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TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

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September 9, 1980

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MARK 16B FLOW INSTABILITY CHARACTERISTICS WITH AND WITHOUT CTR LIMITS

INTRODUCTION

With the introduction of the automatic backup shutdown system using safety computers (ABS-S/C), critical temperature ratio (CTR) limits will no longer be applied to reactor operation. Mark 16B fuel tubes can then be operated at full flow (no flow restrictor) with a higher endfitting pressure drop which can significantly increase reactor power. However, the new flow conditions and increased power raise questions about increased potential for flow-instability. This memorandum describes a study of the effect of endfitting pressure drop on flow instability phenomena. Guidelines are recommended for implementation of full flow operation with the Mark 16B fuel assemblies.

SUMMARY

A new computer code[1] which models the onset of flashing and flow instability phenomena in a Mark 16B assembly with a P reactor endfitting was used to study the operating characteristics of Mark 16B's over a full range of flow conditions. Two-phase flow and initiation of flow-instability can occur in both bottom fitting shell holes and in the assembly channels. The temperature at which two-phase flow occurs and the location are shown to depend on the amount of top stem flow resistance and the number of shell holes. For full flow operation with no top stem restriction, calculations show that endfitting pressure drops (calculated with the monitor pin pressure drop equations[2]) should not exceed 400 in. H_2O. At higher pressure drops, calculations show the current transient protection limits, keyed to the hottest subchannel, are non-conservative and will not protect against flow instability. These results are regarded as interim limits for near term use because additional experimental data reduction and code refinements are anticipated before final limits on endfitting pressure can be specified. They are also treated as applicable to K and C reactors because the K, C endfittings are designed for the same pressure ranges.

RECOMMENDATIONS

It is recommended that an upper limit of 400 in. H_2O endfitting pressure drop be applied on an interim basis for Mark 16B fuel assemblies in all reactors to ensure protection within current Technical Limits. Because of the variations in reactor monitor pin signals, it is recommended that this limit be applied only to test station results. Some additional tests and analyses are required before further refinements in this limit are made. These tests are in progress and final pressure limits will be issued in a subsequent memorandum.

Additional studies are also underway to develop a new bottom fitting insert that will have less restrictive limits on shell hole pressure drop. The design and extensive monitoring tests of the new bottom fitting are expected to require at least 18 months to complete.

DISCUSSION

Background

Operation with CTR limits as a means of confinement protection is being discontinued in favor of the automatic backup shutdown system using safety computers (ABS-S/C) to terminate an accident if safety rods fail to drop on demand. The ABS-S/C injects a neutron poison solution (GD NO_3) into the moderator space, shutting down the reactor in 4 seconds (or less) following a failure of the safety rods. CTR limits required that flow through the fuel assemblies be restricted such that, if an accident occurs, the fuel will melt first introducing negative reactivity and, in effect, shutdown the reactor.

With ABS-S/C, no flow restriction is required for fuel assemblies because accidents will be terminated before melting can occur. Removal of the top stem flow restrictor from Mark 16B's with the same plenum inlet pressure results in higher flows and fluid velocities. The increased flow will, of course, permit higher power. Given the same total pressure drop across the assembly, a larger portion of the pressure drop is taken in the endfitting and consequently pressures are higher in the endfitting. The higher pressure and correspondingly higher saturation temperature potentially allows higher operating temperature limits and additional assembly power.

Flow Instability Phenomena

Of interest in this work is the effect that higher endfitting pressure drops have on two-phase flow and flow instability in the assembly and endfitting. The increase in available coolant flow which permits increased assembly power also raises the possibility of operation closer to the threshold of two-phase flow and consequent flow instability. Initiation of bulk boiling at the bottom of the flow channels is prevented by maintaining the bulk fluid temperature below the saturation temperature. However, areas where incipient two-phase flow are likely to occur are in the lower regions of the assembly subchannels and in the fluid vena contracta of the endfitting shell holes (Figure 1). In the assembly channels there is the risk of subcooled nucleate boiling at the tube surfaces. At the shell holes, the high fluid velocity and resulting pressure drop may cause the saturation temperature to drop below the local temperature resulting in flashing.

Correlations which describe the onset of two-phase flow and flow instability in the assembly channels and the endfitting were developed based on experimental tests in the Heat Transfer Laboratory[1]. These correlations were incorporated in a computer code which models the Mark 16B assembly on a P reactor endfitting. This code was used to study the effects of several variables on conditions that cause two-phase flow and flow instability.

Calculational Procedure

The assembly model used in the computer code was a quarter section of a Mark 16B outer and middle fuel tube arrangement with a P reactor endfitting. The flow resistance in the top stem and endfitting could be adjusted to simulate flow with and without a flow restrictor and to vary the number of shell holes. A top stem flow resistance was chosen, and while maintaining a constant total assembly pressure drop, the number of shell holes was varied over a wide range. At each increment of shell holes, the temperature at which flashing and flow instability occurred was determined. Calculations were made for different inlet temperatures and pressures with and without a top stem flow restrictor (Figure 1a).

Results

Figures 2,3 and 4 describe the effect of increasing endfitting pressure drop on assembly average temperatures at which two-phase flow and flow instability occur for flatzone fuel assemblies at respective plenum inlet temperatures of 24,30, and 45°C. Included on the figures are curves representing operating and Technical Limits. Extreme ranges for the limits are estimated for flowzone one conditions based on data from the P-9 reactor cycle. These figures represent operation with flow restriction in the top stem. At low endfitting pressure drops, two-phase flow typically begins in the subchannels as a result of subcooled nucleate boiling and ultimately proceeds to flow instability as power increases. At higher pressures, flashing and cavitation in the endfitting shell holes become the dominant pressure drop mechanisms and the flow instability temperature curves reach a maximum and gradually fall off. In either case, as two-phase flow is initiated there is an accompanying increase in total pressure drop as the fluid accelerates with increases in specific volume. This effect is also illustrated in Tables II and III which give the two-phase flow pressure drop multipliers in the channel and endfitting over the ranges shown in the figures. An increase in the multiplier above unity indicates the presence of two-phase flow. The location where two-phase flow first begins is identified by the multiplier increasing first in that location. Thus one can see that at lower endfitting pressure drops, two-phase flow begins first in the channels, whereas at higher endfitting pressure drops two-phase flow begins first in the endfitting. At lower plenum inlet temperatures, the effect is less pronounced. At a pressure drop equivalent to 51 shell holes, and the flow restricted, the Technical Limit is shown to prevent flow instability although two-phase flow would occur during a transient. If there were fewer shell holes resulting in higher endfitting pressure drops, calculations show that during an incident flow instability will occur in the endfitting even though the Technical Limit is not exceeded. For all normal flow conditions the operating limit is seen to prevent two-phase flow in both the assembly and endfitting. The monitor pin pressure drops for the number of shell holes shown on the abscissa of the figures are calculated from the Technical Manual equations[2]. The pressure drops therefore represent the difference in pressure immediately across the shell holes. However, in the reactor, the measured pressure drop represents the difference in pressure between an assembly monitor pin and one of the gasport positions. This difference may include tank bottom gradients of up to 60 inches of H_2O.

