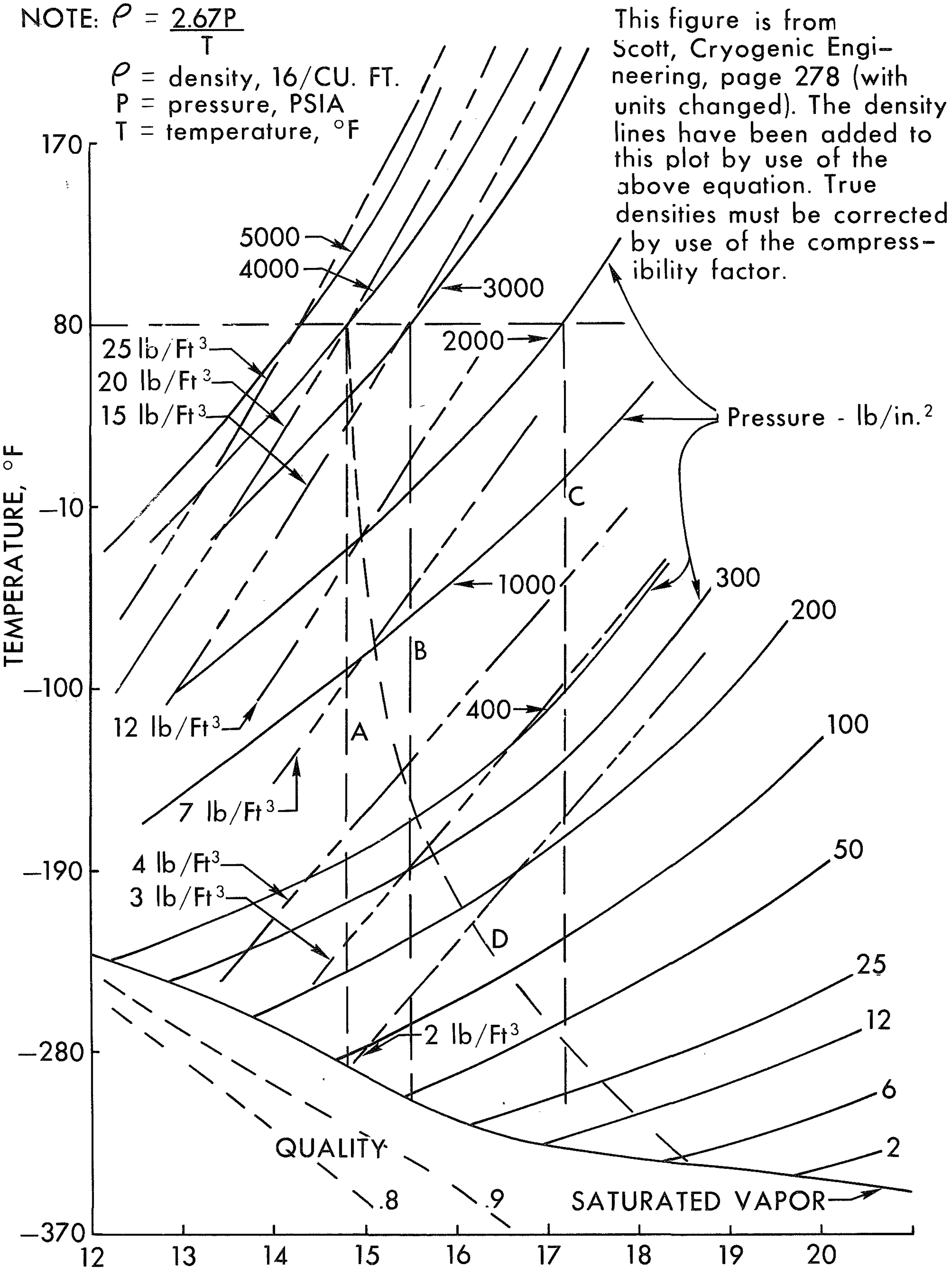


FIGURE 2.- INSTALLATION OF REACTION CONTROL SYSTEM IN LITTLE JOE II.



NOTE: $\rho = \frac{2.67P}{T}$

ρ = density, 16/CU. FT.
P = pressure, PSIA
T = temperature, °F

This figure is from Scott, Cryogenic Engineering, page 278 (with units changed). The density lines have been added to this plot by use of the above equation. True densities must be corrected by use of the compressibility factor.

FIGURE 3.- NITROGEN T-S DIAGRAM.

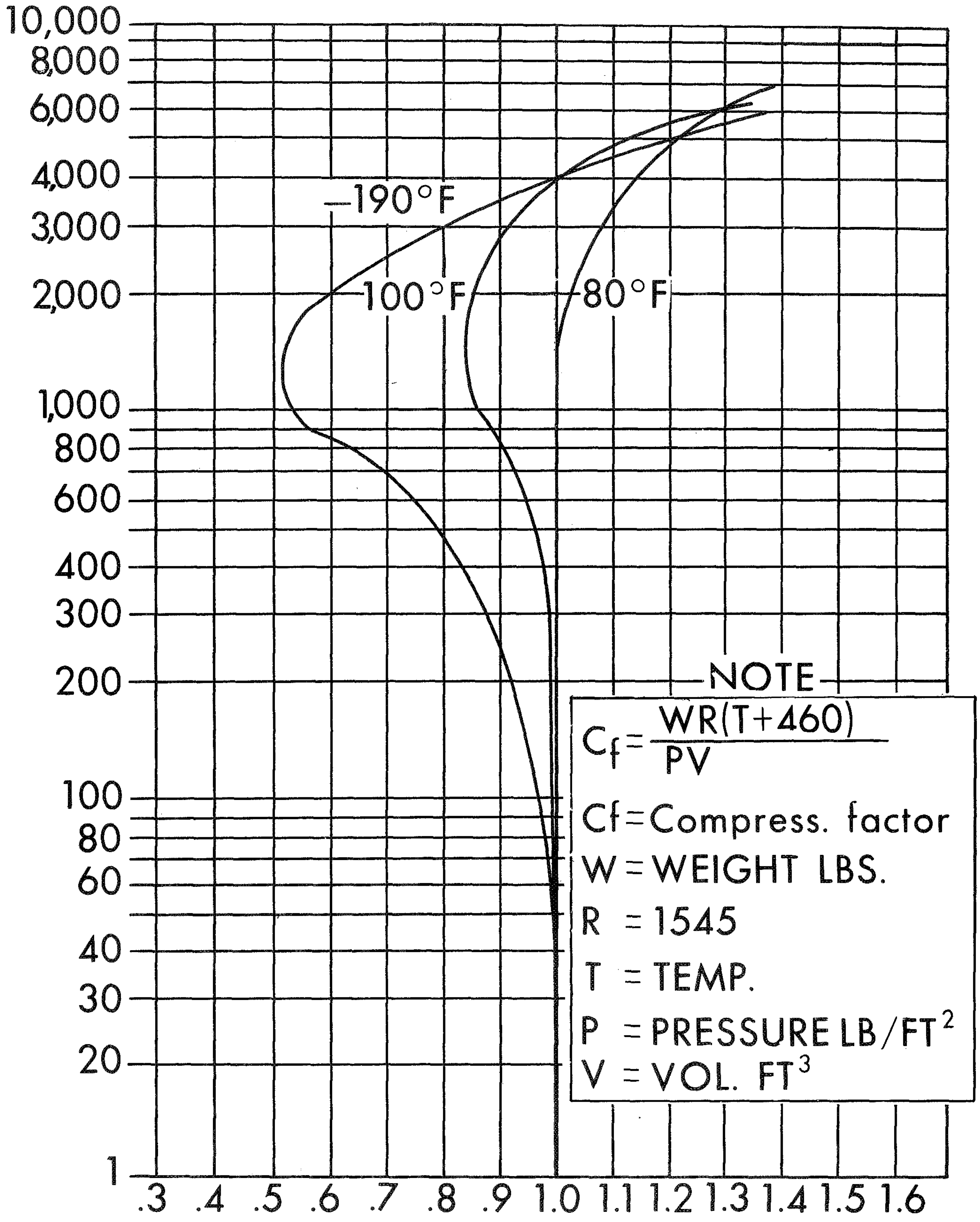


FIGURE 4.- COMPRESSIBILITY FACTOR FOR NITROGEN.

