Chapter 12B

HEAT TRANSFER AND FLOW PHENOMENA II

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12B.1 Introduction

In forced convective boiling the boiling crisis* occurs when the heat flux is raised to such a high level that the heated surface can no longer support continuous liquid contact. This heat flux is usually referred to as the critical heat flux (CHF) or dryout heat flux. It is characterized either by a sudden rise in surface temperature caused by blanketing of the heated surface by a stable vapour layer, or by small surface temperature spikes corresponding to the appearance and disappearance of dry patches.

Failure of the heated surface may occur once the CHF is exceeded. High surface temperatures can be avoided by either operating at heat flux levels well below the critical heat flux or by operating at conditions where the post-dryout heat transfer is reasonably effective in keeping the surface temperatures at moderate levels. It is common practice in the thermal design of reactors to avoid dryout.

12B.2 Critical Heat Flux

12B.2.1 General

This chapter discussed the critical heat flux (CHF) for pool boiling or axial flow inside tubes or rod bundles. Axial flow CHF has been extensively studied and many excellent reviews are available (e.g., Tong, 1972; Hewitt, 1978; and Collier, 1980). Much effort has been spent on correlating the available CHF data; it is conservatively estimated that over 400 CHF correlations are currently available. This proliferation of CHF correlations illustrates the sad state-of-the-art in modelling the CHF phenomenon.

12B.2.2 Dryout Mechanisms

In flow boiling the dryout mechanisms may depend strongly on flow regime and phase distributions which in turn are controlled by pressure, flow rate and quality. Figure 1 shows the variation in CHF and dryout mechanisms with quality. The following dryout mechanisms are expected to be the most important ones:

Nucleation induced This type of dryout is encountered at high subcooling where heat is transferred very efficiently by nucleate boiling; bubbles grow and collapse at the wall. Some convection will take place between the bubbles.

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*Other terms used to denote the boiling crisis: burnout, dryout, departure from nucleate boiling (DNB).

Nucleation induced dryout occurs at very high surface heat fluxes. It has been suggested (Collier, 1980; Tong, 1972) that dryout is due to the spreading of drypath following microlayer evaporation under a bubble and coalescence of adjacent bubbles although no definite proof of this is yet available. The occurrence of dryout here only depends on the local surface heat flux and flow conditions and is not affected by upstream heat flux distribution. The surface temperature rise under these conditions is very rapid.

Bubble clouding In subcooled and saturated nucleate boiling the number of bubbles generated depends on the heat flux and bulk temperature. The bubble population density near the heated surface increases with increasing heat flux and a so-called bubble boundary layer (Tong, 1965,1972) often forms a short distance away from the surface. If this layer is sufficiently thick it can impede the flow of coolant to the heated surface. This in turn leads to a further increase in bubble population until the wall becomes so hot that a vapour patch forms over the heated surface. This type of boiling crisis is also characterized by a fast rise of the heated surface temperature.

Annular Film Dryout In the annular dispersed flow regime (high void fraction flow) the liquid will be in the form of a liquid film covering the walls and entrained droplets moving at a higher velocity in the core. Continuous thinning of the liquid film will take place due to the combined effect of entrainment and evaporation. At the dryout location the liquid film eventually breaks down. The temperature rise accompanying this film breakdown is usually moderate.

12B.2.3 Prediction Methods

CHF prediction methods may be subdivided into three types, i.e.:

(i) Local conditions type CHF correlations. CHF = f(P,G,X or α, cross section geometry). These correlations are convenient to use for predicting location and magnitude of the CHF. Effects of axial flux distribution, spacers, flux spikes and flow transients (e.g., flow stagnation) usually require a local conditions approach, sometimes combined with techniques which consider the upstream flow history (e.g., boiling length average approach, F-factor method, grid spacer factor).

(ii) Global conditions type correlations. The burnout power = $f(P,G,H_{in},Lh$, cross-section geometry). These correlations predict only the burnout power; they cannot be used to predict the location or magnitude of the CHF. Also, these correlations are incapable of considering the effect of a variation in axial flux distribution. They are primarily used to predict burnout power for a given geometry and axial flux distribution.

(iii) Standard CHF table method. As most empirical correlations and analytical models have a limited range of application, the need for a more general technique is obvious. Attempts have been made in the USSR to construct a standard table of CHF values for a given geometry (Doroshchuk, 1975). The table approach has been continued at Chalk River, at CEN-Grenoble and at the University of Ottawa using the Chalk River data base (10,000 tube CHF data). Table 1 shows the CHF table for an 8 mm tube and discrete values for P, G and X. Note that this table has the correct asymptotic trends (e.g., CHF = 0 at X = 1.0 and $CHF = CHF_{P_B}$ at G = 0).

12B.2.4 Discussion

Most CHF correlations are based on tube data. In general, the CHF in tubes is greater than the corresponding value in bundles because:

(a) the subchannel with the highest enthalpy usually reaches the boiling crisis before a subchannel at cross section average conditions
(b) of the cold wall effect: a cold wall reduces liquid available for cooling heated rods (Tong, 1972b)
(c) inside a subchannel, significant variation in velocities and near wall void fraction may occur (Groeneveld, 1973). This is particularly evident in the gap between adjacent rods of tightly spaced rod bundles. One can thus expect preferential CHF locations within a single subchannel
(d) upstream or fluid memory effects can become very important, especially in the net quality region. Large differences in subchannel enthalpy rise rates can result in significant asymmetric CHF patterns (McPherson, 1971).

Some of the above effects can be partially incorporated in subchannel codes which predict the flow, enthalpy and pressure in each subchannel. An excellent review of subchannel type analyses has been presented by Weissman (1975). Caution must be exercised when using subchannel codes as, frequently, verification data are lacking. Subchannel CHF correlations, based on bundle CHF data and predicted subchannel conditions are especially unreliable. Their application should be limited to the narrow range of their data base. Subchannel codes currently under development are based on 2- or 3-fluid models, (e.g., Tahir, 1983); they are expected to be capable of predicting the bundle CHF with a much better accuracy than their predecessors.

Tube and annuli CHF correlations may be useful in predicting the CHF behaviour of bundles, especially for well-balanced bundles having wide rod spacings. Correlation factors should then be used to include specific bundle characteristics (Groeneveld, 1974).

12B.3 Transition Boiling

12B.3.1 General

Transition boiling is a rather unique heat transfer mode because, here, the heat flux generally decreases with an increase in surface temperature. It is basically a combination of unstable film boiling and unstable nucleate boiling alternately existing at any given location on a heating surface.

The transition boiling section of the boiling curve is bounded by the critical heat flux and the minimum heat flux (Fig. 2). The critical heat flux has been extensively studied but, there are still wide ranges of conditions where data are virtually nonexistent. The minimum heat flux has undergone less study; it is known to be affected by flow conditions, fluid properties and heated surface properties.

In pool boiling, at surface temperatures just above the boiling crisis temperature, the heated surface is partially covered with unstable vapor patches, varying with space and time. The formation of such dry patches is accompanied by a drastic reduction in heat transfer coefficient corresponding to the change from nucleate boiling to film boiling; the corresponding reduction in local vapor generation permits the liquid to momentarily rewet the heated surface.

TABLE 1 : STANDARD CHF TABLE (kW/m^2)

