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AN INVENTORY OF THE TWO-PHASE CRITICAL FLOW EXPERIMENTAL DATA BASE

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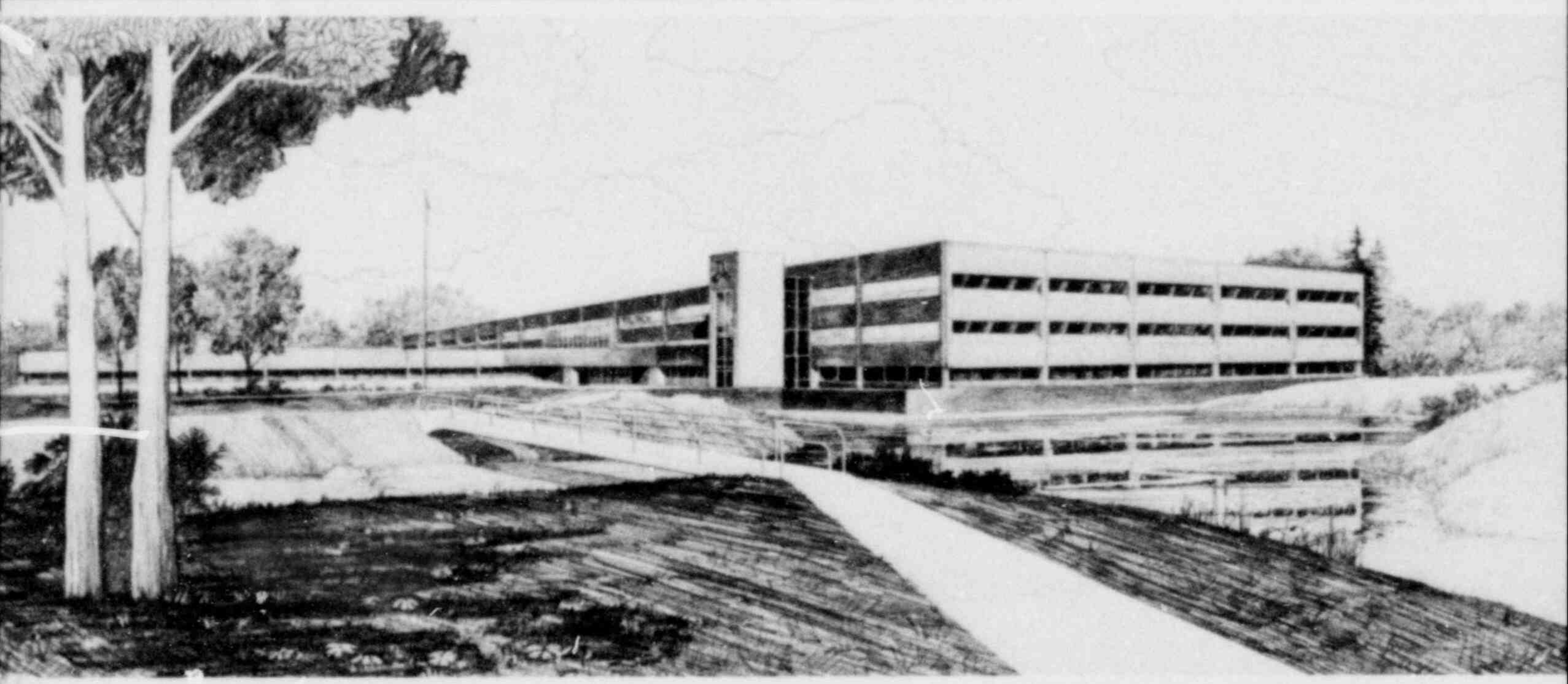

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ABSTRACT

An inventory of currently available experimental critical flow data has been performed. The results of the inventory are displayed in a table which lists key parameters that characterize each experimental program. The distribution of the data base with regard to geometric parameters is presented for three classes of test section. Recommendations for future testing are made in light of deficiencies that have been identified. Additional recommendations to enhance the utility of the current data base and the results of future experimental programs are made. A bibliography of references documenting experimental critical flow studies is also included.

ACKNOWLEDGEMENTS

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CONTENTS

FIGURES

TABLE

SUMMARY

The phenomenon whereby the flowrate of a two-phase fluid has an upper bound for a given set of stagnation conditions has been studied extensively during the past forty years. It was recently decided by the Committee on the Safety of Nuclear Installations (CSNI) of the Organization for Economic Cooperation and Development (OECD) that the state-of-the-art of modeling this phenomenon known as critical or choked flow will be determined and documented. The task includes an inventory of the experimental critical flow data base. The results of such an inventory are reported herein.

Computerized literature searches were performed on the catalogs of seven technical information services. The resulting bibliography was screened and documents reporting experimental critical flow studies were obtained and reviewed. The data base was documented by producing a large table containing information describing each experimental study. The principal dimensions of three classes of test sections; pipes, nozzles, and orifices have been assembled in graphical form to aid in analyzing the distribution of the geometries that have been studied.

The data base inventory showed that significant amounts of experimental data are available for pipes, nozzles, and orifices and that the range of principal dimensions of the test sections in these three categories is considerable. Deficiencies appear to exist in the areas of critical flow data for nozzles and orifices larger than 30 mm, for standard plumbing components (only three references on this subject were found), and for slits which are representative of cracks in pipe walls and in weldments (one reference on this subject was found). In addition to identifying possible deficiencies in the data base, recommendations are made to increase the utility of the data that is presently available and that which will be produced in the future. These recommendations deal with planning future studies to ensure that they mesh with the data presently available, complete documentation of the stagnation state of the flow, and the inclusion of tabulated data and complete measurement uncertainty information in the reporting document.

The report is concluded with a bibliography of references which appear from their abstracts to contain experimental critical flow data. This bibliography is included since the inventory of the experimental data base presented herein is not considered to be complete because of time constraints in performing the inventory, the unavailability of some references, and the inability of the author to review documents not written in or translated to English.