NOTE: The "availability factor is to be applied to the quantity calculated by W = PV/RT and includes the effect of
a) isentropic expansion
b) N^2 remaining
c) compressibility factor

W = WEIGHT - LB.
P = PRESSURE - LB/FT^2
V = VOLUME - FT^3
R = 1545
T = TEMPERATURE, °R = 540

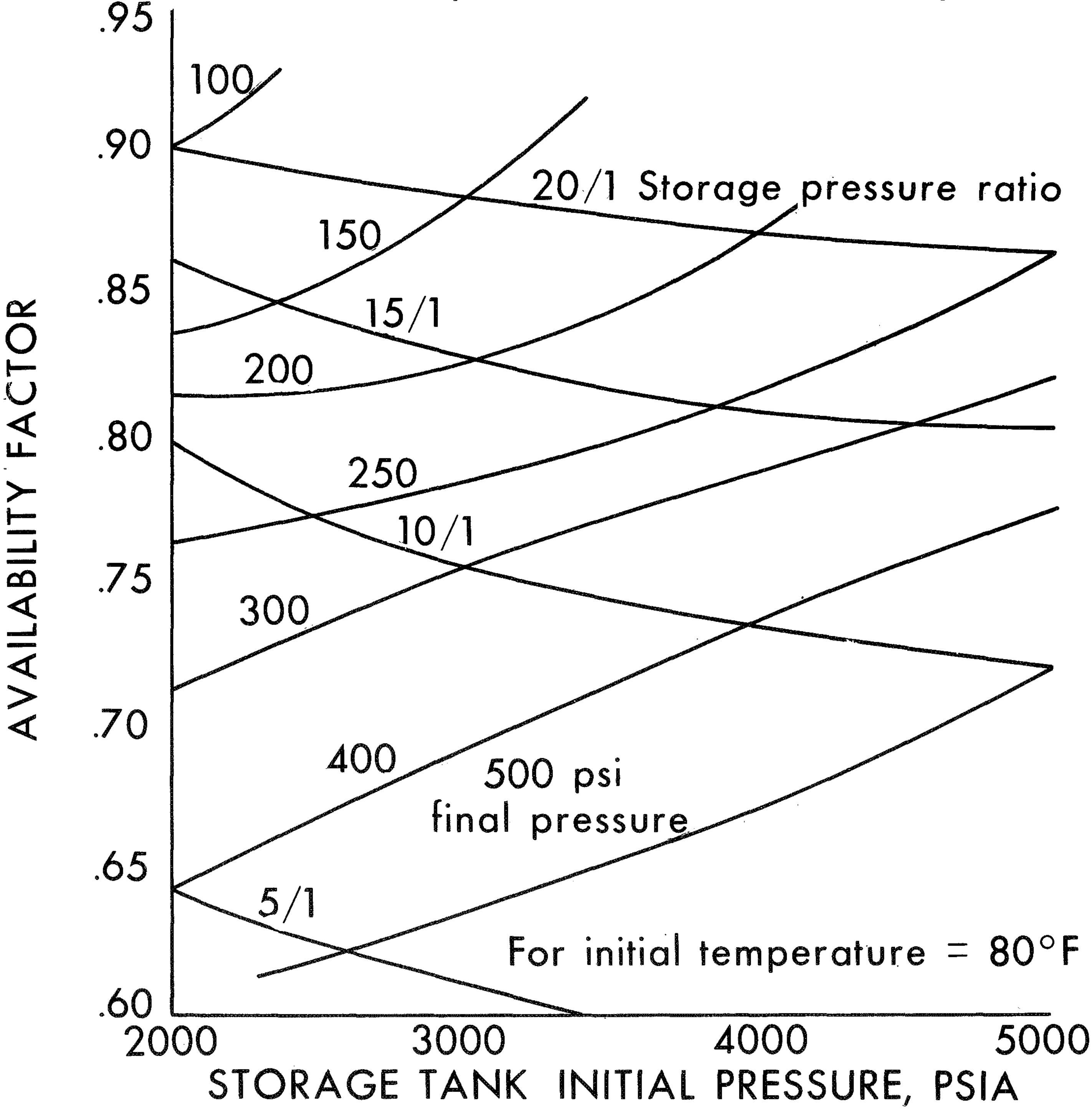
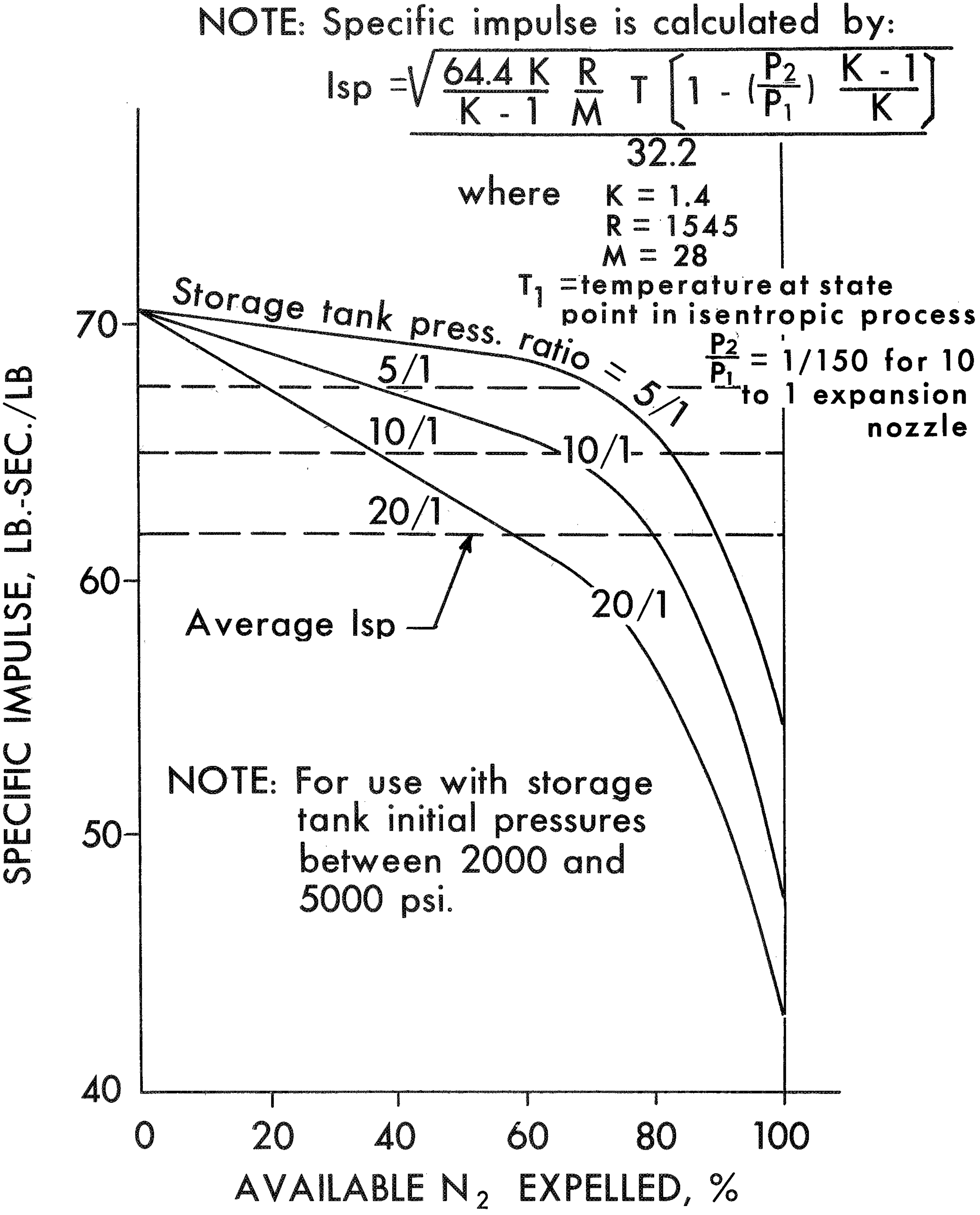