Figures 5,6, and 7 show data for fuel assemblies with no flow restrictor in the top stem. The pressure drop across the endfitting is seen to significantly increase at 50 shell holes (495 in. H_2O vs. 378 in. H_2O) with the flow restrictor removed because the total flow through the assembly has increased (416 gpm vs 364 gpm). The pressure inside the endfitting is therefore higher which increases the saturation temperature. Consequently, the operating and Technical Limits are higher by comparison with Figures 2,3, and 4. The increase in the effluent temperature limits has the potential of providing an additional gain in power in addition to the increase obtained with the higher flow.

However, at high endfitting pressure drops, the temperatures at which flashing and flow instability occur in the shell holes are a function of shell hole velocitites and remain essentially unaffected by the presence or absence of a flow-restrictor. Therefore the limits have been raised relative to temperatures at which two-phase flow can exist in the assembly. As can be seen in Figures 5,6, and 7, at 50 shell holes, if the effluent temperature increases, flow instability will begin in the shell holes before the Technical Limit (which is keyed to the hottest subchannel) is reached. During a power transient (eg. a rod withdrawal incident), if an assembly were operating at its limit, the effluent temperature may momentarily rise above the Technical Limit. Assuming that flow instability would occur first in the hottest subchannel at a temperature above the Technical Limit, it is believed that a momentary excursion in temperature above the Technical Limit would not cause a catastrophic breakdown in the assembly flow. However the calculations now show that for sufficiently high endfitting pressure drops, flow instability would begin well before the Technical Limit is reached. A further complication arises as the inlet temperature increases. At 45^{o} inlet temperature, representing extreme summer conditions, the range of operating temperature limits lies above the temperatures at which two-phase flow occurs for nearly the full range of endfitting pressure drops. A condition where continuous flashing in the endfitting were present would result in a lower actual flow than calculated and the likelihood of cavitation damage.

These results indicate that to regain protection within Technical Limits the operating limit would have to be lowered or the number of shell holes would have to be increased to $\sim$ 60. A comparison of Figures 6 and 8 show that increasing plenum pressure by 10 psi also results in flashing in the endfitting before the operating limit is reached over most of the operating range with no top stem orifice. This occurs only if the increase in plenum pressure were allowed to result in a corresponding increase in endfitting pressure which is expected to occur in the fourth subcycle with no modification of orificing.

Specification of Technical Limits

Eccentricity of one fuel tube with respect to another is the mechanism by which a hot subchannel exists. Technical Limits are currently based on the hottest subchannel. The extent to which effluent temperature from the hottest subchannel exceeds that of the other subchannels depends on the degree of eccentricity with the extreme temperature conditions occurring when two ribs of one tube are in contact with an adjacent tube for the full length of the tube.

This situation is considered unlikely and experiments show that the maximum effect of eccentricity is approximately half that which is theoretically possible[(2)]. The effects of eccentricity in the code are not variable but are included via whatever degree of eccentricity that existed in the experimental facility. The effects of eccentricity on two-phase flow and flow instability would be most pronounced where assembly channel conditions are dominant (i.e. lower endfitting pressure drops). On the figures, this would be to the left of where the flow instability curve peaks. For higher endfitting pressure drops (> 300 - 350 in. H_2O) these calculations show that the hottest subchannel is not necessarily the location for initial flow instability. At these higher ΔP's, hydraulic effects at the shell holes become dominant. Beyond 400 in. H_2O pressure drop, the Technical Limit based on the hottest subchannel becomes in effect meaningless since flow instability will be initiated at the shell holes. Therefore, to maintain protection with the currently defined Technical Limits and transient protection limits it becomes necessary to keep the endfitting pressure drop below 400 in. H_2O.

Endfitting Pressure Drop Limit

Wide variations in monitor pin pressure signals are observed in each reactor and are attributed primarily to tank bottom gradients and to a lesser extent plenum gradients. The variations cause signals ranging to well above 400 in. H_2O in some reactor tank locations. However, the high signals do not necessarily imply higher flows and velocities. If the 400 in. H_2O monitor pin pressure drop limit is based on the recorded monitor pin pressure signals, then the restriction will be too severe and unnecessary power losses will result. Therefore the limit should be applied based on the known flow characteristics of the assembly, from which, given the total assembly pressure drop (plenum inlet-tank bottom), the assembly flow and endfitting pressure drop can be calculated. The hydraulic characteristics of each assembly are tested in the flow test station which provides a good degree of reliability for the calculated endfitting pressure drop. To account for uncertainties in flow test station results, a suitable operating limit somewhat below 400 in. H_2O should be determined.

CMX Data

CMX data showing the test flow ranges and monitor pin pressure drop signal for the monitor pins and various shell hole numbers are shown in Table VIII. Because of the linearity of the data, a certain amount of extrapolation is considered acceptable. The recommended limit for a flow increase above that shown in the tables is $\sim$ 15 percent. At 50 shell holes in P reactor the maximum pressure drop would be approximately 400 in. H_2O. The onset and impact of shell hole cavitation is not well enough defined to warrant additional extrapolation of the data.

K and C Reactor

Two-phase flow data and correlations for the K, C reactor endfittings are not available for similar calculations at this writing. There is less flow through the shell holes of the K and C endfittings but they are designed to operate in the same pressure ranges as P endfittings (Table VIII). Consequences of two-phase flow in the K and C endfittings would not be more severe than the P endfitting.

Shell Hole Flashing

Although maintaining endfitting pressure drop below 400 in. H_2O provides protection against flow instability during an incident, at high plenum inlet temperatures some steady state flashing in the endfitting is predicted at full flow (Figure 7). The flashing results in a slightly reduced flow than that predicted by hydraulics equations (∿ 1.5%). Also to some extent, flashing results in shell hole cavitation damage and is undesirable. Figures 2-4 with restricted flow do not predict any steady-state flashing. However, for extreme operating limits, the approach to flashing is seen to be very close under certain conditions. Assuming there is an uncertainty range in the predicted flashing temperatures, it is probable that some degree of flashing in the endfitting exists at times.

There are currently no guidelines or limits in the Technical Standards[4] relating to the existence of steady-state flashing in reactor assemblies, endfitting, or moderator space. The results of this study indicate that flashing may exist in reactor operation now and will be more prevalent at full flow operation. To monitor the existence or extent of shell hole cavitation damage a representative examination of endfittings may be desirable. In the long range, elimination of potential flashing at the shell holes is one of the objectives of a new program on endfitting design in progress in SRL. Additional two-phase flow test work and refined calculational procedures should also permit a more exact prediction of the ranges for flashing and flow instability.

