NASA TECHNICAL NOTE

NASA TN D-5509
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APPLICATION OF
PRESSURIZED LIQUID NITROGEN INSIDE
PARAMETRIC-AMPLIFIER STRUCTURES FOR
INPUT-NOISE-TEMPERATURE IMPROVEMENT

by Hans-Juergen C. Blume

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1969

1. Report No. NASA TN D-5509	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle APPLICATION OF PRESSURIZED LIQUID NITROGEN INSIDE PARAMETRIC-AMPLIFIER STRUCTURES FOR INPUT-NOISE-TEMPERATURE IMPROVEMENT		5. Report Date October 1969
		6. Performing Organization Code
7. Author(s) Hans-Juergen C. Blume		8. Performing Organization Report No. L-6373
		10. Work Unit No. 125-21-04-05-23
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23365		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Note
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The temperature rise caused by power dissipation in lossy capacitance diodes in cooled parametric amplifiers, especially in monostatic high-power radar systems, diminished the noise-reduction effect of the coolant. To obtain good heat conduction from the diode so that it would remain at ambient temperature, liquid nitrogen under helium gas pressure was employed as dielectric material surrounding the lossy diode. All adjustments for optimum performance of a 400-MHz amplifier were accomplished at room temperature before immersion into liquid nitrogen by using calculated and measured values from curves that showed resonant frequency variation of each circuit due to the change of the relative dielectric constant from 1 to 1.435, the slight change of the physical dimension caused by thermal contraction, and the change of the operating frequency at high gain.

17. Key Words Suggested by Author(s) Parametric amplifiers Liquid nitrogen cooling Noise reduction Helium gas pressurization Temperature rise in capacitance diodes	18. Distribution Statement Unclassified — Unlimited		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 30	22. Price* $3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

APPLICATION OF PRESSURIZED LIQUID
NITROGEN INSIDE PARAMETRIC-AMPLIFIER STRUCTURES FOR
INPUT-NOISE-TEMPERATURE IMPROVEMENT

By Hans-Juergen C. Blume
Langley Research Center

SUMMARY

Cooled parametric amplifiers, especially in monostatic high-power radar systems, exhibit a higher ratio of input noise temperature to ambient temperature when operating at liquid nitrogen temperatures rather than at room temperatures. This behavior is due to the temperature rise in the diode as a result of pump power dissipation and leakage power dissipation in the diode loss resistance. This paper describes a technique whereby liquid nitrogen under helium gas pressure is used as the dielectric material surrounding the lossy diode within the parametric-amplifier structure. With this technique the heat conduction from the lossy diode is sufficient to maintain the diode at ambient temperature. However, all adjustments for optimum amplifier performance are required to be made at room temperature before insertion of the structure into a pressurized container. These adjustments are made by using experimental and theoretical curves showing the variation of the resonant frequency of each circuit with the dielectric constant, which increases to 1.435 in the presence of liquid nitrogen. The noise temperature of a 400-MHz amplifier was reduced from 330° K at room temperature to 88° K at liquid nitrogen temperature of 77° K. Although a lossy diode was used in the amplifier, the ratio of the input noise temperature to ambient temperature at 77° K was only slightly higher than the theoretically determined value.

INTRODUCTION

The demand for ultra-low-noise preamplification, especially in long-range telemeter and radar systems, has stimulated the development of liquid-nitrogen-cooled parametric amplifiers. When this cooling method is used, the structure of the parametric amplifier is partially or completely immersed in the coolant. The coolant is usually kept out of spaces with electromagnetic fields; therefore the active element, the varactor diode, is located in the coolant-free space. The loss resistance of the varactor diode generates heat which is due to ac pumping and, for radar systems, the leakage power from transmitters. Because of the low heat conduction in the internal construction of varactor diodes, the ambient temperature of the lossy element is increased. Consequently, the

noise-reduction effect of the coolant is diminished. An increase of 100° K to 150° K in ambient temperature of the lossy section of the varactor diode is common. Because of this effect, liquid-nitrogen-cooled parametric amplifiers have exhibited higher input noise temperatures than theoretically predicted, especially in monostatic high-power radar systems which use medium-quality varactor diodes.

In reference 1 it was shown that the pressurized liquid nitrogen inside cavity resonators served to keep the temperature rise in the lossy diode to a minimum. The results of reference 1 suggest that a similar improvement in maintaining the temperature constant could be realized for parametric-amplifier structures.

In the present report, the application of pressurized liquid nitrogen inside parametric amplifier structures is discussed and methods for fabrication of an internally cooled 400-MHz parametric amplifier are described. The pretuning requirements for successful operation of the example amplifier and the procedures for inserting liquid nitrogen into the amplifier structure are also described. Test results for the parametric amplifier at 400 MHz are given both for room temperature and for liquid nitrogen temperature and are compared with the theoretical values.

SYMBOLS

C	dynamic varactor diode capacitance, farads
C_D	feed-through capacitance, farads
C_O	diode bias capacitance, farads
C_6	tuning capacitance, farads
C_7	coupling capacitance, farads
C_7', C_7''	equivalent capacitance, farads
C_8	capacitance, farads
f_i	idler frequency, hertz
f_i'	pretuned idler resonant frequency at room temperature, hertz
f_p	pump frequency, hertz

f_p'	pretuned pump resonant frequency at room temperature, hertz
f_s	signal frequency, hertz
f_s'	pretuned signal resonant frequency at room temperature, hertz
$f_{s,l}$	resonant frequency of signal circuit immersed in liquid nitrogen, hertz
F	noise figure
$j = \sqrt{-1}$	
l_7	line length, centimeters
L_6	inductance of pump input transformer, henries
L_6', L_7'	equivalent inductance at idler frequency, henries
L_8	inductance of signal input transformer, henries
Q	resonant circuit quality factor
R	negative resistance, ohms
R_g	generator impedance, ohms
R_s	loss resistance in diode, ohms
R_1	loss resistance in signal circuit, ohms
R_2	loss resistance in idler circuit, ohms
R_6	loss resistance in pump circuit, ohms
R_6'	equivalent loss resistance at idler frequency, ohms
T	measured input noise temperature, $^{\circ}K$
T^*, T^{**}	calculated input noise temperature, $^{\circ}K$

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T_a ambient temperature, $^\circ K$

T_d ambient temperature of diode, $^\circ K$

T_o room temperature, $^\circ K$

T_1 ambient temperature of signal circuit, $^\circ K$

T_2 ambient temperature of idler circuit, $^\circ K$

V_o bias voltage, volts

V_p amplitude of pump voltage, volts

$\dfrac{X_s}{Z_o}$ normalized reactance

$\dfrac{\Delta X}{Z_o}$ additional normalized reactance

Δ prefix denoting relative frequency variation in resonant circuit

PRESSURE CONTAINER

An obvious approach to the reduction of the temperature rise in the varactor diode of parametric amplifiers is the use of liquid nitrogen as a coolant, both inside and outside of the parametric-amplifier structure. This method was found to be successful in keeping the active element cool. However, bubble formation developed especially in the neighborhood of the active element. This bubble formation causes the resonant frequency of the tuned circuit to change erratically because of the difference in dielectric constant of the liquid and gaseous states of the coolant, the ratio being 1.435:1 (ref. 2, p. 7.004). This difficulty was overcome by use of liquid nitrogen under helium gas pressure as dielectric material surrounding the lossy diode inside the parametric-amplifier structure. In addition, this technique allows good heat conduction from the diode which, in turn, maintains the ambient temperature of the diode.

To keep the liquid nitrogen inside the parametric amplifier under pressure, the entire structure was enclosed in a pressure container. A disassembled pressure container dimensioned for the housing of a 400-MHz parametric amplifier is shown in figure 1. The pressure container is cylindrical and is shown with the top open. In operation, the top of the pressure container was closed by the pressure container cover. The cover was provided with three coaxial feed throughs having glass seals at both ends and

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two lines for liquid nitrogen. The liquid nitrogen input tubing supplied the liquid nitrogen to the parametric amplifier as shown in the flow diagram of figure 2. This line can be closed with valve K. The other line of the pressure container fed the liquid nitrogen into the condenser coil which in turn was connected to the pressure gage and valve I. The condenser coil was provided for the purpose of liquefying the residual nitrogen gas after the filling procedure, as explained in a subsequent section. Since, in practice, large pressure containers may develop leaks due to frequent cooling and heating, the container was kept as small as possible and was designed as a body having rotational symmetry. For this reason, the parametric amplifier was kept small.

PARAMETRIC-AMPLIFIER DESIGN FOR OPERATION
IN PRESSURIZED LIQUID NITROGEN

The parametric amplifier had three distinct design characteristics:

(1) The liquid nitrogen, under pressure within the coaxial lines, was to act as a cold dielectric.

(2) The entire structure was to be kept as small as possible.

(3) The circuit development was to be based on the characteristics of a varactor diode with a loss resistance R_S of 2.77Ω and a capacitance C_O of 0.658 pF at the bias voltage V_O of -0.67 volt.

The basic requirements in designing and building parametric amplifiers are well documented (ref. 3). In order to obtain a parametric amplifier with negative resistance behavior operated with a circulator as described in reference 3 (pp. 57-60), the parametric-amplifier structure was designed as shown in figure 3. To keep the amplifier to a reasonable size, the pump circuit and the idler circuit were housed in one coaxial line. This coaxial line was tuned to two different resonant frequencies by use of two variable capacitances C_6 and C_7. To the left is the pump resonant circuit with its input and tuning capacitance C_6. The coupling capacitance C_7, which could be varied by means of the knurled idler tuning screw, would slightly change the resonant frequency of the pump circuit. However, this change could be compensated by means of C_6. The signal circuit with the input transformer and the diode is coupled to the coaxial line by the capacitance C_8.