INTRODUCTION

The phenomenon of critical or choked flow occurs in a wide range of technologies. Because of its importance, a large number of experimental studies of the phenomenon have been conducted during the last 40 years. The importance of the phenomenon in predicting the results of a nuclear reactor loss-of-coolant accident was primarily responsible for accelerating the rate at which experimental studies were conducted beginning in the 1960s. The results of the experimental studies have been used to develop numerous analytical models of the phenomenon. It is clear to those accustomed to utilizing the existing analytical critical flow models that the problem of predicting the critical flow rate and the thermodynamic state of the choke point is not a closed case for many flow situations of interest. This problem is a result of the large variety of flow geometries of interest and the wide range of fluid conditions over which the phenomenon must be predicted.

In the interest of avoiding duplication of effort, maximizing the utility of past research, and providing direction for future research, it is beneficial to periodically document the level of understanding and the art of predicting a particular physical phenomenon. At its November 1978 meeting the Committee on the Safety of Nuclear Installations (CSNI) of the Organization for Economic Cooperation and Development adopted a proposal by the United States that the Committee should undertake the preparation of state-of-the-art reports (SOAR) on selected topics of interest. At the November 1979 meeting the Committee adopted a list of topics submitted by committee members. It was further decided that two SOARs would be prepared in time for the November 1980 meeting. One of those reports would document the state-of-the-art of critical flow modeling. An outline for the critical flow SOAR was assembled by a group of technical experts in January 1980. It was determined that the document would contain inventories of the critical flow experimental data base and the available analytical models as well as assessments of how well the models predict the critical flow phenomenon.

An inventory of the critical flow experimental data base was performed as the United States Nuclear Regulatory Commission's contribution to the production of the critical flow SOAR. The results of the inventory are documented herein. The principal parameters describing each experimental study that has contributed to the data base are presented in the next section. A discussion of ranges of parameters for which data is available is presented in the third section. The fourth section of the report contains conclusions regarding the availability of experimental critical flow data and recommendations for future experimental work. The report is concluded with a bibliography of references describing experimental critical flow studies.

DATA BASE INVENTORY

The experimental critical flow data base was inventoried by reviewing as many references documenting experimental critical flow studies as possible. Documents were selected by reviewing the results of computerized literature searches of the catalogs of the following information services for the indicated years:

Nuclear Safety Information Service - 1967-1980
DOE Energy Data Base - 1974-1980
Nuclear Science Abstracts - 1967-1976
Government Reports Anouncements (National Technical Information Service) - 1964-1980
Engineering Index - 1970-1979
Science Abstracts - 1969-1979

References for years prior to 1964 were identified by reviewing reference sections and bibliographies contained in the later reports.

The critical flow data base is summarized in Table 1 which lists parameters that characterize each experimental program. The table does not present a complete inventory of the experimental data base, but does contain many of the experimental data sources that have been referenced in the literature during the past 20 years. The table entries are divided into four groups: pipes, nozzles, orifices, and other geometries. The entries within each group are listed in chronological order from the most recent to the earliest . The author's name appearing on the reference documenting the experiment study has been used to identify each study with an accompanying reference notation referring to an entry in the reference section of the report. Exceptions to this convention have been made in the cases of data generated during the extensive test programs of the Marviken CFT Project and the Semiscale Project. Data from these programs are referred to by the project name. The document publication date is given generally by month and year. This date does not necessarily correspond closely to when the testing was conducted. The general type of test section or flow geometry in which choking occurred is listed followed by the size or range of sizes of the minimum test section cross section.

CRITICAL FLOW EXPERIMENTAL DATA BASE

SOURCE	DATE	TYPE	SIZE (mm)	FLUID	REGIME	PRESSURE LEVEL (bars)	COMMENTS
		P I P E S					
Boivin[1]	12-79	pipe (rec)	12-50	H_2O	sub	p_o = 20-101	L/D = 38 - 53 ; test section lengths not clearly reported
Marviken CFT Project[2]	1978-79	pipe (rec)	200-509	H_2O	sub & sat (2ϕ)	p_o = 40-50	L/D = 0.3 - 3.7
Jeandey and Pinet[3]	6-78	pipe (sec?)	14	H_2O/N_2	simulated 2ϕ	p_p = 2-6	L/D = 169; stagnation conditions not reported; pressure in upstream portion of the pipe (p_p) reported
Ardon and Ackerman[4]	6-78	pipe (sec)	26	H_2O	sub	p_p = 1.4	L/D = 39; stagnation conditions not reported; static pressure in upstream portion of the pipe (pp) reported
Reocreux[5]	8-77	pipe (sec)	20	H_2O	sat (2ϕ)	p_e = 1.5-2.0	L/D = 124; stagnation conditions not reported; static pressure at the exit of the constant section(p_e) reported
Semiscale Project[6]	6-77	pipe (cec)	18	H_2O	sub & sat (2ϕ)	p_o = 3-103	L/D = 4; system blowdown experiment
Rassokhin, et al.[7]	5-77	pipe (sec)	30	H_2O	sub & sat	p_o = 1-32	L/D = 0.3; flow rates not reported
Khlestkin, Kanish - chev, and Keller[8]	3-77	pipe (sec)	4	H_2O	sub & sat	p_o = 6-228	L/D = 0.5-6.0; flow rates are in nondimensional form
Prisco, Henry, Hutcherson, and Linehan[9]	3-77	pipe (sec)	20	Freon-11	sub & sat (2ϕ)	p_o = 67-115 kPa	L/D = 2.8 - 100.0
Morrison[10]	10-76	pipe (rec)	28	H_2O	sub & sat (2ϕ)	p_o = 58-67	L/D = 4.8

Note: cec = conical entrance contour
rec = radiused entrance contour
sec = sharp entrance contour

sat = saturated liquid state
sat (2ϕ) = saturated two-phase state
sub = subcooled state

CRITICAL FLOW EXPERIMENTAL DATA BASE (Cont.)