PRESSURE (KPA)	G ($KG/M^2/S$)	QUALITY -.15	-.10	-.05	0.00	.05	.10	.15	.20	.25	.30	.40	.50	.60	.70	.80	.90	1.0
100	0	3930	3430	2045	1200	1000	980	800	750	740	733	500	500	450	356	212	89	0
100	50	4000	3500	2400	1700	1600	1500	1250	1200	1150	1108	873	756	710	506	386	350	0
100	100	4800	4200	3100	2200	2100	2000	1450	1000	850	820	750	727	700	667	493	330	0
100	200	5600	4900	3800	2600	2550	2500	1500	1400	1350	1300	1200	1160	1108	863	532	407	0
100	300	6400	5600	4500	3000	3000	3000	2200	2100	2000	1978	1900	1774	1443	827	620	450	0
100	500	7200	6300	5200	3600	3550	3500	3450	3350	3300	2486	2354	2318	1251	662	633	440	0
100	750	8000	7000	5900	5500	5000	4700	4572	4105	3186	2986	2887	2394	1308	905	700	400	0
100	1000	8800	7600	6600	4800	4600	4400	4230	3552	3536	3400	3319	2534	1514	1100	600	300	0
100	1500	9600	8200	7000	5500	4830	4200	4600	4500	4500	4000	3823	3266	2200	1100	600	300	0
100	2000	10000	8800	7700	5900	5400	5300	5260	5100	5050	5000	4900	4840	2900	1100	600	300	0
100	3000	10500	9400	8400	7300	6500	6000	5992	5400	5300	5200	5017	3500	2700	1100	600	300	0
100	4000	11000	10000	9000	6800	6683	6500	6100	5300	5000	4600	4000	3000	2000	1000	500	300	0
100	5000	11500	10600	9500	8358	7951	7600	7400	5200	4400	3800	3000	2500	1500	900	500	300	0
100	7500	12000	11000	10000	9500	9200	9000	7500	5000	4000	3000	2200	2000	1200	800	400	300	0
150	0	4000	3500	2400	1350	1200	1100	950	947	900	887	680	600	560	377	236	111	0
150	50	4100	3600	2700	1900	1800	1700	1500	1400	1390	1265	984	793	600	521	403	300	0
150	100	4800	4200	3200	2400	2200	2000	1900	1800	1400	1072	944	920	900	890	680	450	0
150	200	5400	4800	3800	2700	3600	2500	2100	1600	1500	1400	1325	1304	1200	1100	1000	500	0
150	300	6000	5400	4400	3000	3000	3000	2700	2400	2200	1700	1650	1600	1500	1400	800	500	0
150	500	6600	6000	5000	3700	3600	3500	3100	2700	2227	1800	1668	1500	1300	1100	670	450	0
150	750	7200	6600	5600	4300	4150	4000	3500	2200	2000	1900	1800	1700	1500	1170	650	400	0
150	1000	7800	7200	6200	5000	4700	4400	3700	3400	3100	2900	2700	2300	2200	1100	600	350	0
150	1500	8400	7600	6800	5500	5200	4800	3800	3600	3400	3100	3000	2800	2500	1100	550	300	0
150	2000	9000	8200	6000	5500	4988	4529	4135	4000	3900	3700	3500	3400	3000	1000	550	300	0
150	3000	9600	6240	5800	5600	5400	5200	4600	4100	3800	3300	3250	3200	2500	1000	500	300	0
150	4000	10000	6636	6000	5766	5214	5000	4700	4200	3600	2800	2800	2600	2000	1000	450	300	0
150	5000	10500	9900	9100	8901	7254	6500	5700	4000	3100	2600	2300	2000	1500	900	450	300	0
150	7500	11000	10400	9700	9000	8600	8000	6500	5000	3000	2200	1800	1600	1000	600	400	300	0
200	0	4820	3700	2774	1450	277	262	248	233	219	204	175	146	117	87	58	29	0
200	50	4955	4000	3094	2313	1794	1641	1562	1483	1405	1326	1244	1044	700	600	593	468	0
200	100	5000	4100	3200	2600	2300	2100	2000	1900	1300	1200	1085	900	751	700	650	315	0
200	200	5200	4300	3400	2800	2500	2300	2150	1400	1350	1325	1300	1250	1200	1142	800	315	0
200	300	5400	4450	3500	3000	2700	2400	2200	2150	2100	2000	1810	1461	1000	700	600	350	0
200	500	5600	4650	3700	3150	2900	2500	2250	2100	2000	1800	1649	1500	1100	800	450	300	0
200	750	5800	4850	3900	3300	3000	2650	2350	2118	2066	1826	1767	1600	1000	600	450	300	0
200	1000	6000	5000	4000	3400	3000	2600	2350	2140	1958	1800	1700	1600	1000	600	450	300	0
200	1500	6200	4600	3800	3300	3000	2600	2350	2284	2119	1800	1700	1500	1000	600	450	300	0
200	2000	6400	4500	4000	3500	3000	2600	2350	2150	2050	1800	1700	1400	1000	600	450	300	0
200	3000	7000	5742	4287	3900	3000	2600	2350	2150	2050	1800	1700	1400	1000	600	450	300	0
200	4000	8500	6411	4800	4500	3000	2600	2350	2150	2050	1800	1700	1400	1000	600	450	300	0
200	5000	6607	6120	5267	4845	3000	2600	2350	2150	2050	1800	1700	1400	1000	600	450	300	0
200	7500	6590	6465	5581	5077	3000	2600	2350	2150	2050	1800	1700	1400	1000	600	450	300	0
300	0	4650	3667	2683	1700	325	308	291	274	257	240	205	171	137	103	68	34	0
300	50	5063	4292	3296	2975	2481	2327	2248	2168	2014	1860	1551	1067	637	592	549	500	0
300	100	5200	4500	3500	3400	3200	3000	2900	2800	2600	2400	1212	900	856	825	800	700	0
300	200	5600	4700	3600	3500	3200	2900	2800	1760	1717	1301	1209	1200	1170	1140	849	600	0
300	300	4592	3324	3300	3250	3200	2800	2700	2600	2500	2400	2091	1746	1084	511	287	250	0
300	500	4634	3367	3300	3250	3200	2700	2600	2575	2550	2500	1988	1373	945	400	250	200	0
300	750	6000	5000	3900	3800	3200	2600	2500	2400	2337	2100	1687	1400	1396	386	281	200	0
300	1000	6200	5200	4000	3900	3200	2600	2500	2400	2229	2100	1800	1500	1200	700	400	200	0
300	1500	6400	4154	4100	4000	3200	2600	2500	2456	2301	2100	1800	1500	1200	700	400	200	0
300	2000	6600	4300	4200	4100	3200	2600	2500	2294	2200	2100	1800	1500	1200	700	400	200	0
300	3000	7778	5690	4800	4706	3200	2600	2500	2294	2200	2100	1800	1500	1200	700	400	200	0
300	4000	8443	6302	4518	4400	3200	2600	2500	2294	2200	2100	1800	1500	1200	700	400	200	0
300	5000	5419	4851	3967	3525	3200	2600	2500	2294	2200	2100	1800	1500	1200	700	400	200	0
300	7500	5816	5198	4236	3630	3200	2600	2500	2300	2200	2100	1800	1500	1200	700	400	200	0
450	0	4540	4222	1900	1313	380	360	340	320	300	280	240	200	160	156	93	90	0
450	50	5035	4627	2330	2250	2195	2115	2035	1993	1950	1870	1860	1625	896	633	567	500	0
450	100	5200	4100	3400	2900	2800	2700	2600	2550	2200	2000	1500	1234	1217	1090	949	585	0
450	200	5600	4150	3400	3000	2800	2600	2550	2500	2200	1700	1650	1600	1500	1243	841	572	0
450	300	4145	2896	2850	2825	2800	2600	2500	2450	2400	2375	2358	1841	1677	744	447	414	0
450	500	4187	2939	2900	2850	2800	2600	2400	2400	2400	2400	2200	1738	1240	435	275	254	0
450	750	6000	4300	3400	3100	2800	2600	2300	2150	2000	2785	1439	1024	876	395	300	256	0
450	1000	6200	4400	3400	3200	2800	2600	2100	1976	1821	1500	1300	1000	564	500	300	200	0
450	1500	6400	4145	3060	3200	2800	2600	2000	2004	1849	1500	1250	673	450	500	300	200	0
450	2000	6600	3521	3400	3300	2800	2600	2100	1800	1500	1300	1200	1000	700	500	300	200	0
450	3000	9216	5752	4146	3716	2800	2600	2200	1800	1500	1300	1200	1000	700	500	300	200	0
450	4000	9594	6210	4292	4076	2800	2600	2200	1800	1500	1300	1200	1000	700	500	300	200	0
450	5000	6619	6002	5440	3500	2800	2600	2200	1900	1500	1300	1200	1000	700	500	300	200	0
450	7500	6878	6271	5707	3600	2800	2600	2200	2000	1600	1300	1200	1000	700	500	300	200	0
700	0	4482	4264	2059	1488	448	424	401	377	354	330	283	236	189	97	72	47	0
700	50	5021	4669	2488	1971	2212	2056	1825	1594	1363	1133	971	809	496	363	424	472	0
700	100	5200	4200	3500	3000	2800	2600	2300	2000	1700	1400	1200	1000	842	764	691	572	0
700	200	5600	4250	3600	3200	3000	2900	2700	2600	2500	1900	1650	1589	1500	1450	947	647	0
700	300	5800	4300	3700	3400	3000	2800	2700	2600	2550	2500	2461	2404	1600	1140	662	529	0
700	500	5900	4400	3800	3500	3000	2900	2800	2700	2650	2600	2500	2396	1376	645	419	359	0
700	750	6000	4600	3900	3600	3000	2700	2600	2500	2400	2300	2229	1419	717	412	410	376	0
700	1000	6200	5060	4094	3600	3000	2800	2700	2690	2133	1593	1306	888	484	269	250	200	0
700	1500	6400	4991	4025	3600	3000	2500	2400	2380	1837	1022	1138	722	274	199	175	150	0
700	2000	6600	5200	4400	3600	3000	2500	2200	1800	1500	1300	1300	900	250	200	200	150	0
700	3000	6800	5400	4600	3600	3000	2500	2200	1800	1500	1300	1200	900	250	200	200	150	0
700	4000	7000	5600	4800	3600	3000	2500	2200	1800	1500	1300	1200	900	250	200	200	150	0
700	5000	7200	5800	4900	3600	3000	2500	2200	1900	1500	1300	1200	900	250	200	200	150	0
700	7500	7400	6000	5000	3600	3000	2500	2200	2000	1600	1300	1200	900	250	200	200	150	0
1000	0	4480	3866	3240	2620	509	483	456	429	402	375	322	268	214	161	107	54	0
1000	50	5620	5092	4560	4105	3427	3271	3114	3032	2801	2569	2330	1942	1104	875	814	426	0
1000	100	6000	5500	5000	4600	4400	4200	4000	3900	3600	3300	3000	2500	1400	1113	1050	550	0
1000	200	8000	7500	7000	6000	5800	5600	5400	5100	4700	4400	4300	4200	2327	1697	1139	702	0
1000	300	8000	7500	7000	6500	6300	5600	5400	5100	4700	4400	4250	3914	2202	1544	918	683	0
1000	500	8000	7500	7000	6500	6200	5600	5400	5100	4800	4663	4500	3726	2083	1095	609	437	0
1000	750	8000	7500	7000	6500	6100	5600	5400	5000	4900	4785	3936	2297	1134	683	549	500	0
1000	1000	8000	7500	7000	6500	6000	5600	5300	5100	4845	4193	2934	1613	867	575	376	250	0
1000	1500	8000	7500	7000	6500	5900	5300	5000	4800	4459	3354	2366	1307	624	276	188	100	0
1000	2000	8000	7500	7000	6500	5700	5200	4830	4400	3354	3300	3226	2493	800	250	150	100	0
1000	3000	8000	7500	7000	6500	5500	5100	4700	4200	3573	3400	3326	1300	750	250	150	100	0
1000	4000	8000	7500	7000	6500	5300	5000	4500	4000	3400	2800	1850	1150	700	250	150	100	0
1000	5000	8000	7500	7000	6500	5400	4900	4400	3800	3300	2600	1650	1000	650	250	150	100	0
1000	7500	8000	7500	7000	6500	5500	4800	4300	3600	3200	2300	1500	900	600	250	150	100	0

