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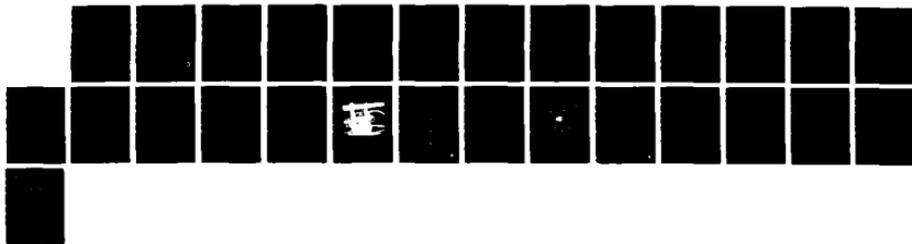
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V WANG ET AL. 04 MAR 88 N00014-07-C-0340

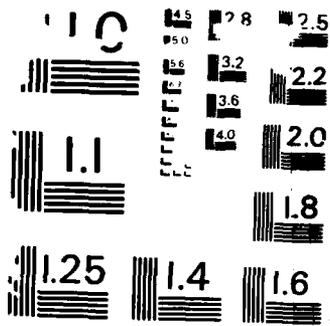
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BEAM COMBINING BY PHASE TRANSITION NONLINEAR MEDIA

FIRST SEMI-ANNUAL INTERIM REPORT
1 JUNE 1987 THROUGH 31 JANUARY 1988

AD-A194 116

(This Document is Unclassified)

Date: 4 March 1988
Contract N00014-87-C-0340
CDRL SEQ. A002

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EXECUTIVE SUMMARY

INTRODUCTION/OBJECTIVES -- Rocketdyne, a division of Rockwell International, is conducting this research program to study, develop, and demonstrate the use of a gas or liquid near a phase transition as an efficient phase conjugation material. We expect to observe enhanced efficiencies of Degenerate Four Wave Mixing (DFWM) and Stimulated Brillion Scattering (SBS) in liquids undergoing cavitation (also referred to as incipient or nucleate boiling or as superheated) or in gases undergoing supersaturated (supercooled) condensation. We will achieve these nonequilibrium conditions via the sudden pressure drop obtained by flowing the fluid through a nozzle. Since the change of state from liquid to gas can be made to occur more readily near the fluid's critical point as compared with other conditions, we are choosing to work with fluids whose critical points are near room temperature, thus simplifying problems of thermal control.

MATERIAL CHOICE: CRITICAL FLUID SELECTION -- We compiled a list of many fluids and examined them from the point of easy access to their critical points and from the consideration of their material safety. We have selected hexafluoroethane (freon 116) as our preferred fluid due to considerations of safe material properties, near room temperature critical point, and comparatively low critical pressure. We have identified four other materials as secondary choice fluids: freon 13, freon 23, sulfur hexafluoride and xenon. These five fluids as a group provide a variety of chemical form while having reasonably safe and convenient fluid properties.

LIQUID NUCLEATION AND DEGREE OF SUPERHEATING -- We have calculated the limits of superheating for three of our five chosen fluids. For fluids near their critical pressure, the limit of superheating becomes substantially smaller than the limit at pressures of one to ten atmospheres. We therefore expect to obtain rapid bubble formation in the fluid flowing through nozzle using moderate fluid flow rates.

EXPERIMENTAL PROGRAM -- We have completed the design of two different fluid cells. The first is a static cell, which offers us a quick approach to getting data in the limited parameter space consisting of the critical point and points at small but finite pressure and temperature decrements from the critical point, where bubble formation occurs so readily that the laser beam itself can generate them. The second is a flow cell, which provides a depressurization zone via fluid flow through a nozzle, and is therefore capable of forming bubble clouds over a larger range of thermodynamic operating conditions. The static cell has already been fabricated and installed in our laboratory; we have preliminary results indicating that we have observed Stimulated Brillouin Scattering (SBS) phase conjugation of a 351 nm excimer laser beam. The drawings of the flow cell have only recently been completed, quoted by vendors, and are now being ordered for fabrication. We are still designing the flow system hardware needed in order to circulate fluid through the flow cell.

T A S K 1.0 A N A L Y S I S

MATERIAL CHOICE: CRITICAL FLUID SELECTION

Table 1 lists a large number of fluids whose critical points are given in the literature. The fluids have been sorted by temperature in order to readily identify fluids whose critical points fall near room temperature. Such fluids are of particular interest to our project since their useage reduces the technical difficulties associated with thermal control and avoids adverse effects due to severe thermal gradients on the optics. For these reasons, many fluids whose critical temperatures fall outside the range of zero to one hundred degrees centigrade have been omitted from the table.

The right hand column of the table identifies safety issues associated with the various fluids. The capital letters E, F, I, N, and T identify explosive, flammable, irritant, narcotic, and toxic hazards respectively. The small letters h, s, and w are modifiers indicating highly, slightly, or weakly. An asterisk (*) designates a relatively benign substance whose only hazards are those associated with the high pressure at the critical point, the displacement of breathable air in case of a vapor release, and any cryogenic fluid which may be produced as a result of a vapor release.

Arrows in the right hand margin of the table indicate fluids which we are considering for use as a phase conjugating medium. The length of the arrow corresponds to the level of our interest in the particular substance.