SOURCE	DATE	TYPE	SIZE (mm)	FLUID	REGIME	PRESSURE LEVEL (bars)	COMMENTS
Seynhaeve, Giot, and Fritte[11]	8-76	pipe (sec & cec)	12.5, 20	H_2O	sub	p_e = 1.4-6.7	L/D = 17.7 - 124.5; stagnation conditions not reported; static pressure at the exit of the constant area section (p_e) reported
Hutcherson[12]	11-75	pipe (cec)	108	H_2O	sat (2ϕ)	p_o = 1-18	L/D = 3; system blowdown experiment
Sozzi & Sutherland[13]	7-75	pipe (sec & rec)	13	H_2O	sub & sat (2ϕ)	p_o = 30-71	L/D = 0.4-140
Prisco[14]	2-75	pipe (sec)	8	CCl_3F	sub?	po = 67-115 Pa	L/D = 2.8-12.8
Howard[15]	1-75	pipe (sec & rec)	2-6	Freon-11	sub	p_o = 52-165 kPa	L/D = 25-300
Edwards & Jones[16]	1974	pipe (sec)	32	H_2O	sat(2ϕ)	p_o = 2-54	L/D = 28; system blowdown experiment
Mal'tsev, Kolestkin, and Keller[17]	6-72	pipe (sec)	3, 3.5	H_2O	sat	p_o = 20-220	L/D = 0.5-9.0
Klingebiel & Moulton[18]	3-71	pipe (cec)	13	H_2O	sat (2ϕ)	p_e = 2-5	L/D = 44; stagnation conditions not reported; static pressure at exit of constant area section (p_e) reported
Henry[19]	9-70	pipe (rec)	8	H_2O	sub	p_e = 10-20	L/D = 115; stagnation conditions not completely reported; static pressure at exit of constant area section (p_e) reported
Allemann et al.[20]	6-70	pipe (sec)	21-173	H_2O	sub & sat (2ϕ)	p_o = 42-165	L/D = 0.5-4.3; system blowdown experiment
Henry[21]	3-68	pipe (rec)	3, 8	H_2O	sub	p_e = 2-10	L/D = 115, 274; stagnation conditions not fully reported; static pressure at exit of constant area section (p_e) reported

Note: cec = conical entrance contour; rec = radiused entrance contour; sec = sharp entrance contour; sat = saturated liquid state; sat (2ϕ) = saturated two-phase state; sub = subcooled state

CRITICAL FLOW EXPERIMENTAL DATA BASE (Cont.)

SOURCE	DATE	TYPE	SIZE (mm)	FLUID	REGIME	PRESSURE LEVEL (bars)	COMMENTS
Kelly[27]	1-68	pipe (sec?)	2-3	H_2O	sub & sat (2ϕ)	p_e = 1-6	L/D = 90; stagnation conditions not specified; static pressure at exit of constant areas section (p_e) reported
Uchida & Nariai[23]	8-66	pipe (sec)	4	H_2O	sub & sat	p_o = 0.2-0.8	L/D = 25-625
Fauske[24]	1965	pipe (sec)	6	H_2O	sat	p_o = 7-124	L/D = 0-40
Zaloudek[25]	1-64	pipe (cec)	13	H_2O	sat (2ϕ)	p_o = 28-124	L/D = 20
Zaloudek[26]	5-63	pipe (sec & rec)	6-16	H_2O	sub	p_o = 8-25	L/D = 1-6
Cruver[27]	1963	pipe (cec)	13	H_2O	sat (2ϕ)	p_e = 1-3	L/D - 52; stagnation conditions not fully reported; static pressure at the exit of the constant area duct (p_e) reported
Fauske & Min[28]	1-63	pipe (sec?)	?	Freon-11	sat	p_o = 103 kPa	L/D = 2-55
Fauske[29]	10-62	pipe (sec)	3-12	H_2O	sat (2ϕ)	p_e = 3-25	L/D = 228-880; stagnation conditions not reported; static pressure at exit of constant area section ((p_e) reported
James[30]	1962	pipe (?)	76, 152, 203	H_2O	sat (2ϕ)	p_e = 1-4	Test section length not reported; stagnation pressure not reported; static pressure at exit of constant area duct (p_e) reported
Friedrich & Vetter[31]	1-62	pipe (sec & rec)	4	H_2O	sub & sat (2ϕ)	p_o = 6-30	L/D = 0.2-15
Friedrich[32]	10-60	pipe (sec & rec)	1.5-4	H_2O	sub & sat (2ϕ)	p_o = 2-61	L/D = 0.2-2.5

Note: cec = conical entrance contour
rec = radiused entrance contour
sec = sharp entrance contour

sat = saturated liquid state
sat (2ϕ) = saturated two-phase state
sub = subcooled state

CRITICAL FLOW EXPERIMENTAL DATA BASE (Cont.)

SOURCE	DATE	TYPE	SIZE (mm)	FLUID	REGIME	PRESSURE LEVEL (bars)	COMMENTS
Isbin, Moy, and Da Cruz[33]	9-57	pipe (cec)	10-26	H_2O	sat	p_e = 27-296 kPa	L/D = 23-64 assuming L = 610 mm (2 ft.) stagnation conditions not reported; static pressure at exit of constant area section (p_e) reported
Moy[34]	1-55	pipe (cec)	6-25	H_2O	sat (2ϕ)	p_e = 27-296 kPa	L/D = 35-96; stagnation conditions not reported; static pressure at exit of constant area section (p_e) reported
Pasqua[35]	5-52	pipe (sec & rec)	1-3	Freon-12	sub & sat	6-9	L/D = 4-24
Linning[36]	1952	pipe (sec?)	1.5,3	H_2O	sub	p_o = 2	L/D = 1125, 2400
Burnell[37]	12-47	pipe (sec & rec)	5-38	H_2O	sat	p_o = 1-12	L/D = 0-656
Silver & Mitchell[38]	1945	pipe (rec)	5,13	H_2O	sub & sat	p_o = 1-3	L/D = 0.3-11.4
Danforth[39]	5-41	pipe (rec)	3	H_2O	sub	p_o = 3-7	L/D = 1
			N O Z Z L E S				
Martinec[40]	12-79	Nozzle	3	Freon-11	sub	p_o = 16-22	
Zimmer et al.[41]	4-79	Nozzle	25	H_2O	sub	p_o = 1-10	
Semiscale Project[42]	12-78	Nozzle	17	H_2O	sub & sat (2ϕ)	p_o = 3-100	System blowdown experiment
Karasev, Vazinger, and Mingaleeva[43]	6-77	Nozzle	4,19	H_2O	sat	p_o = 20-100	