TABLE 1 : STANDARD CHF TABLE (cont'd)

PRESSURE (KPA)	G (KG/M²/S)	QUALITY -.15	-.10	-.05	0.00	.05	.10	.15	.20	.25	.30	.40	.50	.60	.70	.80	.90	0.0
1500	0	4525	4007	3488	2970	584	553	523	492	461	430	369	307	246	184	123	61	0
1500	50	5781	5100	4922	4493	3596	3513	3356	3273	3115	2883	2567	2327	1149	1021	879	426	0
1500	100	6200	5500	5400	5000	4600	4500	4300	4200	4000	3700	3300	3000	1450	1300	1131	548	0
1500	200	7100	6900	6600	6400	6200	6000	5700	5400	5000	4100	3600	3100	2131	2062	1314	779	0
1500	300	7400	7100	6700	6500	6300	6000	5700	5300	5200	4400	3800	3294	3000	2122	1334	843	0
1500	500	7700	7200	6700	6400	6100	5800	5500	5300	5300	4649	4500	4297	3152	1859	997	608	0
1500	750	8000	7200	6700	6300	5900	5600	5400	5200	5150	5100	4551	2990	1765	1087	681	443	0
1500	1000	8000	7200	6700	6250	5700	5600	5550	5500	5450	5169	3733	2116	1125	793	450	366	0
1500	1500	8000	7200	6700	6250	5500	5300	5275	5271	4969	4591	2913	1511	873	455	236	200	0
1500	2000	8000	7200	6700	6200	5500	5200	4900	4100	4000	3977	2505	1418	1000	800	400	200	0
1500	3000	7529	6720	6700	6100	5600	5100	4800	4813	4200	3700	2300	2100	1000	800	400	200	0
1500	4000	7645	6836	6700	6100	5600	5000	4700	3800	3800	3100	1900	1800	1000	800	400	200	0
1500	5000	8500	7500	6900	6300	5600	4800	4400	3600	3500	2600	1700	1500	1000	800	400	200	0
1500	7500	9000	8000	7100	6300	5500	4700	4100	3600	3300	2350	1600	1200	1000	800	400	200	0
2000	0	4581	4130	3680	3230	643	609	575	541	507	474	406	338	271	203	135	68	0
2000	50	5870	5420	4970	4708	3836	3752	3594	3510	3352	3118	2801	2710	1193	941	927	434	0
2000	100	6300	5850	5400	5200	4900	4800	4600	4500	4300	4000	3600	3500	1500	1287	1191	556	0
2000	200	7000	6900	6800	6700	6600	6300	6000	5600	5300	4800	4400	4000	2151	2020	1311	824	0
2000	300	7600	7350	7200	6900	6600	6600	5900	5700	5500	5200	4950	4181	4313	2749	1500	869	0
2000	500	8200	7800	7500	7200	6600	6600	6200	5964	5514	5183	4750	4457	3688	2222	1274	777	0
2000	750	8400	8000	7600	7200	7000	6981	6361	6200	6100	6096	5129	3590	2319	1281	954	586	0
2000	1000	8700	8400	7800	7762	7061	6718	6331	6047	5573	5581	4234	2769	1713	1029	607	479	0
2000	1500	8800	8400	7800	7144	6867	6459	5649	5000	4900	4870	3239	1909	1041	704	316	300	0
2000	2000	9200	8500	7800	7000	6500	5800	5078	4650	4395	4111	2218	1073	481	415	400	300	0
2000	3000	8944	8135	7800	7000	6200	5600	5506	4918	4717	4508	3217	1600	1200	1000	400	300	0
2000	4000	9060	8251	7800	6900	5900	5500	5080	4900	4889	4415	2816	1400	1200	900	400	300	0
2000	5000	10000	8500	7000	6500	5800	5500	5200	4600	4500	4202	2400	1400	1200	900	600	500	0
2000	7500	10300	8500	7200	6100	5500	5200	4930	4500	4324	2800	1700	1500	1300	1100	800	600	0
3000	0	4650	4290	3930	3570	919	690	651	613	575	536	460	383	306	230	149	147	0
3000	50	6038	5573	5108	4868	4130	3997	3913	3753	3594	3359	3040	2721	2327	882	391	323	0
3000	100	6500	6000	5500	5300	5200	5100	5000	4800	4600	4300	3900	3500	3000	1223	831	726	0
3000	200	8000	7500	7000	6600	7000	6700	6300	6000	5700	5400	4800	4000	3503	2055	1425	837	0
3000	300	9000	8500	7352	7029	7900	7700	7300	6970	6600	6260	5500	4233	4200	2614	1664	884	0
3000	500	9600	9300	7968	7645	8000	7700	6734	6479	6272	5902	5589	4064	3719	2522	1769	1035	0
3000	750	9800	9300	8700	8410	7227	6948	6945	6388	6175	6133	5519	3637	2825	1996	1281	663	0
3000	1000	9800	8000	7187	7679	7010	6648	6500	6380	5755	5239	4174	3246	2257	1823	1074	1006	0
3000	1500	9800	7552	7184	7000	6749	6548	5690	5200	4771	4486	3410	2545	1787	1623	1500	1275	0
3000	2000	9900	9000	8500	8000	7500	6975	5878	5125	4374	4107	2795	2099	1288	1000	1000	600	0
3000	3000	10000	9000	7600	8400	7482	5986	5401	4973	4443	3043	1943	2109	1133	1050	1000	600	0
3000	4000	10500	9000	7500	6517	5754	5409	5014	4629	3915	2134	2000	1900	1750	1350	1000	600	0
3000	5000	10800	8342	7171	6020	5367	5164	4685	4117	3564	2100	1900	1900	1750	1350	1000	600	0
3000	7500	11200	8608	7200	5504	4590	4117	3779	3600	3424	2200	2150	2000	1800	1500	1200	700	0
4500	0	4676	4400	4125	3850	1362	793	730	687	644	601	515	429	344	240	134	100	0
4500	50	5669	5300	5006	4713	3941	3573	3482	3247	2711	2175	1629	1232	836	372	338	300	0
4500	100	6000	5600	5300	5000	4800	4500	4400	4100	3400	2700	2000	1500	1000	800	746	666	0
4500	200	7900	7300	6700	6000	5800	4900	4700	4600	4200	3700	3200	2800	2500	1600	1419	954	0
4500	300	8100	7600	6490	6367	6300	5400	5300	5200	4700	4600	4440	3627	3480	2240	1620	1049	0
4500	500	8200	7800	7106	6783	5900	5516	5035	4500	4181	3852	3480	3067	2500	2358	1691	1103	0
4500	750	8300	8000	7500	6600	5593	5121	4802	4500	4300	4200	3923	2704	2602	2301	1631	965	0
4500	1000	8700	6500	6244	6067	5803	4800	4622	4385	4350	4336	3731	3032	2554	2552	1400	875	0
4500	1500	8900	6138	5724	5600	5500	5407	4846	4511	4083	3974	3178	2663	1976	1713	1200	800	0
4500	2000	6239	6484	5422	5422	5400	5233	4754	4204	3906	3821	2762	2064	1415	1300	1000	200	0
4500	3000	6580	6177	5453	5100	5054	4818	4606	4161	3743	3156	2013	1324	639	391	300	224	0
4500	4000	8901	6682	6034	5248	4849	4506	4248	3849	3251	2446	1700	1600	1500	393	309	200	0
4500	5000	9200	7836	6453	4917	4528	4273	4018	3671	2975	2263	1700	1600	1500	1300	1100	900	0
4500	7500	9400	8354	6800	4923	4375	3915	3613	3600	3214	2770	2600	2200	1800	1500	1300	1000	0
7000	0	4538	4348	4160	3970	1921	1221	868	761	713	666	570	475	380	195	121	100	0
7000	50	5485	5137	4790	4443	3780	3380	3142	2965	2578	1966	1493	1169	920	525	288	200	0
7000	100	5800	5400	5000	4600	4400	4100	3900	3700	3200	2400	1800	1400	1100	900	668	660	0
7000	200	6500	6000	5500	5093	4800	4600	4500	4400	4000	3500	3000	2300	1600	1450	1300	1165	0
7000	300	7000	6300	5600	5122	5000	4800	4700	4400	4100	4000	3500	2630	2568	1914	1521	1236	0
7000	500	7250	6500	5800	5500	5300	5200	5000	4414	4293	3224	2662	2438	2235	2069	1587	1083	0
7000	750	7500	7000	6200	5700	5600	5557	5044	3907	3692	3272	2839	2618	2292	1937	1497	1046	0
7000	1000	7700	5802	5626	5122	5100	4416	4170	3575	3400	3215	2853	2557	2243	1431	1009	800	0
7000	1500	7900	5453	4966	4800	4747	4392	3915	3469	3206	3016	2505	1538	1482	721	600	400	0
7000	2000	5966	5889	4956	4638	4349	3680	3170	3167	2878	2659	1712	1013	634	313	176	115	0
7000	3000	6286	5858	5138	4213	3787	3205	3028	3078	2823	2178	1088	465	262	213	171	124	0
7000	4000	8217	6382	5757	4604	3737	2942	2687	2437	2075	1668	1068	600	255	234	175	110	0
7000	5000	8600	7814	6357	4465	3603	2857	2453	2428	2298	1770	1136	600	400	300	250	150	0
7000	7500	9100	8400	6903	4857	4046	3169	2478	2300	2200	1953	1700	700	500	400	300	200	0
10000	0	4144	4019	3894	3770	2280	1584	1181	918	748	698	598	498	399	300	250	200	0
10000	50	4486	4230	4000	4018	3495	2946	2545	2180	1837	1524	1200	950	700	450	400	397	0
10000	100	4600	4300	4200	4100	3500	2731	2688	2636	2469	1807	1716	1659	1590	1067	800	754	0
10000	200	5000	4600	4450	4400	2861	2700	2600	2538	2398	2100	1800	1650	1550	1327	1280	1150	0
10000	300	5100	4311	4300	4197	3938	3600	3575	3299	3139	2799	2396	1989	1698	1391	1120	844	0
10000	500	5873	5089	4460	4000	3700	3682	3426	2956	2803	2513	2259	1849	1371	1027	735	598	0
10000	750	5076	4815	4465	3635	3500	3475	3265	2910	2680	2227	1897	1443	1023	680	443	301	0
10000	1000	4500	4400	4385	4035	3671	3388	3329	3150	2731	2163	1556	1164	803	600	550	400	0
10000	1500	4859	4606	4445	3919	3652	3393	3087	2596	2114	1678	1050	678	623	500	400	300	0
10000	2000	5900	5023	4783	4070	3602	2962	2233	1899	1670	1346	761	390	362	275	230	166	0
10000	3000	6400	5472	5174	3650	3256	2561	2024	1637	1811	1428	866	277	223	220	209	168	0
10000	4000	7100	6120	5200	3659	3061	2539	1826	1600	1564	1182	768	700	500	400	177	160	0
10000	5000	8322	7155	5532	4080	3113	2586	1967	1879	1700	1545	1262	800	500	400	177	160	0
10000	7500	6835	7855	6052	4555	3681	2872	2262	2200	2100	1800	1554	1000	500	400	170	160	0
15000	0	3103	3046	2987	2930	2206	1731	1395	1145	952	798	577	481	385	300	250	199	0
15000	50	3176	3087	2997	2908	2501	2158	1999	1786	1663	1549	1419	795	696	500	450	404	0
15000	100	3200	3100	3000	2900	2400	2200	1900	1800	1700	1615	1513	1308	1173	772	578	550	0
15000	200	3200	3200	3000	2500	1800	1600	1500	1417	1400	1350	1300	1200	1125	863	654	650	0
15000	300	3300	2728	2700	2632	2573	2300	2284	2000	1878	1600	1500	1083	795	548	370	379	0
15000	500	3300	3200	2946	2400	2200	2124	2090	1706	1578	1434	1163	796	465	289	211	173	0
15000	750	3400	3400	3004	2447	2149	2214	2041	1560	1362	1127	744	460	312	222	200	173	0
15000	1000	3100	3000	2978	2576	2257	1893	1646	1420	1299	1037	523	311	250	225	200	173	0
15000	1500	3272	3089	2855	2340	2009	1666	1414	1193	893	748	395	283	250	225	200	173	0
15000	2000	3819	3595	3107	2421	2171	1816	1439	1009	726	694	565	586	530	225	200	173	0
15000	3000	4400	3847	3573	2661	2241	1813	1457	1176	1150	954	885	800	530	225	200	173	0
15000	4000	5100	4200	3154	2860	2437	2031	1491	1362	1592	1102	1033	900	700	225	200	173	0
15000	5000	5583	4658	4056	3694	2976	2438	2100	1983	1800	1495	1291	1000	750	710	400	200	0
15000	7500	5791	5301	4387	4480	3773	2822	2400	2274	2100	1877	1669	1100	950	910	400	200	0
20000	0	1107	1087	1066	1045	907	791	692	607	533	467	357	269	200	150	100	50	0
20000	50	1133	1101	1069	1037	922	813	762	687	642	598	544	308	264	199	170	146	0
20000	100	1142	1106	1070	1034	927	820	785	713	678	642	606	321	285	563	368	399	0
20000	200	1142	1142	1070	1034	927	820	785	700	640	606	571	560	496	488	420	404	0
20000	300	1177	1150	1100	1000	900	850	785	713	650	571	535	440	334	260	184	150	0
20000	500	1177	1142	1013	1097	903	820	813	722	652	547	415	290	211	122	100	98	0
20000	750	1213	1213	1000	963	907	895	755	636	475	401	361	250	158	110	100	98	0
20000	1000	1280	1268	1251	999	901	875	853	634	510	500	350	253	161	110	100	98	0
20000	1500	1296	1260	1100	1050	1000	998	968	682	590	564	412	340	189	110	100	98	0
20000	2000	1560	1408	1200	1190	1144	1143	1141	857	747	679	595	507	189	110	100	98	0
20000	3000	1882	1700	1606	1550	1450	1400	1343	1267	1131	986	833	639	189	110	100	98	0
20000	4000	2500	2400	2300	2200	2100	2000	1800	1517	1410	1248	983	649	189	182	178	143	0
20000	5000	3085	2831	2771	2561	2373	2350	2180	1927	1689	1405	940	700	268	253	250	214	0
20000	7500	3268	2969	2900	2800	2758	2500	2412	2164	1950	1557	1016	750	339	325	321	250	0