Figure 4 shows the equivalent circuits used to calculate the dimensions of the structure of figure 3. Considering all components, the equivalent circuit in figure 4(a) is obtained. The signal circuit consisted of the input transformer with the inductance L_8 at the secondary side, of the varactor having capacitance C and loss resistance R_s, and of loss resistance R_1. The parallel resonant circuit for the pump frequency with

C_6 and L_6 was connected in parallel with the signal circuit by the capacitance C_7 and the line of length l_7. Since the resonant frequency of the pump circuit with C_6 and L_6 was about four times higher than the signal frequency, the pump circuit represented a short circuit for the signal frequency, if the pump generator was so loosely coupled that the resonant circuit was only slightly loaded. For this short circuit the equivalent circuit of figure 4(b) may be applied. The transformation of the reactance of the capacitance C_7 by the line of length l_7 from reference plane 2 to reference plane 1 results in the equivalent circuit of figure 4(c). The capacitance C_8 must be chosen for small influence of the equivalent capacitance C_7' upon the signal circuit. Consequently, C_8 and C_7' in series represented an additional capacitance to the bias capacitance C_0 of the diode and it affected the resonant frequency of the signal circuit. This equivalent capacitance increased the resonant quality factor Q of the input circuit but decreased the bandwidth of the amplifier.

Since the idler frequency is

$$f_i = f_p - f_s \tag{1}$$

for amplification in this mode of operation (ref. 3, p. 50), the inductance L_8 in the signal circuit represented a high reactance which can be neglected at the idler frequency. Figure 4(d) represents the equivalent circuit for the idler frequencies. The pump resonant circuit forms the equivalent inductance L_6' with the loss resistance R_6. The resistance R_6 stems from pump generator coupling. To keep the idler circuit noise small, the coupling of the pump generator to the pump resonant circuit must be loose. The combination of C_7', L_6', and R_6 at the idler frequency results in the equivalent circuit of figure 4(e). In figure 4(f) is shown the final equivalent circuit for f_i after C_7'' and R_6 are transformed from reference plane 2 to reference plane 1. This equivalent circuit was to be tuned to f_i by adjustment of C_7 so that L_7' was in resonance with the series combination of C and C_8. Similar combinations may be applied for the pump frequency. At this frequency it is only important, however, that the diode capacitance is changed over its entire range for maximum amplification.

Further design characteristics of the parametric amplifier of figure 3 were as follows:

(a) The capacitance C_8 consisted of teflon disks and teflon tubing which formed a capacitance of 1 pF between the faces of the central conductor.

(b) The reactance of the coaxial line at f_s was $-j600\Omega$ which resulted in a value of C_7' of 5.5 pF.

(c) The coupler for the idler test circuit was magnetic and was located in the range of maximum idler current.

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(d) The idler test point was not used during amplifier operations but was necessary for tuning the idler circuit to the proper resonant frequency before filling the amplifier with liquid nitrogen.

(e) The coaxial line had a characteristic impedance of 77Ω at room temperature and 65Ω when filled with liquid nitrogen.

The diode was biased at a value V_O of -0.67 volt which resulted in a value of C_O of 0.658 pF. The combination of C_8 (1 pF), C_7' (5.5 pF), and C_O (0.658 pF) was tuned to resonance at f_s'. This resonant frequency f_s' differed from the operating signal frequency f_s because of detuning effects such as the filling with liquid nitrogen. For this amplifier, f_s' is 440 MHz, as shown subsequently. To achieve this frequency, the secondary coil of the transformer had two turns (fig. 3). The diode holder contained a spiral spring to allow for dimensional changes in the cool-down process.

The dc voltage for biasing the diode was supplied through the secondary coil of the input transformer of the signal circuit. The grounding end of the secondary coil was shorted for the signal frequency with the feed-through capacitance C_D as shown in figure 3. To form an effective low-pass filter, an additional inductance was connected and is visible in the photograph of the assembled parametric amplifier shown as figure 5. The amplifier structure was provided with input tubing for insertion of liquid nitrogen. All teflon spacers as well as the bottom of the amplifier structure were perforated to prevent the formation of tightly sealed spaces.

Since the frequency tuning for the amplification condition in equation (1) could not be executed when the amplifier was inside the filled pressure container, a well-predetermined tuning procedure at room temperature was developed. For this tuning, the parametric amplifier was connected to the coaxial feed throughs of the pressure-container cover by flexible 50Ω coaxial cables (fig. 1). In this manner the coaxial lines became a part of the amplifier, and the measuring reference plane was located above the pressure-container cover. This tuning, however, also included the self-detuning effect for maximum amplification occurring in parametric amplifiers.

CALCULATION OF PARAMETRIC-AMPLIFIER TUNING
PRIOR TO LIQUID NITROGEN IMMERSION

To obtain maximum gain and minimum input noise temperature for operating in liquid nitrogen, it was necessary that the required tuning at room temperature include the change of the relative dielectric constant from 1 to 1.435, the slight change of the physical dimension with temperature, and the frequency corrections at high gain. Accurate measurements and calculations of the relative resonant frequency variation of each circuit when immersed in liquid nitrogen were obtained to facilitate the tuning process. The

frequency variations of each circuit are given by the following equations:

$$\Delta f_s = \frac{f_s - f_s'}{f_s'}$$ (2)

$$\Delta f_i = \frac{f_i - f_i'}{f_i'}$$ (3)

$$\Delta f_p = \frac{f_p - f_p'}{f_p'}$$ (4)

where f_s', f_i', and f_p' are the resonant frequencies of the respective circuits at room temperature. Equations (2), (3), and (4) were solved for f_s, f_i, and f_p. Substituting these solutions in equation (1) and solving for f_p' results in

$$f_p' = f_i' \left(\frac{1 + \Delta f_i}{1 + \Delta f_p} \right) + f_s' \left(\frac{1 + \Delta f_s}{1 + \Delta f_p} \right)$$ (5)

Through measurements, the following variations in frequency were obtained for the idler and pump circuits of the example parametric amplifier:

$$\left. \begin{array}{l} \Delta f_i = -13.3 \text{ percent} \\[2ex] \Delta f_p = -14.55 \text{ percent} \end{array} \right\}$$ (6)

The frequency variation of the signal circuit was subdivided into the detuning due to liquid nitrogen and the detuning due to high gain operation. By introducing $f_{s,l}$ as the resonant frequency of the signal circuit immersed in liquid nitrogen and noting that f_s is the resonant frequency of the same circuit in operation, equation (2) changes to

$$\Delta f_s = \frac{f_{s,l} - f_s'}{f_s'} + \frac{f_s - f_{s,l}}{f_s'}$$ (7)

The measured detuning of the first term on the right-hand side of equation (7) was

$$\frac{f_{s,l} - f_s'}{f_s'} = -8.93 \text{ percent}$$ (8)

The resonant frequencies of the idler circuit and of the pump circuit changed more extensively than those of the signal circuit since, in addition to the variation in static capacitance of the diode, the wave impedance of the coaxial lines dropped from 77Ω to 65Ω.

Since the desired operating frequency was 400 MHz, the signal circuit must be detuned by 8.93 percent toward higher frequencies by changing the inductance in the input transformer. Initially a frequency of 440 MHz was selected at a diode bias of -0.5 volt. The frequency change from $f_{s,l}$ to f_s resulted from the nonlinear relation of the input circuit reactance to diode voltage shown in figure 6. The sinusoidal pump voltage is projected from the nonlinear curve of the normalized signal circuit reactance X_s/Z_o plotted against the diode voltage to the right with a resulting nonsinusoidal input reactance. The first term of the Fourier series which defines this curve is the additional reactance $\Delta X/Z_o$ that causes the detuning of the input circuit resulting from operation. The bias voltage V_o and the amplitude of the pump voltage V_p determine the amount of reactance $\Delta X/Z_o$. For the example amplifier, the bias voltage V_o in operation was -0.67 volt and the amplitude of the pump voltage V_p was determined to be 0.67 volt. By assuming that the projected normalized reactance curve was sinusoidal enough to neglect all other higher Fourier terms, the first Fourier term was

$$\frac{\Delta X}{Z_O} = 0.7 \tag{9}$$

This value caused a detuning of the signal circuit to the positive or inductive side of the resonant circuit. The corresponding frequency shift is shown in figure 7, which is the Smith chart of the input impedance of the signal circuit as a function of frequency. The construction and use of this frequency scale are described in reference 4 (pp. 403-412). The second term on the right-hand side of equation (7) then was determined from figure 7 to be

$$\frac{f_s - f_{s,l}}{f_s'} = 0.12 \text{ percent} \tag{10}$$

The relative frequency shift in equation (2) is therefore

$$\Delta f_s = -8.81 \text{ percent} \tag{11}$$

which results in a room temperature tuning f_s' of 440 MHz for the signal circuit in order to achieve an operating frequency of approximately 400 MHz.

Introducing the values of equations (6), (8), and (11) into equations (5) and (7) results in

$$f_p' = 1.015 f_i' + 0.469 \tag{12}$$

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in GHz. This equation is plotted in figure 8. It is obvious that for each assumed tuning point of the pump resonant circuit, only one idler frequency exists and the idler circuit has to be tuned to this resonant frequency. This tuning curve was successfully used for the pretuning of the 400-MHz parametric amplifier before immersion in liquid nitrogen.

FILLING WITH LIQUID NITROGEN

The assembled tuned amplifier was inserted into the pressure container as shown in figure 9. The V-shaped rings on the flange of the pressure container and on the pressure-container cover, which face each other, cut into the teflon gasket. The advantage afforded by this teflon gasket was the retention of a plastic state to temperatures below the boiling point of liquid nitrogen. The pressure container was then placed in the Dewar flask.