Table 1
CRITICAL FLUIDS SORTED BY TEMPERATURE

Material	Freon #	Formula	Critical Temperature °C	Critical Pressure atm	* = Benign Explosive Flammable Irritant Narcotic Toxic
hydrogen		H2	-239.9	12.8	hF
deuterium		D2	-234.6	16.4	hF
neon		Ne	-228.5	26.9	*
nitrogen		N2	-146.8	33.5	*
carbon monoxide		CO	-140	34.5	F hT
argon		Ar	-122	48	*
methane		CH4	-82.3	45.8	F
krypton		Kr	-63.6	54.3	*
tetrafluoromethane	14	CF4	-45.45	37.43	*
boron trifluoride		BF3	-12.26	49.2	T
ethylene		C2H4	9.91	50.5	F wN <--
carbonyl fluoride		CF2O	14.7	33.52	hT
xenon		Xe	16.75	58	* <---<<
hexafluoroethane	116	C2F6	19.7	29.8	* <---<<<
trifluoromethane	23	CHF3	25.6	48.37	* <---<<
chlorotrifluoromethane	13	CClF3	28.9	38.2	* <---<<
difluoroethylene	1132a	C2H2F2	29.70	44.63	F sT <--
carbon dioxide		CO2	31	72.9	T
ethane		C2H6	32.4	48.2	F
tetrafluoroethylene		C2F4	33.3	40.50	E F sT
acetylene		C2H2	35.5	61.6	hF N
fluoromethane		CH3F	44.55	58.74	F
sulfur hexafluoride		SF6	45.7	37.1	* <---<<
bromotrifluoromethane	1381	CBrF3	67	39.1	*
perfluoropropane		C3F8	71.9	26.80	* <--
difluoromethane	32	CH2F2	78.4	58.30	?F sT
chloropentaF-ethane	115	C2ClF5	80.2	31.6	*
hexafluoroacetone		C3F6O	84.1	28.41	I T
propene		C3H6	92.1	45.4	F sN
chlorodifluoromethane	22	CHClF2	96	49.1	*
propane		C3H8	96.9	42	F N
dichlorodiF-methane	12	CCl2F2	112	40.6	*
perfluorobutane	610	C4F10	113.3	24.27	* <--
perfluorocyclobutane	C318	C4F8	115.22	27.77	*
propadiene		C3H4	120	43.6	F sN
propyne		C3H4	128	52.8	F N
ammonia		NH3	132.5	112.5	hT
dichlorotetraF-ethane	114	C2Cl2F4	145.7	32.62	*
n-butane		C4H10	152	37.5	F N
n-butene		C4H8	155.6	40.5	F sT
methylamine		CH5N	156.9	40.2	F I T
neo-pentane		C5H12	160.6	31.6	F N
dichlorofluoromethane	21	CHCl2F	178.5	51	sT
boron trichloride		BCl3	178.8	38.2	T
fluorinert liquids	Mol.Wt. 340 to 971		178 to 373	18 to 9	* <--
trichlorofluoromethane	11	CCl3F	198	43.5	*
acetone		C3H6O	235.5	47	F T
fluorobenzene		C6H5F	287	44.6	F T
benzene		C6H6	288.9	48.6	F T

PRIMARY AND SECONDARY MATERIAL CHOICES -- We have selected five fluids for study as phase transition non-linear media. These five materials and their properties are listed in table 2;

Table 2

PROPERTIES OF
PRIMARY AND SECONDARY MATERIALS

Material	hexafluoro-ethane	trifluoro-methane	chloro-trifluoro-methane	sulfur hexafluoride	xenon
Refrigerant #	116	23	13		
Formula	C ₂ F ₆	CH ₃ F ₃	CClF ₃	SF ₆	Xe
Cost per Critical Point Gallon	\$44	\$84	\$82	\$40	\$6850
Critical Temperature	OC 19.7 OF 67	25.6 78	28.9 84	45.7 114	16.75 62
Critical Pressure	atm 29.4 PSI 432	47.7 701	38.2 561	37.1 546	58 853
Critical Density	0.608	0.516	0.581	0.735	1.110
Estimated Critical Index of Refraction	1.08	1.16	1.09	1.12	1.19
Molecular Weight	138.01	70.014	104.46	146.05	131.1

the chosen fluids include the four benign fluids which are critical in the immediate vicinity of room temperature plus sulfur hexafluoride, a benign fluid which is critical at a hotter, though still safe, temperature. Our primary choice among these five fluids is hexafluoroethane (freon 116), since it has the lowest critical pressure and is incidently one of the two least expensive of the five, at about \$44 per critical point gallon. Damzen, Hutchinson, and Schroeder (IEEE JOE-23 pp328-334, March 1987) reported on the stimulated brillouin scattering (SBS) properties of four of these five fluids:

chlorotrifluoromethane (freon 13), hexafluoroethane (freon 116), sulfur hexafluoride, and xenon. Although we intend to emphasize degenerate four wave mixing (DFWM) over SBS, we plan to test these same four fluids since as a group they offer some variety in their chemical makeup and therefore may be of interest in evaluating the effects of molecular form upon nonlinear response. One of our fluids, trifluoromethane (freon 23), was not tested by Damzen et al. As a result of its fairly high critical pressure and low molecular weight, we expect it to have a higher index of refraction than the other two freons; the index should be midway between those expected for xenon and sulfur hexafluoride. Therefore it may be a good fluid for evaluating the significance of differences in chemistry. As a result of the above considerations, we have flagged our primary material choice with the longest arrow in table 1 and have flagged the four secondary material choices with medium length arrows.

TERTIARY MATERIAL CHOICES -- Five other fluids are flagged with short arrows to indicate that, although they have some interesting characteristics, they also have some adverse properties which limits our interest in them. Ethylene and difluoroethylene (freon 1132a) each have a double bond and therefore can be expected to have a high polarizability. However, they are both flammable. Dupont claims that freon 1132a is slightly toxic and therefore declines to offer it for sale; on the other hand Union Carbide lists flammability as its only hazard in their catalog. Perfluoropropane and perfluorobutane are interesting in that they have relatively low critical pressures, although their critical temperatures of 71.9 and 113.3 degrees centigrade are significantly above room temperature. For perfluorobutane, this may offer some safety advantages, since its vapor pressure is 3 to 4 atmospheres at 30 to 40 degrees centigrade; thus the phase conjugating apparatus can be safely filled with the liquified gas under pressure (only 30 to 45 psi above ambient) at room temperature and then be heated to achieve the appropriate temperature and pressure when needed. In other words, it offers a safety trade-off by being a lesser hazard while in storage and fill situations, while being a twin hazard (temperature and pressure) under operating conditions, as opposed to room temperature critical materials which are pressure hazards all of the time.

The last fluid entry in the table flagged by a short arrow is the "fluorinert liquids". These are high molecular weight fully fluorinated carbon chains which have the notable advantages of being liquids at room temperature at one atmosphere pressure, of having low critical pressures (as low as 9 atmospheres for the highest molecular weight fluid), and of having a sound velocity at the critical point which is about half that of freon 116 for the heaviest molecular weight fluid, which would be an advantage since it results in a lower SBS redshift as compared to freon 116. The fluid can be poured as an open air liquid into the fluid apparatus, then heated to the critical temperature while expanding a piston accumulator against nitrogen pressurized at the fluid's critical pressure. To shut down the experiment, simply disconnect the power to the heater and release the nitrogen pressure; the apparatus will then safely cool off to room temperature and pressure. However, the advantages of these fluids are not strong enough to overcome the technical difficulties of working at their high critical temperatures, particularly if the use of DFWM rather than SBS is preferred as a phase conjugating process.

IN CONCLUSION -- We have selected hexafluoroethane (freon 116) as our preferred fluid due to considerations of safe material properties, near room temperature critical point, and comparatively low critical pressure. As secondary fluids, we have identified freon 13, freon 23, sulfur hexafluoride and xenon as giving a variety of chemical form while having reasonably safe and convenient fluid properties.