Liquid contact with the heated surface is frequent at low wall superheats but becomes less frequent at higher wall superheats. A similar heat transfer process takes place during low quality convective transition boiling, but here the convective velocities improve the heat transfer coefficient both in film boiling and nucleate boiling.

In the high quality region, most of the heat transferred during transition boiling is due to convection to the vapor and to droplet-wall interaction. Initially, at surface temperatures just in excess of the boiling crisis temperature, a significant fraction of the droplets deposit on the heated surface, but at higher wall superheats, the vapor repulsion forces become significant and repel most of the droplets before they can contact the heated surface.

12B.3.2 Data Trends

A thorough review of the transition boiling literature was conducted by Groeneveld (1976,1977) and Fung (1978). Parametric trends have been deduced from the data (Groeneveld, 1976). In general, an increase in mass flux increases the transition boiling heat flux, especially at higher wall superheats because of its strong positive effects on film boiling heat transfer. The effect of an increase in subcooling is similar but the effect of quality is less clear. The data suggest that at low wall superheats, an increase in quality will have a negative effect on the transition boiling heat flux (similar to its effect on CHF). At higher wall superheats, the film boiling mode dominates and hence, the reverse is true. Fig. 3 illustrates the above trends. Note also the change in slope of the transition boiling curve from a negative value to a positive value at high flows and qualities. This trend is discussed in greater detail by Groeneveld (1980a).

12B.3.3 Correlations

Despite the scarcity of transition boiling data, a large number of correlations have been proposed. They may be divided into three groups:

(i) Correlations containing boiling and convective components, e.g., Ramu (1974), Mattson (1974) and Tong (1972a). These correlations usually have the form

$$h = A \exp(-B\, \Delta T_w) + \frac{k_v}{D_e}\, a\, Re_v^b\, Pr_v^c$$

where the first term on the right-hand side represents the boiling component (which becomes insignificant at high wall superheats) and second term represents the convective component. These correlations are often claimed to be valid both in the transition boiling and film boiling region.

(ii) Phenomenological correlations, e.g., Iloeje (1974), Tong and Young (1974). These correlations are based on a physical model of heat transfer in the transition boiling region. Because of an inadequate physical understanding they still contain many empirical constants.

(iii) Emprical correlations, e.g., Ellion (1954), Berenson (1960) and McDonough (1961). These correlations all have a very simple form and generally cannot be extrapolated outside the range of data on which they are based. Some of these correlations are based on the conditions at the boiling crisis (CHF and T_{CHF}).

12B.3.4 Recommendation

Groeneveld (1976) has shown that frequently (i) the correlations often do not agree with each other, and (ii) their data base is questionable. Hence none of the current correlations can be fully recommended. The most reasonable prediction was obtained by connecting the experimentally determined CHF and minimum film boiling points by a straight line on a log-log plot of q vs. ΔT_w:

$$\frac{q_{TB}}{q_{min}} = \left(\frac{CHF}{q_{min}}\right)^{n_1} \qquad \text{where } n_1 \triangleq \frac{\ln(\Delta T_{min}/\Delta T_w)}{\ln(\Delta T_{min}/\Delta T_{CHF})}$$

or

$$\frac{\Delta T_w}{\Delta T_{min}} = \left(\frac{\Delta T_{CHF}}{\Delta T_{min}}\right)^{n_2} \qquad \text{where } n_2 \triangleq \frac{\ln(q_{TB}/q_{min})}{\ln(CHF/q_{min})}$$

If experimental values or predictions for q_{min} (to be obtained from $h_{FB}.\Delta T_{min}$), ΔT_{CHF} and ΔT_{min} are questionable or unavailable the following correlation is tentatively suggested:

$$q_{TB} = \max\left\{\left(q_{FB},\ CHF\left(\frac{\Delta T_{CHF}}{\Delta T_w}\right)\right)\right\}$$

where ΔT_{CHF} is obtained from $\Delta T_{CHF} = CHF/h_{CHEN}$ (Chen, 1963), q_{FB} is obtained from an appropriate film boiling model or correlation (Chapter 12B.5), and ΔT_{min} is obtained from the correlation recommended in chapter 12.B.4.