D. A. Ward
Research Manager

W M Massey

by: W. M. Massey
Nuclear Engineering Division

REFERENCES

1. Muhlbaier, D. R.,"Flow Instability-Experimental Results and Mathematical Model", DPST-80-201.

2. DPSTM-16 (H), Technical Manual-Hydraulics and Heat Transfer of the Mark 16-16B Assembly.

3. DPSTM-110, Technical Manual-Technical, Transient Protection, and Confinement Protection Limits for SRP Reactors.

4. DPSTS-105, 105 Building Technical Standards.

TABLE I

INITIATING TWO PHASE FLOW

MULTIPLIERS

WITH FLOW RESTRICTION

PLENUM PRES = 75 PSIG

PLENUM TEMP = 24°C

# SHELL HOLES	FLOW, GPM	MONITOR PIN ΔP, IN H_2O	ENDFITTING MULTIPLIER	CHANNEL MULTIPLIER
30	310	683	1.0	1.034
40	342	496	1.0	1.023
50	364	378	1.0	1.023
60	380	299	1.0	1.024
70	393	242	1.0	1.025
80	402	201	1.0	1.003
90	410	169	1.0	1.023
100	417	145	1.0	1.015

TABLE II

INITIATING TWO PHASE FLOW

MULTIPLIERS

WITH FLOW RESTRICTION

PLENUM PRES = 75

PLENUM TEMP = 30

# SHELL HOLES	FLOW, GPM	MONITOR PIN ΔP, IN. H_2O	ENDFITTING MULTIPLIER	CHANNEL MULTIPLIER
30	310	683	1.030	1.031
40	342	496	1.0	1.028
50	364	378	1.0	1.037
60	380	299	1.0	1.014
70	393	242	1.0	1.016
80	402	201	1.0	1.032
90	410	169	1.0	1.021
100	417	145	1.0	1.016

TABLE III

INITIATING TWO PHASE FLOW

MULTIPLIERS

WITH FLOW RESTRICTION

PLENUM PRES = 75

PLENUM TEMP = 45

# SHELL HOLES	FLOW GPM	MONITOR PIN ΔP, IN. H_2O	ENDFITTING MULTIPLIER	CHANNEL MULTIPLIER
30	310	683	1.035	1.0
40	342	496	1.015	1.0
50	364	378	1.012	1.0
60	380	299	1.0	1.031
70	393	242	1.0	1.007
80	402	201	1.0	1.038
90	410	169	1.0	1.035
100	417	145	1.0	1.037

TABLE IV

INITIATING TWO PHASE FLOW

MULTIPLIERS

WITHOUT FLOW RESTRICTION

PLENUM PRES = 75

PLENUM TEMP = 24

# SHELL HOLES	FLOW GPM	MONITOR PIN ΔP, IN. H_2O	ENDFITTING MULTIPLIER	CHANNEL MULTIPLIER
30	341	826	1.048	1.0
40	384	630	1.026	1.003
50	416	495	1.020	1.035
60	441	403	1.0	1.032
70	461	334	1.0	1.007
80	477	282	1.0	1.008
90	490	242	1.0	1.026
100	502	210	1.0	1.025

TABLE V

INITIATING TWO PHASE FLOW

MULTIPLIERS

WITHOUT FLOW RESTRICTION

PLENUM PRES = 75

PLENUM TEMP = 30

# SHELL HOLES	FLOW GPM	MONITOR PIN ΔP, IN. H_2O	ENDFITTING MULTIPLIER	CHANNEL MULTIPLIER
30	341	826	1.033	1.0
40	384	630	1.023	1.0
50	416	495	1.033	1.0
60	441	403	1.036	1.011
70	461	334	1.007	1.023
80	477	282	1.0	1.032
90	490	242	1.0	1.023
100	502	210	1.0	1.026

TABLE VI

INITIATING TWO PHASE FLOW

MULTIPLIERS

WITHOUT FLOW RESTRICTION

PLENUM PRES = 75

PLENUM TEMP = 45

# SHELL HOLES	FLOW GPM	MONITOR PIN ΔP, IN. H_2O	ENDFITTING MULTIPLIER	CHANNEL MULTIPLIER
30	341	826	1.010	1.0
40	384	630	1.022	1.0
50	416	495	1.016	1.0
60	441	403	1.019	1.0
70	461	334	1.021	1.0
80	477	282	1.016	1.0
90	490	242	1.020	1.0
100	502	210	1.030	1.0

TABLE VII

INITIATING TWO PHASE FLOW

MULTIPLIERS

WITHOUT FLOW RESTRICTION

PLENUM PRES = 85

PLENUM TEMP = 30

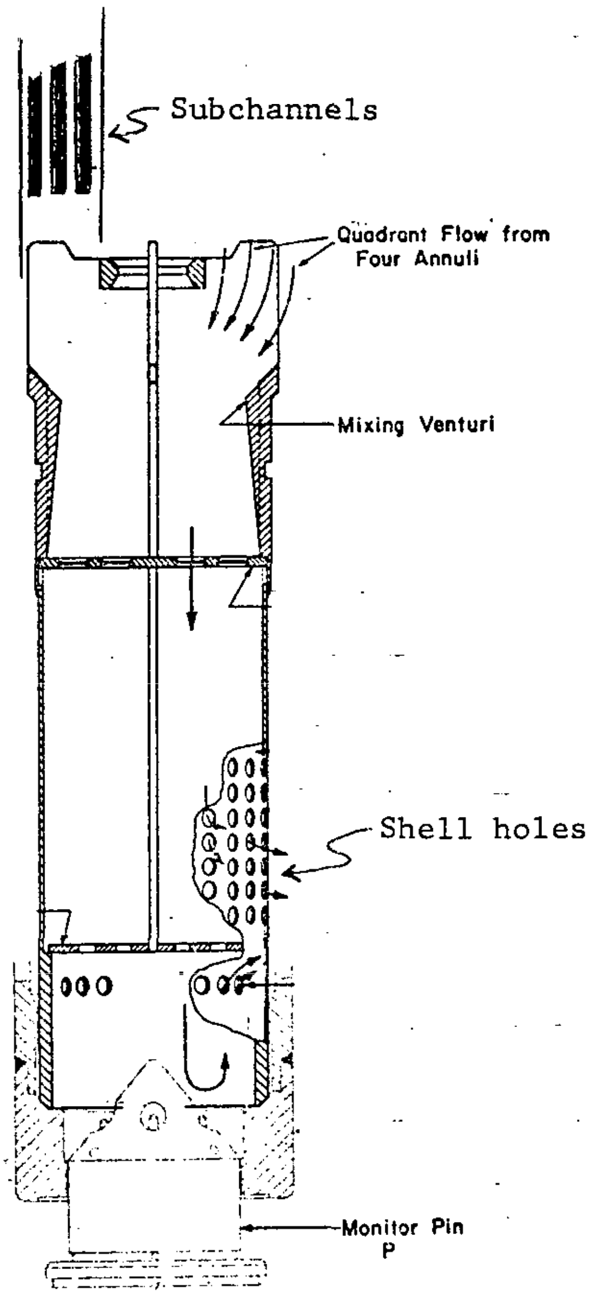
# SHELL HOLES	FLOW GPM	MONITOR PIN ΔP, IN. H_2O	ENDFITTING MULTIPLIER	CHANNEL MULTIPLIER
30	363	934	1.001	1.0
40	408	709	1.011	1.0
50	443	560	1.016	1.0
60	469	455	1.015	1.0
70	491	378	1.019	1.0
80	508	319	1.020	1.0
90	522	273	1.012	1.010
100	534	237	1.011	1.013

