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**Critical Boiling, Vapor Block, and
Prospects for Single-Sweep Training of
Superconducting Solenoids**

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Fig

NOMENCLATURE

a	Fitted coefficient of Eq. (2)
b	Number of resistive segments or channels involved in a miniquench
b ₁	Number of channels, spacers, or wire segments in one turn of a magnet winding
B, B(S)	Shape-dependent dimension of cross-section number; B = 0.15 cm for S = 1; 0.19 cm for S = 2; and 0.63 cm for S = 4. In fitting the data we use the empirical relation $B(S) = 0.23 - 0.14 S + 0.06 S^2$.
c	Total number of magnet cooling channels
Ch	Channel number, SL/D, Table B-II equations
CHF	Critical nucleate boiling heat flux; breakaway flux; W/cm ²
C _L	Specific heat of liquid helium
Cr	Cross-section number, D/(D + B), Eq. (2), Table B-II equations
D	Either the diameter of a tubular channel or the distance between plates of a parallel plate channel
Fr	Froude number, $G(\Delta\rho/\sigma g)^{1/4}/\rho_L$
g	Gravitational acceleration, cm-s ⁻²
G	Helium mass flux, g/cm ² -s
$\bar{G}$	Average helium mass flux, g/cm ² -s
G _a	Eq. (4) mass flux
G _L	Helium mass flux in channels that contain only liquid
G _M	Helium mass flux in channels containing a mixture of liquid and vapor
i ² r	Joule heat resulting from current i in a quenched conductor of resistance r
i ² r ₁	Joule heat flux resulting from current i and resistance r ₁ in a quenched conductor comprising 1 cm ² of the channel wall

NOMENCLATURE (cont)

k	Thermal conductivity of channel wall (annealed valves were assumed in Tables B-I and B-II equations)
k_L	Thermal conductivity of liquid helium
K'	Kapitza conductance of copper-liquid helium interface ($K' = 0.05 \text{ W cm}^{-2}\text{K}^{-1}$ was used in Table B-I equations)
ℓ	Total number of magnet winding layers
L	Real or apparent length of a channel corresponding to an increase in x from zero to X
L_h	Actual length of channel heater when $\neq L$ (Refs. 3 and 4)
Le	Lehongre number, $1/[1 + 0.022 (LS/D)^{0.88}]$, Eq. (1), Table B-II equations
m.d.	Mean deviation
MPZ	Minimum propagating zone (Ref. 16)
MQ	Miniquench: a quench involving up to one full turn of a conductor; an isolated MQ means that there is no other MQ in the same channel
n	Number of simultaneous MQs per channel
P	Channel perimeter
Pr	Prandtl number, $C_L \eta_L / k_L$
R	$100 \ln(\phi/\phi_i)$; approximately equal to percentage deviation of observed CHF from Eq. (i) value
Re	Reynolds number, GD/η_L
S	Shape factor, DP_h/A ; for circular tubes $S = 4$; for parallel plate channels $S = 1$ if one plate is heated, $S = 2$ if both are heated
s.d.	Standard deviation
t	Conductor turns per layer; conductor segments per channel
T	Helium bath temperature

NOMENCLATURE (cont)

T_w	Channel exit wall temperature at CHF
W	Circumferential dimension; distance between spacers
W_{Δ}	Wall number, $k\tau/(K'L^2T^3)$
x	Quality; mass fraction of vapor in a vapor-liquid mixture
x_{in}	Quality at inlet to test section [see Eq. (A-1) discussion]
X	Critical quality, $X = \phi LS/\lambda GD$; critical mass fraction of vapor at the exit of a channel
ΔT	$T_w - T_i$; temperature rise of wall at steady-state CHF
ΔT_t	Transient temperature rise of wall t seconds after application of heat
λ	Helium latent heat of vaporization
η_L	Helium liquid viscosity, g/cm-s
η_V	Helium vapor viscosity, g/cm-s
ρ_L	Helium liquid density
ρ_V	Helium vapor density
σ	Surface tension of helium
τ	Thickness of channel wall; for tubes $\tau = (\text{wall cross section}) / (\text{perimeter of wall-fluid interface})$
ϕ	Observed CHF, W/cm ² ; critical heat flux for onset of film boiling with increasing heat flux
ϕ_R	Observed critical heat flux for complete recovery of nucleate boiling with decreasing heat flux, W/cm ²
β	First density number in Table B-II equations and elsewhere; $\beta = \rho_L/\rho_V$
γ	Second density number, $1 + 32/(\rho_L/\rho_V)^2$

CRITICAL BOILING, VAPOR BLOCK, AND PROSPECTS FOR SINGLE-SWEEP TRAINING OF SUPERCONDUCTING SOLENOIDS

by

Stephen G. Sydorik

ABSTRACT

Data of seven groups who have measured steady-state critical nucleate boiling heat flux (CHF) from a channel wall to helium flowing at known mass flux G are correlated to $\pm 13\%$. None of the plots shows any trend in CHF deviation with respect to six relevant experimental variables. To achieve quench control in a partially quenched, multichanneled, straight solenoid, the average mass flux $\bar{G}$ must exceed G to avoid vapor block in the quench-affected channels. Equations derived for $\bar{G}/G$ are based on both laminar- and turbulent-flow models. In a proposed method of quench control, every miniquench, MQ (involving up to one full turn of the conductor), that exists in the absence of another MQ in one or more of its channels is automatically suppressed by maintaining a calculable coolant flow provided by an immersed circulating pump in parallel with the magnet channels. Two MQs that involve the same channel can be eliminated by a rapid doubling of mass flux. On the basis of the observed frequency of such double MQs, the ramp rate can be held low enough to reduce nearly to zero the probability that three MQs will involve the same channel simultaneously. Prospects for single-sweep training free of current reversals are enhanced by the fact that in typical forced-flow channel boiling, as contrasted to typical pool boiling, the first (breakaway) and second (recovery) CHF's are identical. The available transient mass flux at onset of a quench is also superior to that for both pool boiling and natural convection boiling because it exceeds the planned-for steady-state value.

I. INTRODUCTION

Recent interest in forced-flow cooling of superconducting magnets has resulted in a large body of data¹⁻⁷ on the critical nucleate boiling heat flux (CHF, or ϕ) to helium flowing at temperature T , mass flux G , and inlet quality x_{in} in a heated channel of varied shape, size, and wall material.

Those data are used here to develop a CHF known-flow correlation equation. The objective is to develop procedures by which a magnet can be trained with the fewest possible full-scale quenches. A key element is a circulation pump mounted below the magnet. The pump forces liquid helium into a total of c identical magnet-cooling channels in the magnet, which could have either a helical or a spiral

(pancake) winding. Here we assume a helical winding.

In Sec. II we give a correlation of single-channel known-mass-flow-rate CHF measurements. A dimensionless equation is obtained, as is a simpler and more useful parametric (separated parameters) equation. The data base and details of the correlation appear in the appendixes.

In Sec. III we discuss the ratio of critical heat fluxes for breakaway from and recovery of nucleate boiling—a ratio that ranges up to a factor of 5 in the liquid helium pool-boiling literature but that differs from unity in only one of the many reports on forced-flow CHF.

In Sec. IV we account for the effect of vapor block in a partially quenched magnet. Two flow models are considered in calculating the ratio of $\bar{G}$, the average mass flux, to G_M , the flux in the quench-affected channels. In one model the flow of the mixture is assumed to be homogeneous and laminar (Poisueille); in the other it is homogeneous and turbulent (Reynolds).

Procedures and prospects for control of isolated miniquenches (MQs) are discussed in Sec. V, where we also describe a test section that can be added for *in situ* studies of quench propagation and control.

In Sec. VI we describe the approach to steady-state boiling and discuss published transient heat flux measurements.

II. KNOWN-FLOW CHF CORRELATION EQUATION

A. Notation and Definitions

In general, symbols refer to the condition of CHF or, to be more explicit, to the condition for onset of film boiling with *increasing* heat flux. The condition is identified experimentally as the point at which there is a break in the slope of a plot of wall temperature T_w vs heat flux. Typically, T_w at critical heat flux ϕ exceeds the bath temperature T by ~ 0.5 K for $T \sim 4.2$ K. Numerical subscripts of ϕ are CHF correlation-equation numbers of this report. Burnout, first and second critical heat flux, peak nucleate boiling, and other synonyms for CHF appropriate to a discussion of CHF in pool boiling are avoided because they are not usually pertinent to channel boiling.