LIQUID NUCLEATION AND DEGREE OF SUPERHEATING

Phase transformations are considered to proceed discontinuously through the birth and subsequent growth of small nuclei of the new material phase. In the absence of nucleation sites, these nuclei appear at random throughout the original phase, and the nucleation is termed homogenous. Bubbles are formed as density fluctuations occur in the liquid. From visual observation and heat capacity measurements, it is observed that simple fluids can be superheated more than expected on the basis of classical nucleation theory. In its simple form, this theory predicts that the steady-state rate of formation of vapor nuclei J , at which bubbles of a new phase nucleate out of the parent phase is given by [1]

$$J = 3.73 \times 10^{35} \left(\frac{\rho_l^2 \gamma}{M^3 B} \right)^{1/2} \exp \left[\frac{-1.182 \times 10^5 \gamma^3}{T(nP_\infty - P_0)^2} \right] \quad (1)$$

where J has units of $\#/cm^3 s$, P_∞ , atm; P_0 , atm; T , $^\circ K$; γ , erg/cm^2 ; ρ_l , g/cm^3 ; M , $g/mole$. Also $B=1$ for cavitation and approximately $2/3$ otherwise.

The factor n is defined as

$$n = \exp \left[\frac{V_l (P_0 - P_\infty)}{RT_l} \right] \quad (2)$$

where V_l is specific volume of the liquid. P_∞ and P_0 are the pressures corresponding to the liquid superheated temperature T_∞ and the saturation temperature T_s , respectively.

The physical implications of Eq. (1) can be examined as follows: the preexponential terms vary slowly with temperature. However, any temperature change inside the exponential will have a very strong effect on the rate of nucleation. Consider nucleation at an ambient pressure P_0 of 1 atm. One observes experimentally that the nucleation occurs at about $0.89 T_c$. Using the values for surface tension, vapor pressure; density and molecular weight into (1), one finds that at $0.89 T_c$, the predicted rate of nucleation is about 10^6 bubbles/cm³ sec. and that the rate changes about three to four orders of magnitude per degree C. The major reason for this extreme sensitivity to temperature is that, so close to the critical temperature, the exponential is of the order of 10^{-30} and the fractional change in the magnitude of the surface tension is very large per degree. For example, increasing T by 1 degree, decreases γ by about 7 to 9% [2,3]. In addition to this, the denominator of the exponent contains T and $(n P_\infty - P_0)^2$, both of which increase with increasing temperature; the vapor pressure $n P_\infty$ especially so. Thus these factors also decrease the argument of the exponent.

Knowing the values of J , Eq. (1) may be used to determine the kinetic limit of superheating. Rearranging (1) gives

$$n P_\infty - P_0 = \frac{1.182 \times 10^5 \gamma^3}{T \ln \left[\left(\frac{3.73 \times 10^{35}}{J} \right) \frac{P_0^2 \gamma}{M^3 B} \right]^{1/2}} \quad (3)$$

Thermodynamic tables will yield the desired superheat temperature, T_∞ , as a function of the superheat pressure, P_∞ , and the saturation temperature, T_s , as a function of the saturation pressure, P_0 . The validity of Eq. (3) has been experimentally verified for a large number of organic liquids [1].

In the following sections we will estimate the superheating limit using Eq. (3) for Xenon, (Xe), hexafluoroethane, (C_2F_6); and chlorotrifluoromethane ($CClF_3$).

The physical properties of Xe, C_2F_6 and $CClF_3$ are listed in Table 3.

TABLE 3. PHYSICAL PROPERTIES OF Xe, C₂F₆ and CClF₃

	M (g/mole)	T _c (°K)	P _c (atm)	ρ _c (Kg/m ³)	γ (erg/cm ²)
Xe	131.1	289.95	58	986	18.7(T=-110°C)
C ₂ F ₆	138.02	292.9	29.8	608	16 (at T=-73°C)
CClF ₃	104.458	302.1	38.2	581	17 (at T=-73°C)

The surface tensions required in using Eq. (3) can be estimated based on the corresponding-state correlation proposed by Brock and Bird [4]

$$\gamma = P_c^{2/3} T_c^{1/3} (0.133 \alpha_c - 0.281) (1 - T_r)^{11/9} \quad (4)$$

T_r is the reduced temperature, α_c the Riedel factor [4] and P_c and T_c are the critical pressure and temperature in atmospheres and degrees Kelvin. Eq. (4) has been correlated to surface tensions of 84 widely different nonpolar organic compounds and permanent gases with an average deviation of about 3 percent.

Using Eqs (3) and (4), the liquid superheat limit, T_∞, of Xe, C₂F₆ and CClF₃ at one atmosphere pressure were calculated and the results are summarized in Table 4. Also included in Table 4 are the saturation temperature T_s, liquid and gas densities ρ_l and ρ_v, and the surface tension, α.

TABLE 4. THERMODYNAMIC PROPERTIES OF Xe, C₂F₆ and CClF₃

	P (atm)	T _s (°K)	ρ _l (Kg/m ³)	ρ _v (Kg/m ³)	α erg/cm ²	P _∞ (atm)	T _∞ (°K)
Xe	1	161.35	3057	9.86	3.30	29.3	258.06
C ₂ F ₆	1	194.95	1608	8.86	2.51	13.4	261
CClF ₃	1	191.65	1526	6.94	4.29	28.5	268.9

The results of Table 4 were obtained for one atmosphere of pressure. For pressures other than one atmosphere, we estimated the superheat limits based on the correlations obtained experimentally by Blander and Katz[2] as shown in Fig. 1. The results are summarized in Tables 5, 6 and 7 for Xe, C₂F₆ and

CClF₃ where the degree of superheating $\frac{T_{\infty}}{T_c}$ is shown as a function of