Note: cec = conical entrance contour
rec = radiused entrance contour
sec = sharp entrance contour

sat = saturated liquid state
sat (2ϕ) = saturated two-phase state
sub = subcooled state

CRITICAL FLOW EXPERIMENTAL DATA BASE (Cont)

SOURCE	DATE	TYPE	SIZE (mm)	FLUID	REGIME	PRESSURE LEVEL (bars)	COMMENTS
Semiscale Project[44]	6-77	Nozzle	25	H_2O	sub & sat (2ϕ)	p_o = 3-90	System blowdown experiment
Semiscale Project[45]	1-77	Nozzle	4	H_2O	sub & sat (2ϕ)	p_o = 17-124	System blowdown experiment
Morrison[10]	10-76	Nozzle	28	H_2O	sub & sat (2ϕ)	p_o = 58-67	
Shrock, Starkmann, and Brown[46]	8-76	Nozzle	4-11	H_2O	sub & sat (2ϕ)	p_o = 8-91	
Semiscale Project[47]	7-76	Nozzle	13	H_2O	sub & sat (2ϕ)	p_o = 3-110	System blowdown experiment
Simoneau[48]	12-75	Nozzle	4	N_2	sub	p_o = 5-66	
Semiscale Project[49]	11-75	Nozzle	18	H_2O	sub & sat (2ϕ)	p_o = 6-103	System blowdown experiment
Hendricks, Simoneau, and Barrows[50]	9-75	Nozzle	4	N_2	sub & super-critical	p_o = 9-102	
Sozzi & Sutherland[13]	7-75	Nozzle	13-76	H_2O	sub & sat (2ϕ)	p_o = 30-71	
Dryndrozhik[51]	2-75	Nozzle	6,11	H_2O	sat (2ϕ)	p_o = 2-5	
Adachi & Yamamoto[52]	12-74	Nozzle	10	H_2O	sat (2ϕ)	p_o = 18-30	
Hendricks, Simoneau, and Ehlers[53]	8-72	Nozzle	3	N_2	sub & super-critical	po = 12-102	
Deich et al.[54]	4-69	Nozzle	32.5	H_2O	sat (2ϕ)	p_o = 1	
Vogrin[55]	7-63	Nozzle	5	Air/H_2O	simulated 2ϕ	p_o = 1-7	
Neusen[56]	1-62	Nozzle	6,11	H_2O	sat (2ϕ)	p_o = 8-65	

Note: cec = conical entrance contour
rec = radiused entrance contour
sec = sharp entrance contour

sat = saturated liquid state
sat (2ϕ) = saturated two-phase state
sub = subcooled state

CRITICAL FLOW EXPREIMENTAL DATA BASE (Cont.)

SOURCE	DATE	TYPE	SIZE (mm)	FLUID	REGIME	PRESSURE LEVEL (bars)	COMMENTS
			O R I F I C E S				
Covelli[57]	1976	orifice	22.5, 30	sand/water	sat (2ϕ)	2-4	
Edwards & Jones[16]	1974	orifice	22.5	H_2O	sat (2ϕ)	p_o = 2-54	System blowdown experiment
Uchida & Nariai[23]	8-66	orifice	4	H_2O	sub & sat	p_o = 0.2-0.8	
Zaloudek[26]	5-63	orifice	13	H_2O	sub	p_o = 8	
Friedrich & Vetter[31]	1-62	orifice	4	H_2O	sub & sat (2ϕ)	p_o = 6-30	
Friedrich[32]	10-60	orifice	1.5-4	H_2O	sub & sat (2ϕ)	p_o = 2-61	
Monroe[58]	'-57	orifice	6-16	H_2O	sat	p_o = 2-11	
Pasqua[35]	5-52	orifice	1-3	Freon-12	sub & sat	p_o 6-9	
Silver & Mitchell[38]	1945	orifice	5	H_2O	sub & sat	p_o = 1-3	
Benjamin & Miller[59]	7-41	orifice	6-22	H_2O	sat	p_o = 1-21	
			O T H E R				
Martinec[40]	12-79	globe valve, relief valve	3 4	Freon-11	sub	p_o = 6-22	
Grison & Lauro[60]	12-78	pump	80 entrance	H_2O	sat (2ϕ)	p_i = 35-85	Stagnation conditions not reported; static pressure at pump inlet (p_i) reported
Zaloudek[61]	3-65	tee, elbow	16	H_2O	sat (2ϕ)	p_e = 1-6	Stagnation conditions not reported; static pressure near exit constant area section (p_e) reported

Note: cec = conical entrance contour
rec = radiused entrance contour
sec = sharp entrance contour

sat = saturated liquid state
sat (2ϕ) = saturated two-phase state
sub = subcooled state

CRITICAL FLOW EXPERIMENTAL DATA BASE (Cont.)

SOURCE	DATE	TYPE	SIZE (mm)	FLUID	REGIME	PRESSURE LEVEL (bars)	COMMENTS
Fauske & Min[28]	1-63	aperture (9 shapes)	d = 2-7 equivalent	Freon-11	sat	p_o = 103 kPa	
Faletti[62]	12-59	annulus (cec)	d = 5-9 equivalent	H_2O	sat (2ϕ)	p_e = 2-7	Equivalent L/D = 3-107; Stagnation conditions not completely reported; static pressure at exit of constant area section (p_e) reported
Moy[34]	1-55	annulus	d = 6-25 equivalent	H_2O	sat (2ϕ)	p_e = 27-296 kPa	Equivalent L/D = 35-96; stagnation conditions not reported; static pressure at exit of area section (p_e) reported

Note: cec = conical entrance contour
rec = radiused entrance contour
sec = sharp entrance contour

sat = saturated liquid state
sat (2ϕ) = saturated two-phase state
sub = subcooled state

Sizes are given to the nearest half millimeter. The fluid that was used to perform the tests is indicated in the table. While the majority of the experiments were conducted using water as the test fluid; Freon, nitrogen, and gas-water mixtures were also used. The thermodynamic regime(s) in which the flow stagnation conditions resided is listed in the table as "sub", "sat" or "sat(2)". These abbreviations denote subcooled conditions, saturated liquid conditions, and saturated two-phase mixture conditions respectively. In order to convey "where the data is" thermodynamically, a range of pressures at which data was recorded is included as a table parameter. It was intended that this parameter would refer to stagnation pressure; however, some of the references did not report stagnation pressures. In these references, the pressure measurement nearest the end of the constant area section was considered of prime importance. Therefore, the range of this pressure has been substituted for these references. A commment section follows the parametric data. These comments provide supplementary information required to adequately describe the experiment or the availability of information.