FIGURE 5 - PROPELLANT AVAILABILITY.



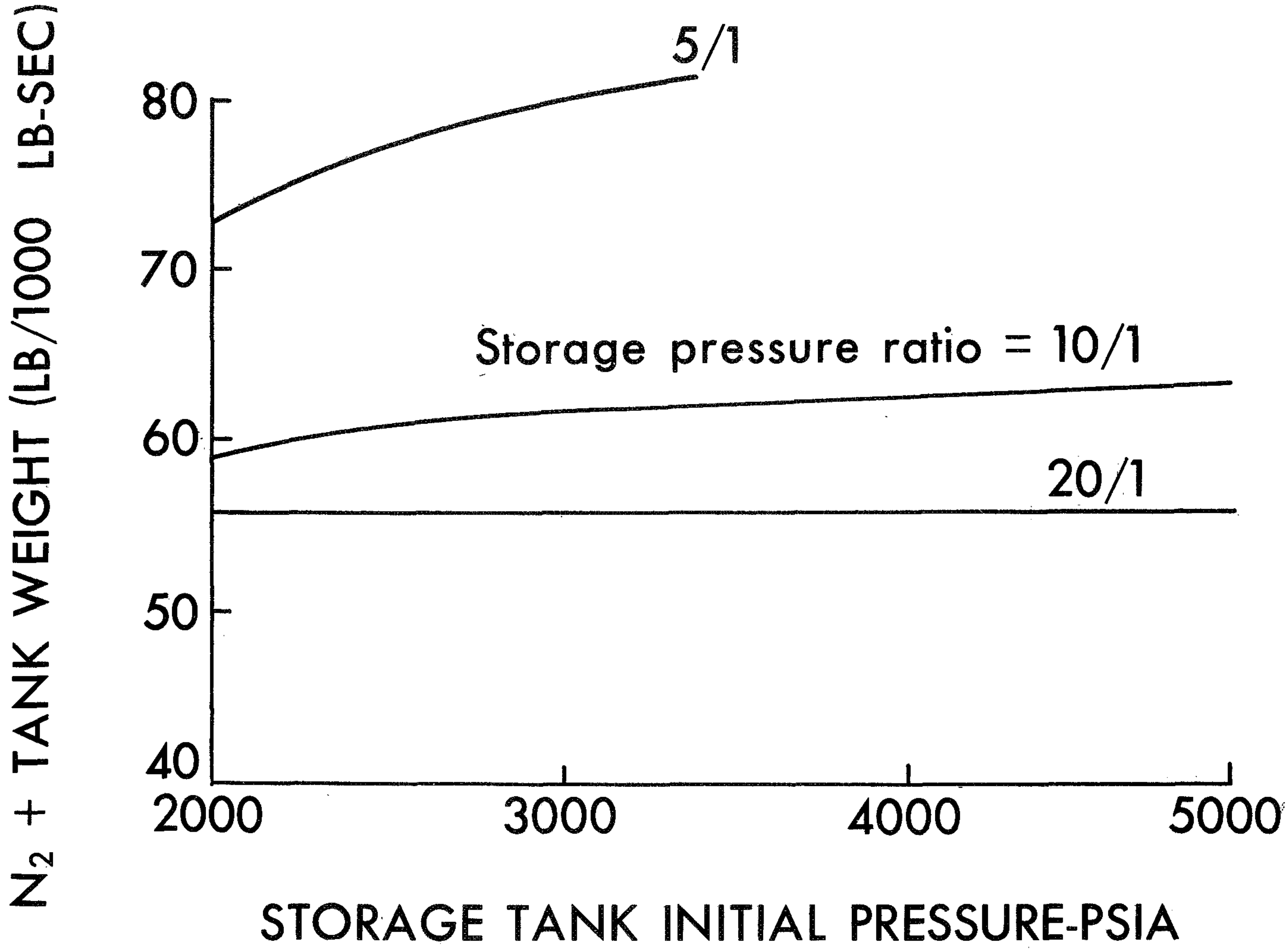
NOTE: Specific impulse is calculated by:

$$Isp = \frac{\sqrt{\frac{64.4\,K}{K-1}\,\frac{R}{M}\,T\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}\right]}}{32.2}$$

where $K = 1.4$
$R = 1545$
$M = 28$
T_1 =temperature at state point in isentropic process
$\frac{P_2}{P_1} = 1/150$ for 10 to 1 expansion nozzle

NOTE: For use with storage tank initial pressures between 2000 and 5000 psi.

FIGURE 6.- NITROGEN IMPULSE CHARACTERISTICS.



NOTE: Tank weight is based on cylindrical titanium tank L/D = 8/1 with S. F. = 2/1

FIGURE 7.- PROPELLANT STORAGE SYSTEM WEIGHT.