The six system parameters needed to predict the value of ϕ in a single channel are:

- 1) D , either the diameter of a tubular channel or the distance between parallel plates, one or both of which are heated.
- 2) Shape factor $S = (D) (\text{heated perimeter}) \times (\text{cross-section area})^{-1}$. For tubes, $S = 4$; for parallel plates, $S = 1$ (2) if 1 (2) plates are heated.
- 3) L , length of channel corresponding to an increase in quality (mass fraction of vapor) from zero to the critical quality X .
- 4) $k\tau$, thermal conductance of a channel wall of conductivity k and thickness τ .
- 5) T , liquid helium bath temperature, based on a measured vapor pressure. Because both phases are present and because hydrostatic and hydrodynamic pressure drops are small, the fluid temperature is essentially constant throughout a test channel.
- 6) $G; G_*$, mass flow rate per unit cross-section area of a channel; G_* , mass flow rate at the value of CHF given by Eq. (4).

B. Published Correlations

In Ref. 3, Giarratano, Hess, and Jones (GHJ) correlate to $\pm 19\%$ their 65 CHF measurements and 12 measurements of Johannes and Mollard² (JM) with an equation containing 5 fitted dimensionless terms including Reynolds, Froude, and Weber numbers. Solving for ϕ requires an iterative procedure because it appears in the GHJ correlation with exponents of 1 and 3.92. In more recent data obtained with channel walls of high thermal conductance,^{6,7} the observed CHF is as much as three times greater than values given by the GHJ correlation.

Keilin, Kovalev, Likov, and Pozvonkov⁸ (KKLP) fit their 48 measurements ($\pm 10\%$ maximum deviation) with a dimensionless equation having only one fitted coefficient and one fitted exponent. Unfortunately, the absence of S , D , and L from their equation makes it inappropriate for comparison with other data. However, the high quality of their fit indicates that the Froude number might well be included in a dimensionless correlation equation for forced-flow channel boiling.

Channels used in 83% of the published known-flow CHF measurements have been circular tubes of

$D \doteq 0.1$ cm (11%) or $D \doteq 0.2$ cm (72%). To overcome the paucity of data for $S = 1$ (15%) or 2 (6%) and $D \neq 0.1$ or 0.2 cm, we make use of published natural convection data correlations^{8,9} to show how ϕ depends on D and S , as shown below.

JM (Ref. 2) found that natural convection data for their 12 flat-plate channels fitted to $\pm 20\%$ a correlation originally proposed by Lehongre et al.⁶ In our units they found

$$\phi_1 = \frac{1}{1.7[1 + 0.022(LS/D)^{0.88}]} \quad (1)$$

For convenience we define a Lehongre number as $Le = 1/[1 + 0.022(LS/D)^{0.88}]$. We also find Le to be a reasonably good form for one of the terms of a known-flow correlation.

An even better fit to natural convection data is obtained with a correlation of CHF data for 72 helium natural convection evaporators proposed by Sydorak,⁹

$$\phi_2 = \frac{D}{D + B(S)} \alpha \sqrt{\frac{\rho_V \Gamma_L^8}{L}} \quad (2)$$

It is convenient to define a channel cross-section number $Cr = D/[(D + B(S))]$. For 26 channels having one heated wall ($S = 1$) the shape factor $B(1)$ was found to be 0.148 cm for a mean deviation (m.d.) of ϕ from ϕ_2 of $\pm 8.5\%$. Data on 46 channels having two heated walls ($S = 2$) yielded $B(2) = 0.185$ cm and a $\pm 10.2\%$ deviation from ϕ_2 . To apply this formulation to the present data, many of which were obtained with tubular channels ($S = 4$), we can either let $B(4)$ float or we can use an unpublished value of $B(4) = 0.63$ cm, which we fitted recently (to $\pm 8.6\%$) to nine tubular experiments of Lehongre et al.⁶ With either procedure the number Cr provides an excellent D -dependence term for a known-flow correlation equation. Although the form of Eq. (2) is based on a hydrodynamic theory of natural convection channel boiling,¹⁰ the present results appear to validate the application of the assumptions of that theory to high levels of forced flow boiling as well.

C. Known-Flow CHF Data

The seven principal sources¹⁻⁷ of known-flow liquid helium data are tabulated in Table I and represent a remarkable variety of experimental ap-

proaches and a wide range of each of the six relevant parameters. Table preparation is described in Appendix A.

Experimental approaches and apparatus descriptions include natural convection² and forced flow;^{1,3-7} open-^{2,5,6} and closed-loop^{1,3,4} systems; mass flow rate from liquid-level variations,⁷ a liquid-helium turbine,² a 4 K orifice meter,⁵ a 300 K orifice meter,⁴ a Venturi tube,¹ a calibrated tube,⁶ and an unspecified meter;⁵ flow direction through test section upward^{1,2,4-7} and downward;³ tubular^{1,3-6} and flat-plate^{2,7} channels; one² and both^{2,7} (flat-plate) walls heated; test-section walls made of Monel,¹ stainless steel,^{2,4} copper,^{6,7} and silver;⁵ heated-wall thicknesses of 0.001 cm,² 0.010 cm,¹ 0.016 cm,³ 0.026 cm,⁴ 0.05 cm,⁶ 0.45 cm,⁵ and 1.0 cm.⁷ Ranges for the six relevant parameters are given in Table II. For measurements in which the inlet quality x_{in} is not zero, the value of L is an extrapolation (x_{in} positive) or an interpolation (x_{in} negative).⁸ [See discussion of Eq. (A-1).]

D. New Known-Flow Correlation Equations

Two types of correlation equation are derived. Both adequately represent 131 of the 136 measurements of CHF. Five listed measurements are shown to have been omitted from the final fittings because their standard deviation (s.d.) exceeded the $\pm 12.8\%$ s.d. of the accepted fits by more than a factor of 4. Details of the derivation and demonstrations of adequacy are given in Appendix B.

An adequate dimensionless equation is

$$\frac{\phi_{3SL}}{\lambda_{GD}} = 1.49 \lambda \left(\frac{D}{D + B} \right)^{0.571} \left(\frac{GD}{\eta_L} \right)^{0.085} \left[\frac{G}{\rho_L} \left(\frac{\Delta \rho}{6g} \right)^{1/2} \right]^{-0.850} \left(\frac{c_L \eta_L}{k_L} \right)^{-1.360} \left(\frac{\rho_L}{\rho_V} \right)^{-1.889} \left(\frac{SL}{D} \right)^{0.888} \left(\frac{k \tau}{K' L^2 T^3} \right)^{0.062} \quad (3)$$

where $B = 0.23 - 0.14S + 0.06S^2$. Thus $B(S)$ has the desired values of 0.15 for $S = 1$, 0.19 for $S = 2$, and 0.63 for $S = 4$. Fitted terms 2, 3, and 4 are the

TABLE I
KNOWN-FLOW CHF BOILING DATA FOR HELIUM

Loc. ^a	S	D (cm)	x _{in}	L (cm)	G (g/cm ² -s)	T (K)	Φ (W/cm ²)	Deviation ^b from	
								Φ _s (~%)	Φ _f (~%)
Johannes: ¹ Monel tube, 0.010-cm wall, kτ = 5.5 x 10 ⁻⁵ W/K									
f 1	4	0.212	0	29.6	7.92	4.670	0.147	-26	-24
					13.1	4.670	0.179	-18	-17
					18.0	4.670	0.252	9	10
					23.1	4.670	0.276	12	13
					24.6	4.670	0.271	9	10
					6.06	4.320	0.131	-14	-20
					10.1	4.320	0.160	-6	-12
					12.8	4.320	0.168	-7	-12
					17.1	4.320	0.201	4	-1
					20.3	4.320	0.201	0	-5
					10 pt. av, %:			-4 ± 13	-6 ± 13
Johannes and Mollard: ² 0.001-cm stainless steel, kτ = 3.0 x 10 ⁻⁶ W/K									
t 1	1	0.210	0	10.0	2.92	4.224	0.300	9	17
	1	0.247		10.0	2.42		0.300	6	17
	1	0.155		10.0	3.19		0.290	17	21
	1	0.093		10.0	2.88		0.220	18	16
	1	0.104		20.0	4.10		0.150	-17	-19
	1	0.145		20.0	3.24		0.180	-11	-8
	6 pt. av, %:			4 ± 15	7 ± 17				
	2	0.210		10.0	2.94		0.218	16	18
	2	0.247		10.0	2.63		0.275	9	13
	2	0.155		10.0	2.98		0.260	2	20
	2	0.093		10.0	2.53		0.180	18	9
	2	0.104		20.0	3.92		0.120	-23	-30
	2	0.145		20.0	3.07		0.152	-12	-15
	6 pt. av, %:			5 ± 18	2 ± 20				

^aDesignates the figure (f), page (p), or table (t) where measurement appears in respective reference.