The apparatus used to force liquid nitrogen into the amplifier structure and into the pressure container is schematically illustrated in figure 10. The excess pressure of the nitrogen pressure bottle A pushed the liquid nitrogen of the reservoir B through the transfer tube C into the pressure container F and from there into the Dewar flask D. The advantage of this method of transferring liquid nitrogen was that at the beginning of the cooling process, the pressure container F and the amplifier were thoroughly purged with nitrogen gas to eliminate water vapor and other impurities.

During the transfer of liquid nitrogen from the reservoir B to the Dewar flask D, a mixture of about 30 percent liquid and 70 percent gas existed despite good insulation. Hence, after transfer of the liquid nitrogen, the pressure container F was partially filled with nitrogen gas. Condenser coil G was provided to eliminate this gas residue.

The procedure for filling and pressurizing the parametric amplifier was as follows:

(1) Valves M, H, K, and I were opened. Liquid nitrogen flowed through pressure container F into Dewar flask D.

(2) After the Dewar flask D was filled, output valve I was closed. It was necessary to apply a pressure of about 1.5 atm to the condenser coil G and the pressure container F to liquefy the nitrogen gas. Condenser coil G provided the heat exchange for liquefaction.

(3) Valves M and H were closed and output valve I was opened. The transfer tube C was removed from valve K.

(4) Valve K was closed. The output tubing for Dewar flask D was removed and helium gas from pressure bottle E flowed through valve I. If all nitrogen gas between valve I and the pressure container was liquefied and replaced by helium gas, an oscillating process of liquefaction and vaporization occurred between the pressure container and valve K. Valve I was closed and the helium bottle E was then connected to the input line at valve K. Valve K was opened.

(5) When substantially all the nitrogen gas in the input and output tubes had been liquefied and had been replaced by helium gas, a pressure of 1.3 to 1.5 atm was maintained for the prevention of nitrogen bubble formation inside the amplifier and the pressure container.

Results of theoretical and experimental investigations reported in reference 1 indicated that for heat conduction through the pressurized liquid nitrogen and the wall of the pressure container, a temperature rise of about 4° K above 77° K at the diode was to be expected for a 50-mW heat dissipation in the lossy section of the diode.

EXPERIMENTAL SETUP

The setup which is shown in the form of a block diagram in figure 11 and as a photograph in figure 12 was used for tuning, measurement of the gain, and measurement of the input noise temperature. The test amplifier which was filled with liquid nitrogen under pressure is labeled "Parametric amplifier 1" in the figures. The pressure container with parametric amplifier 1 was immersed in liquid nitrogen in the open Dewar flask. The important heat dissipation took place outside the pressure container by boiling off liquid nitrogen in the open Dewar flask.

The pump power of pump generator 1 at 1.665 GHz was supplied through an isolator and attenuator into the pump resonant circuit of the test amplifier. The dc source 1 was connected to the low-pass filter for biasing the diode. Circulator 1 served as separator between incident and reflected power waves of parametric amplifier 1. Circulator 2 functioned as an isolator and increased the stability of the setup. Circulator 3 separated the incident and reflected power waves of parametric amplifier 2 which served as a preamplifier before the mixer stage. Parametric amplifier 2 was supplied with pump power by pump generator 2. The supplied pump power was stabilized by the isolator and adjusted by the attenuator. The dc source 2 delivered the bias voltage for amplifier 2.

The second parametric amplifier operated at room temperature. This amplifier was provided to decrease the influence of the large noise figure of the mixer stage upon the input-noise-temperature measurement. The mixer following parametric amplifier 2 converts the signal frequency to an IF of 30 MHz. The IF amplifier had enough gain so that the losses of the precision attenuator had no effect on the noise figure of the mixer. The precision attenuator was fabricated especially for measurements of noise temperature and had a maximum error of 0.005 dB per 1 dB of indication. The short time stability of the 30-MHz link was 0.01 dB.

For tuning parametric amplifier 2 to the operating frequency of the parametric amplifier under test, the sweep generator was connected with its output R to the port P of circulator 1. After tuning parametric amplifier 1 for high gain, amplifier 2 was adjusted

to the same signal frequency by tuning the signal circuit, pump frequency 2, the idler circuit, and the bias voltage 2. The adjustment of the two amplifiers to the same signal frequency was then determined quite accurately by observing the output of the receiver on the screen of an X-Y oscilloscope. However, it was important that the bandwidth of the IF stages was wider than the bandwidth of the parametric amplifiers in order to see the amplifier response curves on the X-Y oscilloscope.

After this tuning, the signal source was connected with its output S to port P of circulator 1. Then, parametric amplifier 2 was adjusted to a convenient gain (17 dB was used) and the gain of the test amplifier was measured with the aid of the precision attenuator in the IF link by using the substitution method.

The device which is identified in figure 12 as a hot-cold-body noise source contained the two noise source standards of 77° K and 390° K shown in figure 11. For the measurement of the input noise temperature of the device under test, the output T of the noise sources was connected to port P of circulator 1, and the coaxial switch determined which source was applied to the input of parametric amplifier 1. During this switching process, an output power difference of the indicator is measured. This measurement was indicative of the internally generated noise in parametric amplifier 1 as is extensively described in reference 5.

The sweep generator, the resolver, and the Smith chart display on the screen of the X-Y oscilloscope, visible in figure 12, gave a plot of the input impedance as a function of frequency (fig. 7). The Smith chart also gave the ratio $\dfrac{R_1 + R_S}{R_g}$ for the theoretical calculation of the input noise temperature.

RESULTS

For the condition that all ambient temperatures T_a of the circuits and of the diode are equal, the theoretical input noise temperature T^* is

$$T^* = T_a\left(\frac{R_1 + R_S}{R_g} + \frac{f_s}{f_i}\frac{R}{R_g}\right) \tag{13}$$

as derived in the appendix. The ratio $\dfrac{R_1 + R_S}{R_g}$ represents the ratio of the signal circuit loss resistance to the generator impedance. If the generator impedance and the characteristic impedances of the lines are equal, this ratio is simply the impedance locus at the real axis of the Smith chart of figure 7. For different ambient temperatures, the following equation, which is derived in the appendix, applies:

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$$T^{**} = T_1 \frac{R_1}{R_g} + T_d \frac{R_s}{R_g} + \frac{f_s}{f_i}\left(1 + \frac{R_1 + R_s}{R_g}\right)\left(T_d \frac{R_s}{R_{T,2}} + T_2 \frac{R_2}{R_{T,2}}\right) \tag{14}$$

The measured and calculated characteristic values of the same amplifier at room temperature and at liquid nitrogen temperature are as follows: For room temperature of 290° K,

$$f_s = 409.75 \text{ MHz}$$

$$\text{Bandwidth (20-dB gain)} = 180 \text{ kHz}$$

$$V_o = -0.9 \text{ V}$$

$$f_i = 1240 \text{ MHz}$$

$$T = 330^\circ \text{ K   (measured)}$$

$$T^* = 292^\circ \text{ K   (calculated from eq. (13))}$$

$$T^{**} = 343^\circ \text{ K   (calculated from eq. (14))}$$

$$\frac{R_1 + R_s}{R_g} = 0.5$$

For liquid nitrogen temperature of 77° K,

$$f_s = 398.05 \text{ MHz}$$

$$\text{Bandwidth (20-dB gain)} = 120 \text{ kHz}$$

$$V_o = -0.67 \text{ V}$$

$$f_i = 1269.4 \text{ MHz}$$

$$T = 88^\circ \text{ K   (measured)}$$

$$T^* = 86^\circ \text{ K   (calculated from eq. (13))}$$

$$T^{**} = 139^\circ \text{ K   (calculated from eq. (14))}$$

$$\frac{R_1 + R_s}{R_g} = 0.6$$

For the calculation of T^{**}, a temperature rise inside the diode of 100° K and $R_2 \ll R_s$ were assumed.

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Ratios of input noise temperature to ambient temperature T^*/T_a, T^{**}/T_a, and T/T_a are presented for the foregoing values in the following table:

	T^*/T_a	T^{**}/T_a	T/T_a
$T_a = 290^O$ K	1.007	1.18	1.14
$T_a = 77^O$ K	1.12	1.81	1.14

The table illustrates very well that at room temperature the calculated ratio T^*/T_a is smaller than the measured ratio T/T_a, but the ratio T^{**}/T_a with an assumed 100° K temperature rise in the diode is quite close to the measured ratio T/T_a. This condition indicates a temperature rise inside the diode due to dissipated pump power in the loss resistance R_S of 2.77Ω.

In spite of having used a lossy diode, the ratio of the measured input noise temperature to ambient temperature at liquid nitrogen temperature of 77° K is only slightly larger than the theoretically determined ratio T^*/T_a and does not come close to the ratio T^{**}/T_a. This condition indicates that an effective suppression of the temperature rise inside the diode had been accomplished with application of pressurized liquid nitrogen inside the amplifier structure.

CONCLUDING REMARKS

The temperature rise in lossy capacitance diodes in cooled parametric amplifiers, especially in monostatic high-power radar systems, is a problem. It has been established that a pressurized liquid coolant inserted inside cavities, such as resonators, waveguides, and diode cavities, is an effective method for suppression of the temperature rise.

The main design features of a pressure container and the tuning of the pressurized parametric amplifier have been described and the filling procedures with liquid nitrogen have been outlined. The design steps for a 400-MHz parametric-amplifier structure which can be accommodated inside the pressure container are given with the emphasis on minimizing the dimensions and determining the components of the resonant circuit considering the 0.658-pF bias capacitance and 2.77Ω loss resistance of the varactor diode.

All adjustments for optimum amplifier performance were accomplished at room temperature before the amplifier is immersed in and filled with liquid nitrogen in spite of the change of the relative dielectric constant from 1 to 1.435; this was done by using calculated and measured resonant frequency values from curves that showed the frequency variation of each circuit with this quantity. Since the tuning of the test amplifier and the measurement of the input noise temperatures are very important for the investigations

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performed, the experimental setup is presented in detail. The experimental results for the 400-MHz parametric amplifier revealed a reduction of noise temperature from 330° K at room temperature to 88° K at liquid nitrogen temperature. A comparison of the measured and theoretically determined ratios of input noise temperature to ambient temperature showed the measured ratio of 1.14 to be slightly higher than the theoretical value of 1.12. This condition indicates that the temperature rise in the lossy section of the varactor diode was effectively suppressed.