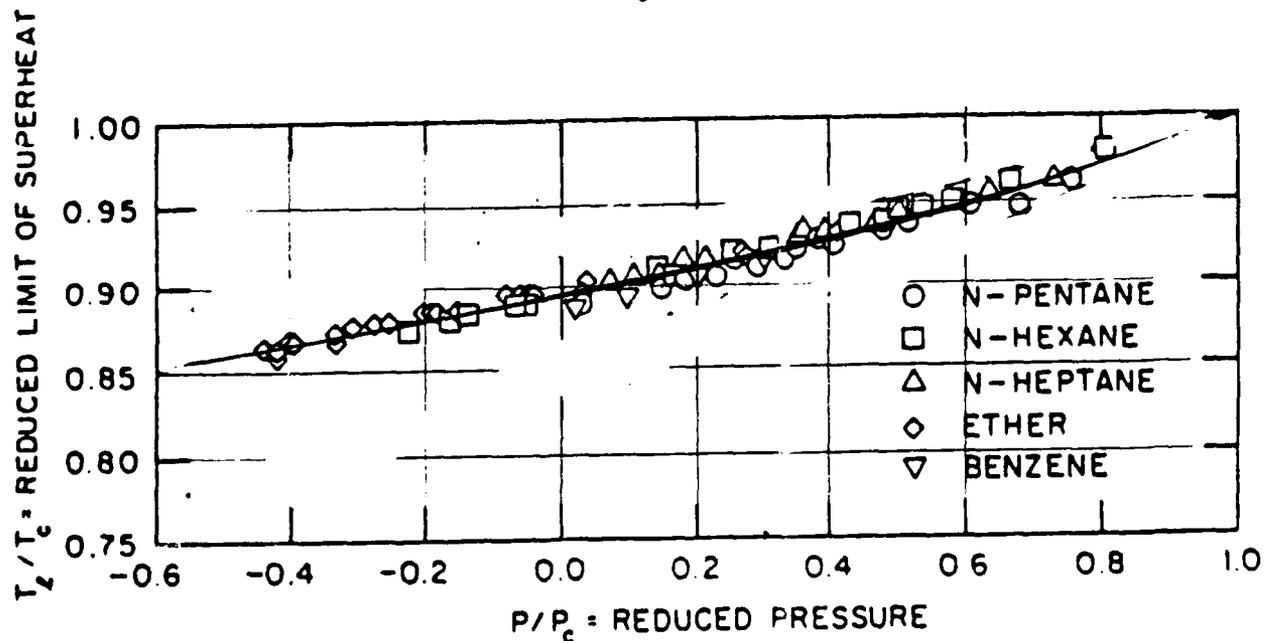


Fig. 1. Experimental Correlations of Superheat Limit [1]

pressure. These results indicate that a liquid can be superheated substantially without the occurrence of a phase transformation even though its state is such that it lies within the two-phase envelope. Under these conditions, the external isotherm must extend into the stable two phase region. Here the fluid is clearly not in its most stable condition, i.e., a mixture of saturated liquid and saturated vapor; nor is it mechanically unstable as long as the slope of the isotherm remains positive. This condition is commonly called metastable.

It also can be seen from tables 5, 6 and 7 that the superheating or metastable limit decreases with increasing pressure. This implies that the limit can be achieved easier when the fluid is heated or expanded at higher pressures than that at low pressures.

TABLE 5. ESTIMATED SUPERHEATING LIMITS OF Xe
AS A FUNCTION OF PRESSURE

P (atm)	P_r	$\frac{T_\infty}{T_c}$	T_S (°K)	T_∞ (°K)
1	0.01724	0.89	161.35	258.06
2	0.03448	0.90	178.2	260.96
5	0.0862	0.905	198.7	262.40
10	0.172	0.910	218.20	263.85
15	0.258	0.915	232.20	265.30
20	0.3448	0.925	243.20	268.20
30	0.517	0.935	258.20	271.10
40	0.689	0.960	270.20	278.35

TABLE 6. ESTIMATED SUPERHEATING LIMITS OF C_2F_6
AS A FUNCTION OF PRESSURE

P (atm)	P_r	$\frac{T_\infty}{T_c}$	T_s	T_∞
1	0.034	0.89	194.95	261
2	0.067	0.90	209.20	263.6
5	0.168	0.91	230.20	266.5
10	0.336	0.92	251.20	269.5
15	0.503	0.93	265.20	273.3
20	0.671	0.96	276.20	279.7
25	0.839	0.975	284.20	285.6

TABLE 7. ESTIMATED SUPERHEATING LIMITS OF $CClF_3$
AS A FUNCTION OF PRESSURE

P (atm)	P_r	$\frac{T_\infty}{T_c}$	T_s	T_∞
1	0.0262	0.89	191.65	268.9
2	0.0524	0.90	207.2	271.9
5	0.131	0.905	228.2	273.42
10	0.262	0.915	248.2	276.44
15	0.393	0.925	263.2	279.44
20	0.524	0.940	273.2	283.97
30	0.785	0.97	290.20	293.04
40	0.916	0.98	298.20	296.06

For our applications, Table 5, 6 or 7 can be used to estimate the pressure reduction requirement for achieving different degree of superheating which in turn determines the rate of bubble nucleation. The pressure reduction process can be easily obtained by using a convergent nozzle. Since

$\frac{T_{\infty}}{T_c}$ is smaller at high pressures or near critical points, one would prefer to generate bubbles at high pressures where the pressure change required, or the input area to nozzle throat area ratio required, for nucleation would be smaller than is required at low pressure nucleation.

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- [2] M. Blander and J. L. Katz, "Bubble Nucleation in Liquids", Aiche Journal, Vol. 21, No. 5, 1975, pp 833
- [3] W. Porteous and M. Blander, "Limits of Superheat and Explosive Boiling of Light Hydrocarbons, Halocarbons, and Hydrocarbon-Mixtures", Aiche Journal, Vol. 21, No. 3, 1975, pp 560
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T A S K 2.0 E X P E R I M E N T

We have completed the design of two different fluid cells. The first is a static cell, which offers us a quick approach to getting data in the limited parameter space consisting of the critical point and points at small but finite pressure and temperature decrements from the critical point, where bubble formation occurs so readily that the laser beam itself can generate them. The second is a flow cell, which provides a depressurization zone via fluid flow through a nozzle, and is therefore capable of forming bubble clouds over a larger range of thermodynamic operating conditions. The static cell has already been fabricated and delivered; the drawings of the flow cell have only recently been completed, quoted by vendors, and are now being fabricated.

STATIC CELL APPARATUS - Figure 2 shows the static cell with its cooling plumbing mounted on the optical table. The static cell utilizes six normal incidence sapphire windows; since these had a long delivery cycle, we are temporarily substituting fused silica windows and are operating the cell at the critical pressure of freon 116. The sapphire windows, which have arrived very recently, are needed for safe use at the higher pressures of the secondary choice fluids.

We have begun conducting experiments with freon 116; the experimental layout is shown in figure 3. A collimated beam from a 351 nm excimer laser passes through a variable attenuator, through an uncoated beamsplitter, through an aberrator plate, and is then focussed by a positive lens into the static cell. Beams travelling in the backwards direction are sampled by the beamsplitter and then observed on the fluorescent card near the beamsplitter. We have preliminary results indicating that we have observed Stimulated Brillion Scattering (SBS) phase conjugation of the 351 nm beam. Although we have not yet confirmed these results with the required SBS red shift and beam quality measurements, we obtained a collimated reflection which was threshold sensitive, which occurred with and without an aberrator plate, and (most significantly) which remained collimated when the lens in front of the cell was translated. Note that a spurious refection from the window of the cell would have gone in and out of collimation as the lens