^bLast two columns show 100 ln (φ/φ_{calc}), where φ_{calc} is dimensionless Eq. (3) or parametric Eq. (4).

TABLE I (cont)

Loc. ^a	S	D (cm)	x_{in}	L (cm)	G (g/cm ² -s)	T (K)	Φ (W/cm ²)	Deviation ^b from	
								Φ_s (~%)	Φ_t (~%)
Giarratano, Hess, and Jones: ^a stainless steel tube, 0.016-cm wall, $k_T = 5.2 \times 10^{-6}$									
p 102	4	0.213	-0.03	7.29	4.50	4.360	0.228	1	1
p 102			-0.02	8.94	4.60	4.302	0.208	0	0
p 101			-0.02	8.55	4.60	4.304	0.212	1	1
p 99			-0.05	6.00	9.50	4.347	0.256	-6	-8
p 103			0	8.60	9.80	4.296	0.257	2	4
p 103	4	0.213	0	9.50	10.3	4.301	0.245	-1	0
p 102			0	9.40	10.5	4.299	0.247	-1	0
p 115			-0.07	2.90	12.5	4.324	0.365	3	4
p 114			-0.07	7.10	13.2	4.276	0.283	3	4
p 114			-0.07	5.27	13.3	4.282	0.302	2	3
p 115			-0.06	6.23	13.5	4.300	0.268	-8	-7
p 103			0	8.40	27.1	4.296	0.297	-8	-6
p 118			0	4.60	28.5	4.293	0.395	6	8
p 109			0	5.90	28.7	4.291	0.350	0	-1
p 108			0	6.40	29.0	4.288	0.343	0	1
p 108			0	6.80	29.4	4.286	0.331	-3	-2
p 103			0	7.60	30.0	4.285	0.313	-7	-5
p 119			0	3.00	30.5	4.286	0.502	21	21
p 114			-0.06	3.51	31.1	4.271	0.404	2	3
p 107			0	8.90	31.5	4.285	0.298	-9	-7
p 119			0	3.80	33.3	4.291	0.431	9	8
p 99			-0.08	4.00	7.10	4.687	0.253	-20	-15
p 100			-0.07	5.80	14.1	4.663	0.270	-18	-17
p 100			-0.07	4.11	14.4	4.671	0.308	-14	-12
p 100			-0.07	5.09	14.5	4.672	0.284	-17	-15
p 110			-0.20	3.00	14.5	4.665	0.350	-9	-7
p 113			0.13	17.00	23.8	4.627	0.273	-6	-4
p 122			0.03	3.57	34.4	4.632	0.467	2	4
p 101			-0.01	7.25	58.3	4.551	0.446	1	2
p 122			0	2.42	59.2	4.563	0.551	-4	-3
p 113			0	4.68	59.5	4.564	0.456	-7	-6
p 101			0	3.42	61.2	4.528	0.530	0	0
p 107			0	8.42	61.3	4.567	0.363	-17	-16
p 118			0	3.35	61.3	4.567	0.498	-7	-6
p 118			0	2.02	62.8	4.570	0.602	-1	0

TABLE I (cont)

Loc. ^a	S	D (cm)	x_{in}	L (cm)	G (g/cm ² -s)	T (K)	ϕ (W/cm ²)	Deviation ^b from	
								ϕ_3 (~%)	ϕ_4 (~%)
p 98			-0.14	3.42	7.20	5.011	0.160	-7	-8
p 109			0.18	20.60	12.3	5.043	0.113	2	0
p 104			-0.03	5.58	13.1	5.035	0.163	3	1
p 116			-0.04	3.30	13.1	5.036	0.180	0	-1
p 104	4	0.213	-0.05	3.34	13.3	5.044	0.172	-1	-2
p 106			-0.04	4.76	13.4	5.034	0.171	5	4
p 120			0.07	4.34	14.7	5.034	0.193	13	12
p 109			0.01	11.4	28.8	5.018	0.193	-10	13
p 121			0	2.90	30.7	5.023	0.244	-4	-5
p 115			-0.07	3.76	12.6	4.309	0.336	4	4
p 110			-0.20	1.50	14.6	4.670	0.366	-21	-20
p 99			-0.16	1.71	7.20	5.031	0.165	-11	-13
p 117			-0.03	1.80	13.3	5.030	0.207	-1	-4
p 119			0	1.10	31.9	4.289	0.686	25	26
p 120			0	1.00	31.9	4.293	0.705	28	27
p 112			-0.10	1.09	43.0	4.570	0.675	4	6
p 121			0	1.02	30.5	5.016	0.301	-10	-10
p 122			0	4.82	42.2	4.626	0.323	-33	-31
53 pt. av, %:								-2 ± 11	-1 ± 10

Ogata and Sato:^a stainless steel tube, 0.026-cm wall, $k_T = 9.4 \times 10^{-5}$ W/K

f 7	4	0.109	0	5.60	9.20	4.684	0.198	2	-4
f 8			-0.06	4.44	7.88	4.960	0.144	7	1
f 7			-0.16	3.17	9.20	4.684	0.276	21	16
f 8			-0.39	1.12	7.88	4.960	0.243	26	20
4 pt. av, %:								14 ± 11	8 ± 12

Omitted OS points:

f 3	4	0.109	0.018	5.90	9.22	4.324	0.384	72	64
f 3			0.064	6.60	9.22	4.324	0.384	74	67

Hildebrandt:^a silver tube, 0.45-cm wall, $k_T \approx 200$ W/K

f 4	4	0.100	0	2.00	6.56	4.107	0.381	-15	-13
f 5					1.14	4.048	0.229	-20	-15
f 5					1.30	4.048	0.229	-24	-18
f 5					2.70	4.048	0.350	2	7
f 5					2.03	4.048	0.255	-23	-18

TABLE I (cont)

Loc. ^a	S	D (cm)	x_{jn}	L (cm)	G (g/cm ² -s)	T (K)	Φ (W/cm ²)	Deviation ^b from	
								Φ_s (~%)	Φ_t (~%)
f 5					5.41	4.048	0.414	2	8
f 5					5.67	4.048	0.470	14	19
f 5					7.10	4.048	0.504	16	21
f 5					3.48	4.048	0.426	15	21
9 pt. av, %:								-4 ± 17	1 ± 17

Keilin, Kovalev, Likov, and Pozvonkov:⁶ copper tube, 0.05-cm wall, $k_T = 0.6$ W/K

f 4	4	0.200	0	10.0	4.76	4.414	0.451	20	18
f 4					6.70	4.504	0.516	22	21
f 4					6.12	4.504	0.516	24	24
f 4					5.47	4.504	0.476	19	18
f 4					4.09	4.504	0.375	15	5
f 4					8.37	4.591	0.540	20	20
f 4					7.61	4.591	0.529	20	21
f 4					6.97	4.591	0.504	17	18
f 4					5.82	4.591	0.463	13	14
f 4					4.70	4.591	0.408	5	6
f 4					9.51	4.673	0.516	16	16
f 4					8.60	4.673	0.503	15	16
f 4					8.13	4.673	0.471	10	10
f 4					7.23	4.673	0.457	9	10
f 4					5.67	4.673	0.404	3	3
f 4					3.91	4.673	0.310	-15	-14
f 6					3.98	4.414	0.361	2	0
f 4					3.16	4.318	0.374	14	15
f 4					2.92	4.318	0.323	1	2
f 4					2.63	4.318	0.288	-8	-7
f 4					2.46	4.318	0.263	-15	-15
f 4					2.29	4.318	0.239	-23	-23
f 4					2.12	4.318	0.239	-21	-21
f 4					4.50	4.414	0.451	21	19
f 4					3.48	4.414	0.373	8	6
f 4					3.26	4.414	0.355	4	3
f 4					2.77	4.504	0.291	-14	-16
f 4					3.67	4.591	0.338	-8	-7
f 6			0.13	11.5	3.98	4.414	0.327	-5	-6
f 4			0	10.0	2.77	4.591	0.264	-26	-25
30 pt. av, %:								5 ± 15	4 ± 15

TABLE I (cont)