12B.4 Minimum Film Boiling

12B.4.1 General

The minimum film boiling temperature separates the high temperature region where inefficient film boiling or vapour cooling takes place, from the lower temperature region where the much more efficient transition boiling or nucleate boiling occurs. It thus provides a limit to the application of transition boiling and film boiling correlations. In the literature, a large number of terms have been used to describe the phenomenon at the boundary between transition boiling and film boiling, e.g., sputtering, departure from film boiling, rewetting, film boiling collapse, Leidenfrost point, minimum film boiling. Several types of film boiling terminations may be encountered as is shown in Fig. 4.

12B.4.2 Prediction Methods

Groeneveld (1982, 1982a) reviewed the minimum film boiling correlations and divided them into the following groups:

(i) Equations based on the Taylor-Helmholtz hydrodynamic instability theory, e.g., Berenson (1961), Henry (1974);
(ii) Equations based on the maximum liquid superheat theory using either an equation-of-state or an equation derived from the classical nucleation analysis, e.g., Spiegler (1963);
(iii) Empirical correlations based only on minimum flow film boiling data, e.g., Groeneveld (1982).

The theoretically derived equations for T_{min}, such as Berenson's (1960) and Spiegler's (1963), are based on the assumption that the heated surface is isothermal. During the rewetting process, large temperature gradients are set up. If liquid-wall contacts are intermittent, e.g., at the initiation of transition boiling during cooling down of a surface, they will be of very short duration. These contacts are usually not immediately noticeable at the thermocouple junction, which is normally embedded in the heated surface and hence measures an average temperature. The difference between the bulk surface temperature and the true liquid-wall interface temperature can be very significant and has been included in several minimum film boiling correlations. It depends on the ratio $(k\ \rho\ Cp)_{\ell}/(k\ \rho\ Cp)_{w}$ and can only be ignored for high-conducting surfaces.

12B.4.3 Recommendation

Groeneveld (1982) has compared the prediction trends of various minimum film boiling correlations and noticed significant differences. The large differences in predicted values and parametric trends are not surprising considering the scarcity of the data, and the very different types of film boiling. Despite these differences, the Groeneveld-Stewart (1982) T_{min} correlation

$$P \le 9000 \text{ kPa} : T_{min} = 284.7 + 0.441\ P - 3.72 \times 10^{-6}\ P^2 + \frac{\Delta H \times 10^4}{(2.82 + 0.00122\ P) H_{fg}}$$

$$P > 9000 \text{ kPa} : T_{min} = (\Delta T_{min,9000\ kPa}) \left(\frac{P_{crit} - P}{P_{crit} - 9000}\right) + T_{sat}$$

is tentatively recommended for the types I-IV film boiling terminations. This recommendation is based on

(i) the approximate agreement of this correlation with the data of Fung (1981), Stewart (1981), Bennett (1966), Bradfield (1967), Lauer (1976), and (ii) on the correct asymptotic trend of pressure and subcooling. Although in these experiments thin oxide layers were present, no large correction in T_{min} due to oxide layers was needed and, consequently, corrections such as suggested by Henry (1974) are thought to be of secondary importance for flow boiling on engineering surfaces (i.e., Inconel, steel, Zircaloy).

12B.5 Film Boiling

12B.5.1 General

During film boiling the heated surface is cooled by radiation, forced convection to the vapour and by interaction of the liquid and the heated surface. The vapour can become highly superheated; its temperature is controlled both by wall-vapour and vapour-liquid heat exchange. The liquid is thought to be in the form of:

(a) a dispersed spray of droplets, usually encountered at void fractions in excess of 80%. The corresponding flow regime is often referred to as the liquid-deficient regime because insufficient liquid is available to maintain a wet wall (Fig. 5).
(b) a continuous liquid core (surrounded by a vapour annulus which may contain entrained droplets) usually encountered at void fractions below 50%. The corresponding flow regime is sometimes referred to as the inverted annular flow regime (Fig. 5).
(c) a transition between the above two cases, usually in the form of slug flow (Fig. 5).

Of the above post-dryout regimes, the liquid deficient regime is most commonly encountered and has been well studied. Its post-dryout temperature is moderate while for flow regimes (b) and (c) the boiling crisis frequently results in a failure of the heated surface.

12B.5.2 Post-Dryout Models

Post dryout models are models based on the three conservation equations for each phase and suitable empirical interfacial correlations. The first post-dryout models were developed by the UKAEA (Bennett, 1967) and MIT (Laverty, 1967). In these models, all parameters were initially evaluated at the dryout location. It was assumed that heat transfer takes place in two steps: (i) from the heated surface to the vapor, and (ii) from the vapor to the droplets. The models evaluated the axial gradients in droplet diameter, vapor and droplet velocity, and pressure, from the conservation equations. Using a heat balance, the vapor superheat was then evaluated. The wall temperature was finally found from the vapor temperature using a superheated steam heat transfer correlation. Bailey (1972), Groeneveld (1972), and Plummer (1976) have suggested improvements to the original model by including droplet-wall interaction, by permitting a gradual change in average droplet diameter due to the breakup of droplets, and by including vapor flashing for large pressure gradients. Additional expressions for the vapor generation rate have recently been suggested by Saha (1980) and Jones (1977).

Recently models have also been developed for the inverted annular flow regime (Fung, 1981; Kaufman, 1976; Elias, 1981; Chan, 1980). They are basically unequal velocity, unequal temperature (UVUT) models which can account for the non-equilibrium in both the liquid and the vapor phase.

12B.5.3 Post-dryout Correlations

Empirical post-dryout correlations may be subdivided as follows:

(i) Thermal equilibrium correlations These are correlations which assume that the liquid is in thermal equilibrium with the vapor, and the heated surface is cooled by forced convection to the vapor only. These correlations are basically forced convective correlations where the vapor velocity is evaluated by assuming either homogeneous flow (Dougall, 1963) or by using a suitable slip ratio correlation (e.g., Quinn, 1966).

Thermal equilibrium correlations usually have the form:

$$Nu_v = a \left[\frac{\rho_v . U_v . De}{\mu_v} \right]^b (Pr_v)^c$$

where

$$U_v = \frac{GX}{\rho_v . \alpha} = \frac{G}{\rho_v} \left[X + \frac{\rho_v}{\rho_\ell} S \ (1-X)\right]$$

This type of correlation assumes that the liquid and vapor are in equilibrium, i.e., $X = X_e$. This assumption is valid only at high mass flows and high void fractions where the liquid-vapor heat exchange is very efficient.

(ii) Empirical correlations Empirical correlations have been developed for both the liquid deficient regime and the inverted annular flow regime. They generally predict a heat transfer coefficient which is based on the temperature difference between wall and saturation. They are simple to use but have a limited range of validity and should not be extrapolated outside their recommended range.

(iii) Phenomenological correlations These predictive methods are based on the typical mechanisms governing this type of heat transfer and use a heat transfer coefficient based on the vapor temperature. For the liquid deficient regime, phenomenological correlations usually predict the degree of thermal non-equilibrium. Values for the actual vapor temperature T_{va}, or actual quality, X_a, can be generated from existing post-dryout data, provided the assumption of forced convective cooling only (i.e., no droplet-wall interaction) of the heated wall in the post-dryout region is correct. This approach has been used by Tong (1974), Plummer (1976), Groeneveld-Delorme (1976a), Chen (1979) and Shah (1980).

Groeneveld (1983) has presented a summary of recent non-equilibrium correlations. In general, these correlations are a significant improvement over the empirical post-CHF correlations. They can be given the correct asymptotic trends to let them smoothly converge with the single-phase superheated-steam cooling correlations.

Attempts have also been made to develop phenomenological correlations for the inverted annular regime (Dougall, 1963; Dalinin, 1969, 1970) and the slug flow film boiling regime (Chi, 1967; Kalinin, 1970). Due to a limited data base, they have not yet been verified.

(iv) Pool film boiling correlations These correlations are applicable in pool boiling and low mass velocities. Most of these correlations basically have the form:

$$h_c = A \left[\frac{g\, k_v^3 \rho_v (\rho_\ell - \rho_v) H'_{fg}}{\mu_v\, \Delta T_s} \right]^{\frac{1}{4}} f(U,\lambda) + h_{rad}$$

which was originally derived by Bromley (1950) from Nusselt's classical analysis of filmwise condensation. The latent heat H'_{fg} is usually modified to include the vapor superheat, while the velocity effect is included theoretically or empirically through $f(U,\lambda)$ where λ is either equal to the diameter, the critical wavelength or the most unstable wavelength.

(v) No evaporation after dryout In addition to the above prediction methods, one can also assume that, in the liquid deficient regime, no evaporation will take place, i.e., the wall heat flux is used only for superheating of the vapor and X_a remains constant. Here the predicted wall temperature is very high since the vapor becomes progressively more superheated. This prediction is pessimistic except at lower flows (Bennett, 1967). It is, however, useful as an upper boundary for the heated surface temperature.