TABLE VIII

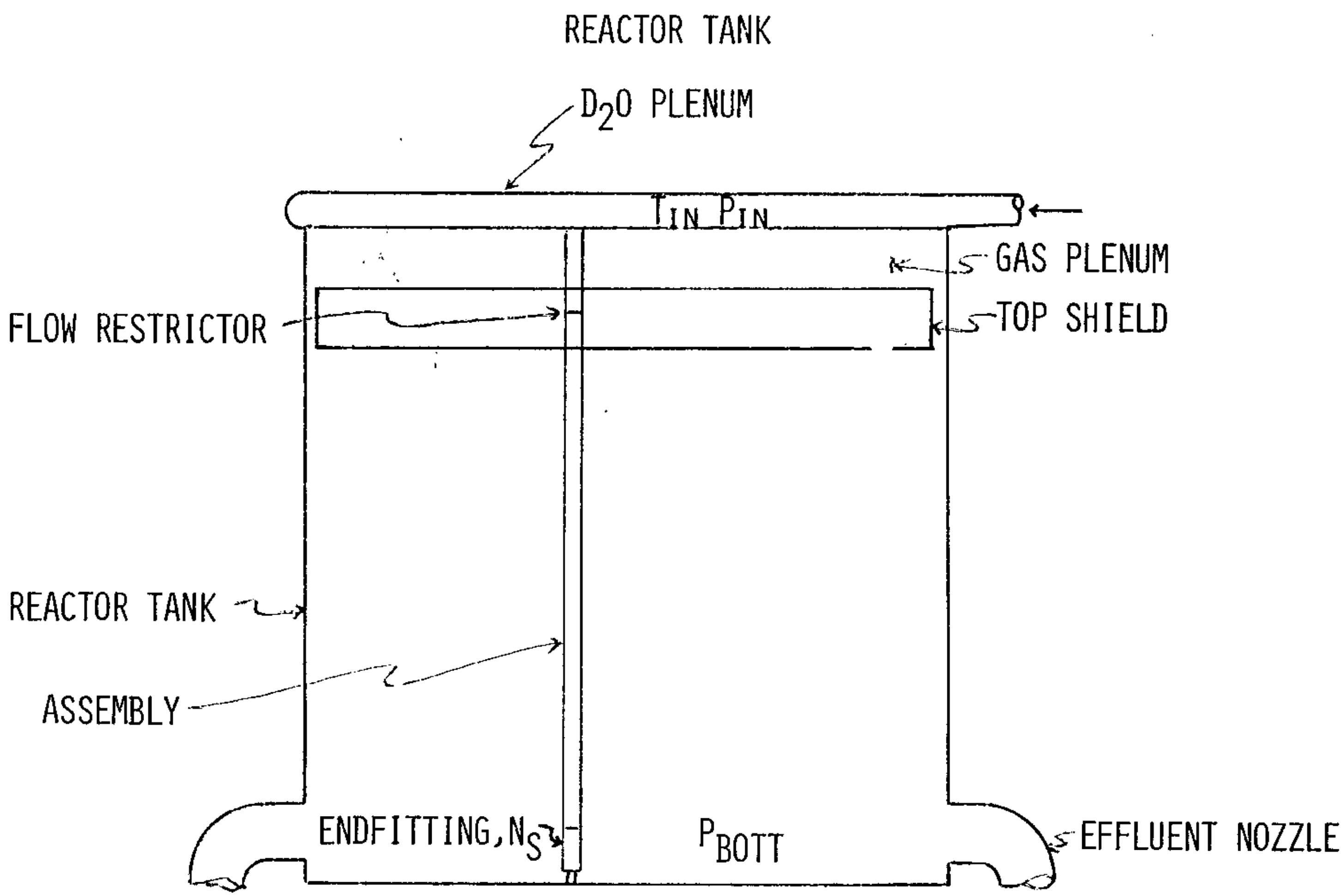
MARK 16 TEST FLOW AND M.P. ΔP RANGES

MONITOR PIN	BFI SHELL HOLES	FLOW RANGE, GPM LOW	FLOW RANGE, GPM HIGH	M.P. ΔP RANGE IN. H_2O LOW	M.P. ΔP RANGE IN. H_2O HIGH
"A"	10	200	297	178	395
(K&C Reactors)	20	208	370	130	428
	30	240	423	135	420
	40	252	476	115	407
	50	283	505	117	365
	60	313	516	120	308
"B"	10	160	295	165	567
(K Reactor)	20	160	295	110	387
	30	160	295	80	275
	40	160	295	65	223
	50	160	295	46	155
"P"	31	159	250	160	375
(P Reactor)	40	194	335	150	449
	50	159	353	72	335
	60	159	388	49	298
	70	194	400	55	240
	80	195	400	44	188

FIGURE 1



MARK 16-TYPE BOTTOM FITTING INSERT
FOR P REACTOR



REACTOR TANK
D2O PLENUM
TIN PIN
GAS PLENUM
FLOW RESTRICTOR
TOP SHIELD
REACTOR TANK
ASSEMBLY
ENDFITTING,NS
PBOTT
EFFLUENT NOZZLE