Loc. ^a	S	D (cm)	x _{in}	L (cm)	G (g/cm ² -s)	T (K)	Φ (W/cm ²)	Deviation ^b from	
								Φ _s (~%)	Φ _e (~%)
Omitted KKLP ^a points:									
f 6	4	0.200	0.81	36.1	3.98	4.414	0.121	-77	-79
f 4			0	10.0	1.70	4.591	0.149	-72	-71
f 6			0.65	25.1	3.98	4.414	0.167	-54	-55
Jergel and Hlasnik: ⁷ 1-cm copper, k _T = 10 W/K									
t 1	1	0.060		1.38	6.80	4.220	0.676	-5	-11
		0.060			8.80		0.701	-7	-14
		0.060			9.80		0.752	-3	-9
		0.060			12.8		0.752	-9	-16
		0.060			10.6		0.822	4	-2
		0.060			11.2		0.857	7	1
		0.060			11.9		0.916	12	6
		0.100			2.00		0.792	10	10
		0.100			6.20		0.861	-8	-8
		0.100			8.20		0.901	-10	-10
		0.100			11.4		0.954	-12	-12
		0.100			14.2		0.974	-15	-15
		0.100			18.8		1.060	-13	-13
13 pt. av, %:								-4 ± 9	- 7 ± 8

131 pt. av, %: 0.1 ± 12.8

TABLE II
MINIMUM AND MAXIMUM PARAMETER VALUES USED BY
VARIOUS AUTHORS IN MEASURING CHF

Author, Ref.	No. Points	k_T (W/K)	S	D (cm)	L_h (cm)	x_{in}	L (cm)	G (g/cm ² -s)	T (K)	ϕ (W/cm ²)	ϕ/ϕ_2^a	X^b
J ¹	10	5.5×10^{-5}	4	0.21	30	0	30	6.1 25	4.32 4.67	0.13 0.28	1.2 3.5	0.28 0.62
JM ²	12	3.0×10^{-6}	1	0.093	10	0	10	2.4	4.22	0.12	0.86	0.24
JM ²	12	3.0×10^{-6}	2	0.25	20		20	4.1		0.30	1.05	0.75
GHJ ³	53	5.2×10^{-5}	4	0.21	10	-0.20 0.18	1.0 42	4.5 63	4.27 5.04	0.11 0.70	0.8 2.7	0.616 0.38
OS ⁴	4	9.4×10^{-5}	4	0.11	8.5	-0.39 0	1.1 5.6	7.9 9.2	4.68 4.96	0.14 0.28	1.2 2.5	0.10 0.26
H ⁵	9	200	4	0.10	2.0	0	2.0	1.1 6.6	4.05 4.11	0.22 0.47	(1.3) (3.1)	0.22 0.76
KKLP ⁶	30	0.60	4	0.20	10	0 0.13	10.0 11.5	2.1 9.5	4.32 4.67	0.24 0.54	(1.8) (4.1)	0.65 1.2
JH ⁷	13	10	1	0.06 0.10	1.4	0	1.4	2.0 19	4.22	0.68 1.06	(1.3) (2.2)	0.038 0.27
All ¹⁻⁷	131	3×10^{-6}	1	0.06	1.4	-0.39	1.0	1.1	4.05	0.11	0.8	0.016
	200		4	0.25	30	0.13	42	63	5.04	1.06	3.5	1.2

^aExtreme values of the ratio of ϕ to the Eq. (2) value for natural convection.

^bCritical quality, $X = \phi LS/\lambda GD$.

Reynolds, Froude, and Prandtl numbers, respectively. Origins of the other four numbers are described in Appendix B.

The simplest adequate parametric equation we obtained is (cgs units):

$$\phi_4 = 27.0 \lambda \left(\frac{D}{D+B} \right)^{0.690} G_4^{0.234} L^{-0.236} (k\tau)^{0.062} \beta^{-2.650} (1 + 32 \beta^{-2})^{-2.039} \quad (4)$$

Fig. 1.

Equation (4) temperature-dependent terms (solid line). Points are the m.d. of the fit for n contiguous (in temperature) measurements of ϕ , plotted with respect to the solid line.

where B values are the same as for Eq. (3). Although it contains fewer fitted exponents than Eq. (3), Eq. (4) has the same $\pm 12.8\%$ s.d.

Figures 1-5 display the Eq. (4) dependence and fit with respect to the six experimental variables. In each figure a solid line is a calculated dependence, e.g., $f(T)$ vs T . For such a dependence the plotted points are $f(T)R$, where R is the mean percentage deviation for several contiguous (in T , for the

Fig. 2.

Equation (4) D -dependence term (solid lines) for flat-plate channels with one wall heated ($S = 1$) or both heated ($S = 2$) and for heated tubes ($S = 4$). Points are the m.d. for the indicated number of measurements at the same S and D , plotted with respect to the corresponding solid line. For $S = 1, 2, 4$, values of $B = 0.15, 0.19, 0.64$ are based on natural convection correlations for CHF.

Fig. 3.
Equation (4) wall-conductance term (solid line). Points are the m.d. from Eq. (4) of the n measurements of ϕ by each group of authors. Standard deviation bars of all authors cross the fitted line.

Fig. 4.
Equation (4) channel-length term and data deviations.

selected example) data points. Throughout the range of each variable the data points scatter on each side of the solid line. Error bars, which represent the s.d. of each group of deviations from their mean, cross the solid line in almost every instance. On the basis of these observations and numerical comparisons made between several similar

parametric equations given in Appendix B, we conclude that Eq. (4) adequately represents the known-flow data. Because the average of the 131 values of $(\phi_s - \phi_e)$ is $-0.1 \pm 3.2\%$, we conclude that ϕ_s also is an adequate correlation of the data.

A brief discussion of Eq. (4) and of other portions of this report is given in Ref. 10.

Fig. 5.
Equation (4) mass-flux term and data deviations.

III. EQUALITY OF BREAKAWAY AND RECOVERY HEAT FLUX

In the publications of the seven groups who have studied known-flow boiling in channels, five^{2-4,6,7} show plots and/or contain statements specifying a continuous, reversible transition between nucleate and film boiling. Johannes¹ makes no comment on this point. Hildebrandt⁸ observes a discontinuous transition from nucleate to film boiling, but it is a most unusual transition in that it occurs at increasing heat fluxes less than the maximum value. Hildebrandt often observed a spontaneous recovery from such a transition. The $k\tau$ for his thick silver-walled channel was much higher (at 200 W/K) than for any other channel. We conclude that for forced flow in channels ϕ and ϕ_R are equal, except perhaps for very high $k\tau$.

Significant additional evidence supports the view that the transition is reversible in the cooling channels of a bundle of wires. When only the central wire was heated or when all wires were heated in a horizontal bundle of nine uniformly spaced copper wires with liquid helium forced to flow between the wires, Cornish et al.¹¹ found that "in both series of tests the heat transfer curve is continuous and is the same for increasing and decreasing heat fluxes." Many of the natural convection data also indicate that $\phi_R = \phi$, but for high $k\tau$, $\phi_R < \phi$ also may be observed.^{12,13} On the other hand, in pool-boiling

results, $\phi_R < \phi$, except for one measurement involving a stainless steel heater.¹⁴

Even at high $k\tau$, a reversible transition may be achieved by (a) choosing a sufficiently low value of D (Ref. 13) or (b) injecting vapor at the channel inlet.¹⁵ A better solution, because it results in increased CHF, is suggested by Groeneveld's¹⁶ observation that for both water and Freon 12 "a reversible transition occurs at high mass flow rates."

IV. VAPOR-BLOCK RATIO $\bar{G}/G_M$

Use of Eq. (4) in predicting conditions for CHF in a superconducting magnet has a serious drawback. Although all channels can be made identical and subject to the same driving pressure, vapor block in quench-affected channels will reduce their mass flux to a fraction <1 of that in vapor-free channels, in accordance with the mass fraction of vapor and the fraction of the channel through which the vapor must pass. Therefore, to achieve ϕ_* , the mass flux must be increased to a value $\bar{G}$ greater than the mass flux of the mixture (G_M), given by an Eq. (4) calculation.

Two estimates of the vapor-block ratio $\bar{G}/G_M$ are given below for a partial quench at inlets to channels in a solenoid—the worst possible places because the low-density vapor has to travel the entire length of the channel. We hope that these tentative,

hypothetical calculations will stimulate discussion and further investigation of the problem.

Consider a vertical-axis solenoid (Fig. 6) containing c vertical cooling channels, each of whose inner walls consists of t segments of a composite superconductor, there being t helical turns per layer of winding. Each layer is surrounded by b_1 narrow axial spacers D centimeters thick and W centimeters apart. A leakproof blanket of thermal and electrical insulation covers the spacers. Only the inner wall of each channel is heated ($S = 1$). An immersed circulation pump located below the magnet draws liquid from a large plenum at the top of the solenoid and delivers it to a plenum at the bottom. Thus the same pressure drop appears across all channels. It is assumed that the pumping speed is sufficient to prevent convective downflow in unheated channels (see footnote to Sec. IV-C).

A quench exists in the bottom segment of each of b contiguous channels in a layer of the solenoid (see

Fig. 6.
Solenoid containing a miniquench. Quenched segments are shaded.