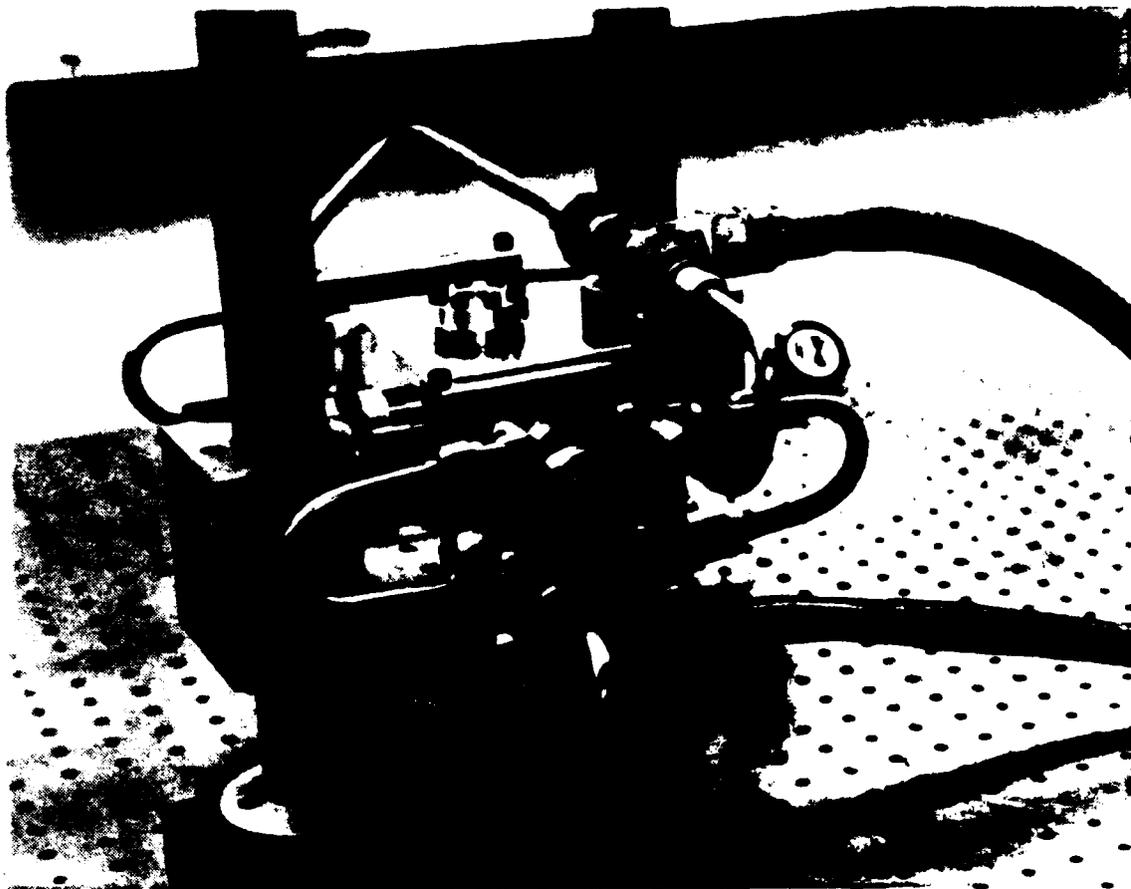
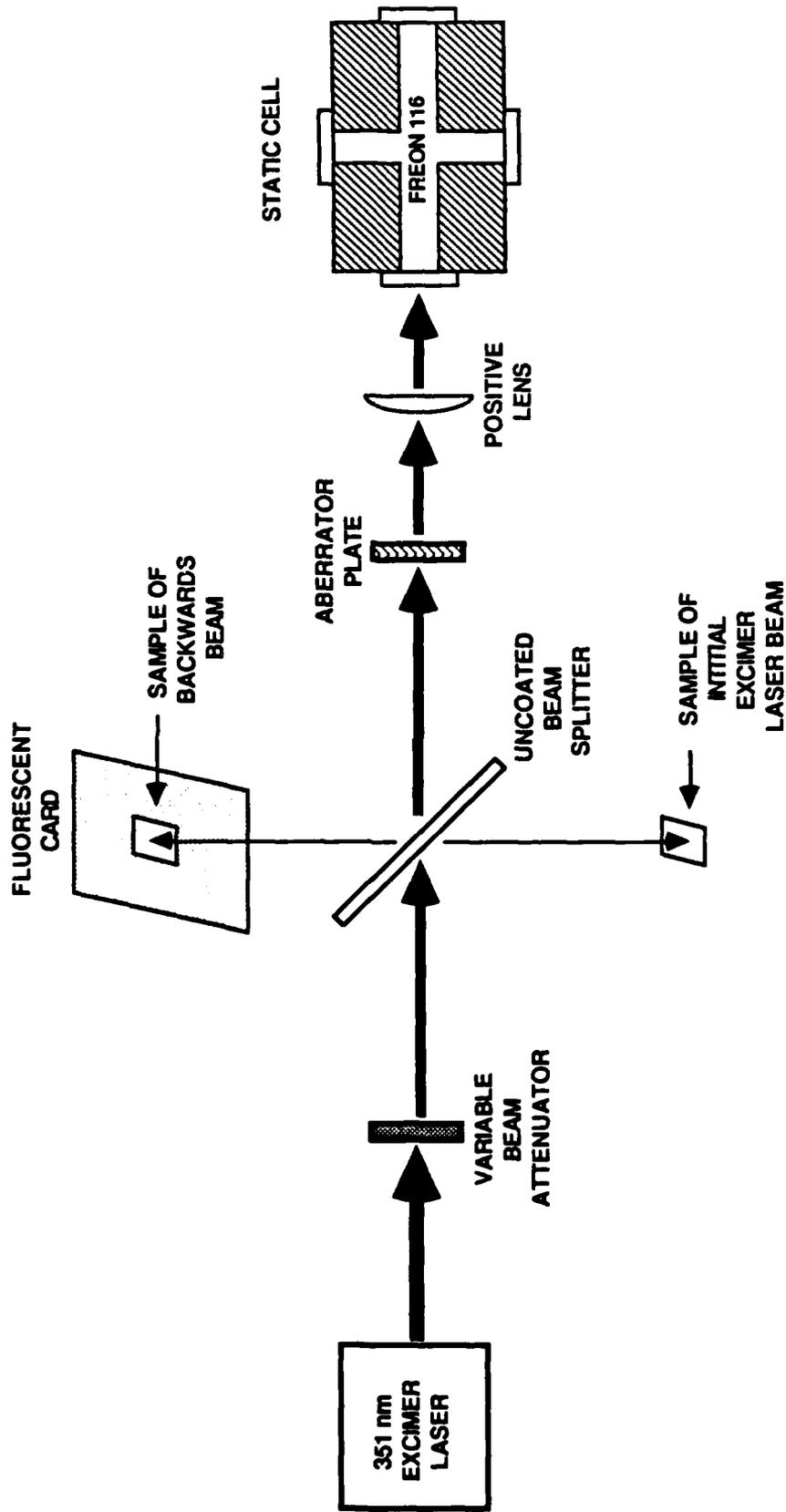


FIGURE 2

FIGURE 3

EXPERIMENT LAYOUT



was translated. We plan to conduct further tests of both SBS and degenerate four wave mixing in the coming months including measurements of the SBS redshift, input and output beam quality, and SBS threshold (or DFWM gain) versus temperature and pressure for the primary and secondary fluids.