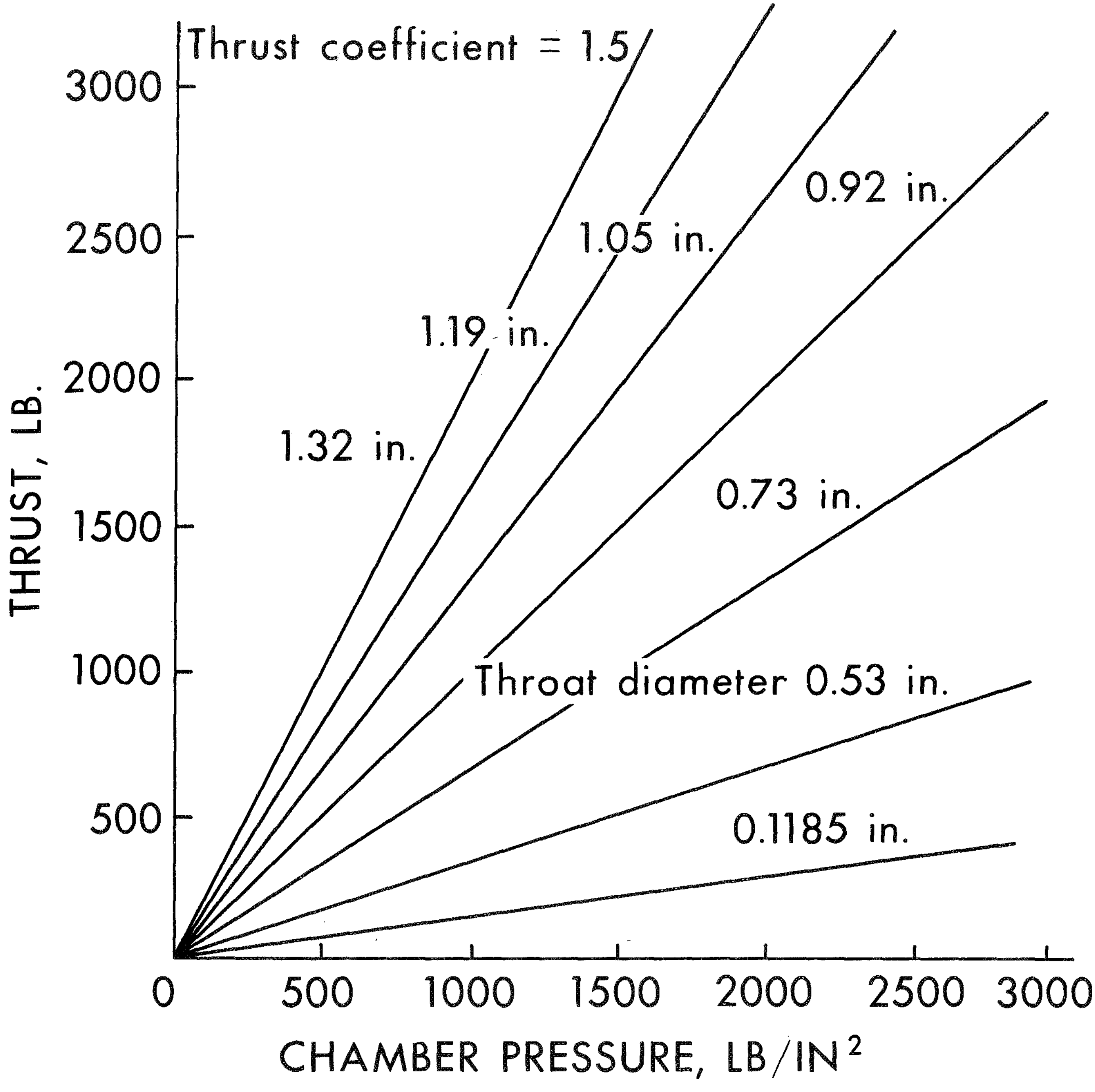
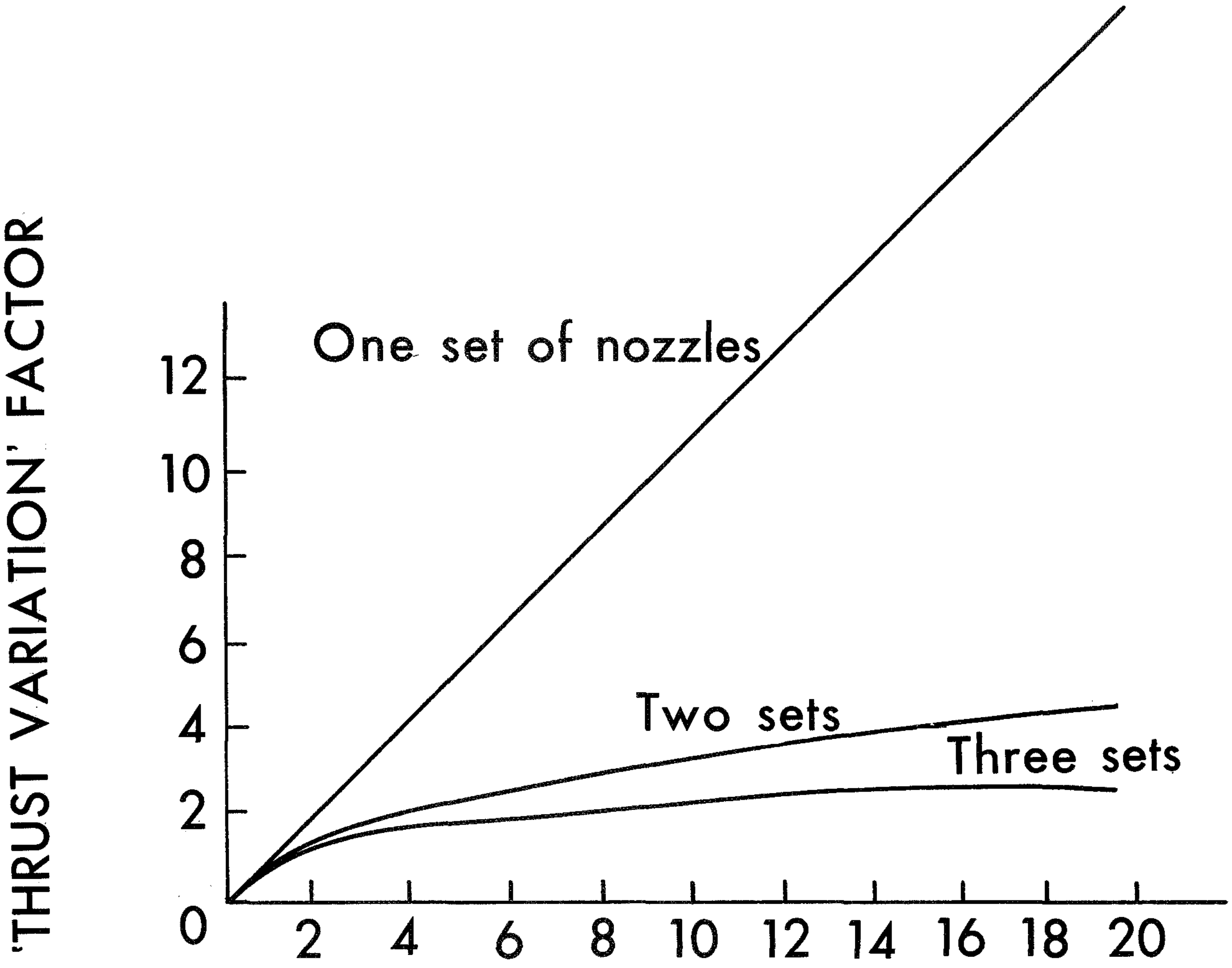


FIGURE 8.- NOZZLE PERFORMANCE.



NOTE: For equal thrusts at the outset of the use of each set of nozzles.

FIGURE 9.- REGULATION EFFECT POSSIBLE IN A BLOWDOWN TYPE REACTION CONTROL SYSTEM.