Langley Research Center,
    National Aeronautics and Space Administration,
        Langley Station, Hampton, Va., August 7, 1969.

APPENDIX

INPUT NOISE TEMPERATURE OF COOLED PARAMETRIC AMPLIFIERS

If the circuits and the varactor diode of a parameter amplifier are at different ambient temperatures, the input noise temperature is determined with equation (3.83) of reference 3 (p. 61). By replacing the circuit resonator frequencies ω_1 and ω_2 by the operating frequencies f_s and f_i, respectively, and assuming the high-gain approximation

$$R \approx R_{T,1} \approx R_g + R_s + R_1 \tag{A1}$$

equation (3.83) of reference 3 changes to

$$F = 1 + \frac{1}{T_o}\left[T_1 \frac{R_1}{R_g} + T_d \frac{R_s}{R_g} + \frac{f_s}{f_i}\left(1 + \frac{R_1 + R_s}{R_g}\right)\left(T_d \frac{R_s}{R_{T,2}} + T_2 \frac{R_2}{R_{T,2}}\right)\right] \tag{A2}$$

where

F   noise figure

T_o room temperature

T_1 ambient temperature of signal circuit with loss resistance R_1

T_d ambient temperature of varactor diode with loss resistance R_s

T_2 ambient temperature of idler circuit with loss resistance R_2

The generator impedance is denoted by R_g and

$$R_{T,2} = R_s + R_2 \tag{A3}$$

The noise figure of equation (A2) is converted into input noise temperature by the relation (ref. 3, p. 18)

$$F = 1 + \frac{T^{**}}{T_o} \tag{A4}$$

Inserting equation (A4) into equation (A2) and solving for T^{**} results in

$$T^{**} = T_1 \frac{R_1}{R_g} + T_d \frac{R_s}{R_g} + \frac{f_s}{f_i}\left(1 + \frac{R_1 + R_s}{R_g}\right)\left(T_d \frac{R_s}{R_{T,2}} + T_2 \frac{R_2}{R_{T,2}}\right) \tag{A5}$$

APPENDIX

It can be seen from equation (A5) that the input noise temperature T^{**} depends linearly on the ambient temperatures T_1, T_d, and T_2. By assuming that equal ambient temperatures T_a exist, that is,

$$T_a = T_1 = T_d = T_2 \tag{A6}$$

equation (A5) simplifies to

$$T^* = T_a\left(\frac{R_1 + R_s}{R_g} + \frac{f_s}{f_i}\frac{R}{R_g}\right) \tag{A7}$$

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1. Blume, Hans-Juergen C.: Suppression of Temperature Rise in Lossy Diodes Inside Resonant Cavities by Application of Pressurized Liquid Nitrogen. NASA TN D-4556, 1968.

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3. Blackwell, Lawrence A.; and Kotzebue, Kenneth L.: Semiconductor-Diode Parametric Amplifiers. Prentice-Hall, Inc., 1961.

4. Ginzton, Edward L.: Microwave Measurements. McGraw-Hill Book Co., Inc., 1957.

5. Blume, Hans-Juergen C.: Error Analysis of Input-Noise-Temperature Measurements of Low-Noise Amplifiers. NASA TN D-4997, 1969.
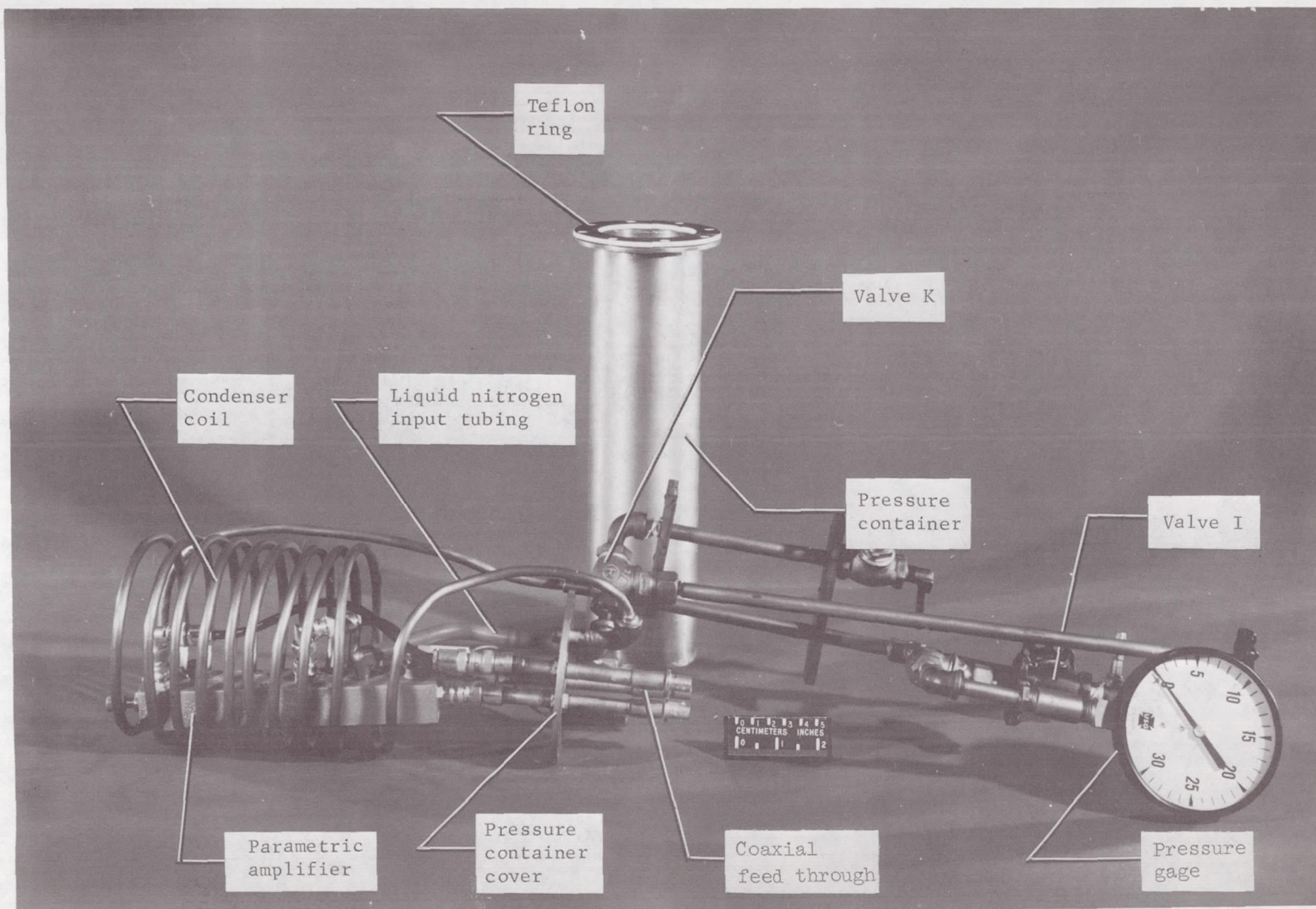
Figure 1.- Pressure container disassembled.