FIGURE 1A

FIGURE 2

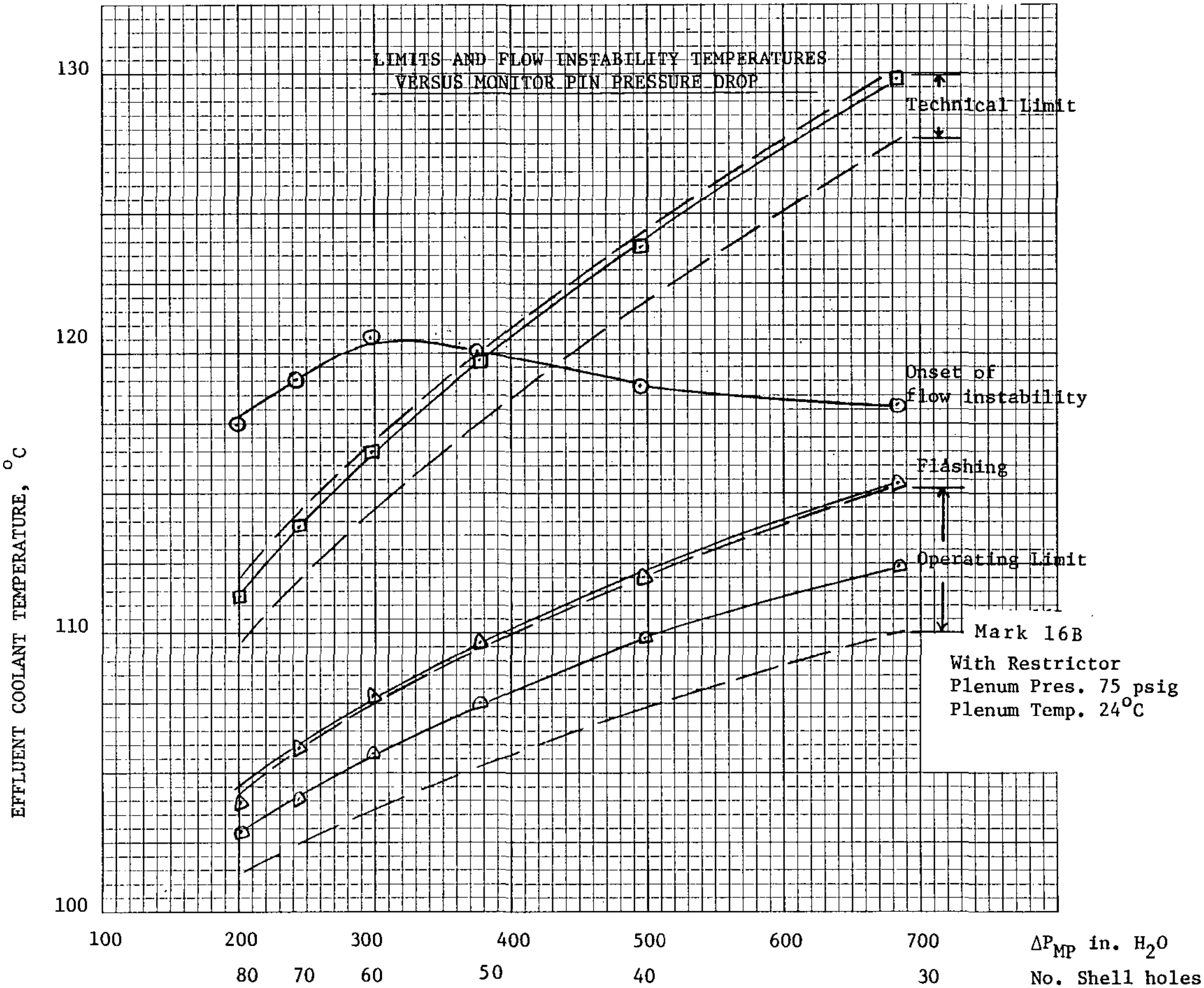

LIMITS AND FLOW INSTABILITY TEMPERATURES
VERSUS MONITOR PIN PRESSURE DROP
130
120
110
100
EFFLUENT COOLANT TEMPERATURE, °C
Technical Limit
Onset of
flow instability
Flashing
Operating Limit
Mark 16B
With Restrictor
Plenum Pres. 75 psig
Plenum Temp. 24°C
100
200
300
400
500
600
700
ΔP$_{MP}$ in. H_2O
80
70
60
50
40
30
No. Shell holes