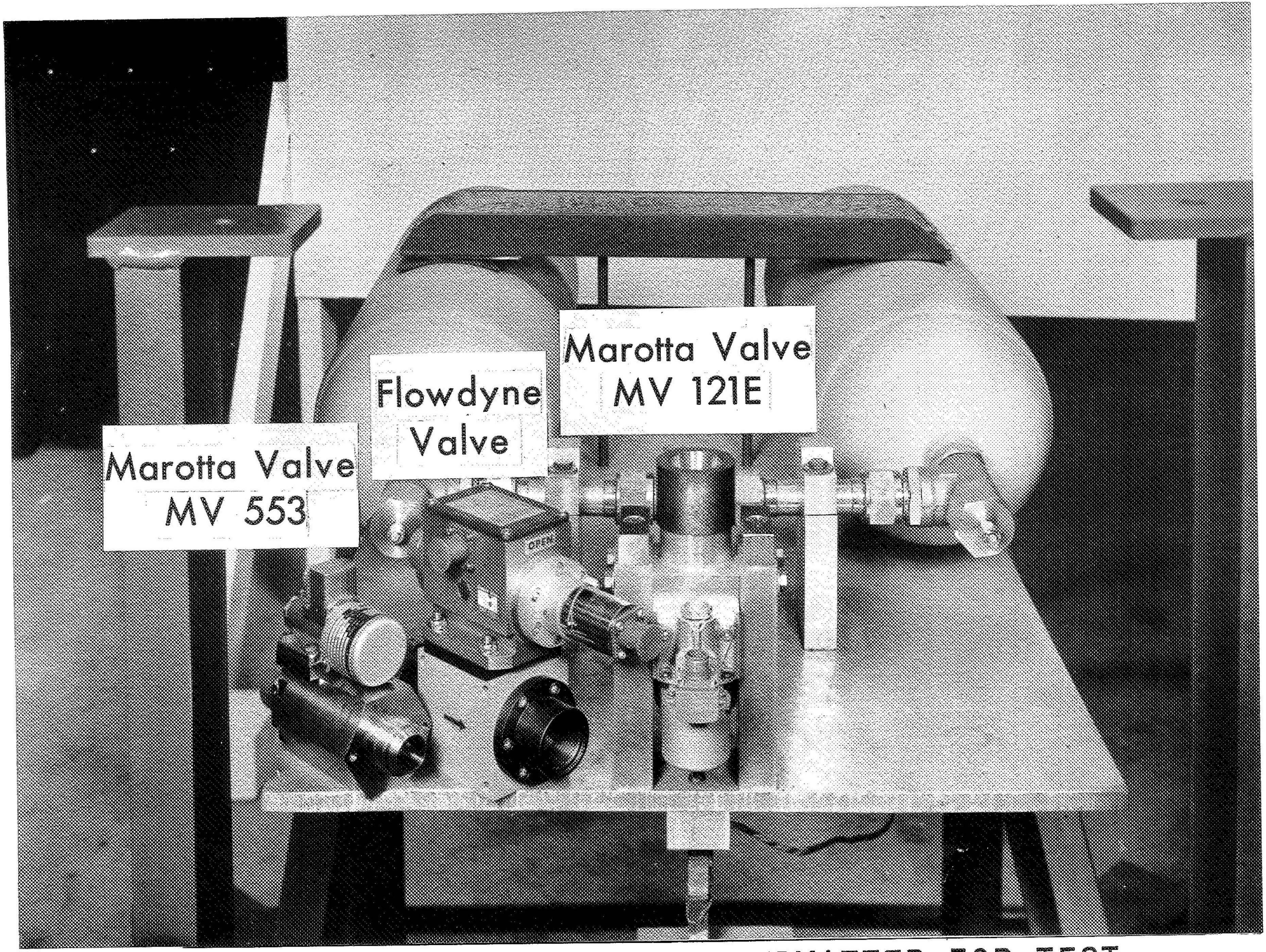


FIGURE 10.- THREE VALVES SUBMITTED FOR TEST.

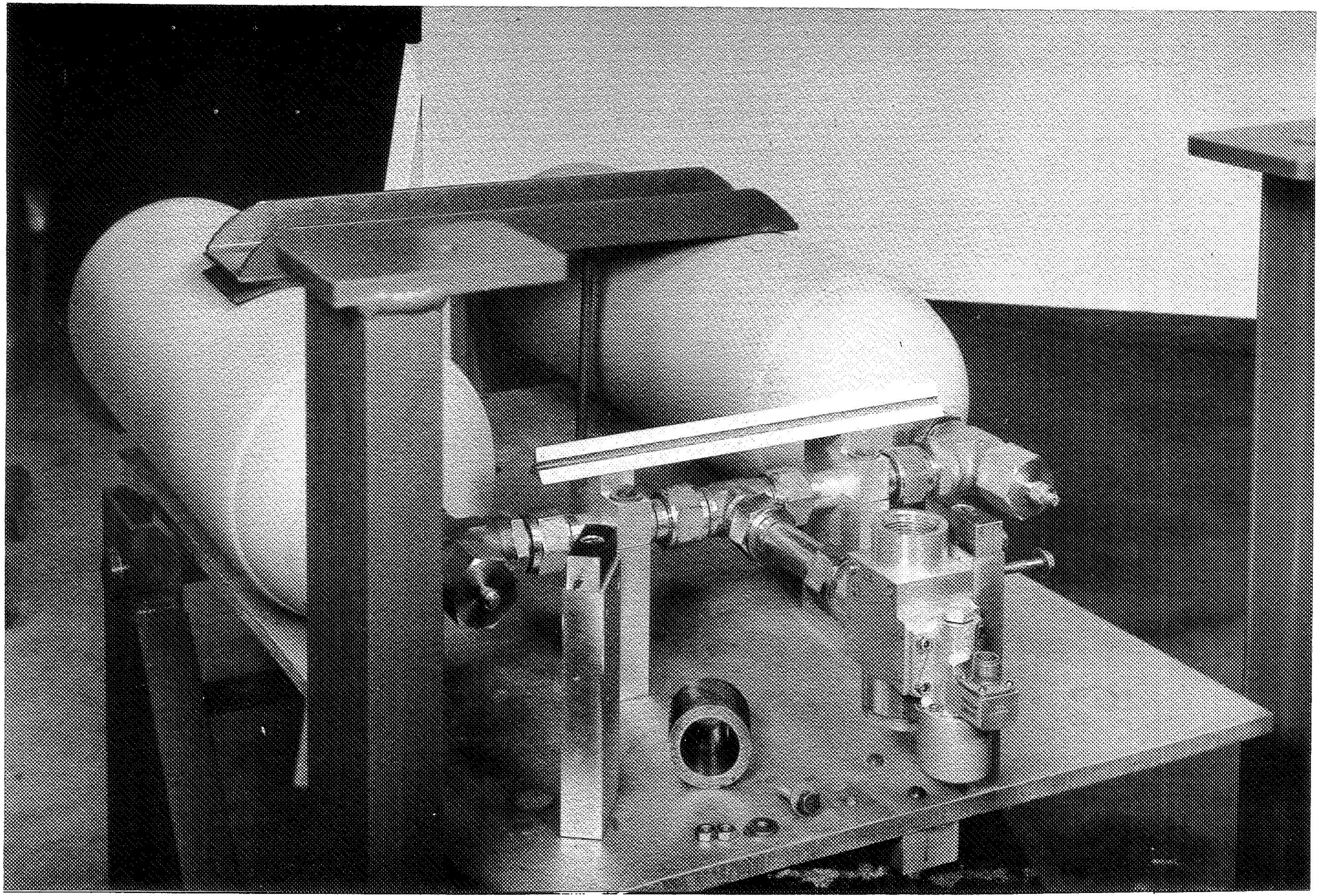


FIGURE 11.- MAROTTA VALVE MV 121E INSTALLED IN THE THRUST STAND.