L-65-2487.1
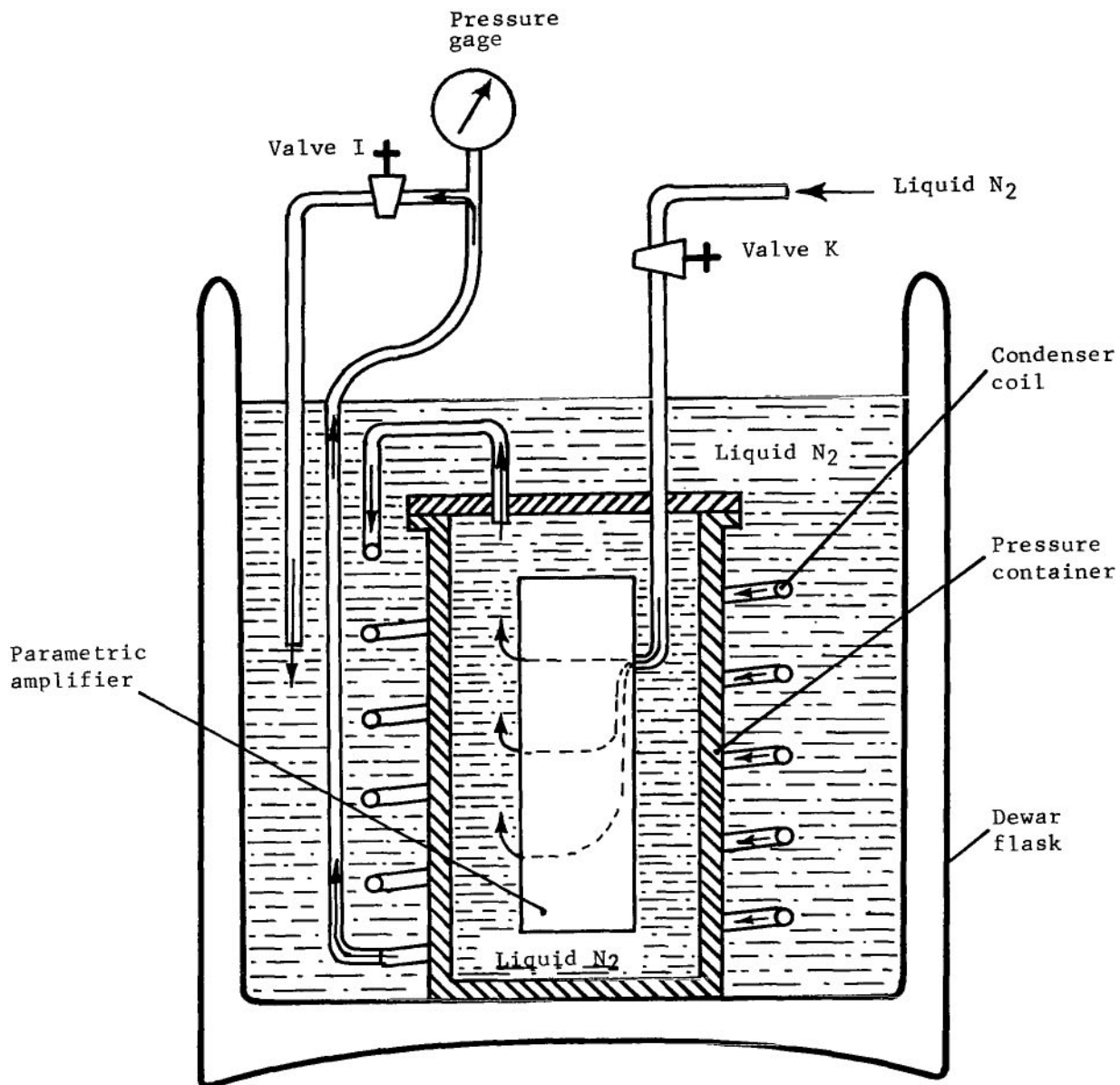
Figure 2.- Flow diagram of liquid nitrogen filling process.
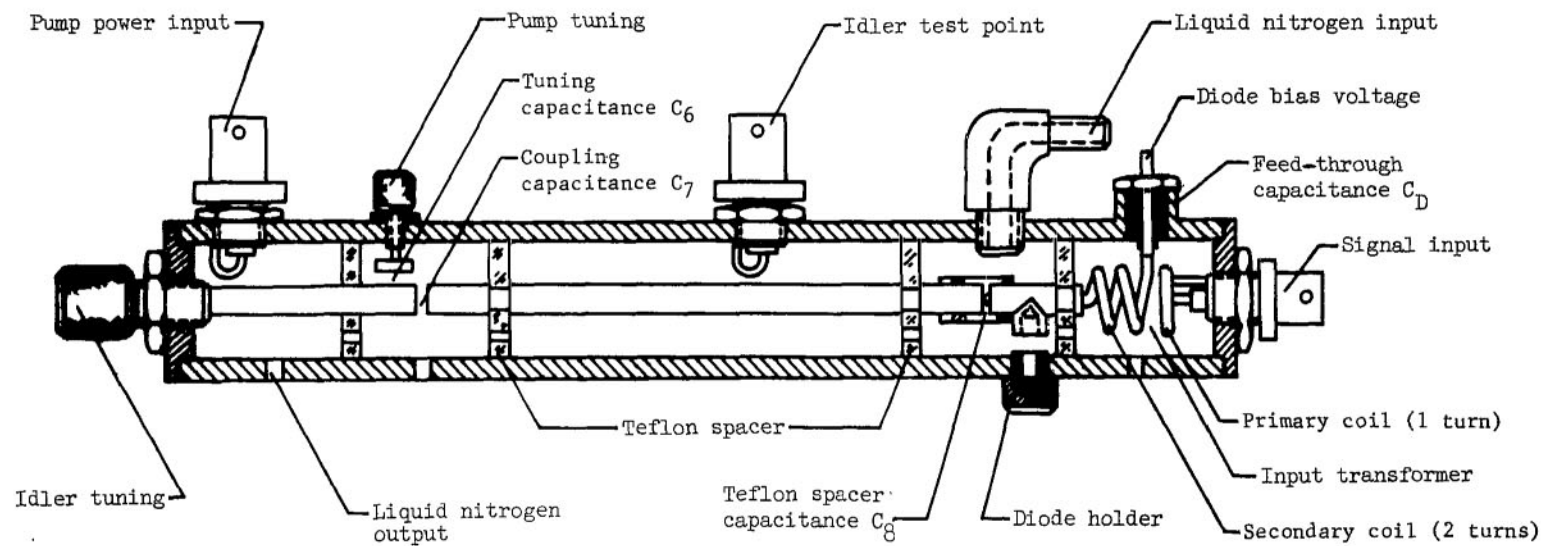
Figure 3.- Cutaway of 400-MHz parametric amplifier for operation in pressurized liquid nitrogen.
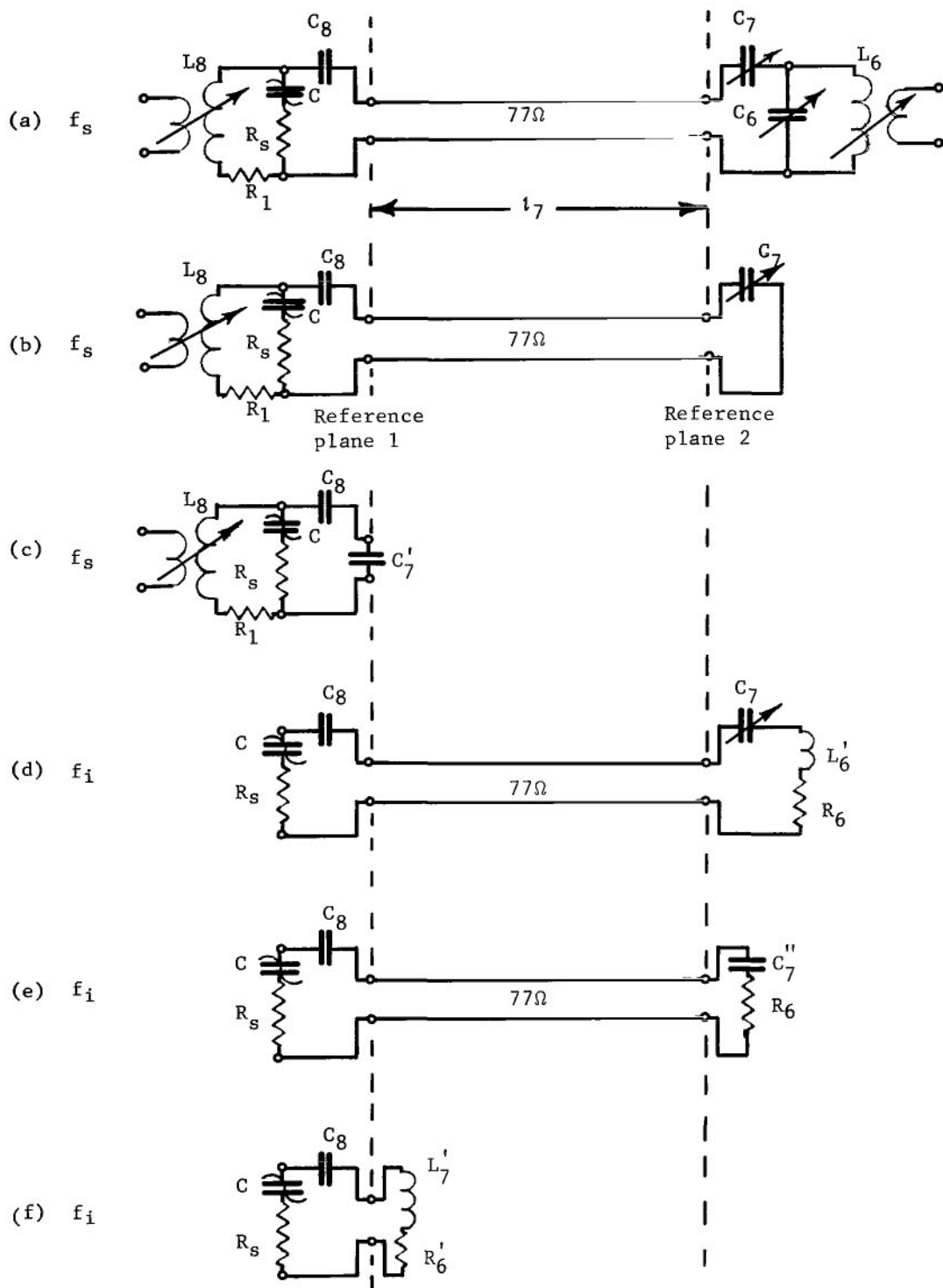
Figure 4.- Equivalent circuits of the parametric amplifier operated in pressurized liquid nitrogen.
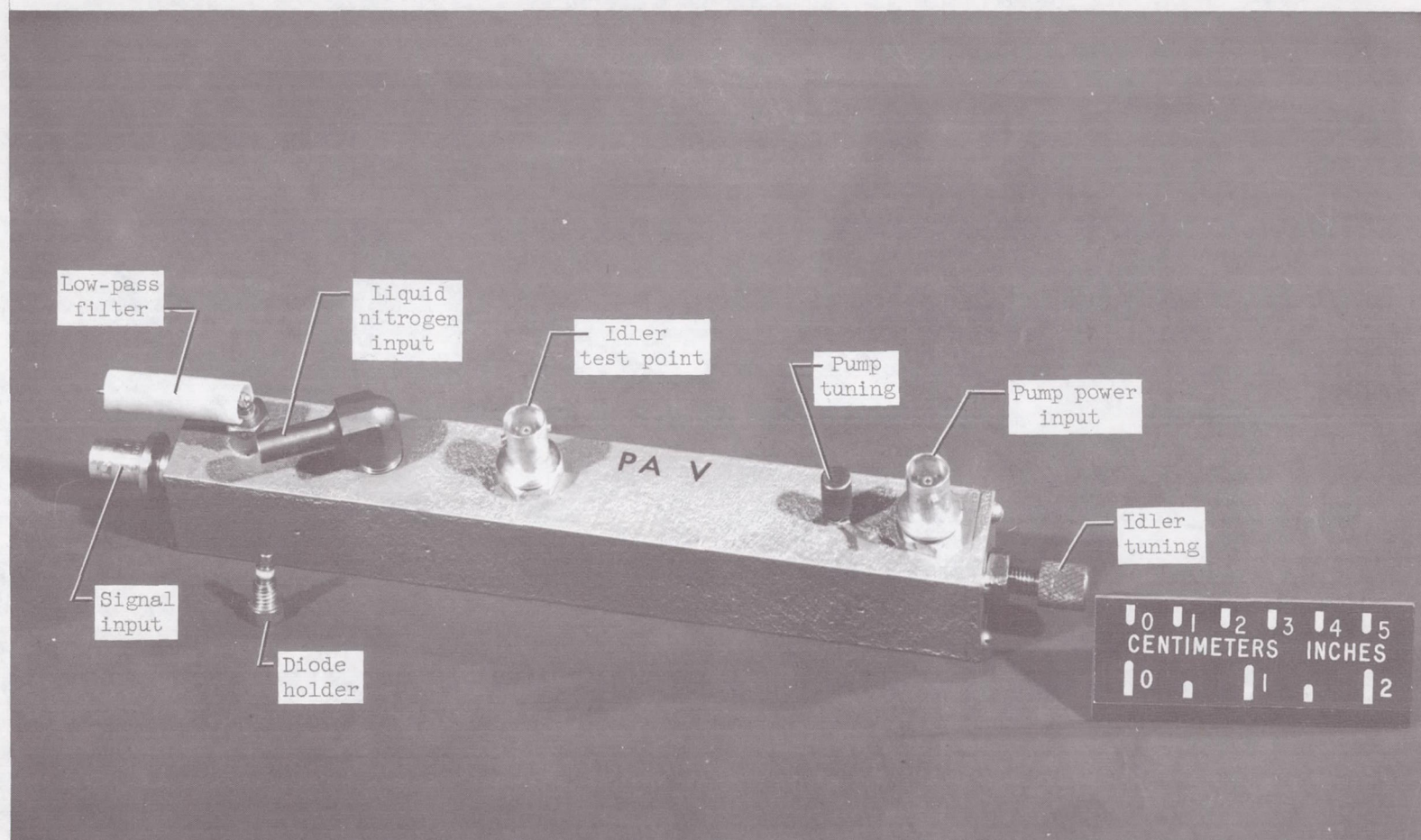
Figure 5.- Parametric amplifier for inside and outside cooling with liquid nitrogen.