12B.5.4 Discussion

During the past fifteen years, much progress has been made in understanding the physical mechanisms governing post-dryout heat transfer. Post-dryout models have been reasonably successful in predicting the post-dryout temperature distribution. These models, however, require accurate values of the dryout quality; they are generally considered useful especially for predictions outside the data base (provided the assumed physical mechanisms are still valid).

Of the prediction methods discussed in the previous section, the phenomenological correlations are considered the most accurate. They tend to satisfy the observed experimental data trends, hence they have a much wider range of applicability than the empirical post-dryout correlations, but they are generally more difficult to use. Figure 6 shows schematically the relative temperature predictions of four of the prediction methods. Note that curve A, based on the "thermal equilibrium after dryout" assumption, represents a lower boundary while curve B, based on the "no evaporation after dryout" assumption represents an upper boundary for the post-dryout temperature.

12B.6 References

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Nomenclature

Cp	Specific heat at constant pressure	$kJ \cdot kg^{-1} \cdot K^{-1}$
CHF	Critical heat flux	$kW \cdot m^{-2}$
D	Tube diameter	m
De	Hydraulic equivalent diameter	m
g	Acceleration due to gravity	$m \cdot s^{-2}$
G	Mass flux	$kg \cdot m^{-2} \cdot s^{-1}$
H	Enthalpy	$kJ \cdot kg^{-1}$
h	Heat transfer coefficient	$kW \cdot m^{-2} \cdot K^{-1}$
k	Thermal conductivity	$kW \cdot m^{-1} \cdot K^{-1}$
Lh	Heated length	m
Nu	Nusselt number (= h.D/k)	-
P	Pressure	kPa
Pr	Prandtl number (= μ.Cp/k)	-
q	Surface heat flux	$kW \cdot m^{-2}$
Re	Reynolds number (= ρ.U.D/μ)	-
S	Slip ratio (= U_v/U_ℓ)	-
T	Temperature	°C
U	Velocity	$m \cdot s^{-1}$
X	Flow quality (vapor weight fraction)	-

Greek

α	Void fraction	-
ΔH	Local subcooling	$kJ \cdot kg^{-1}$
ΔT	Temperature difference (usually with respect to saturation)	K
μ	Viscosity	$kg \cdot m^{-1} \cdot s^{-1}$
ρ	Density	$kg \cdot m^{-3}$
σ	Surface tension	$N \cdot m^{-1}$

Subscripts

a	Actual
c	Critical
do	Value pertaining to onset of dryout condition
e	Equilibrium
f	Saturated liquid
fg	Difference between saturated liquid and saturated vapor
g	Saturated vapor
in	Inlet
1, ℓ	Liquid (may be subcooled)
max	Maximum
min, mfb	Minimum film boiling value
Q	Apparent quench temperature
s, sat	Saturated
sub	Subcooling
v	Vapor
w	Heat wall