Several naming conventions have been used in Table 1 to refer to test sections. All test sections containing a constant area section have been designated as "pipes" regardless of size unless the constant area section was both preceeded and followed by a varying area section. The type of entrance contour is indicated for each test section that has been designated as a pipe. A 90-degree entrance to the constant area section is indicated by "SEC" denoting sharp entrance contour, a rounded entrance is indicated by "REC" denoting rounded entrance contour, and a conical entrance is indicated by "CEC" denoting conical entrance contour. The exit contour following the constant area duct has not been indicated. Most of the pipes had 90-degree exits. However, some had conical exit contours (e.g., Henry[19,21], Prisco[14], Reocreux[5]). The term "nozzle" has been used to denote flow geometries having a varying area section preceding and following the minimum area section. The entrance or diffuser sections may have been conical or of varying radius. The nozzle throat may have been a single cross section or a short constant area section. The term "orifice" has been used to denote flow geometries having a 90-degree entrance and a constant area section having an L/D of 0.1 or less.

DISCUSSION

The experimental critical flow data inventory presented in Table 1 has several noteworthy aspects. It is clear that the majority of the experimental critical flow data has been obtained using constant area ducts (References 1 through 39). A significant number of critical flow experiments have been conducted using converging-diverging nozzles (References 10, 13, 40 through 56). Data for critical flow occurring in orifices are also available (References 16, 23, 26, 31, 32, 57 through 59), but are quite limited compared to those available for the other two classes of geometry. Only three references documenting studies of critical flow in plumbing components were found: one using tees and elbows (Reference 61), one using valves (Reference 40), and one using a pump (Reference 60). Data on critical flow through geometries resembling a split or crack in a pipe wall or a weldment also seem to be very limited. Only one reference for this type of geometry was found (Reference 28). It is also noteworthy that little of the pipe and nozzle data were obtained using flow geometries that can be considered ideal from the standpoint of an avoidance of flow separation at the entry to the constant area section or throat.

The length and diameter of pipe geometries for which references of experimental studies were found are presented in Figure 1a. Only dimensions of geometries that were tested using water as a test medium are presented. Differences in entrance contour are denoted in Figure 1a by clear symbol to denote data for 90-degree entrances, by using a solid symbol to denote data for rounded entrances, and by using a partially solid symbol to denote data for conical entrances. Figure 1a shows that critical flow data are available for pipes having diameters ranging from 1.5 to 500 mm, and lengths ranging from 0.6 to 2800 mm. It is clear from Figure 1a that a great deal of data are available for test sections having diameters less than or equal to 13 mm. On the other hand, the data from the Marviken CFT Project are the only data that were found for test sections having diameters greater than or equal to 200 mm. In addition, only five experiments were found that were conducted with test sections having diameters between 30 and .00 mm.