FIGURE 3

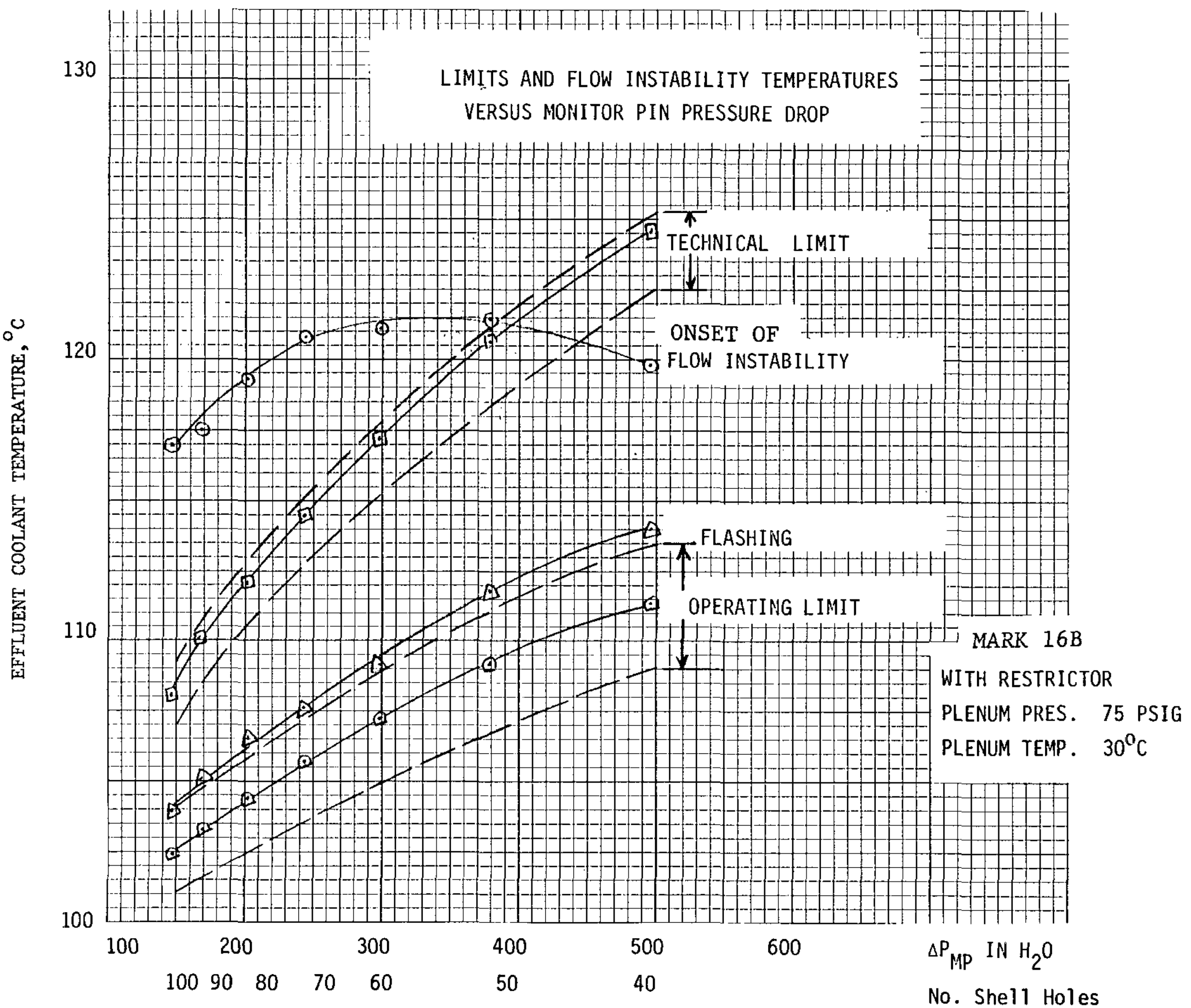
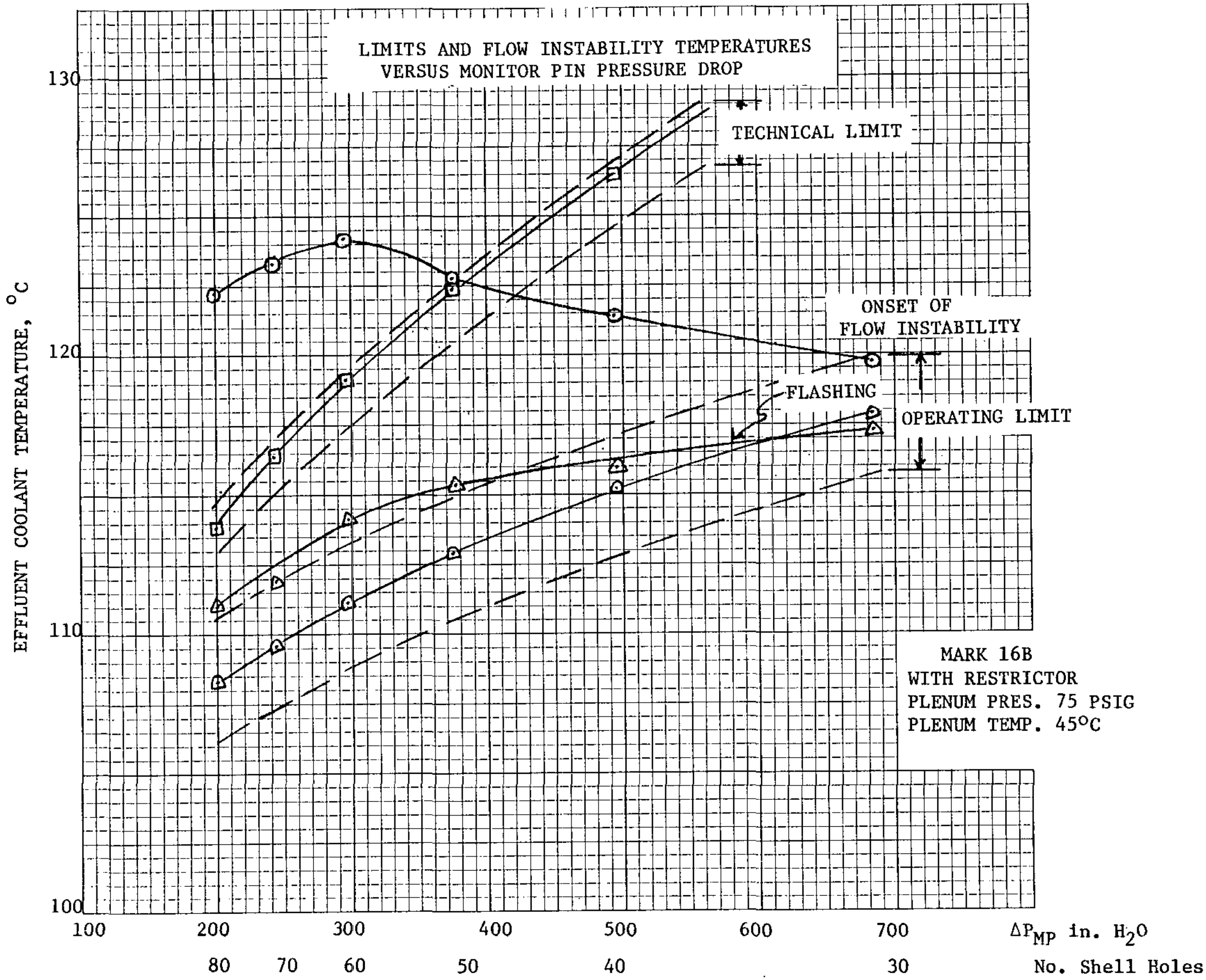
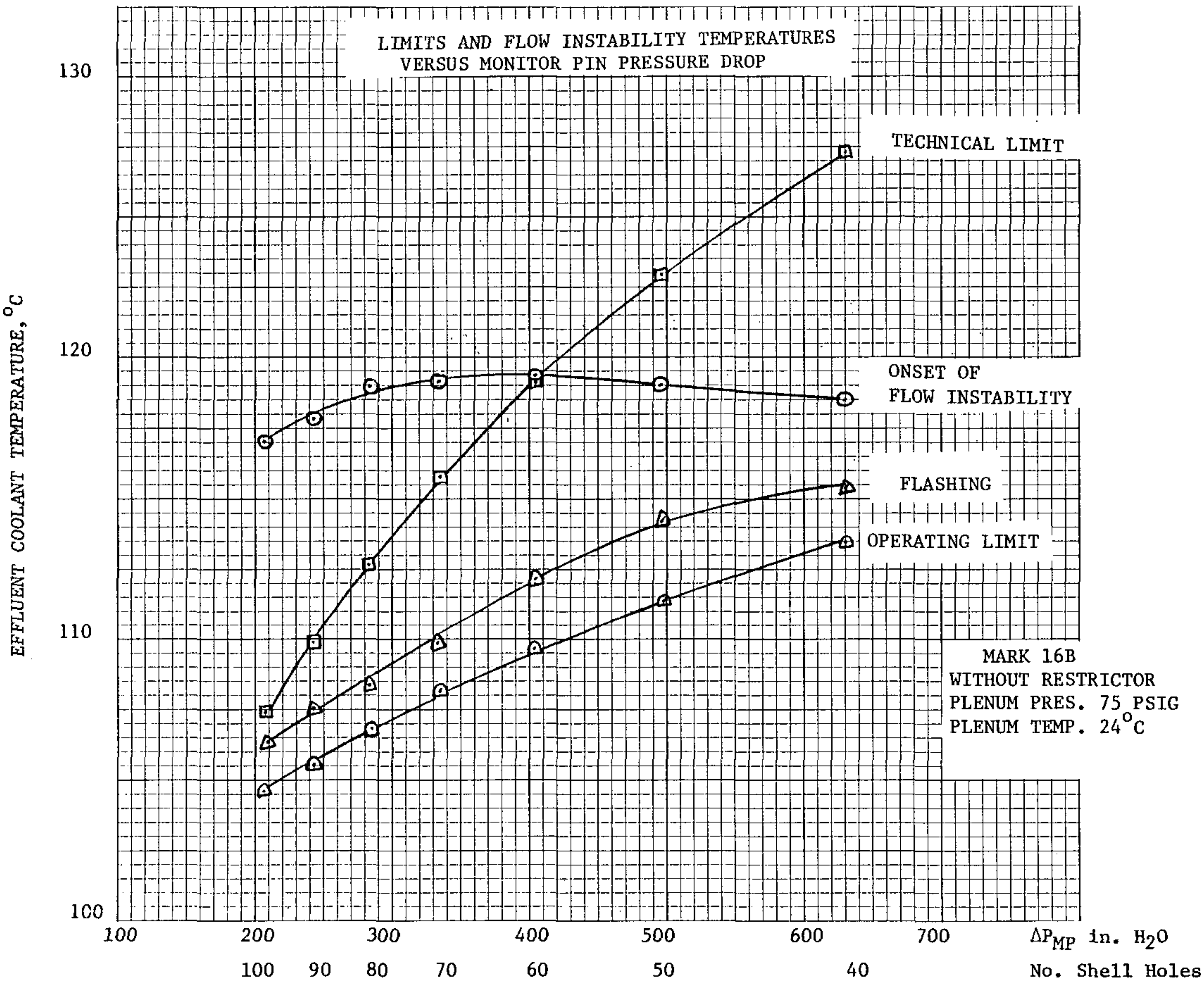

LIMITS AND FLOW INSTABILITY TEMPERATURES
VERSUS MONITOR PIN PRESSURE DROP
TECHNICAL LIMIT
ONSET OF
FLOW INSTABILITY
FLASHING
OPERATING LIMIT
MARK 16B
WITH RESTRICTOR
PLENUM PRES. 75 PSIG
PLENUM TEMP. 30°C
EFFLUENT COOLANT TEMPERATURE, °C
130
120
110
100
100
200
300
400
500
600
ΔP_{MP} IN H_2O
100 90 80 70 60 50 40
No. Shell Holes