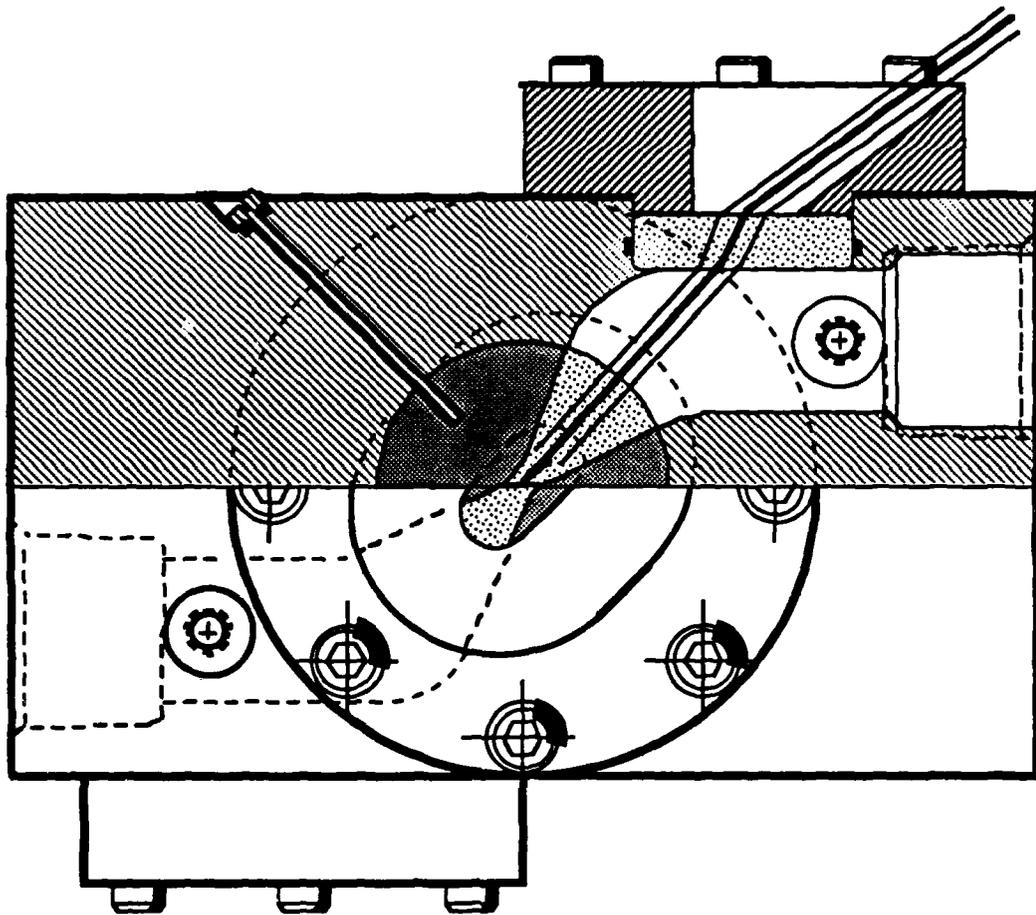
FLOW CELL AND FLOW SYSTEM - Figure 4 is an assembly drawing of the flow cell. The flow cell utilizes one pair of Brewster windows oriented for a beam passing parallel to the fluid flow direction through the nozzle in the cell, plus a pair of normal incidence windows for possible use of beams normal to the fluid flow. The windows are edge polished to allow an o-ring to form a high pressure seal around their diameter, thus avoiding the stresses that would be caused by a face sealed design. The nozzle consists of a pair of inserts each held by a long mounting bolt with an o-ring shaft seal so that we have the option to change the throat spacing without remachining the entire cell. The throat spacing initially will be 2.5mm in the plane of the figure, and 5mm in the plane normal to the figure; the 25mm fluid channels taper down to the 5mm spacing between the pressure taps and the normal incidence windows. The flow cell is currently being fabricated at a vendor machine shop. We have ordered both sapphire windows and fused silica windows. We have received the fused silica windows and expect near term delivery of the sapphire windows.

We have also partially completed a design profile for the plumbing for the flow system. A layout of the flow system is shown in figure 5. The flow system can be operated as a blow down system if the optional pump is omitted. High pressure gaseous nitrogen (G.N₂) flows from the supply tank through the lines shown shaded in gray into the normally open (NO) port of the valve at the right side of accumulator #1. Fluid then flows out of the normally open port of the valve at the left side of accumulator #1 through the heat exchanger, downward through the nozzle in the flow cell, and into the normally open port of the valve at the left side of accumulator #2. Gaseous nitrogen displaced from accumulator #2