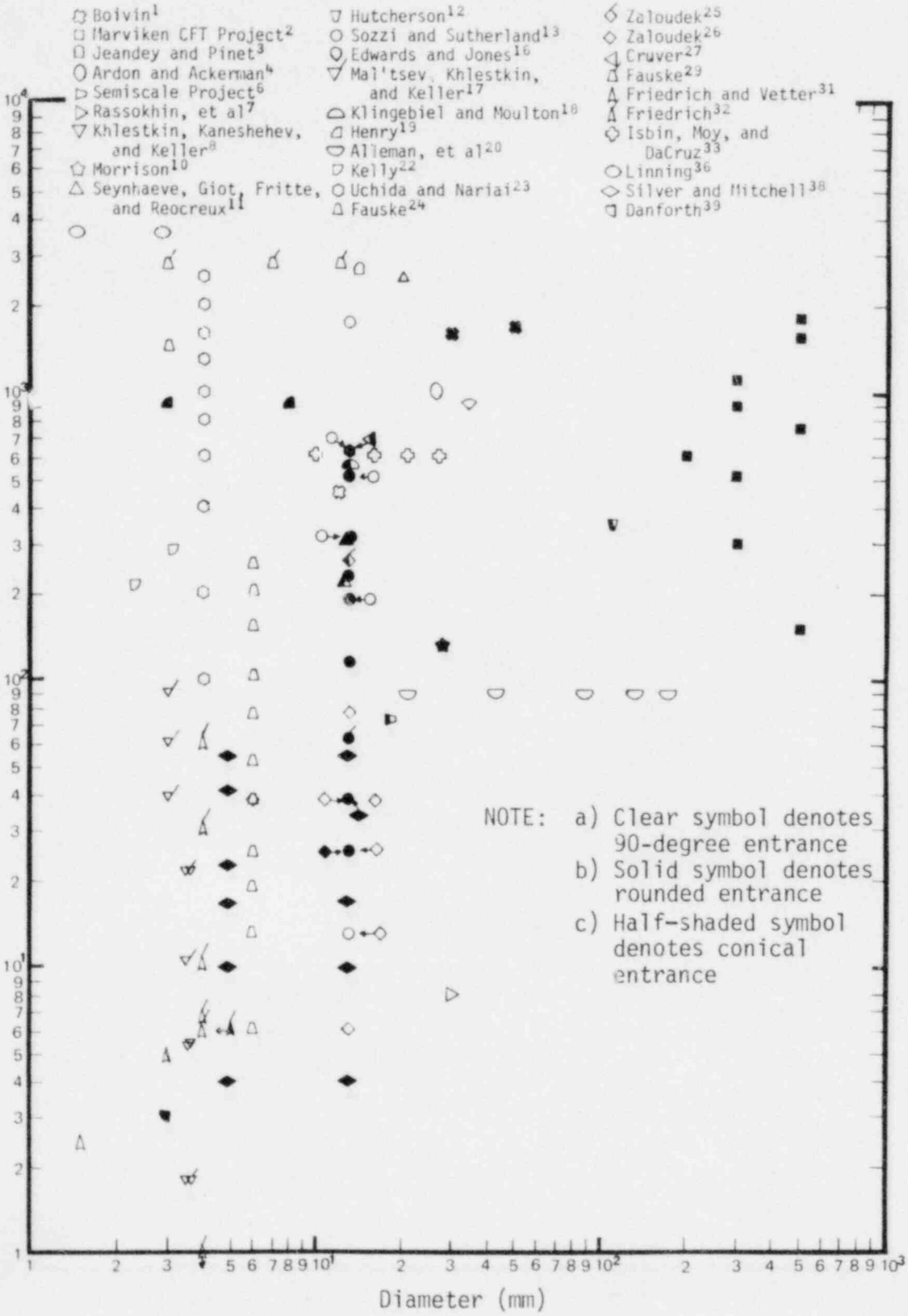

Figure 1a. Lengths and diameters of constant area test sections.

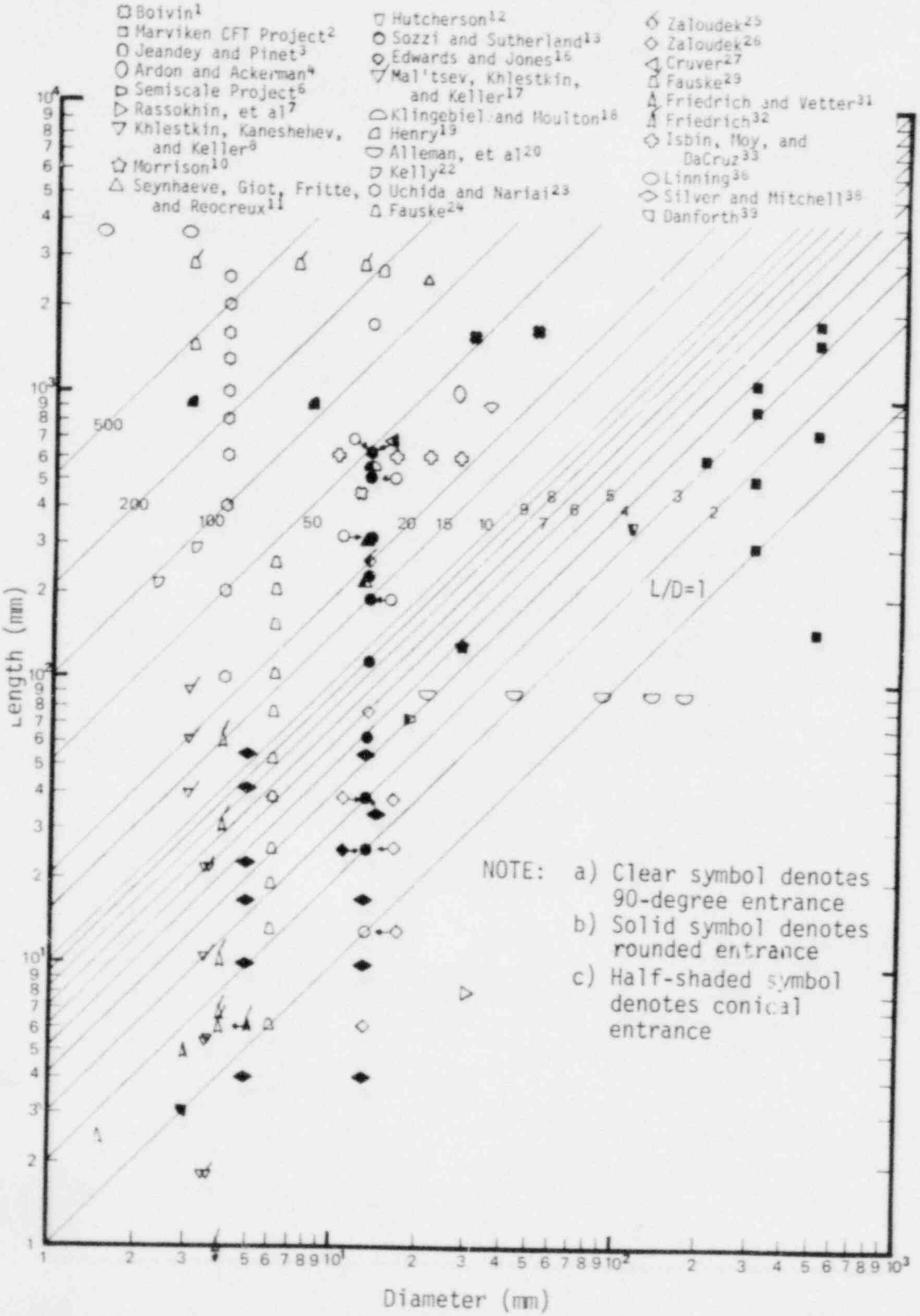

Figure 1b. Length-to-diameter ratio of constant area test sections.

Several studies have been conducted using test sections having the same diameter, but differing in length over a wide range (References 13, 23, 24, and 38). Data are also available for cases in which the test section length was held constant and the diameter was varied (References 20, 29, and 33), although the range of diameter variation was generally more limited than the variation in length at constant diameter in the aforementioned studies.

In order to illustrate the availability of critical flow data in pipes of constant length-to-diameter ratio (L/D), lines of constant L/D have been added to data presented in Figure 1a to produce Figure 1b. This figure shows that data are available for L/Ds ranging from less than 1.0 to over 500. Figure 1b shows that data produced using test sections covering a wide range of size are available at the same L/D for L/Ds less than four. However, comparing experimental results at the same L/D would be hampered by differences in entrance contour. Some of the data were obtained using 90-degree entrance contours while other data were obtained using rounded or conical entrance contours. Another factor which would complicate the comparison of data at the same L/D is that the data are seldom available at the same stagnation conditions.