FIGURE 4



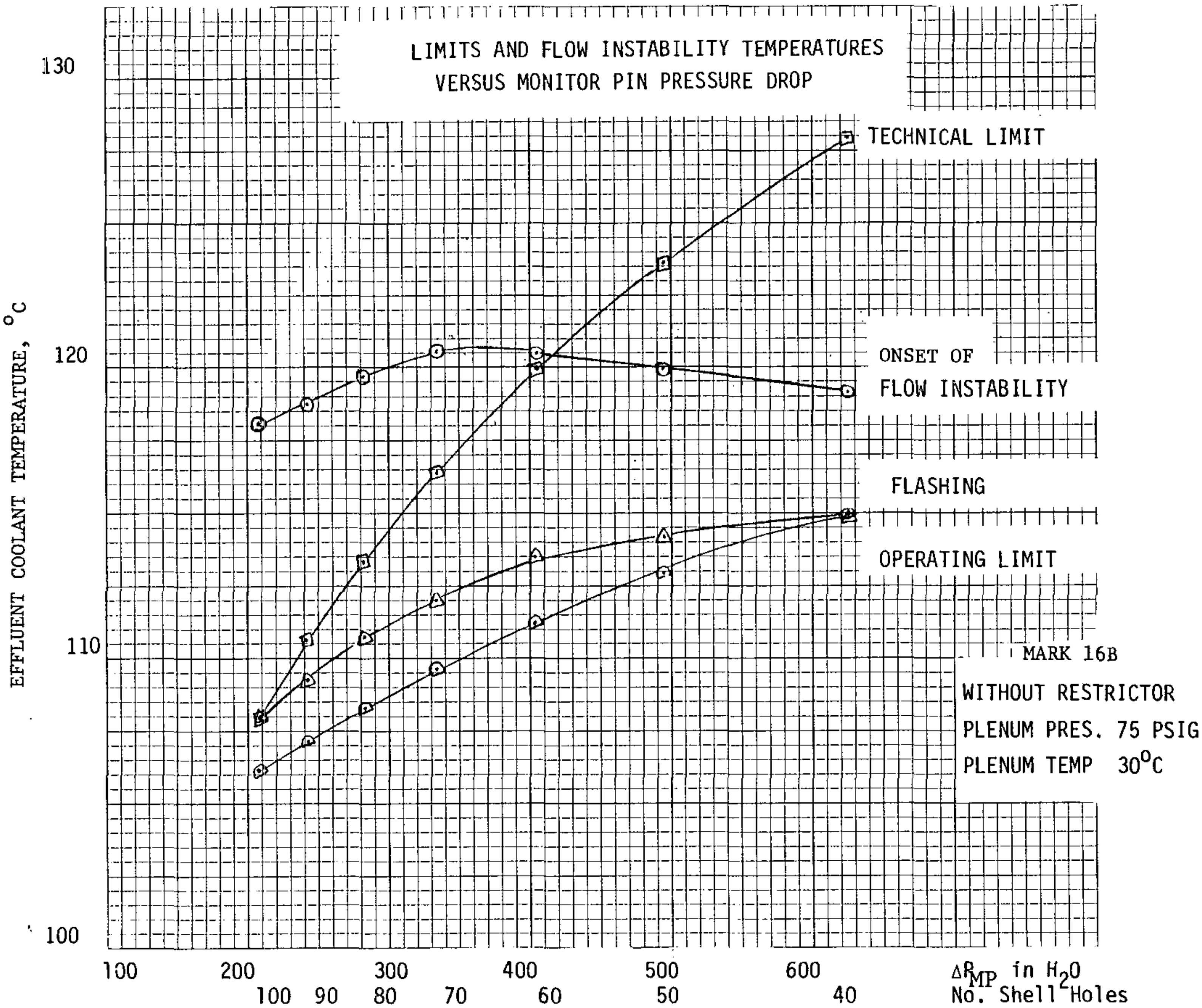
LIMITS AND FLOW INSTABILITY TEMPERATURES
VERSUS MONITOR PIN PRESSURE DROP
TECHNICAL LIMIT
ONSET OF
FLOW INSTABILITY
FLASHING
OPERATING LIMIT
MARK 16B
WITH RESTRICTOR
PLENUM PRES. 75 PSIG
PLENUM TEMP. 45°C
EFFLUENT COOLANT TEMPERATURE, °C
130
120
110
100
100
200
300
400
500
600
700
ΔP_MP in. H2O
80
70
60
50
40
30
No. Shell Holes

FIGURE 5



LIMITS AND FLOW INSTABILITY TEMPERATURES
VERSUS MONITOR PIN PRESSURE DROP
130
120
110
100
EFFLUENT COOLANT TEMPERATURE, °C
TECHNICAL LIMIT
ONSET OF
FLOW INSTABILITY
FLASHING
OPERATING LIMIT
MARK 16B
WITHOUT RESTRICTOR
PLENUM PRES. 75 PSIG
PLENUM TEMP. 24°C
100
200
300
400
500
600
700
ΔP_MP in. H2O
100
90
80
70
60
50
40
No. Shell Holes

FIGURE 6



LIMITS AND FLOW INSTABILITY TEMPERATURES
VERSUS MONITOR PIN PRESSURE DROP
TECHNICAL LIMIT
ONSET OF
FLOW INSTABILITY
FLASHING
OPERATING LIMIT
MARK 16B
WITHOUT RESTRICTOR
PLENUM PRES. 75 PSIG
PLENUM TEMP 30°C
EFFLUENT COOLANT TEMPERATURE, °C
130
120
110
100
100
200
300
400
500
600
ΔP_MP in H2O
100
90
80
70
60
50
40
No. Shell Holes