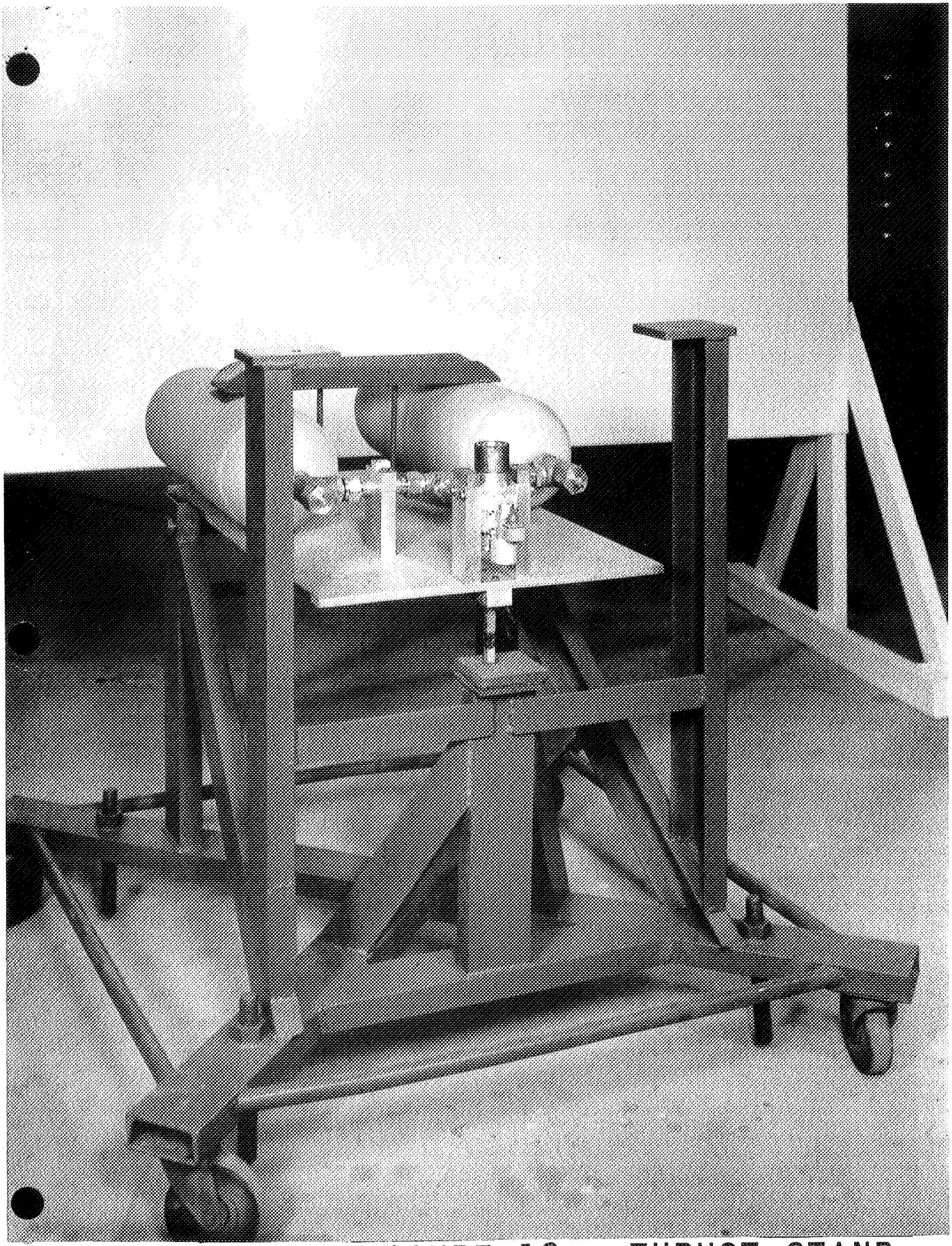


FIGURE 12.- THRUST STAND.