Fig. 6). The quench is in a state of equilibrium because, by design, the heat flux for a heated segment is the CHF of Eq. (4). A negligible increase in heat flux is assumed to occur when the wall temperature increases from that for CHF to that for the S-N transition. We also assume that a negligible fraction of the i^2r heat is conducted out of the quench region through the blanket covering this layer or through the insulation between turns of the layer or through the two ends of the linked segments of resistive conductor. [The last restriction says that the minimum propagating zone (MPZ) described by Wipf¹⁰ is of negligible length.]

A. Laminar-Flow Model

We assume that Poiseuille's equation¹⁷ for viscous laminar flow is applicable everywhere. With the viscosity of the mixture being the weighted sum of vapor and liquid viscosities,

$$1/\eta_M = x/\eta_V + (1 - x)/\eta_L, \quad (5)$$

we equate the pressure drop across the c - b channels containing only liquid (subscript L) to the drop across the b channels containing a mixture (subscript M):

$$\Delta p = CG_L(\eta_L/\rho_L)t = CG_M[(\eta_L/\rho_L)(1/2) + (\eta_M/\rho_M)(t - 1/2)], \quad (6)$$

where C is a function of channel dimensions¹⁷ and t is the number of conductor segments per channel. Edge effects at the spacers are neglected and we replaced the heated part of a channel with one in which all of the i^2r heat is delivered at the horizontal center of the heated segment, there being only liquid up to segment $1/2$ and a mixture of constant quality above that point. The average flux through the c channels is

$$\bar{G}_c = G_L(c - b) + G_M b. \quad (7)$$

Since $1/\rho_M = X_M/\rho_V + (1 - X_M)/\rho_L$, a combination of (5), (6), and (7) yields the vapor-block factor for b channels:

$$\frac{\bar{G}}{G_M} = \frac{b}{c} + \left(1 - \frac{b}{c}\right) \left\{ \frac{1}{2\tau} + \left(1 - \frac{1}{2\tau}\right) \left[1 + X_M \left(\frac{\rho_L}{\rho_V} - 1 \right) \right] \right. \\ \left. \left[1 + X_M \left(\frac{\eta_L}{\eta_V} - 1 \right) \right]^{-1} \right\} \quad (8)$$

or for $1 \ll \tau$,

$$\frac{\bar{G}}{G_M} = \frac{b}{c} + \left(1 - \frac{b}{c}\right) \left[1 + X_M \left(\frac{\rho_L}{\rho_V} - 1 \right) \right] \left[1 + X_M \left(\frac{\eta_L}{\eta_V} - 1 \right) \right]^{-1} \quad (9)$$

B. Turbulent-Flow Model

A turbulent homogeneous flow model also has been applied to a calculation of vapor block. Assuming $1 \ll \tau$ and a friction factor proportional to $Re^{-1/4}$, by conventional hydrodynamics¹⁸ the frictional pressure drop term (i.e., neglecting momentum and gravitational pressure drop) is

$$\frac{\Delta P}{C} = \frac{\eta_L^{1/4} G_L^{7/4}}{\rho_L^{3/4}} = \frac{\eta_M^{1/4} G_M^{7/4}}{\rho_M^{3/4}} \quad (10)$$

with C again a function of channel dimensions. Combining (5), (7), and (1), we find

$$\frac{\bar{G}}{G_M} = \frac{b}{c} + \left(1 - \frac{b}{c}\right) \left[1 + X \left(\frac{\rho_L}{\rho_V} - 1 \right) \right]^{3/7} \\ \left[1 + X \left(\frac{\eta_L}{\eta_V} - 1 \right) \right]^{-1/7}. \quad (11)$$

Results for both models at $b=0$ are shown in Fig. 7 as plots of $\bar{G}/G_M$ vs X. Surprisingly, the correction for vapor block is less for turbulent flow than for

laminar flow, despite the fact that the effect on pressure drop at a given mass flow in all channels is much greater for turbulent flow. This result is fortuitous because Reynolds numbers are likely to exceed the critical value for onset of turbulence. In almost all published known-flow CHF measurements, and even in the natural convection results of Ref. 2, the Reynolds number is indicative of turbulent flow ($Re > 2000$). Figure 7 also shows that the vapor-block effect decreases rapidly with increasing temperature and with decreasing critical quality. In that regard, a given percentage increase in pump speed results in an even larger percentage increase in the mass flux in quench-affected channels. For example, at 4 K and an average mass flux such that the initial quality is unity, a 64% increase in pump speed drops the quality to 0.5 and results in a 100% increase in mass flux in a quench-affected channel.

C. A Prediction of Quench Stability

The vapor-block equations (8)-(11) show that a stable quench may be attainable in a forced-flow multichannel magnet.* Figure 8 shows $\bar{G}/G_M$ vs b [Eq. (11)] at $T = 4$ K. If the pumping speed is constant, the negative slope indicates that G_M will *increase* as the number b of vapor-blocked channels increases. Consider then a real magnet at CHF, with $G_M = G_c$; in other words, the CHF equation is satisfied, with ϕ_c equal to the $i^2 r_t$ heating of a quenched section of conductor comprising 1 cm^2 of the channel wall. If b is suddenly increased by a small heat pulse then, according to Fig. 8, $\bar{G}/G_M$ will decrease. With constant $\bar{G}$ that can happen only if G_M increases. When the pulse is ended, the increased value of G_M will cause b to return to its original value. The probability of a stable quench

*A stable quench caused by vapor block is not to be confused with a second type of quench stoppage which does not involve use of a mechanical pump but which is described by the same concepts and equations used above. A magnet is divided into sections, each of which contains n contiguous channels, all part of the same winding layer and all sharing a common plenum at the bottom end. A result of quench onset will be the establishment of internal natural convection, with sufficient downflow in unheated channels to make up boiling losses from heated channels. Preliminary calculations show that growth of the quench will be sharply limited by the rapidly increasing "deluge" of liquid flowing down the unheated channels as the N-S interface approaches the last of the "set" of n channels. An experimental study of a "deluge sets" cooled magnet has been added to the vapor-block and quench control studies described on p. 18.

Fig. 7.

Maximum vapor-block ratios for turbulent flow [solid lines, Eq. (11)] or laminar flow [dashed lines, Eq. (9)]. The ratio is a maximum because only one conductor segment at a channel inlet is heated ($b = 1$).

has important implications for a safe *in situ* study of quench in a test coil added to an actual magnet (see Sec. V-C).

V. CONTROL OF MINIQUENCHES

A. Stages of Control

We consider here two stages of control. In the first, passive, stage, up to n (probably undetectable) simultaneous MQs per cooling channel are automatically eliminated by maintaining an appropriate coolant-pumping speed. For control against $n + 1$ simultaneous quenches per channel, we propose use of a second, active, stage of control in which the $n + 1$ quenches grow until they are long enough to be detected. The mass flow rate is then increased rapidly to an appropriate calculable level at which all $n + 1$ resistive sections will recover super-

conductivity. The second stage of control permits an important improvement: from the frequency of occurrence of $n + 1$ events one can derive a rational basis for adjusting the ramp rate to avoid a still more extensive and possible uncontrollable quench.

For simplicity we limit further discussion to the case of $n = 1$: passive control shall be used to eliminate automatically all *isolated* MQs (MQs causing i^2R heating of no more than one segment per channel); active control shall be used (1) to eliminate all detected double MQs (by doubling the mass flow rate) and (2) to calculate a safe ramp rate for prevention of triple MQs (from the observed frequency of detected double MQs).

Training is over when the indicated ramp rate has been reduced to zero. The magnet presumably will be operated subsequently at a current slightly lower than the maximum reached during training and the pump will be operated at a suitable standby level (or turned off altogether if natural convection can take

Fig. 8.

Vapor-block ratios, Eq. (11), for one miniquench in solenoids of l layers of 100 channels each and a 4 K bath. The abscissa is the number of heated channel segments in the bottom turn of the layer in which the miniquench exists. Because the slope is negative, the quench length will be stable provided $G_M = G_*$. Stability is greatest for $l = 1$.

care of residual heating caused by resistive joints, eddy currents, support members, etc.).

B. Control Apparatus Requirements

1. Circulation Pump. Liquid helium pumps of very high flow rate but low differential pressure will be required. Fixed displacement pumps are contraindicated because they would inhibit natural convection when turned off. Pumping efficiency may not be important if the pump is needed only during cooldown and during a training session after each warmup to room temperature. Incidentally, use of a circulation pump during cooldown could be important in minimizing temperature-gradient-induced stresses in a magnet winding. For large magnets, days of cooldown time might be saved.