FIGURE 7

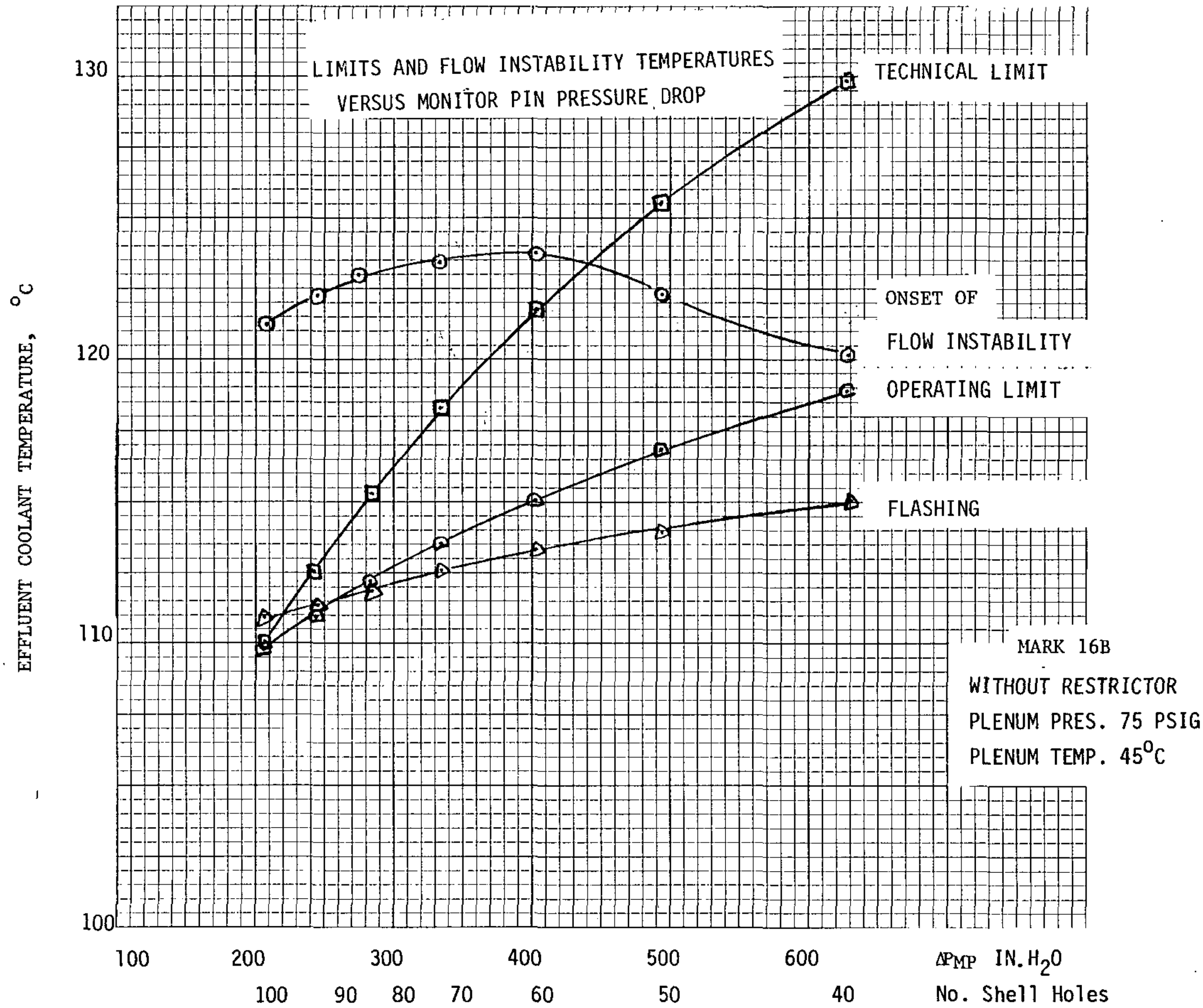
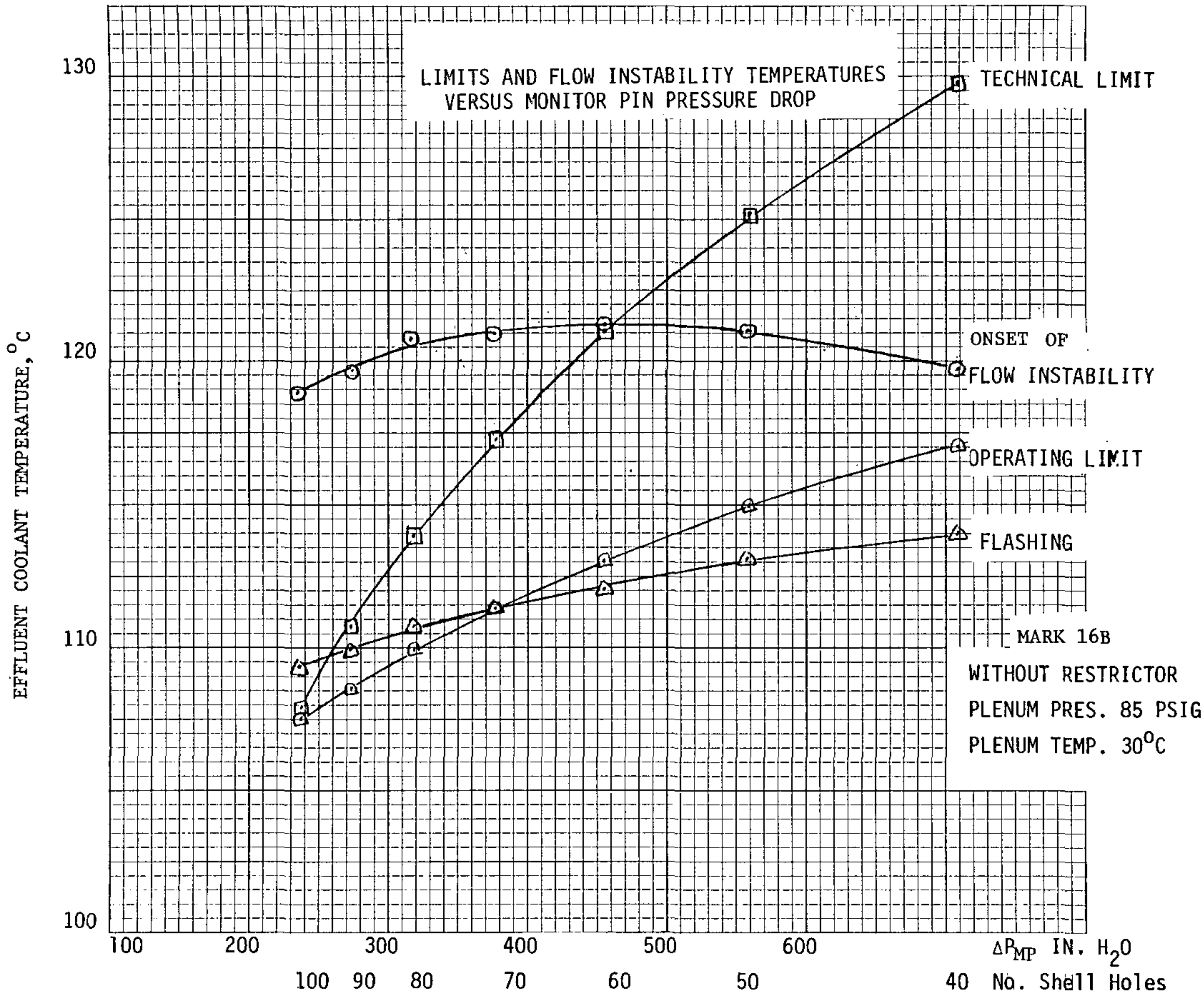

LIMITS AND FLOW INSTABILITY TEMPERATURES
VERSUS MONITOR PIN PRESSURE DROP
TECHNICAL LIMIT
ONSET OF
FLOW INSTABILITY
OPERATING LIMIT
FLASHING
MARK 16B
WITHOUT RESTRICTOR
PLENUM PRES. 75 PSIG
PLENUM TEMP. 45°C
EFFLUENT COOLANT TEMPERATURE, °C
130
120
110
100
100
200
300
400
500
600
ΔPMP IN. H2O
100
90
80
70
60
50
40
No. Shell Holes

FIGURE 8


LIMITS AND FLOW INSTABILITY TEMPERATURES
VERSUS MONITOR PIN PRESSURE DROP
TECHNICAL LIMIT
ONSET OF
FLOW INSTABILITY
OPERATING LIMIT
FLASHING
MARK 16B
WITHOUT RESTRICTOR
PLENUM PRES. 85 PSIG
PLENUM TEMP. 30°C
EFFLUENT COOLANT TEMPERATURE, °C
130
120
110
100
100
200
300
400
500
600
ΔP_{MP} IN. H_2O
100
90
80
70
60
50
40
No. Shell Holes