The throat sizes of converging - diverging nozzles for which experimental critical flow data were found are presented in Figure 2.

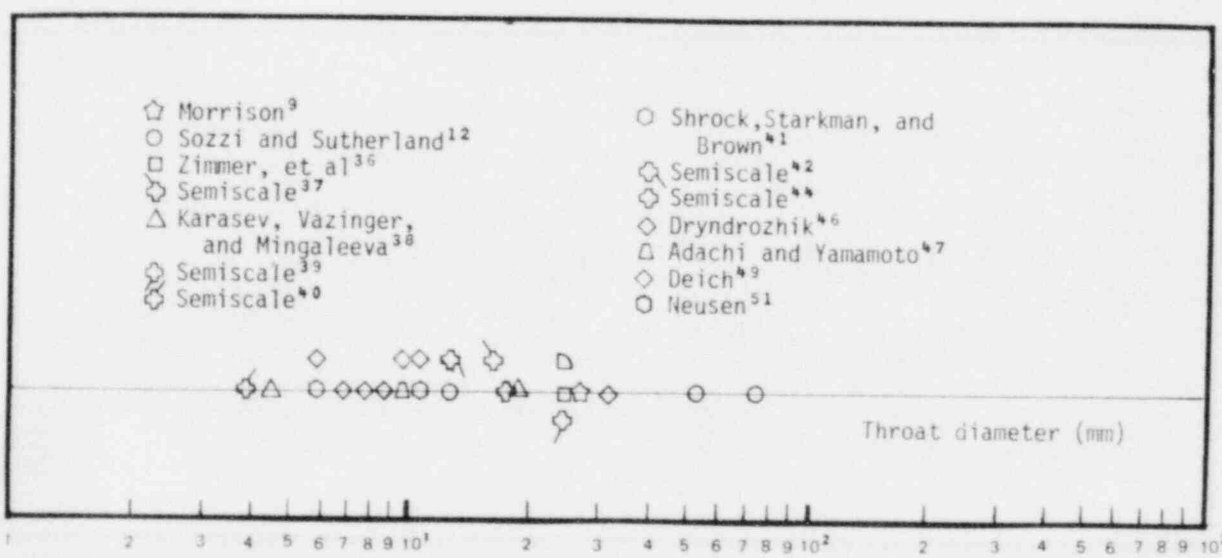

Figure 2. Converging - diverging nozzle throat diameters.

The throat sizes vary from 4 to 75 mm. The data in Figure 2 show that there is little redundancy in size. It - noteworthy that the nozzles vary in entrance contour (conical versus rounded) and in the extent of the minimum area section (a single axial locati:n versus short constant area section).

:.e sizes of orifices for which experimental critical flow data was found are presented in Figure 3.

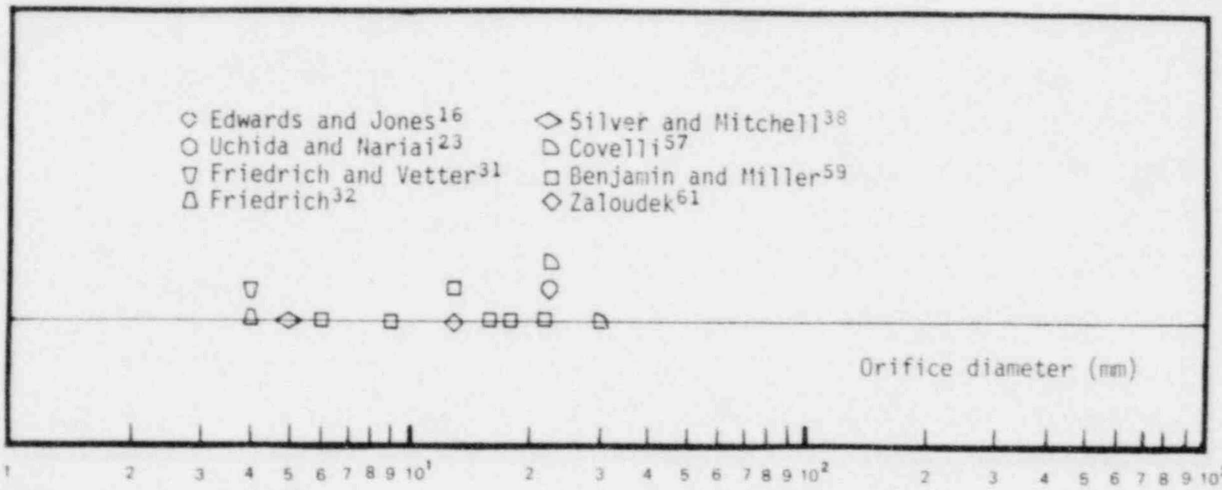

Figure 3. Orifice diameters.

The range of sizes (4 to 30 mm) was quite limited compared to the other two classes of geometries. The orifice size range is reduced to 4 to 22.5 mm if Covelli's data (Reference 57), which were obtained using a sand suspenion in water as the test medium, are not considered. Figure 3 shows that there are only three orifice sizes that have bee. used in more tnan one experimental study.

CONCLUSIONS AND RECOMMENDATIONS

The general conclusions that can be drawn from a review of the critical flow data inventory that has been made are presented in this section. Recommendations for remedying deficiencies in the data base and for improving the design and reporting of future experimental programs are given.

Conclusions

1. *A large amount of experimental critical flow data is available.*

   Sixty-two documents were found that described experimental critical flow studies and contained experimental data. The studies investigated critical flow in constant area ducts, converging-diverging nozzles, orifices, pipe tees and elbows, valves, and slits.

2. *The majority of the data was obtained using constant area ducts.*

   More than half of the references found documented critical flow studies conducted with constant area ducts. The test sections covered large ranges of diameter (1.5 to 500 mm) and length (0.6 to 2800 mm).