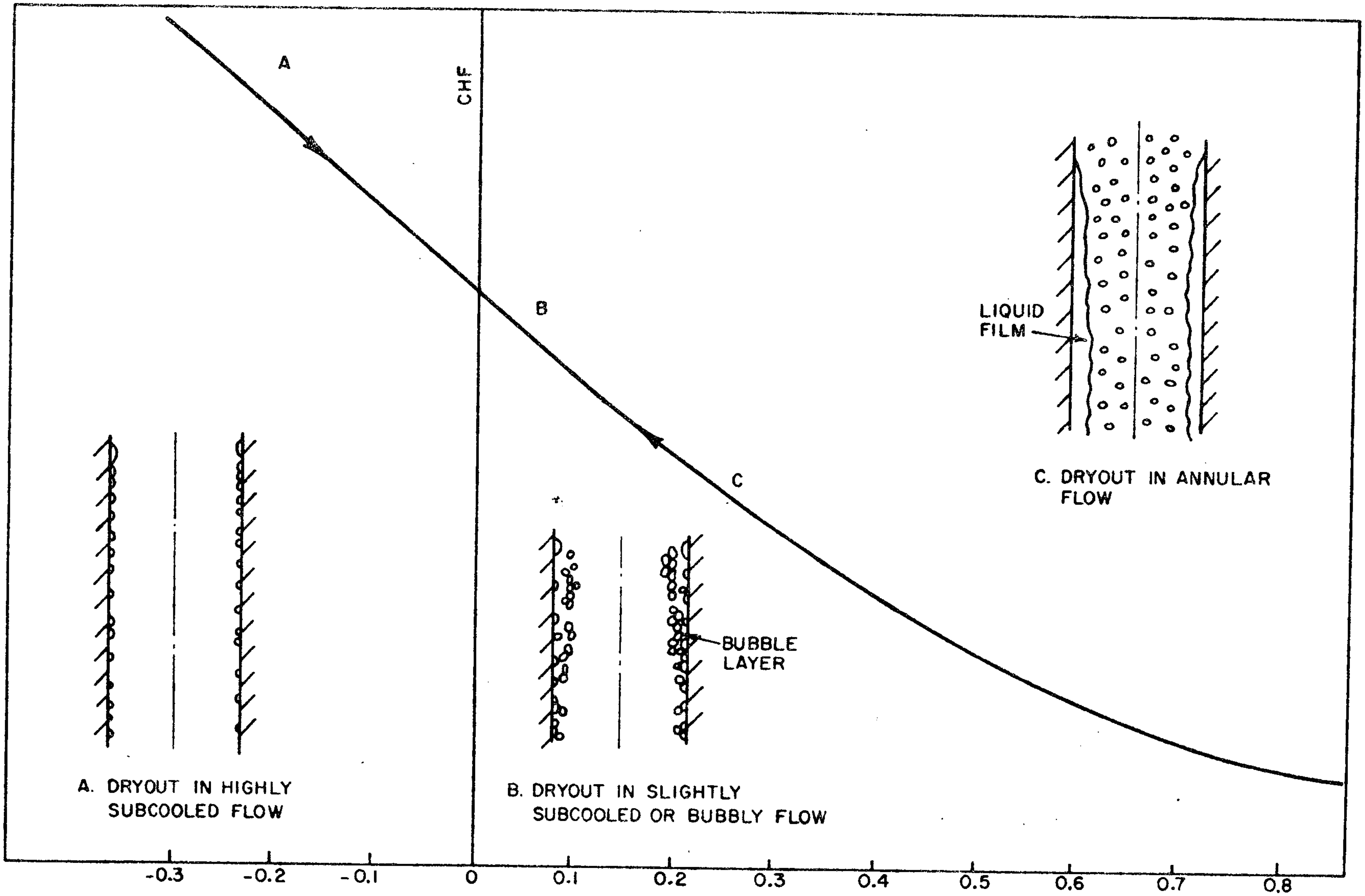


FIGURE 1: EFFECT OF QUALITY ON CRITICAL HEAT FLUX

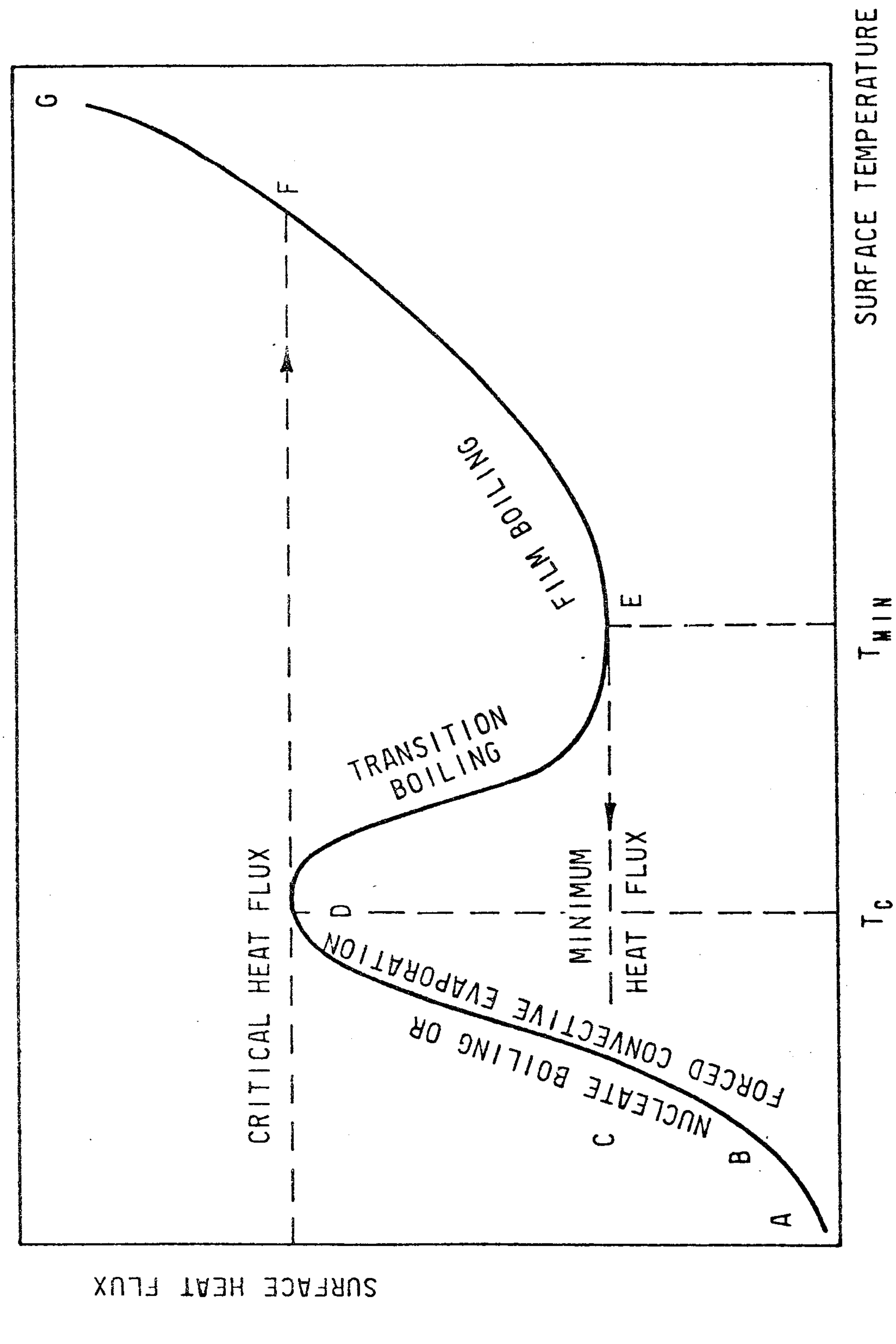
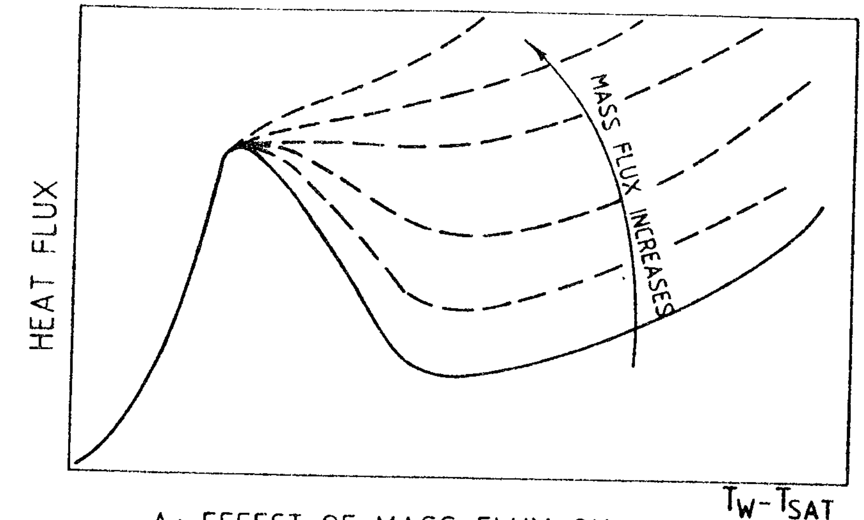
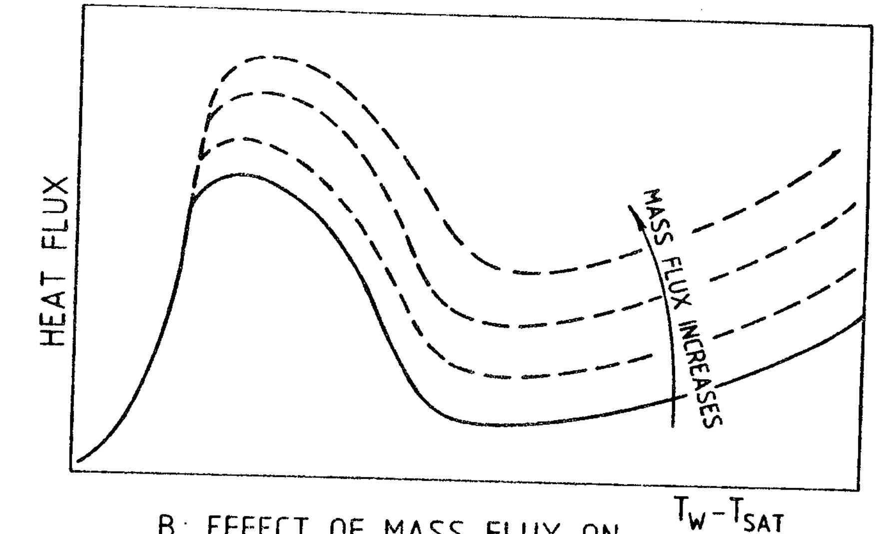


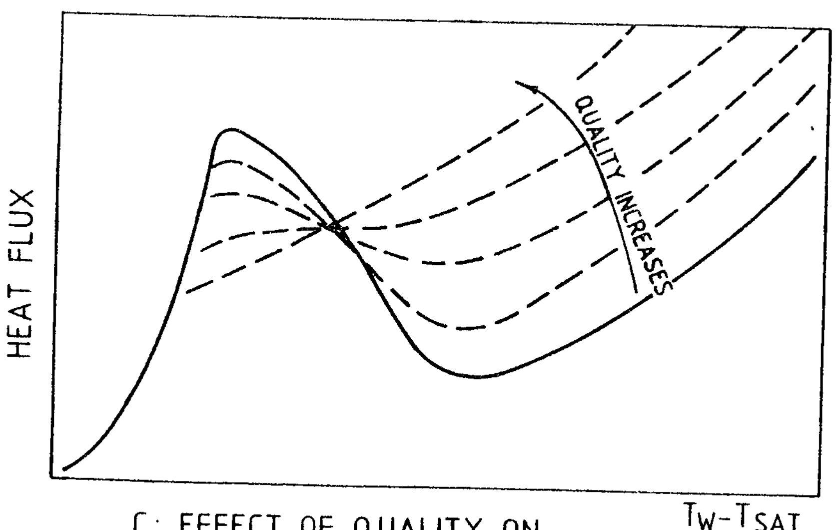
FIG.2 CONVECTIVE BOILING CURVE



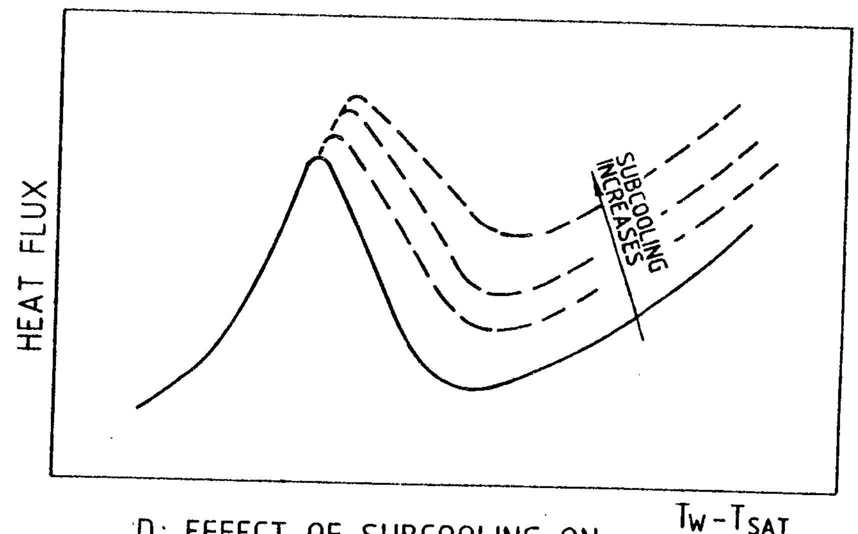
A: EFFECT OF MASS FLUX ON
BOILING CURVE (ANNULAR FLOW REGIME)



B: EFFECT OF MASS FLUX ON
BOILING CURVE (FORCED CONVECTIVE
SUBCOOLED OR LOW QUALITY BOILING)