FIGURE 4

FLOW CELL

TOP HALF SHOWS INTERIOR
BOTTOM HALF SHOWS EXTERIOR



 SAPPHIRE WINDOWS

 NOZZLE INSERTS

 FLOW CELL BODY

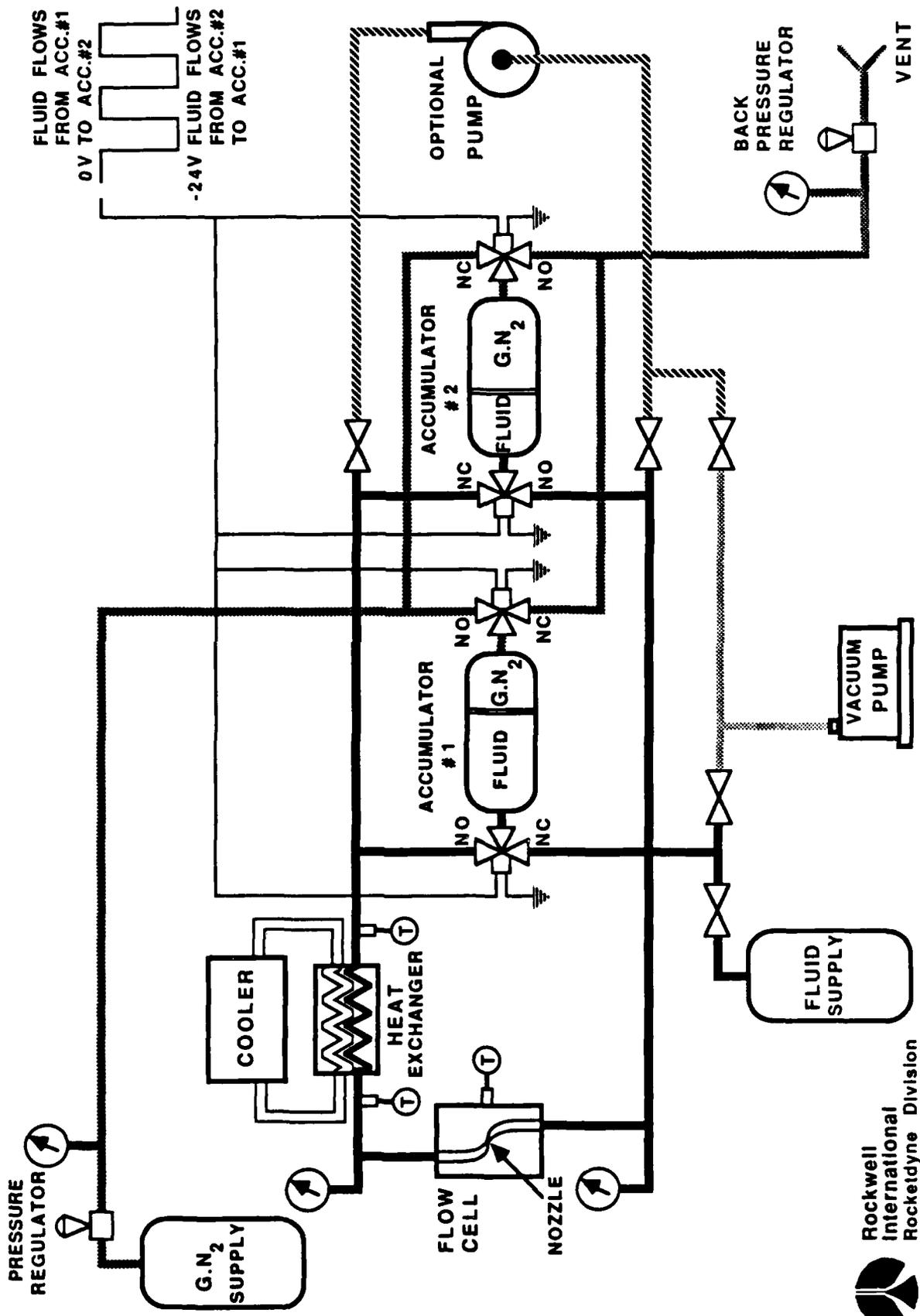
 BREWSTER WINDOW HOLDER

 PRESSURE TAPS

 PATH OF OPTICAL BEAM
THROUGH BREWSTER WINDOWS

FIGURE 5

FLOW SYSTEM



flows out of the normally open port of the valve at the right side of accumulator #2, through the back pressure regulator and is expelled through a roof vent. When accumulator #1 has been filled with gaseous nitrogen and accumulator #2 has been filled with fluid, the control voltage changes from zero to minus twenty-four volts, energizing the solenoids on the three way valves; normally open valves become closed and the normally closed (NC) valves become open. Now fluid flows from accumulator #2 to accumulator #1, but still travelling downward through the flow cell nozzle just as before. The gaseous nitrogen supply tank pressure regulator and the back pressure regulator are adjusted to obtain the desired fluid flow rate at the desired system pressure. Prior to filling the system with fluid, a vacuum pump is used to evacuate the system, then fluid is admitted from the fluid supply tank. Temperature probes (T) monitor the temperature of the fluid at several points, rather than simply the water circulating through the open (unshaded) lines, in order for the cooler to properly maintain the desired system operating temperature. The dashed lines show the connection to the optional fluid pump; with such a pump the accumulators are merely pressurized to the desired system operating pressure since the pump will be adjusted to supply the desired fluid flow rate.

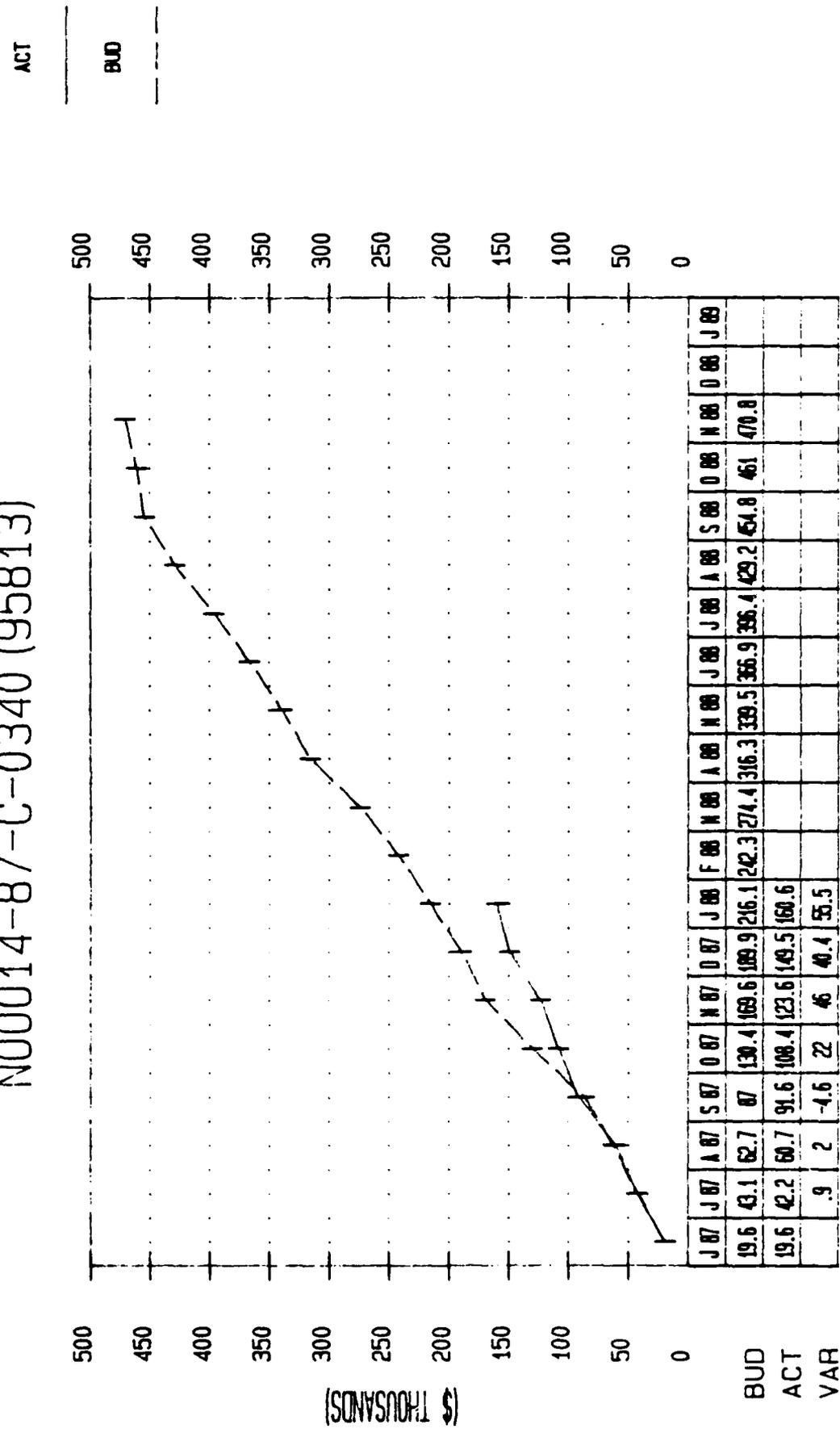
The two flow system design issues still to be resolved are the nature of the heat exchanger and the choice of a pump. The heat exchanger has a technical trade-off involving size, material strength, and coolant temperature. In order to withstand the high pressure, the heat exchanger either must have thick walls and medium tubing diameters or must have normal wall thicknesses and small tubing diameters. The first case requires a larger temperature difference between the high pressure fluid and the coolant, the second case results in a larger pressure drop through the heat exchanger. Higher strength materials require smaller wall thicknesses, but typically have lower heat conductivities. We are obtaining a sample of a commercially available heat exchanger and will come to a make or buy decision after pressure testing the sample. In regard to the pump, a fluid near its critical point cavitates easily, and cavitation can damage certain pump designs. We are currently investigating the sensitivity to cavitation of centrifugal, vane, and screw pumps. We are also investigating the