2. Pump Speed Calculation. A schedule of $\bar{G}$ vs magnet current i is needed for the passive control

method. For a conductor of residual resistance r_1 per unit channel wall area, we equate $i^2 r_1$ to ϕ_* and solve for G_* and critical quality $X = \phi_* SL / \lambda GD$. Finally, from a suitable vapor block equation, tentatively Eq. (11), we arrive at the needed pump speed for c channels of width W , $cWD\bar{G}_{4,11}$. The schedule could be used for manual control or fed into a microprocessor for computer control. For purely passive control of small magnets one might simply run the pump at a level corresponding to the highest anticipated current level.

3. Quench Detection Requirements. For successful active control, rapid detection of (uncontrolled) quenching is imperative so that growth can be arrested before any channel acquires a third heated segment. Fortunately, because the exponent on a doubled L in Eq. (4) is small (0.24), 85% of the needed heat flux will be available at the scheduled value of $\bar{G}_{4,11}$. Consequently, the quench propagation

velocity probably will not be very high, allowing ample time for detection and for flow speedup.

4. Flow Speedup. A rapid doubling of $\bar{G}$ is needed for active quench control with $n + 1 = 2$. This requirement can best be met not by an increase in pump speed but by a decrease in flow resistance: a bypass solenoid valve can be opened faster than a pump can be speeded up (except perhaps for a valve-controlled bellows pump, which is undesirable because it inhibits natural convection when turned off). We therefore propose that the rapid increase in mass flux needed for active quench control be accomplished by means of a fast-acting solenoid valve in parallel with an appropriate constriction in the flow line.

5. Reaction Time Determination: A Test Coil Addendum. For successful active control, one must verify that the sum of times t_Q needed for detection of an MQ plus the subsequent time t_R needed to increase the mass flux to the needed level $2\bar{G}$ is less than the time t_i needed for growth of either quench to one full turn. More than one turn of growth is to be avoided so that a still greater flow rate will not be required when three resistive segments appear in one channel wall.

A test coil mounted at the inlet of an entire layer of dummy channels may be useful for *in situ* measurement of reaction times and other purposes. The device (Fig. 9) consists of two turns of the same conductor used elsewhere in the magnet. It has its own power supply and circulation pump. In addition, adjustable fast-acting solenoid valves and flow meters permit the output of either pump to be altered quickly and measured accurately.

A quench-initiating heat-pulse device is attached at the center of the added turn(s). The time constants for quench detection and circulation control are presumed to be the same for the test section as for equal-field portions of the main magnet. The current in the test coil is always maintained at a level high enough to make the test coil more susceptible to quench than any other part of the magnet. At regular intervals during training, one uses the test coil to determine the dependence of t_i on $\bar{G}$ by measuring the time interval between the application of a heat pulse (and simultaneous increase in circulation) and the appearance of a maximum value in the normal-zone voltage. Minimum acceptable values of $\bar{G}$ determined from these data are fed into a computer which then can control the value of

Fig. 9.

Helical straight solenoid and auxiliary test coil. Shaded regions represent miniquenches.

standby mass flux in the main magnet when comparable susceptibility to quench exists in the main magnet.

The test coil also can be used to check the equation used for vapor-block ratios as well as to evaluate the efficacy of measures taken to prevent quench jumps between turns in the same layer. Jumps between layers also will show up in the test coil, although they do not lead to violation of the requirement that MQs be isolated in a passively controlled magnet.

If used in support of passive control, the test coil can give the operator quantitative information about vapor block and the characteristics of artificially generated quenches. With winding procedures identical to those used in the main magnet, the test coil will have a similar disturbance spectrum¹⁶ and be subject to similar spontaneous MQs. Thus the test coil may make the use of passive control nearly as satisfactory as the more complex active control procedure.

A prototype test coil is being built to be used in vapor-block and quenching studies. It will also be used in an attempt to demonstrate the existence of a stable normal zone and in a study of MQ control concepts described in this report. By presenting these concepts now, we hope to stimulate interest in their development in magnets larger than our 20-cm-diam experimental model.

VI. TRANSIENT HEAT FLUX

Until now we have ignored the fact that a steady state is not established instantly. Here we describe the qualitatively different ways in which one expects a CHF steady state to be approached with different heater and flow geometries, the published measurements of transient heat flux, and implications of these observations on our proposal for control of MQs.

A. Characteristics of Transient Boiling for Various Geometries

We show here that the initial transient boiling heat flux (TBHF) will be greater than a planned-for, steady-state CHF. We then discuss TBHF for other geometries.

1. Forced-Flow Boiling in Parallel Channels.

When a resistive segment first appears in a channel, the mass flux exceeds the flux needed in the steady state by the amount $\bar{G} - G_*$ (see Fig. 10). The extra fluid passing the heated surface lowers the temperature below that corresponding to CHF and also carries off a certain amount of heat in excess of the CHF value. Thus, if the design of a superconductive solenoid is based on appropriate CHF and vapor-block equations, forced flow provides a more than adequate transient mass flux.

2. Natural Convection Channel Boiling.

Characteristics of natural convection channel boiling are illustrated in Fig. 11. Although our known-flow, steady-state CHF equation fits both natural convection² and forced-flow^{1,5,7} measurements equally well, the approach to the steady state is altogether different in these two regimes because with natural convection the flow is identically zero when vapor first appears, whereas with forced flow the initial flow in the affected channel(s) is then at its highest level, $\bar{G}$.

These two regimes also differ in that opposite ends of the cooling channel are more vulnerable when the steady state has been reached. With natural convection a heated top, or downstream, segment will generate less mass flow than will a heated bottom segment, owing to the chimney-like (hydrostatic

Fig. 10.

Transient heat and mass flux for a forced-flow, parallel-channel cooling mode. G_* is obtained from Eq. (4).

Fig. 11.

Schematic of natural-convection channel boiling. A chimney effect is reported in Ref. 19.

head) effect¹⁹ of vapor above the bottom segment. With forced flow the reverse may be true—the upstream end probably is more vulnerable because of the effect of vapor block. (The preceding statement could be in error if the forced flow were generated by a blower or fan-type pump that allowed the channel to sense the hydrostatic head of the external bulk liquid.) Only with respect to time of equilibration are the segments in the same sequence for both cooling regimes.

3. Pool Boiling. A schematic representation of pool boiling, Fig. 12, shows the steady state being reached almost immediately because bubbles rising from a horizontal surface can influence liquid influx only when they are within a few bubble-breakaway diameters of the heater (0.5 mm for helium at the boiling point).²⁰ The high levels of transient heat flux from pool walls, observed by Steward,²¹ are not evident in Fig. 12 because for purposes of comparison with critical boiling we assume that $\Delta T (= T_{\text{wall}} - T_{\text{bath}})$ is of the order of 0.5 K, a typical value at CHF. Not included in the pool-boiling curve are the consequences of homogeneous (explosive) nucleation so elegantly demonstrated by Brodie et al.²² in liquid helium experiments, which unfortunately were limited to sub-CHF conditions. Figure 12 shows that even where critical pool boiling is rele-

Fig. 12.

Schematic of pool boiling for $\Delta T \sim 1$ K. A square-root wall-height dependence predicted by Eq. (2) (at $D \rightarrow \infty$) is noted in Ref. 9. Orientation effects for a 1-cm-diam. surface are noted by Lyon.²¹ The indicated area dependence for boiling from the bottom side of a heater is speculative. The high values of transient heat flux reported by Steward²¹ are not shown because they occur only at wall temperatures in excess of steady-state CHF temperatures, $\Delta T \sim 1$ K.

vant, as in the design of a potted solenoid, CHF is reached first at the under surface of the magnet, where the CHF is much lower than at the top surface and where there may be an as yet unlooked-for size effect on CHF.

4. Effects of Porous Walls. Porous channel walls alter both natural convection and forced flow, but changes appropriate to a calculation of CHF would be irrelevant in the case of natural convection and probably intractable in the case of forced flow. For natural convection the CHF will be reduced for a heated bottom segment because a leaky chimney does not draw well. However, the limiting CHF is that of the top segment, whose CHF is unaffected by porosity below it. It therefore follows that, for natural convection, cooling, leaky channel walls will tend to increase the frequency of MQs, but will not decrease the limiting CHF. For forced flow, the

vulnerable bottom segment will be less affected by vapor block in the presence of leaky walls, but by how much? The answer will be difficult to determine and probably differ for every magnet winding, operating temperature, and flow rate. However, the effects are generally beneficial and can be ignored without compromising the design of a porous-wall forced-flow magnet.