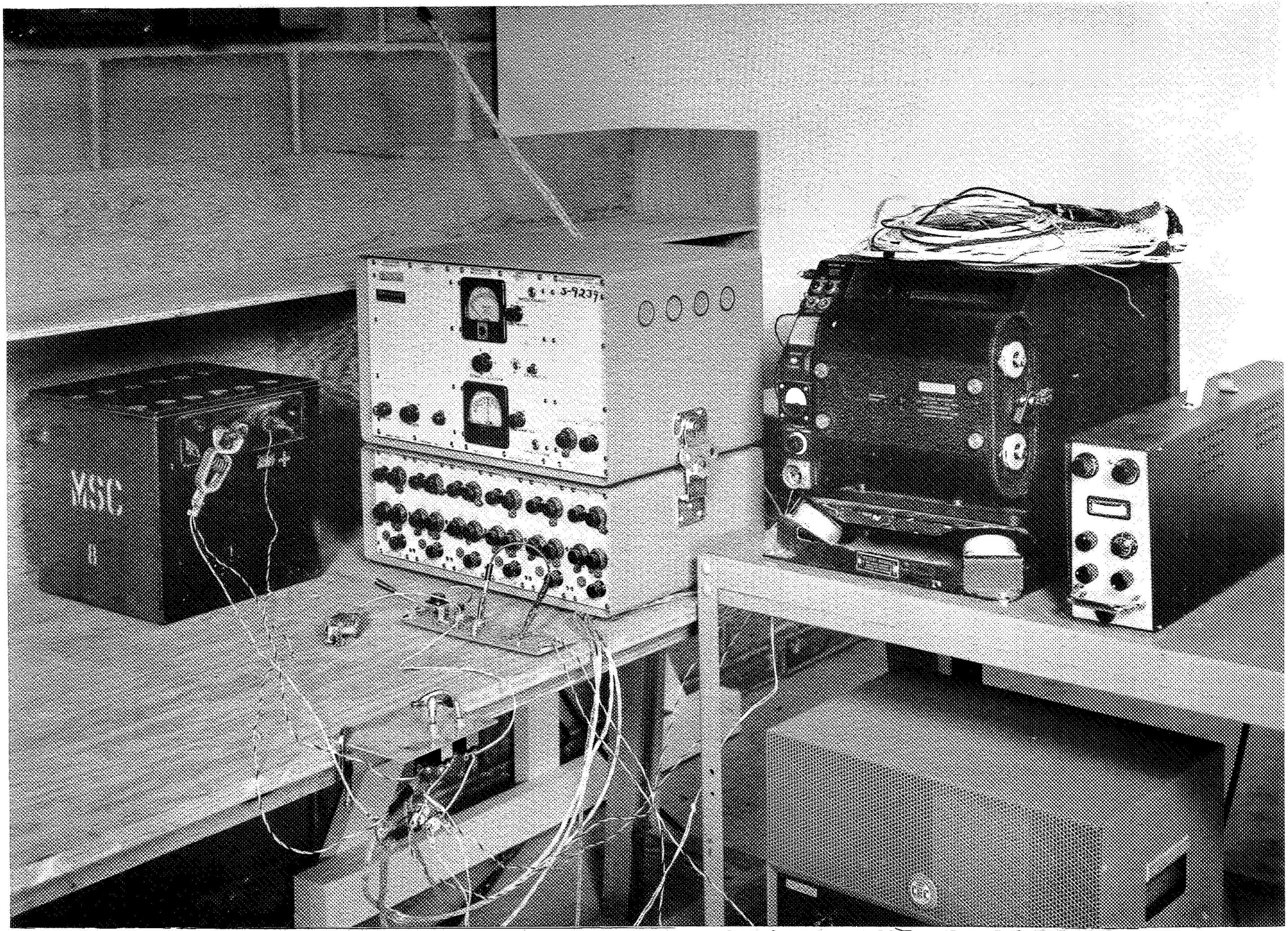


FIGURE 13.- CARRIER AMPLIFIER AND RECORDER.

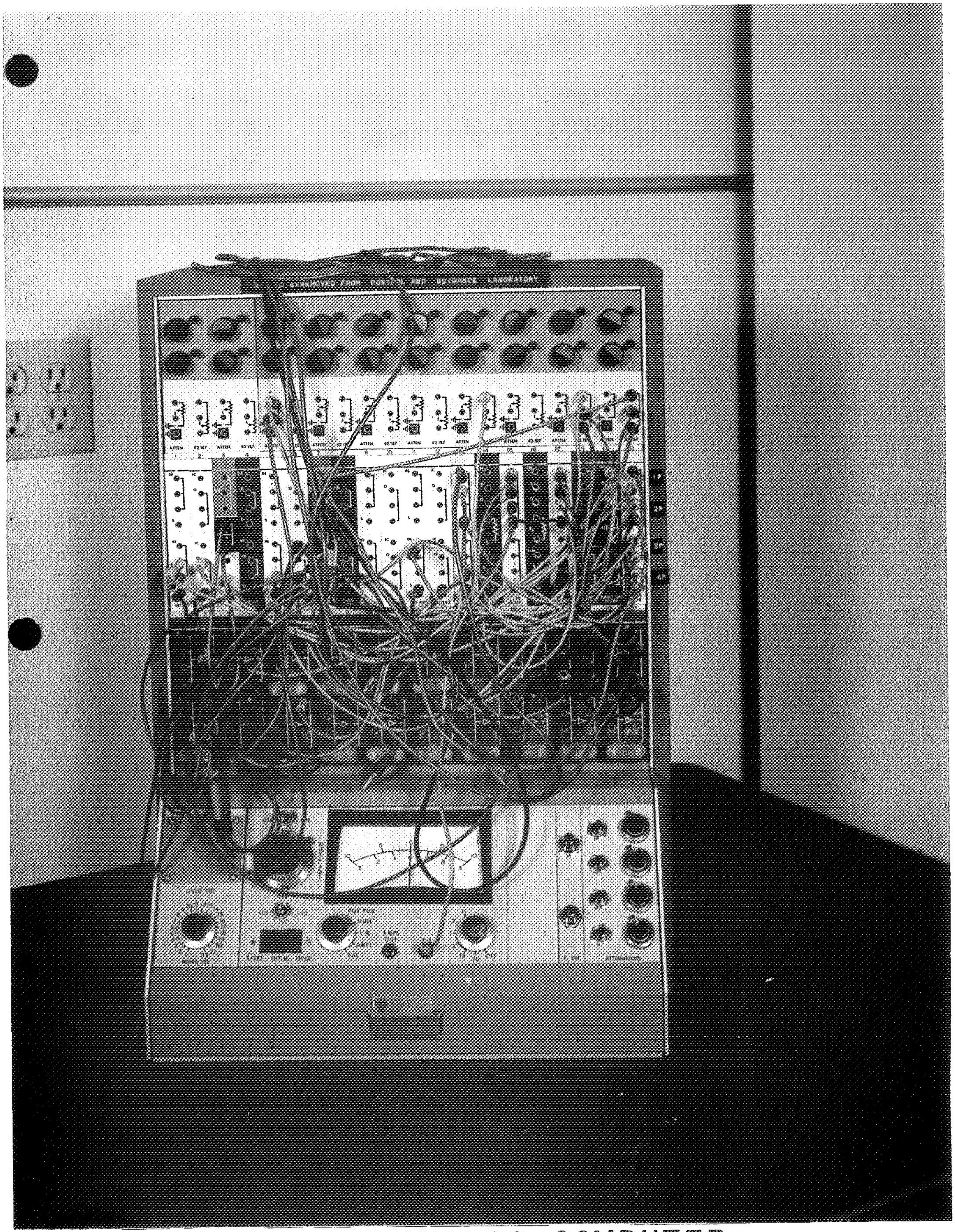


FIGURE 14.- ANALOG COMPUTER.