C: EFFECT OF QUALITY ON
FORCED CONVECTIVE BOILING CURVE



D: EFFECT OF SUBCOOLING ON
BOILING CURVE

FIG. 3 PARAMETRIC TRENDS OF FLOW BOILING CURVE

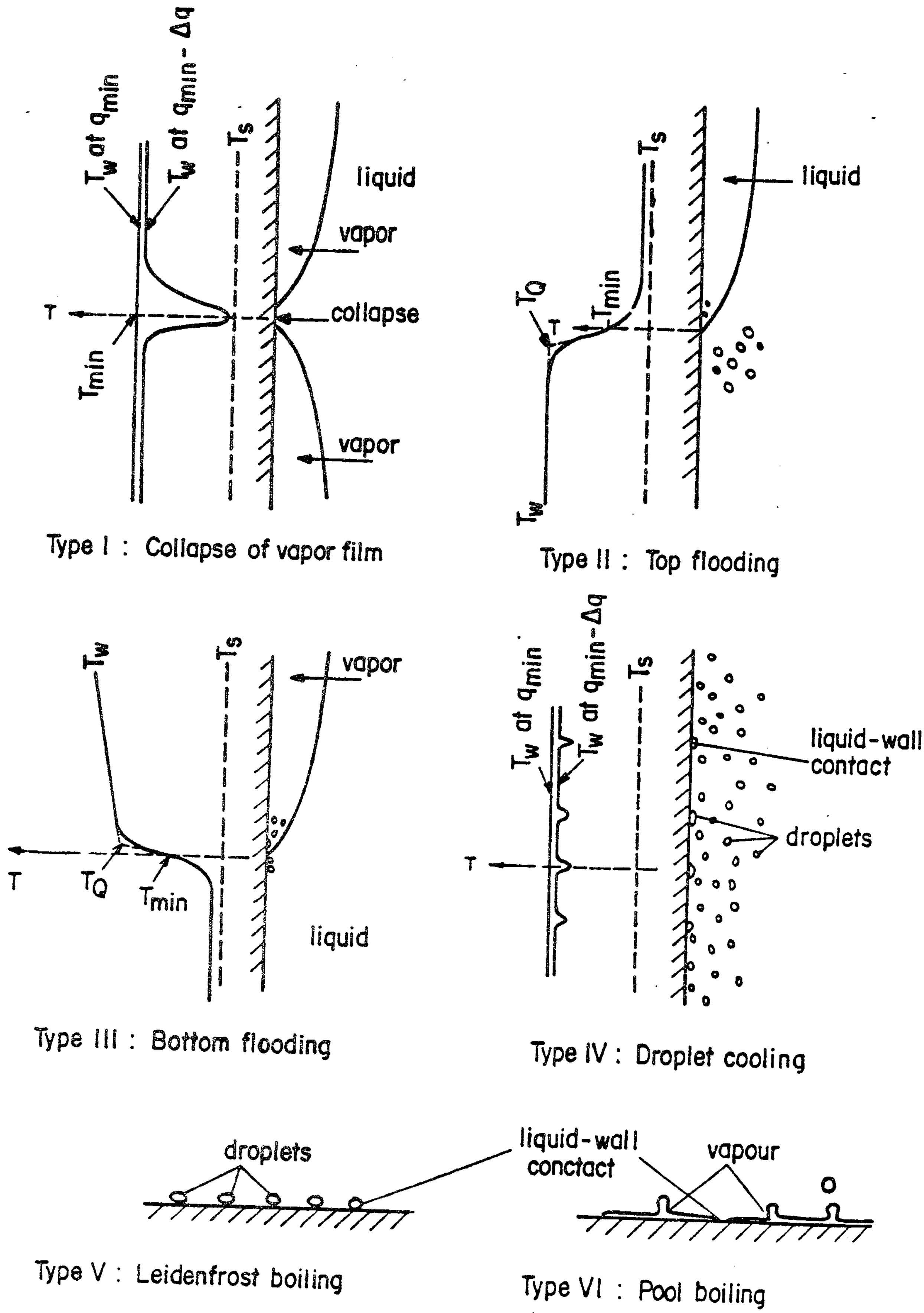


FIG. 4: FILM BOILING TERMINATION TYPES

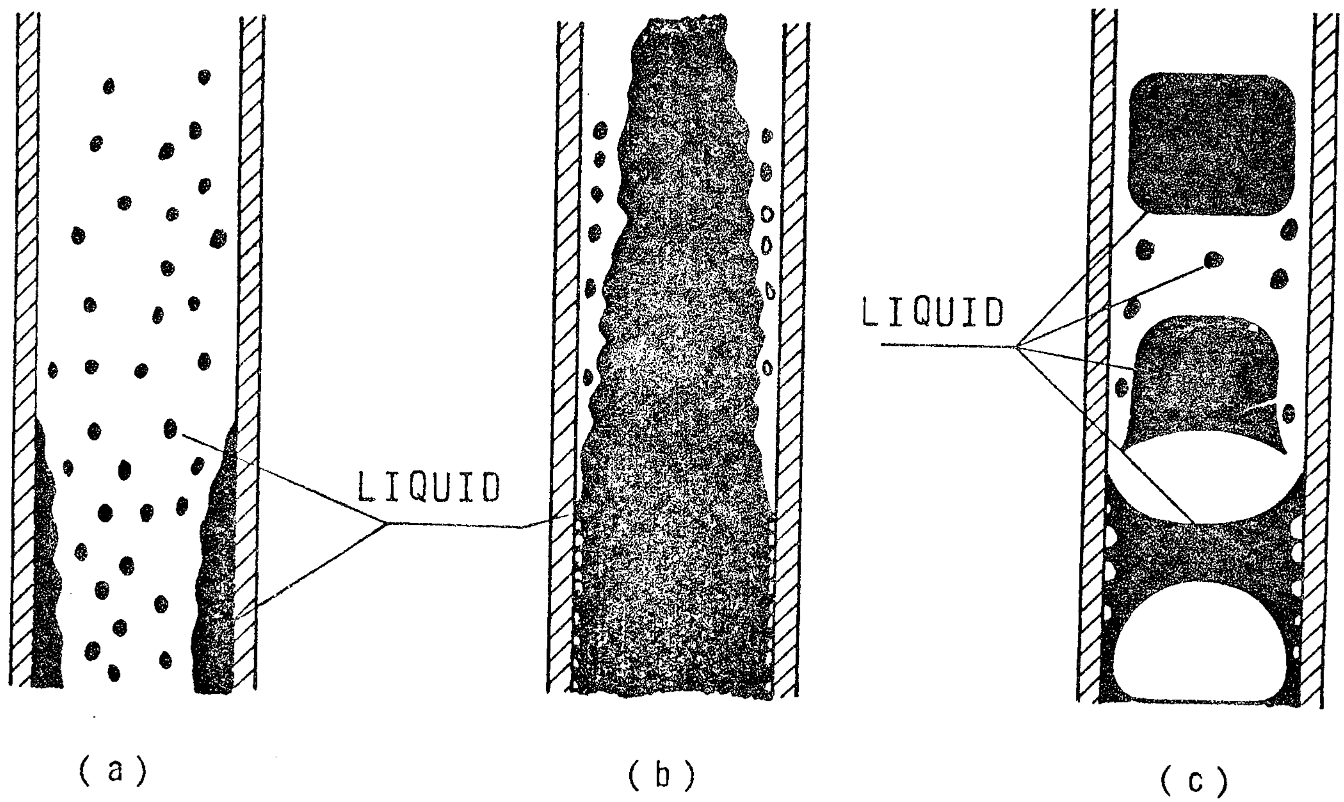


FIG.5: FLOW REGIMES DURING FILMBOILING

(a) LIQUID DEFICIENT FLOW
(b) INVERTED ANNULAR FLOW
(C) SLUG FLOW

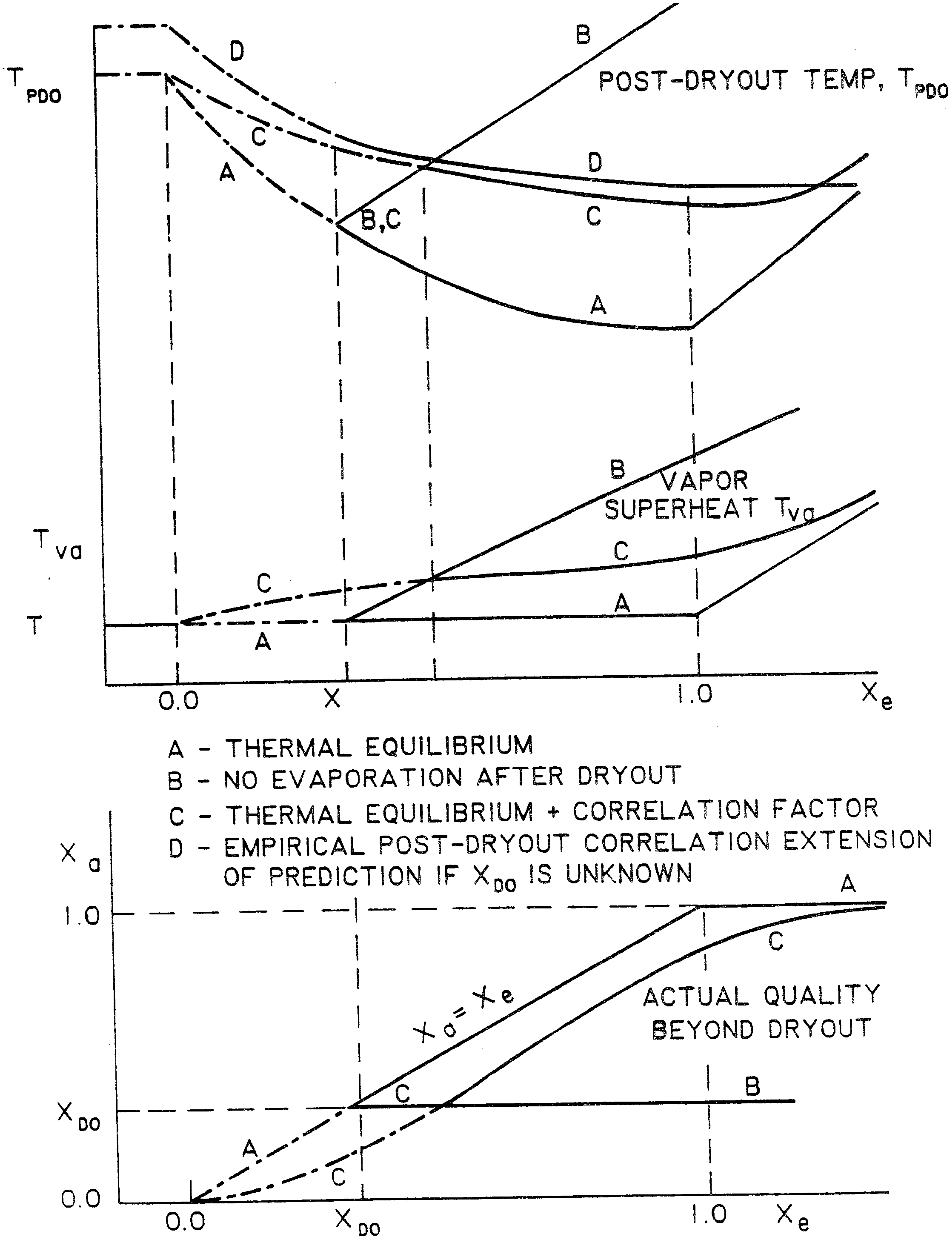


FIGURE 6 : VARIOUS PREDICTIONS OF POST-DRYOUT PARAMETERS