possibility of precooling the fluid before the pump then reheating the fluid afterwards. We will then evaluate the trade-off between the cost of a non-cavitating pump versus the additional cost of a precooling/reheating scheme versus the cost of pressurized nitrogen for long term use of the blowdown configuration. This issue does not affect most of the items in the fluid apparatus design profile, such as pressure gauges, fittings, and valves.

F I N A N C I A L S T A T U S

Figure 6 shows the contract budget and actual spending to date. As of January 31, we have spent and committed \$160,600, out of the currently funded \$242,990. In addition to the funds already spent, in the immediate future we expect to spend an additional \$25,000 on parts for the flowing fluid apparatus, about half of which is the cost of the pump. We also anticipate a transitory increase in the rate of spending during the next month while several fluids engineers from Rocketdyne's Space Shuttle Main Engine-Fluid Dynamic Analysis Group complete the design of the flowing fluids apparatus and order the required parts. These two areas of expected expenditures will bring the actual spending curve into a closer fit to the budget curve. Figure 7 shows the labor hours, both budgeted and actual. We expect that the hours to be charged by the fluids engineers will bring the actual hours curve into agreement with the budgeted hours curve.

FIGURE 6
BEAM COMBINING BY PHASE
 TRANSITION N/L-MEDIA
 N00014-87-C-0340 (95813)



01/31/88

FILE: BUB DLR

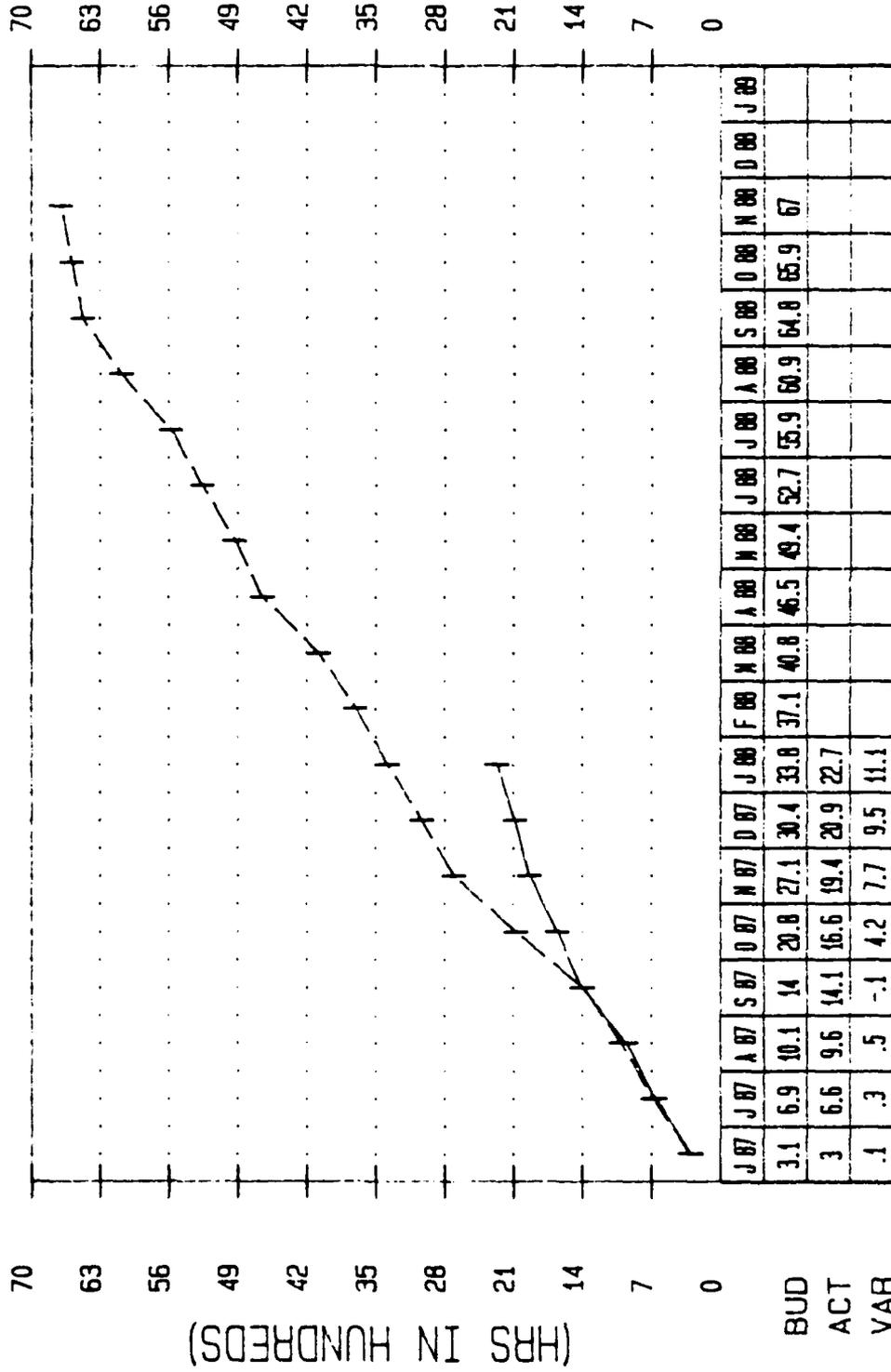
FIGURE 7

BEAM COMBINING BY PHASE

TRANSITION N/L-MEDIA

N00014-87-C-0340 (95813)

ACT
BUD



01/31/88

FILE: BUB HRS

END

DATE

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July 88