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An Assessment of the Literature Related to LWR Instability Modes

Prepared by R.T. Lahey, Jr., D.A. Drew

Rensselaer Polytechnic Institute

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ABSTRACT

The purpose of this Topical Report is to present the results of an extensive literature survey on instability modes of relevance to LWR technology. The current understanding of relevant thermal-hydraulic and nuclear-coupled instability modes is summarized and specific recommendations are made for future work.

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INTRODUCTION

The stability of boiling flows is important in many energy conversion processes. A sufficiently large excursion, or oscillation, could effect the efficiency of the process, erode thermal margins, or cause damage to mechanical components. Due to the size and complexity of a light water nuclear reactor (LWR), it is impractical to do prototypical experiments to study the effects of varying the various parameters. Tnus, the most efficient method to study the stability of a LWR is a judicious combination of small and large scale experiments and analysis.

The purpose of this study is to review the status of the current analytical understanding and data base. In addition, specific recommendations for further LWR safety-related work are given. It is recommended that this report be read in conjunction with the previous surveys by Bouré et al (1973) and Yadigaroglu (1978), since it is assumed that the reader is somewhat familiar with the field.

Let us now review the status of modelling and analysis capabilities. A summary of the significant literature is given in Appendix-I. Important observations and conclusions are given below.

METHODS OF ANALYSIS

The analysis of boiling instabilities can be done in three ways: (i) phenomenological arguments, (ii) direct numerical integration of the conservation equations, and, (iii) analytical solution of the conservation equations. By a phenomenological argument, we mean an argument based on the recognition of the effect of several reinforcing effects. An example of a phenomenological argument is the classical density-wave oscillation argument. Specifically, a fluctuation in the inlet flow rate is convected into the heated channel, causing a fluctuation in the position where boiling is initiated. It is possible that the phase lag introduced can be such that the resultant pressure drop fluctuation can reinforce the inlet flow rate fluctuation. The intuition involved in this approach often suggests the appropriate model to study the phenomena, however, without accompanying mechanistic based analysis, these phenomenological arguments are little more than educated speculation.

Numerical solutions are of great practical value, both to help understanding the mechanisms involved and to describe the phenomena. It is usually expensive to perform systematic stability studies using solutions obtained by direct numerical integration of the non-linear (time-domain) conservation equations. In addition, an inadequate numerical method can show false instabilities in the numerical solution, even when the real solution is stable. These numerical instabilities are often easily recognized, but there remains the problem of distinguishing real and numerical instabilities. Nevertheless there are a large number of fairly reliable time domain numerical codes available to do transient studies, including stability studies.

There are a number of analytical techniques which are of value in two-phase flow stability studies. Needless to say, there are no general solution techniques for nonlinear differential equations. Therefore, linearized models are the most frequently studied. Linearized models can presumably predict the threshold for the onset of instabilities and the decay of infinitesimal disturbances when the state is stable, but cannot predict any truly nonlinear effects, such as a limit-cycle oscillation. The current state-of-the-art is such that numerical techniques are normally used to deal with large amplitude (ie: fully nonlinear) disturbances.

The most popular, and easiest method to study the linear stability of boiling flow is to use Laplace transforms, and to determine the location of the roots of the characteristic equation in the complex plane. If any of the roots have a positive real part, we conclude that the state is linearly unstable. In using this method for a distributed system, some account must be taken of the spatial variation, both in the steady-state flow, and in the disturbances. Basically, there are three approaches: (i) discretization in space; (ii) numerical integration of the spatial part of the differential equations, or, (iii) direct solution of the partial differential equations by integrating along the characteristics. A variation on approach (iii) is to assume that the steady-state and disturbance profiles are "known", and to use these profiles for computation. It is well known that this method does not give reliable results, and consequently, it is not normally used.

When the characteristic equation, $1 + G(S)H(S)$, in terms of the Laplace transform variable S, has been derived, it must be determined for what parameter values the state is stable. This can be done by determining the root with the largest real part for each value of the flow parameters. Root finding can thus be done by a numerical method, like Newton's method. The analysis can also be done in the frequency domain by using the Nyquist criterion. In this method, the root is replaced by, $S = j\omega$, and ω is varied from zero to large positive values. If the locus of the open-loop transfer function, $G(S)\ H(S)$, encircles $S = -1$ in the complex plane, then a root with positive real part exists. Whichever technique is chosen, the procedure must be carried out for a sufficient number of values of the flow parameters to create a reasonable picture of the marginal stability surface in parameter space. There are other techniques, but they have not been widely used in the analysis of such systems, and thus will not be described here.

INSTABILITY MECHANISMS

For many reasons it is important to identify the basic mechanisms involved in LWR instabilities. First, it is possible to derive simplified criteria to predict instabilities, only if these mechanisms are well understood. To see this effect on a limited scale, consider the well known acoustic and density-wave oscillation mechanisms. Most models for density-wave oscillations neglect compressibility effects. That is, the period of the oscillations is sufficiently long so that an incompressible model is adequate. Obviously, such a model cannot predict acoustic waves, nor can it predict the effects of interactions. If the difference between the oscillation mechanisms was not clearly understood, erroneous conclusions could be drawn from the analysis.