L-65-2491.1
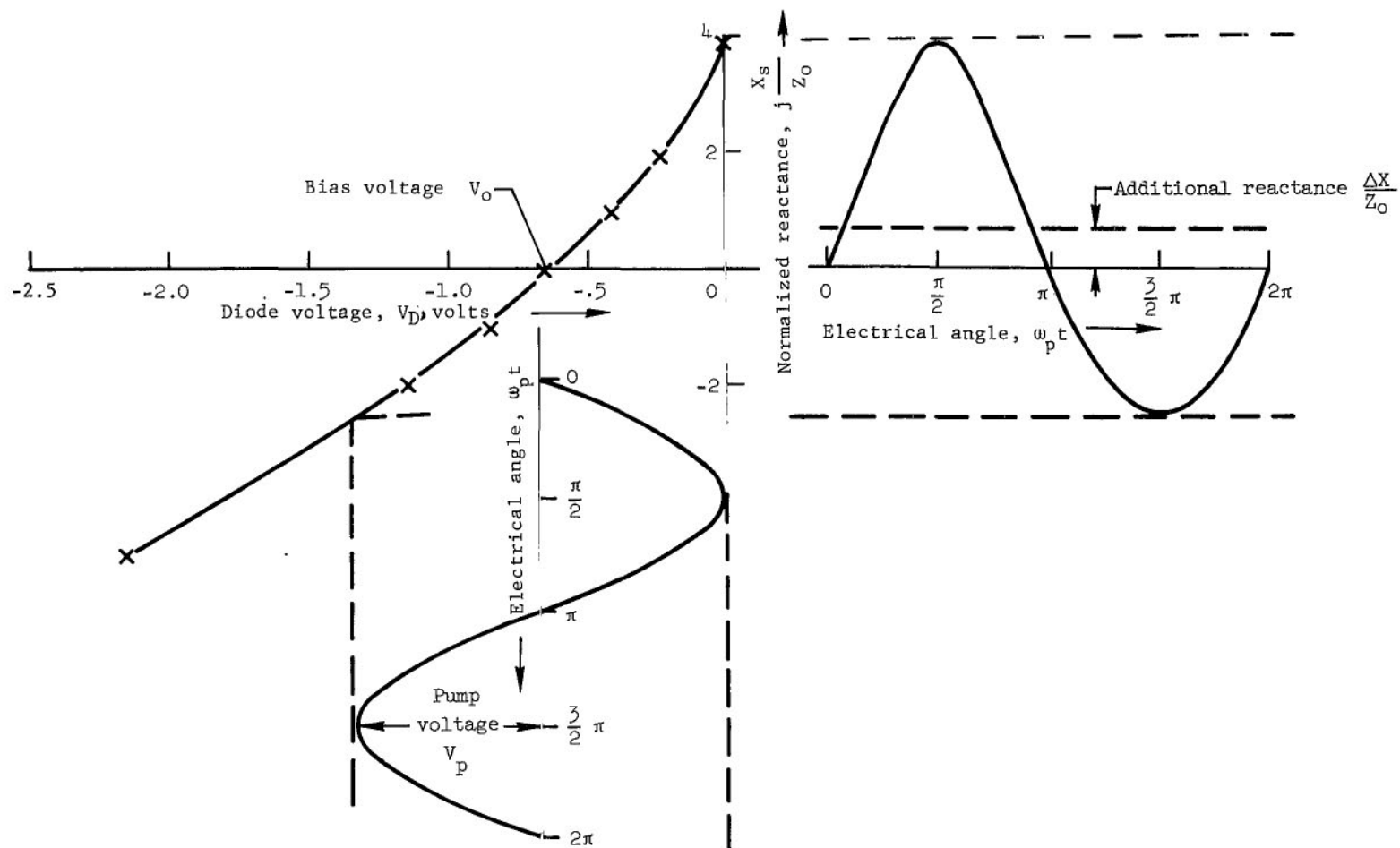
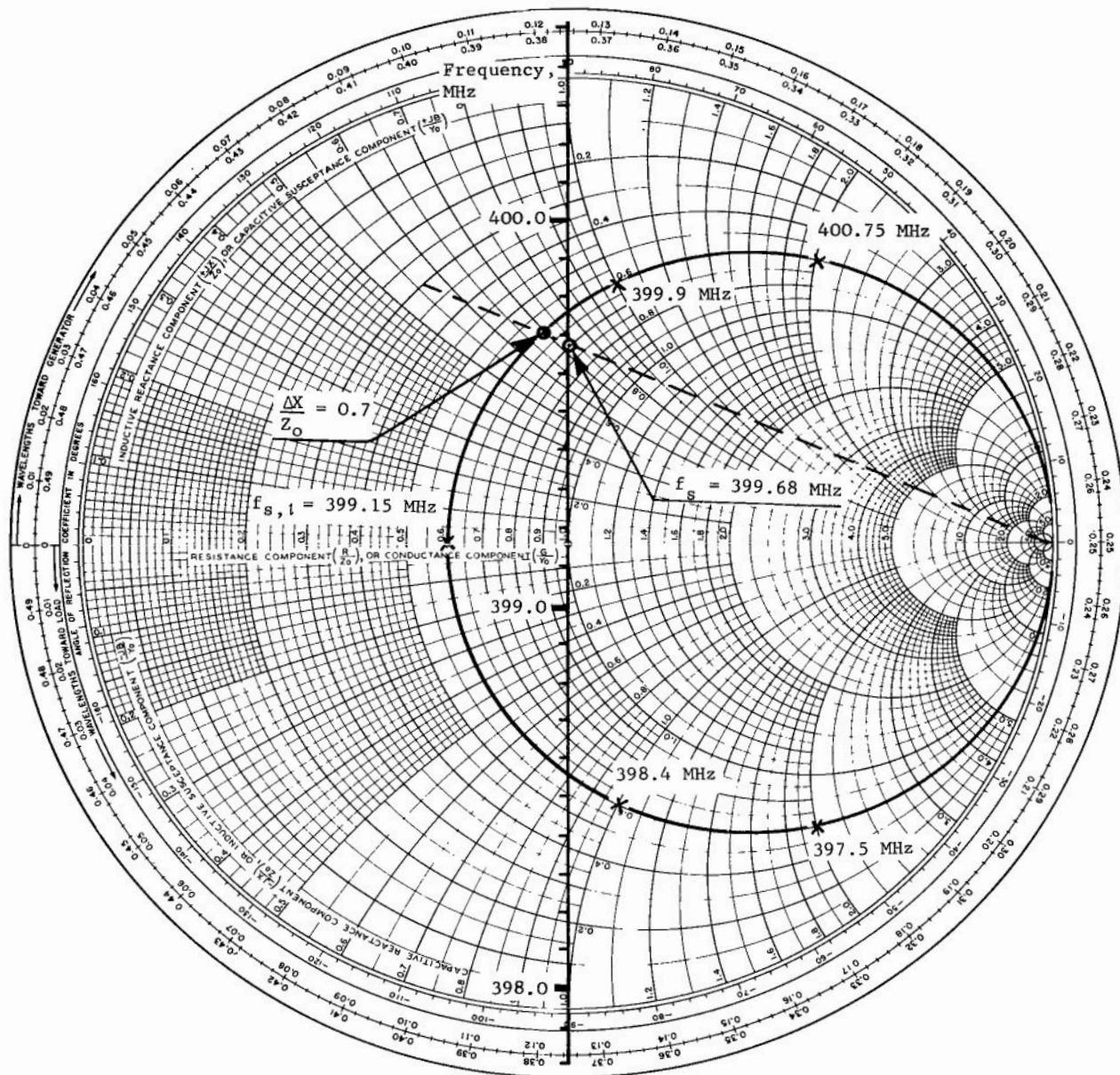Figure 6.- Additional reactance caused by parametric-amplifier operation.