5. Natural Convection Plus Forced Flow. Characteristics of transient boiling with natural convection *plus* a small added forced flow may be significantly better than in the absence of forced flow, especially if hard, low-friction insulation and spacers are used in the winding.^{23,24} The addition of forced flow guarantees continual mass flow in all portions of the magnet. Even an initial flow of an order of magnitude less than steady-state CHF for natural convection may provide a significant improvement over the near-zero initial mass flow available with natural convection alone.

Low coefficients of friction reduce the total slip-caused heating during training. If the sliding surfaces are also hard, many small slippages will occur instead of a few large ones. If the resulting heat pulses are small enough and if vapor is removed continuously from all disturbance sites, the conductor may never reach the S-N transition temperature (or would reach only resistive zones smaller than the MPZ¹⁸).

B. Relevant Transient Heat Flux Measurements

There is some experimental evidence that the condition of critical nucleate boiling is unique in the rapidity with which the temperature rise of a heated vertical wall (ΔT_c) reaches the critical steady-state value, ΔT . Stewards's measurements on two different geometries²¹ show that within 0.02 ms after

imposition of a heating rate typical of CHF, 0.5 W per wetted cm², $\Delta T_c = 0.9 \Delta T$. At one-fifth or double this heating rate, 10 ms are needed for a temperature rise of 90% of ΔT . Thus an equilibrium wall temperature is reached quickly under CHF conditions but is reached orders of magnitude more slowly at higher or lower heat fluxes.

The measured geometry was either a vertical film of graphite in bulk liquid or that forming one wall of a 0.15-cm-thick forced-flow channel.

C. Implications for Miniquench Control

Heat pulses of interest here are those that raise the temperature of a conductor by ~ 0.5 K or more, since CHF occurs at $\Delta T \sim 0.5$ K. For recovery of superconductivity, any excess ΔT_c above 0.5 K must be taken up sooner or later by an increase in heat flow above the CHF value. Several modes of heat transfer may participate in reducing ΔT_c to 0.5 K: (1) heat flow in the conductor itself, through the N-S interface; (2) a high level of transient heat flux such as has been observed by Steward²¹ at high ΔT_c ; (3) the excess transient mass flux $\bar{G} - G_c$; and (4) a slight increase in steady-state mass flux above the value G_c predicted by Eq. (4). Mode (4) may indeed result in a very slight increase in G because the excess heat in the original heat pulse beyond that taken up by modes (1) and (2) will cause trouble only if it causes a significant rise in conductor temperature at a point 1/2 turn distant from the point of origin of the heat pulse that initiated the MQ.

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APPENDIX A

PREPARATION AND EVALUATION OF TABLE I

I. THERMAL CONDUCTANCE OF CHANNEL WALL, $k\tau$

The channel-wall conductance term, $k\tau$, has the values given in Table I. These were calculated by us from the stated wall material and thickness and from published values of thermal conductivity.²⁵ To account properly for the high axial conductance of heavy-walled tubular channels,^{6,6} we consider τ to be the ratio of wall cross section to wall-fluid perimeter. Of the listed properties, $k\tau$ has by far the greatest variation—a factor 10^7 . For copper^{6,7} and silver,⁸ k depends strongly on the degree of annealing, even in commercial-grade material. Because of the large uncertainty in the actual value of k for pure metals, we usually made two fits, using "annealed k " and "work-hardened k " values. In general, the s.d. for "annealed k " values gave a slightly better fit; therefore, in Table I and in all equations in this report k represents annealed commercial-grade material.

A $k\tau$ term definitely is needed to fit the data of Table I. When formulations not containing $k\tau$ were fitted, $\phi_{\text{obs}}/\phi_{\text{calc}}$ followed a definite trend, ranging from 0.5 at the lowest $k\tau$ to 1.7 at the highest $k\tau$, and the s.d. of the fit rose by a factor of 2.

With low $k\tau$, heat produced in any part of the channel must flow into and cause vaporization of liquid near the point of origin of the heat. With high $k\tau$, a fraction of heat originating at the (critical) downstream end of the channel need not enter that liquid-deficient part of the channel but instead may proceed toward the upstream end where liquid is more plentiful. In effect, a high $k\tau$ is equivalent to an increase in the effective area of contact between the heated wall and the liquid.

In one important qualitative aspect, the experiments of Refs. 1-7 do not describe adequately the effect of wall conductance in the cooling channel of a real magnet, where alternating segments of high- k wire are separated by low- k insulation. In that case one might expect ϕ to be limited by the low- k segments, which prevent the upstream flow of heat.

II. SHAPE FACTOR, S

In Table I, 111 of the measurements are for tubing ($S = 4$); 19 are for $S = 1$ (1 wall heated); only 6 are for $S = 2$ (both walls heated). Thus most of the data apply to a tubular channel—a shape unlikely to be found in channels between the windings of a magnet. To counteract the problem, the role of S was considered in the solution of a similar problem, namely, development of a correlation equation for CHF in natural convection boiling of helium in channels. In that case the situation is reversed: there is a minimal amount of data for $S = 4$ (9 measurements)⁸ and a large amount for $S = 1$ (26 measurements) or 2 (46 measurements).⁹

III. DIAMETER OF TUBE OR SEPARATION BETWEEN CHANNEL WALLS, D

The data on D are somewhat out of balance because 119 are for $D = 0.1$ or 0.2 cm. As in the case of S , functional forms^{8,9} used successfully in fitting natural convection data must be used to select the form of a dependence of ϕ on D .

IV. NUCLEATE BOILING LENGTH, L

Boiling length L is the distance required for the quality (mass fraction of vapor) to change from zero (liquid at its boiling point) to X , the critical quality. In the GHJ measurements⁸ the onset of film boiling could be detected at any point along the 10-cm-long heated test section, where temperature was monitored at 10 equally spaced positions. To determine the point of film onset (or CHF point) at distance ℓ_c from the channel entrance, we analyzed data from 53 plots of wall temperature vs position, assuming $T_w - T = 0.5$ K to be indicative of CHF. (Data for which $L < 1$ cm were omitted because the percentage uncertainty in L was too great.) For data

sets other than those of GHJ the heat flux was controlled to cause film boiling to begin at a selected thermometer, usually one located at the downstream end of the heated channel.

In 40 measurements where nonzero quality occurred at test-section inlets, we calculated the position, ℓ_o , of zero quality on the assumption that

$$L/X = (\ell_c - \ell_o)/X = (\ell_c - \ell_{in})/(X - x_{in}) , \quad (A-1)$$

which is equivalent to an assumption of uniform heat flux at the interface of wall and fluid and of zero heat flow along the channel wall. Negative x_{in} is representative of supercooled liquid at the inlet and $L < \ell_c - \ell_{in}$. For cases of positive x_{in} , L is an apparent boiling length extending upstream from the test section.

In support of Eq. (A-1), the fitted $x_{in} = 0$ data show no clear trend when deviations are plotted against x_{in} . Also, a linear least squares fit to the 33 accepted points yields deviations of $[1.2 \pm 0.011 (x_{in})] \%$, with a coefficient of determination $r^2 = 0.01$. (If $r^2 = 1$ we have a perfect fit; if $r^2 = 0$ there is no correlation.) We conclude that Eq. (A-1) is acceptable.

V. TEMPERATURE-DEPENDENT PROPERTIES OF THE FLUID

Instead of listing the many relevant temperature-dependent properties we list only the fluid temperature because it provides access to all other properties.²⁰ The 4.05 to 5.4 K variation in T is sufficient to show that for a given channel ϕ reaches a peak value within that interval. Data between 4.7 and 5.0 K are lacking, but Eq. (3) indicates a peak at 4.77 K and Eq. (4) indicates a peak at 4.54 K. The average of those temperatures, 4.66 K can be compared with the latent heat of vaporization, which has a peak at 3.0 K; with CHF for pool boiling of helium,²⁷ which peaks at 3.8 K; with the peak of the Kutateladze pool-boiling number²⁸ at 4.1 K; and with Eq. (2), based on an approximation to a hydrodynamic theory of channel boiling,¹⁰ which has a peak at 4.46 K. By the exact equation of that theory, at high pressure drop (high Z_0 in Eq. (3) of Ref. 10), $\phi \propto \rho_L \lambda \sqrt{\beta - 1}$, which has a peak at 4.63 K, in excellent agreement with the above average of the two best forced-flow correlations in this report.