3. *Significant amounts of critical flow data are available for converging-diverging nozzles and orifices over a limited range of sizes.*

   Nineteen references were found documenting critical flow studies using converging-diverging nozzles and 10 references were found documenting critical flow studies using orifices. The nozzle throat and orifice diameters ranged from 4 to 75 mm and 4 to 30 mm respectively.

4. *Little data are available for critical flow occurring in standard piping components and for geometries resembling piping failures other than a guillotine break.*

Three references were found in which critical flow was studied in standard plumbing components. These studies utilized small scale elbows, tees, valves, and a small scale pump. Only one reference was found in which critical flow was studied in slits simulating a localized pipe failure and again the apparatus used was small scale.

5. *Critical flow data obtained at loss-of-coolant accident fluid conditions and obtained using full-scale test apparatus is very limited.*

The 27 tests conducted during the Marviken CFT Project are the only known source of data obtained at high pressure/temperature conditions using test sections having diameters greater than 200 mm. Data for test section diameters in the tens of millimeters are also quite limited. Large amounts of data are available only for diameters less than 13 mm.

6. *Little data are available for idealized flow geometries that are designed to avoid entrance separation.*

Most of the constant area ducts had 90-degree, conical, or small radiused entrances (i.e., approximately equal to half the test section diameter). Most of the nozzles had conical entrances of large half-angle and many had an abrupt change in slope at the entrance of the minimum area section and large half-angle diffusers. Very few test sections had gradual approaches to the minimum area section with a continuous change in slope.

7. *Utilization of some of the data is hampered by dissimilarities in test section geometry and fluid conditions and by a lack of essential information.*

Differences in test section entrance contour, nozzle throat geometry, and diffuser angle would contribute additional uncertainties if the data were used to assess the effect of geometric variables. Such assessments would also be complicated by a lack of data at common stagnation conditions. Several references did not contain sufficient data to completely specifiy the stagnation state of flow passing through the nozzle which greatly limits their usefulness for critical flow model assessment and development.

Recommendations

1. *Future experimental critical flow studies should be designed to ensure optimal use of and integration with the present data base.*

A large amount of experimental critical flow data is available. This data base should be carefully reviewed as part of planning for future critical flow research to ensure that testing is directed towards expansion of the distribution of geometries for which data is available instead of unnecessary duplication of effort. Test section geometries and stagnation fluid conditions should also be selected to ensure that straightforward comparisons can be made with existing data.

2. *Tabulated experimental data including a complete specification of the stagnation condition of the flow at the entrance to the test section should be included in the document reporting a critical flow study or a reference to the source from which such data can be obtained should be included.*

The enclosure of tabulated data in the document reporting an experimental critical flow study greatly increases the usefulness of the information. This practice eliminates the need for taking data from report figures. Extracting data from report figures produces data of questionable quality due to possible distortions of the data in producing the plot or in report reproduction, a lack of resolution when using small report figures, and possible errors in reading the data from the plot. Reporting of sufficient data to completely define the stagnation thermodynamic state of the choked flow is important because the flow rate and critical thermodyanamic state are primarily a function of the stagnation state. Furthermore, most critical flow models require the stagnation state as input to compute the critical flow rate and critical state. Experimental data which does not include a complete definition of the stagnation state thus cannot be used for model assessment.

3. *Additional data on critical flow in plumbing components and in pipe failure geometries other than the guillotine break appear to be needed.*

The current interest in small break loss of coolant accidents would seen to increase the need for critical flow data in plumbing components and pipe failures. Modeling of critical flow through safety and relief valves has already been identified as an area of study by the USNRC and other agencies. With the consideration of small breaks, the path to where the flow is being exhausted to the containment may be long and contain numerous plumbing components which are prospective choking locations. The interest in breaks having higher probabilities of occurrence than the guillotine break should increase the interest in critical flow in pipe failure geometries such as pipe splits and weldment cracks.

4. *The range of sizes of converging-diverging nozzles and orifices for which critical flow data is available is rather limited and may need to be expanded.*

Most of the data for converging-diverging nozzles and orifices have been obtained with test sections having minimum area sections ranging in size from 4 to 20 or 30 mm. Additional data may be required if larger scale applications for hardware from these two classes are identified. The most likely requirement would come from a need to meter flow since these two geometries are typically used in metering devices.

5. *More complete information on the uncertainties of all measurements made in a critical flow study are needed with particular emphasis on the uncertainty of the measured flow rate.*

Less than half of the references found included measurement uncertainty information. The information that was reported included fluid property measurement uncertainties but generally did not include the uncertainty of the flow rate measurement. In most cases the uncertainty information was not explained so it could be properly interrupted. Inclusion of measurement uncertainty is essential to determine if significant differences in the data exist that might indicate parametric influences. Measurement uncertainties are also essential in performing analytical model or system code assessment since a clear picture of the uncertainty of the model or code requires knowledge of the uncertainty associated with the data being used to assess the model or code.

6. *The critical flow data for pipes that are available should be used to assess the effect of scale on critical flow phenomena.*

A basic 'umption in performing reactor safety studies is that models based on small-scale data can be used to predict the hydraulic response of full-scale systems. The phenomena modeled are thus assumed to be independent of scale or a method of adjusting the modeling techniques for the effect of scale must be known. Since critical flow data are available for constant area ducts ranging in diameter from 1.5 to 500 mm, it appears that the effect of scale can be assessed for critical flow through a geometry representative of a reactor vessel nozzle and attached pipe stub. Such a study may be complicated by a lack of data obtained using test sections having the same entrance contour and length-to-diameter ratio and obtained at the same stagnation conditions. Future testing should be defined to add to the data set needed for a straightforward demonstration of the effect of scale.

7. *The experimental critical flow data identified in this study should be assembled in a topical data bank to be included in the USNRC Data Bank.*

The utility of the existing experimental data would be greatly increased if it were available in a uniformly formatted form with supporting software for rapid retrieval and data display and manipulation. The USNRC Data Bank currently provides software which allows rapid retrieval and data display and manipulation. Adding of the existing data to the data bank would be a time consuming but not insurmountable task. The benefits of increased understanding of the phenomenon and of improving the state of the art of critical flow prediction justify the effort.

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