Figure 7.- Input impedance of signal circuit as function of frequency.
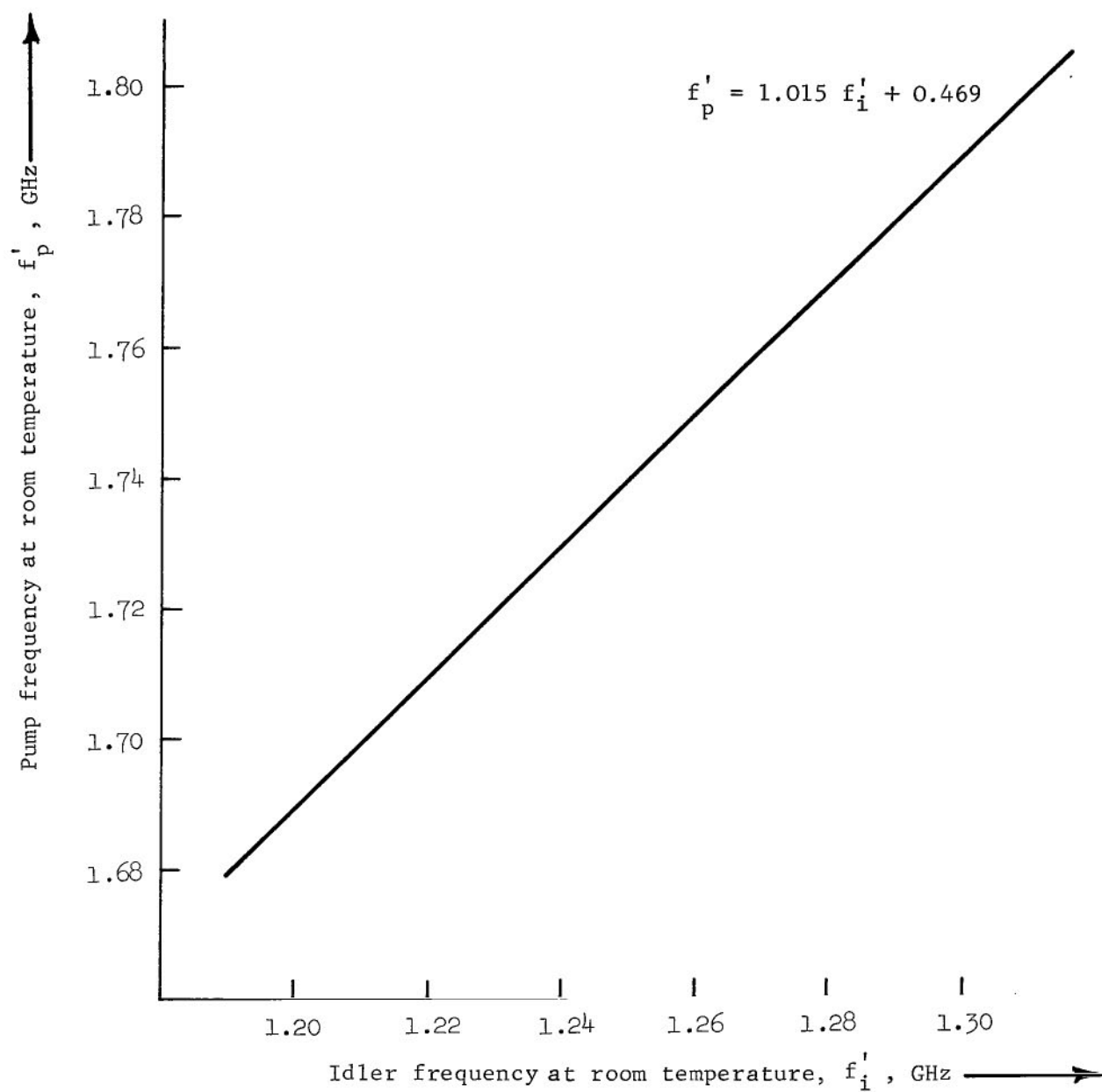
Figure 8.- Tuning curve for parametric-amplifier adjustment at room temperature.
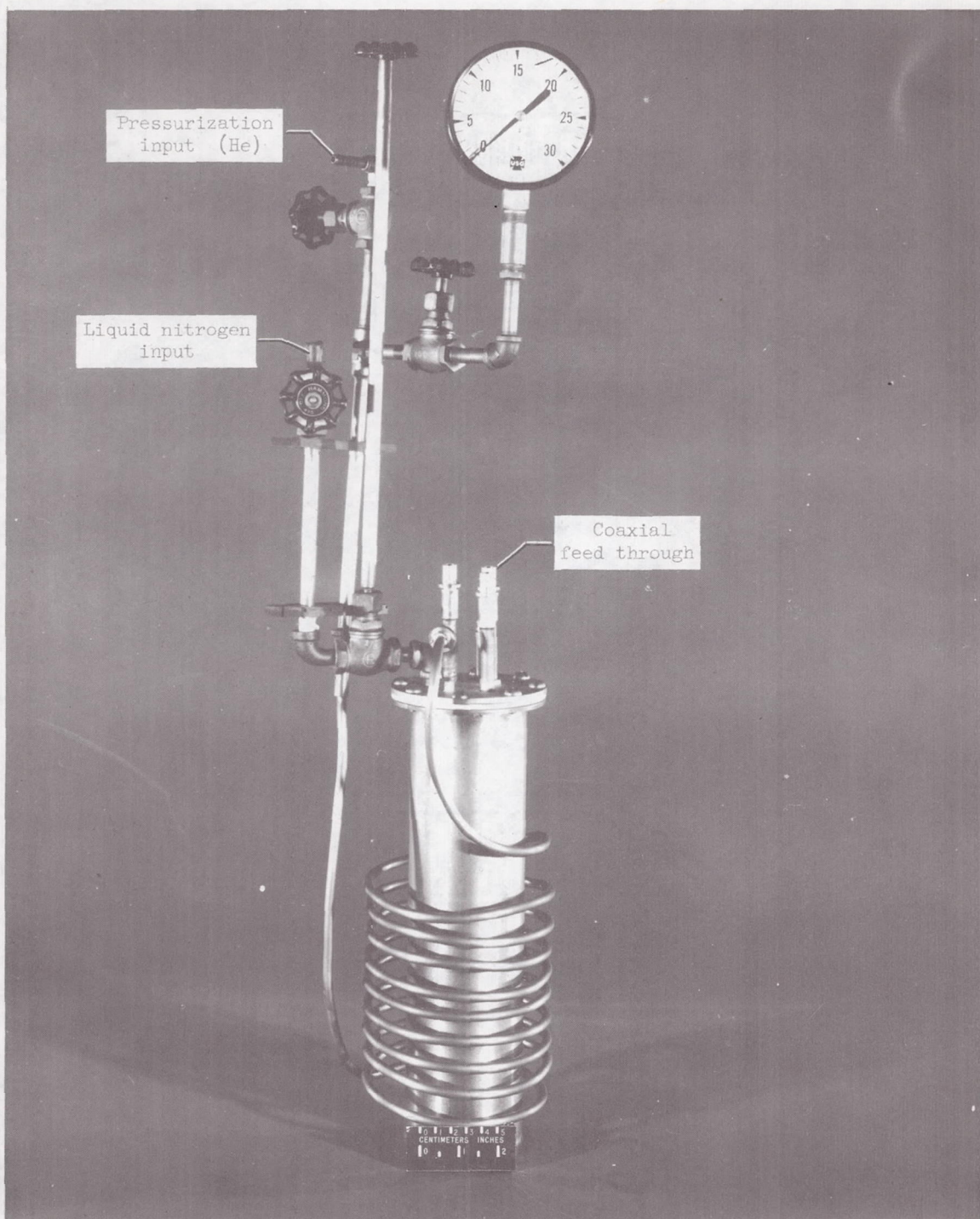
Figure 9.- Pressure container assembled.