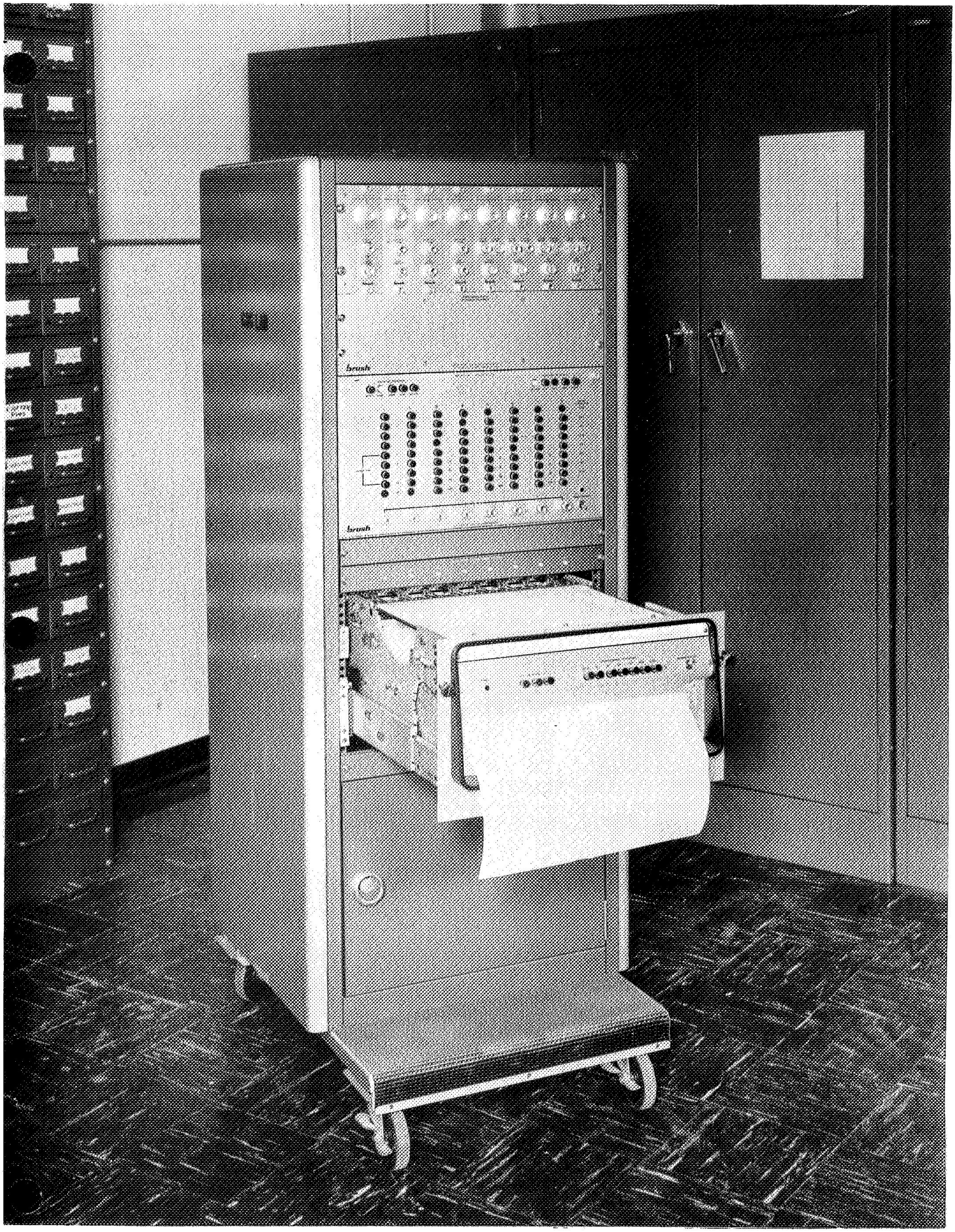


FIGURE 15.- 8-CHANNEL RECORDER.

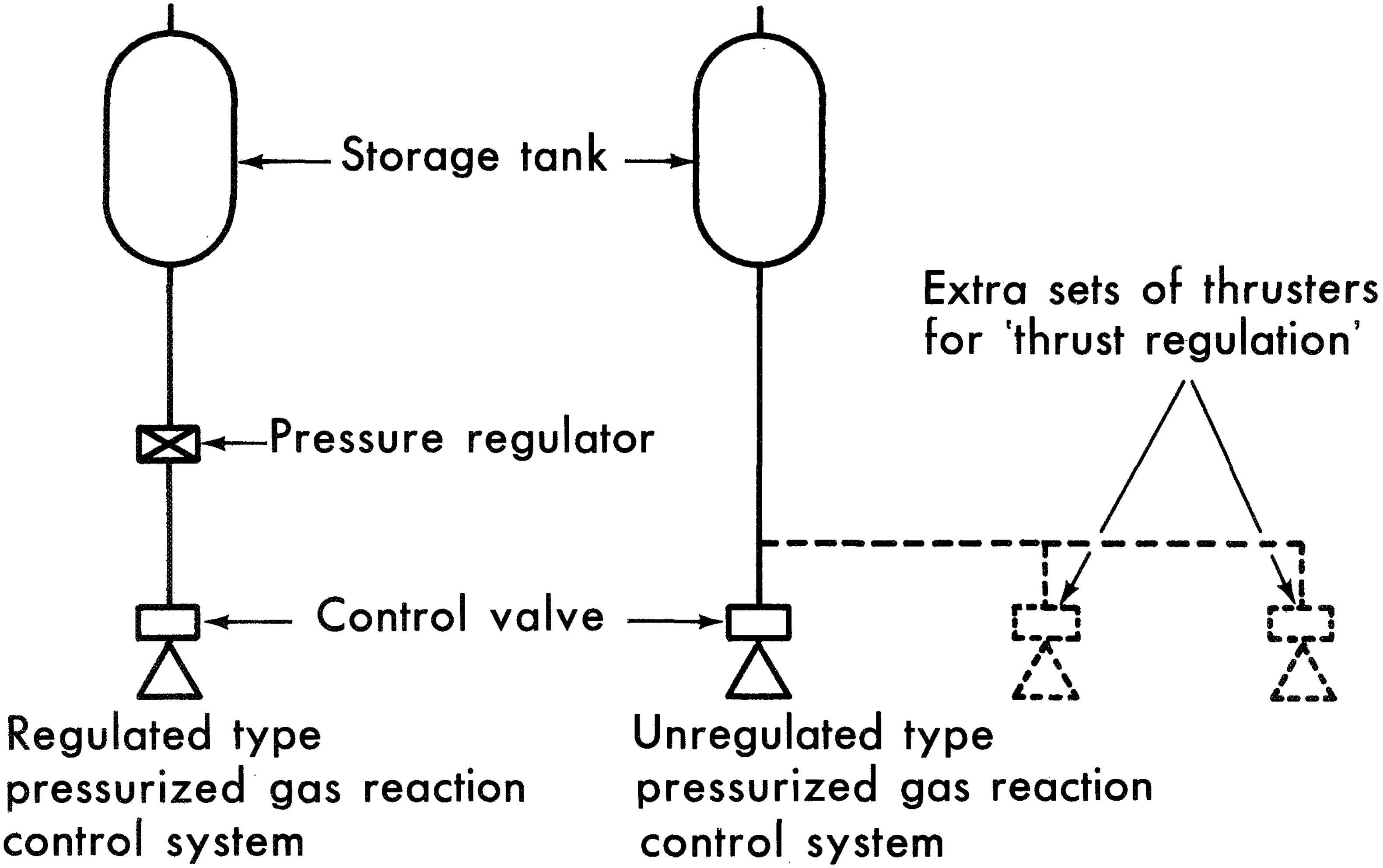


FIGURE 16.- SCHEMATIC OF REGULATED AND UNREGULATED REACTION CONTROL SYSTEMS.

MONO-PROPELLANT SYSTEM

Component name	Failure Rate/Hour
N_2 tank	8×10^{-6}
fill valves (2)	86×10^{-6}
arming valve	50×10^{-6}
pressure regulator	600×10^{-6}
N_2 plumbing (36 connections)	180×10^{-6}
check valve	190×10^{-6}
relief valve (2)	280×10^{-6}
H_2O_2 tanks (4)	32×10^{-6}
H_2O_2 bladders (4)	32×10^{-6}
H_2O_2 plumbing (16 connections)	80×10^{-6}
back pressure valve	150×10^{-6}
solenoid valves (2)	140×10^{-6}
decomposition chambers (2 summed)	200×10^{-6}
	2128×10^{-6}

R_1 = 1 - failure rate

R_1 = reliability of one system

$q = 1 - R_1$

$R_t = R_1^4 + 2 R_1^3 q$

$R = (.99787)^4 + 2(.99787)^3 (1-.99787) = .99573$

PRESSURIZED GAS SYSTEM

Component name	Failure Rate/Hour
N_2 tank (12)	96×10^{-6}
fill valve	43×10^{-6}
N_2 Plumbing (36 connections)	180×10^{-6}
N_2 relief valve	190×10^{-6}
solenoid valves (16)	1120×10^{-6}
	1629×10^{-6}

R = 1 - Failure Rate

$R = .99837$

FIGURE 17 - RELIABILITY COMPARISON FOR LITTLE JOE II REACTION CONTROL SYSTEM