APPENDIX B

DERIVATION OF CORRELATION EQUATIONS

A least squares computer program was used to minimize deviations of the logarithm of expressions of the form

$$X \text{ or } \phi/\lambda = C_c Y_1^{C_1} Y_2^{C_2} \dots Y_i^{C_i} , \quad (B-1)$$

where each Y_i is a function of one or more of the parameters of Table I. For dimensionless correlation equations, the dependent variable is the critical quality, $X = \phi LS/(\lambda GD)$, and all Y 's are dimensionless numbers containing two or more parameters, some of which may appear in several of the i numbers. For what we call parametric equa-

tions the dependent variable is ϕ/λ , and Y_i is usually a function of only one parameter but may contain a product of independent parameters that do not appear elsewhere in the equation. For example, $1 + C_k L/D$ qualifies as a parametric term, provided neither L nor D is present elsewhere; both $Y_1 = \rho_L/\rho_V$ and $Y_2 = 1 + C_j \rho_L/\rho_V$ can be present because ρ_L and ρ_V are unique functions of bath temperature T .

In some early formulations of Eq. (B-1) as many as three functions were composed of two added terms, such as $1 + C_k L/D$. To avoid developing a new program to handle each two-term function, the best value of C_k was read at the minimum of a plot of the s.d. of a fit vs several estimates of C_k . The

technique is practical for three such functions only if they are independent of each other, as is the case in a parametric equation but not necessarily so in a dimensionless one. In this way we determined that all temperature-dependent properties of the liquid could be accounted for by two terms containing only $\beta = \rho_L/\rho_V\beta^b$ and $(1 + 32/\beta^2)^c$. We also determined that 0.49 cm was typically the best value of $B(S)$ for $S = 4$. The value $B(4) = 0.63$ cm, which fits the tubular natural convection CHF data of Lehongre et al.⁸ also can be used in a forced-flow equation if the exponent of the cross-section number $Cr = D/[D + B(S)]$ is free to float in the least squares analysis. Similar adjustments were made in the constants of the Lehongre number Le [cf. Eq. (1)] but only a minor reduction of the s.d. of the fit was obtained, so we retained the form applicable to natural convection.

Selected dimensionless correlation equations, arranged in order of decreasing s.d. of the fit, are shown in Table B-I. The fit is better by several per cent when Cr^1 replaces Le^1 . A further improvement of 2.6% occurs when the exponent of Cr is allowed to deviate from its best-for-natural-convection value, 1.

The other dimensionless numbers in Table B-I equations were selected mainly because the s.d. of a fit generally was lower with that set of numbers than with other tested combinations.

The number labeled Wa is defined as the ratio of the term $k\tau(P/L)$ (representative of axial heat flow in the channel wall of heated perimeter P) to the term $K'LPT^*$ (representative of Kapitza heat flow across the interface between wall and fluid). Despite the different wall materials involved in Refs. 1-7, we used only one value of K' because the wall materials have comparable densities and because small variations in K' when raised to the small (expected) value of the Wa exponent are negligible. For all data sources we used $K' = 0.05 \text{ W cm}^{-2}\text{K}^{-1}$, an average of the published values for copper.²⁹

A similar comparison of selected parametric equations is shown in Table B-II, again in order of decreasing s.d. of the fit. Again using Cr , we find the

fit to be better by several per cent than when Le^1 is used. The floating exponent on Cr also makes a small additional improvement.

Not only must a low s.d. be achieved but also the number of fitted exponents must be as small as possible and plots of ϕ/ϕ_{calc} vs each relevant property must be free of obvious trends. Only by close examination of selected portions of the data can the equations of Tables B-I and B-II be evaluated adequately.

The dependencies of greatest concern are those involving S and D because of the relatively small amount of data for which $S = 1$ or 2 or for which $D \neq 0.1$ or 0.2 cm. The last three columns of Tables B-I and B-II show the m.d. and s.d. of ϕ in these small portions of the data. A good fit to all three subsets is achieved by the last, and only the last, equation of each table: Eqs. (3) and (4). Also, m.d. $\ll$ s.d. only in all three subsets of Eqs. (3) and (4). Evidently only Eqs. (3) and (4) provide adequate representations of the effect of S and D on ϕ .

The dependence and fit of Eq. (4) with respect to selected experimental variables are shown in Figs. 1-5. The error bars almost always cross the solid line. We conclude that the last parametric equation of Table B-II provides an adequate representation of the data of Table I.

The exponents above G , L , and $k\tau$ are nearly the same for ϕ_3 as for ϕ_4 . For a more comprehensive comparison, we determined the s.d. of ϕ_4/ϕ_3 . For the 131 fitted points, ϕ_3 differs from ϕ_4 by $-0.1 \pm 3.2\%$. We conclude that ϕ_3 also provides an adequate representation of the data of Table I.

Seven fitted exponents were needed to achieve an adequate dimensionless equation, whereas only six were needed for a parametric equation of comparable adequacy. After dozens of attempts to improve the dimensionless equation by incorporating terms of varying complexity and presumed physical significance, nothing worked better than the assortment that appears in ϕ_3 . We conclude that any physical significance attached to either of the two adequate equations resides in those dependencies common to both equations.

TABLE B-I
DIMENSIONLESS CORRELATION EQUATIONS FOR FORCED-FLOW CHF TO HELIUM

Columns 1-9 give C's of the equation $\phi SL/\lambda GD = C_0 \pi^4 Y_1^{C_1}$.
 Columns 10-13 give mean of 100 $\ln(\phi_{obs}/\phi_{calc})$ for portions of the fitted data.
 Columns 10-13 also give the standard % deviation of each fit.

$C_0 \backslash Y_1$	Le	Cr	Re	Fr	Pr	β	Ch	Wa	Mean $\pm$ Standard Deviation (~%)			
	$[1 + 0.022(Le/D)^{0.68}]^{-1}$	$(D/[D+B(S)])$	(GD/η_1)	$[G/\rho_1(\Delta P/6g)^{1/4}]$	$[(C_L \eta_1)/k_L]$	(ρ_L/ρ_v)	(SL/D)	$(k\tau/K'L^2T^3)$	All Data	S = 1 Data	S = 2 Data	D $\neq$ 0.1 or 0.2 cm
1.17	1	0	-0.015	-0.810	~ 1.855	-2.273	1.257	0.043	0 $\pm$ 21.1	18 $\pm$ 16	14 $\pm$ 15	13 $\pm$ 10
2.11	-0.423	0	0.154	-1.001	~ 1.726	-2.201	0.562	0.043	0 $\pm$ 16.8	10 $\pm$ 9	16 $\pm$ 20	15 $\pm$ 11
1.30	0	1	0.069	-0.760	~ 1.055	-1.637	0.978	0.077	0 $\pm$ 15.4	-12 $\pm$ 15	-3 $\pm$ 20	-3 $\pm$ 15
1.49	0	0.571	0.085	-0.850	~ 1.360	-1.889	0.888	0.062	0 $\pm$ 12.8	4 $\pm$ 20	-1 $\pm$ 12	4 $\pm$ 12

TABLE B-II
PARAMETRIC CORRELATION EQUATIONS FOR FORCED-FLOW CHF TO HELIUM

Columns 1-10 give C's of the equation $\phi/\lambda = C_0 \pi^4 Y_1^{C_1}$.
 Columns 11-14 give mean value of 100 $\ln(\phi_{obs}/\phi_{calc})$.
 Columns 11-14 also give the standard % deviation of each fit.

$C_0 \backslash Y_1$	Le	Cr	D	S	L	G	β	$1 + 32\beta^{-2}$	$k\tau$	Mean $\pm$ Standard Deviation (~%)			
	$[1 + 0.022(Le/D)^{0.68}]^{-1}$	$[D/(D+B)]$	(cm)		(cm)	(g/cm ² -s)			(W/K)	All Data	S = 1 Data	S = 2 Data	D $\neq$ 0.1 or 0.2 cm
1200	1	0	0	0	0	0.127	-4.369	-3.511	0.043	0 $\pm$ 23.3	-4 $\pm$ 7	18 $\pm$ 6	0 $\pm$ 14
30.9	0.576	0	0	0	0	0.201	-3.027	-2.418	0.051	0 $\pm$ 16.5	13 $\pm$ 12	20 $\pm$ 17	13 $\pm$ 12
25.7	0	1	0	0	-0.226	0.260	-2.474	-1.846	0.070	0 $\pm$ 14.8	-15 $\pm$ 19	-5 $\pm$ 19	-7 $\pm$ 14
45.3	0	0	0.545	-0.509	-0.241	0.223	-2.594	-2.014	0.060	0 $\pm$ 13.2	-3 $\pm$ 10	19 $\pm$ 18	7 $\pm$ 15
27.0	0	0.690	0	0	-0.236	0.234	-2.650	-2.039	0.062	0 $\pm$ 12.8	-3 $\pm$ 13	2 $\pm$ 20	2 $\pm$ 14

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