L-65-2492.1
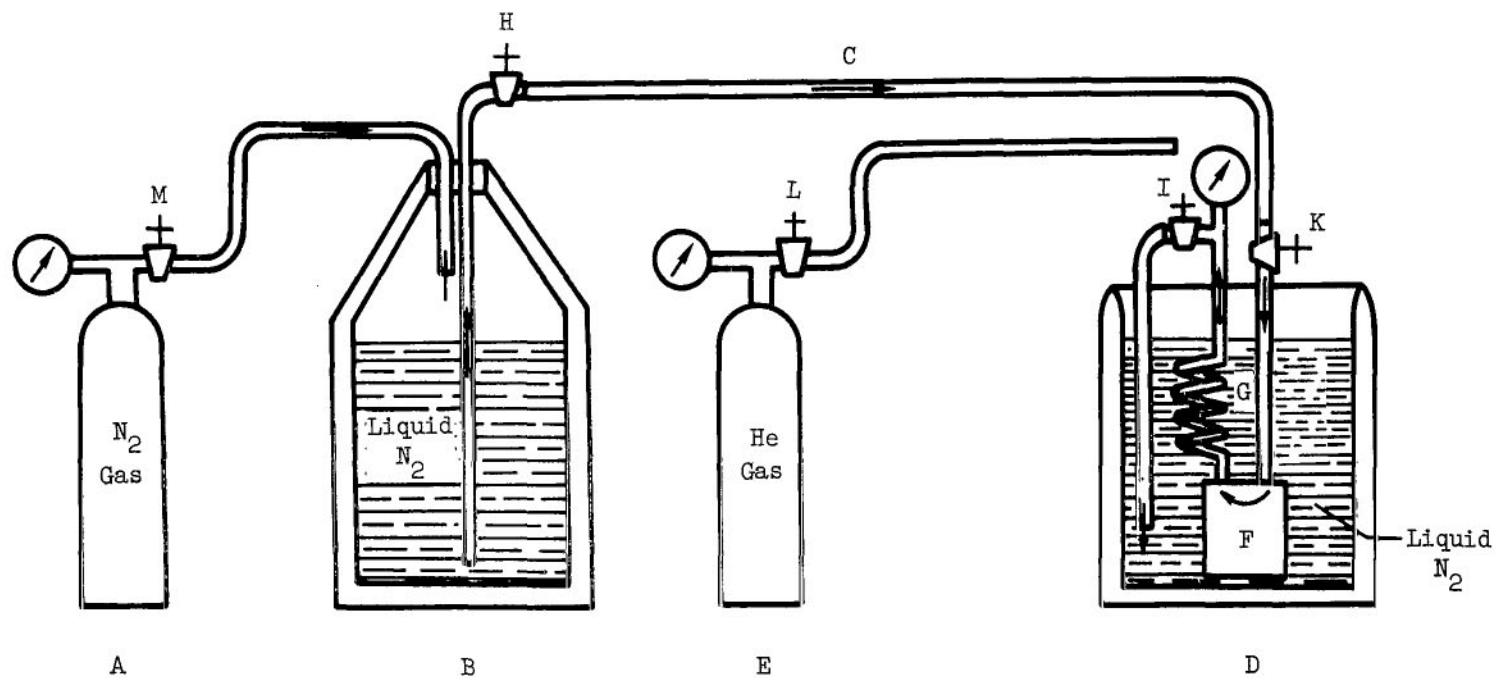
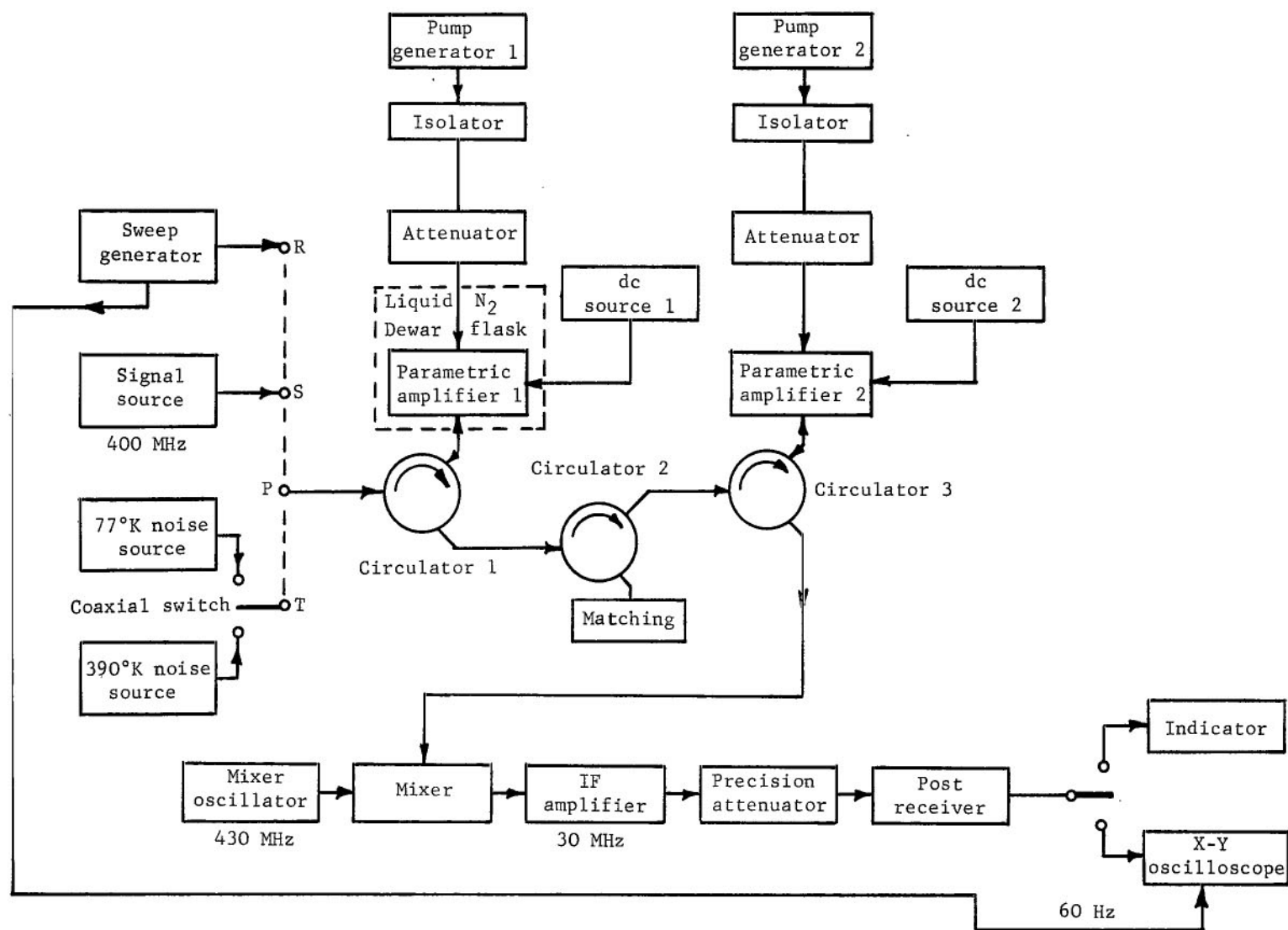Figure 10.- Apparatus used to fill the parametric amplifier with liquid nitrogen and for pressurizing with helium gas.

Figure 11.- Block diagram of the measuring setup for the parametric amplifier operated in pressurized liquid nitrogen.
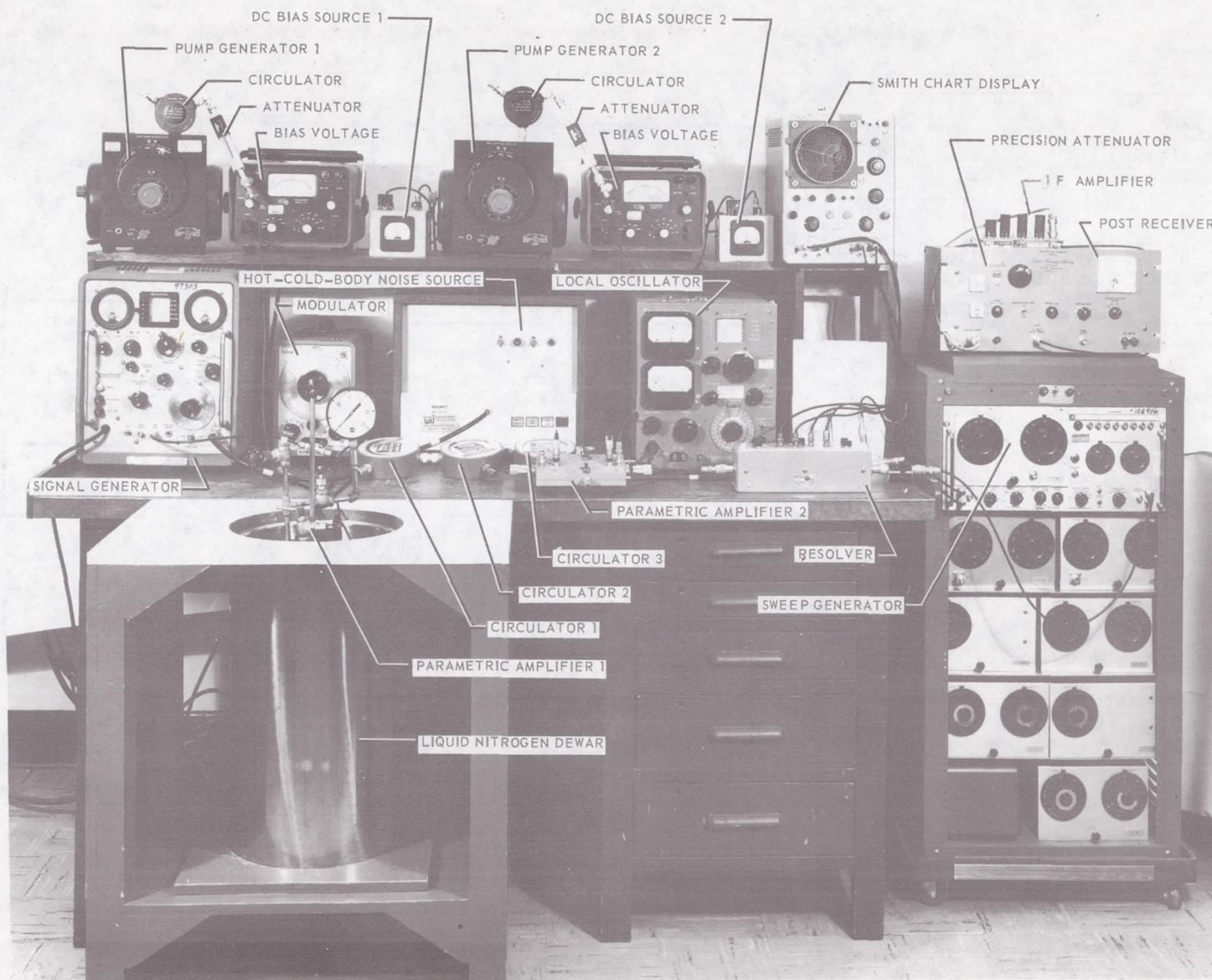
Figure 12.- Laboratory test setup for parametric-amplifier research.

L-69-5078

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