A second reason for needing to understand instability mechanisms is so that the engineer is able to design devices to avoid the instability. For example, the appearance of the Ledinegg instability depends on the external Δp characteristic, which in turn depends on the pump head-flow characteristics. Understanding the coupling mechanism between the internal and external Δp characteristics causing the instabilities gives requirements on pump characteristics for stable operation.

An excellent review of the physical instability mechanisms has been given by Boure, Bergles and Tong (1973). For convenience, we have included as Table-I an expanded version of the Table given in that paper, which summarizes the known and anticipated modes of instability.

Instabilities which involve flow in a heated channel are reasonably well understood. They include the Ledinegg instability (entry 1.1, type 1, of Table I), and density-wave oscillations (entry 2.1, type 2).

Ledinegg instability is a flow excursion which may occur when the system can operate at different flow rates. For simplicity consider a heated channel operating subject to a constant external pressure drop (eg, a parallel channel arrangement). Suppose that the conditions are such that an increase in flow rate for the channel causes a decrease in the internal steady-state pressure drop. When connected to a constant externally impossed pressure drop, a positive flow rate perturbation causes the channel to experience a flow excursion, which may lead to insufficient cooling.

Density-wave oscillations occur when the feedback between a perturbation in the inlet flow rate, the resulting fluctuation in the position of the boiling boundary, and the change in density in the two-phase section is such that the inlet flow perturbation is reinforced. An increase in the inlet flow rate causes an increase in the mass in the channel, and a change of the pressure drop. If the propagation of this effect occurs with a sufficient delay, the tendency for the density head increase to decrease the flow rate will reinforce a subsequent decrease in the inlet flow rate. Thus, the instability is oscillatory, and depends on the transit time taken for a density-wave to propagate through the channel. It is now well known that this time is related to propagation time for kinematic waves in the channel.

Fukuda and Kobori (1978) have recently proposed a detailed subclassification of density-wave oscillations. Their classification is based on which term is dominant in the pressure drop at the onset of instability, and is classified as a Ledinegg-like instability if the dominant term contributes to a negative slope in the Δp-flow characteristic at zero frequency. This subclassification may well prove practical for a designer, who can attempt to modify the dominant term (eg: by varying the system hydraulic loss) producing the instability in order to make a more stable system.

The principle involved in acoustic wave instability is similar to that for the "organ pipe" oscillation in one-phase gas flow. That is, a pressure fluctuation propagates at the (two-phase) speed of sound to the other end of the apparatus, where it is reflected, possibly with a phase inversion. If the resulting reflected wave reinforces the inlet perturbation, a self-excited oscillation can be maintained.

Several of the mechanisms listed in Table I can be understood by considering profile effects. For example, the flow pattern transition instability is a result of the fact that the pressure drop due to a bubbly flow and a slug flow at the same (time-averaged) void fraction have different pressure drops. Thus, the change in flow regime can lead to oscillations. For example, the flow may start out as bubbly flow,but if it is more advantageous (ie, lower pressure drop) for the flow to be slug flow, the void profile may "relax" toward this flow regime. This will cause the total flow rate to increase, with the result that the gas flow rate may not be able to maintain slug flow. Thus, the flow will "relax" toward bubbly flow. In addition, if the system stays in slug flow, the periodic nature of this flow regime may excite the system leading to so-called Flow Regime Induced Instability. Clearly these mechanisms can lead to a cyclic process in improperly designed process equipment.

The boiling transition (class 1.1, type 2) and thermal oscillation (class 2.2, type 1) mechanism are similar to the flow pattern transition mechanisms, in that the heat transfer and flow regime may change to cause an excursion towards a different thermal-hydraulic state. In this cause, however, the system may reach a new operating state (boiling transition induced excursion), or it may eventually "relax" toward the initial state (thermal oscillations).

In these three mechanisms, the differences between the different regimes are normally modelled through correlations, which relate the macroscopic variables (flow rates and pressure drops for slug and bubbly flows in the flow regime-induced instability mechanism; heat transfer rates in the boiling transition and thermal oscillation mechanisms). The instabilities can be understood by noting if the correlations give possible operating states other than the primary one.

Thermal relaxation instabilities (class 1.3) are caused by the existance of a thermodynamically metastable condition which causes a substantial amount of liquid superheat to build-up prior to nucleation. When boiling is initiated, it occurs rapidly, and fluid is expelled from the heated channel. The build-up of liquid superheat is often due to a lack of nucleation sites, and thus this instability mechanism can be mitigated through proper design.

Three other type of instability mechanisms (nuclear-coupled instability, class 2.2, type 2; parallel channel instability, class 2.2, type 3; and pressure drop oscillations, class 2.3) involve the interaction of the flow in the heated channel with other parts of the flow loop, or the external boundary conditions. Nuclear-coupled instability involves the interaction of the void fraction, or mixture density, fluctuations with the nuclear fission process. A decrease in the mixture density in an LWR causes a decrease in the heat generated by the nuclear reaction. If this decrease in heat transfer is sufficiently delayed, it can reinforce a subsequent decrease in void fraction, by causing reduced boiling.

The parallel channel instability mode, classified by Boure, Bergles, and Tong (1973) as a dynamic instability, is often treated as a relaxational mode (Akagawa, Sakaguchi, Kono and Nishimma, 1971). In this mode, it is possible for some of the channel to operate at different conditions, and the flow can "jump" between the various possible conditions.

In pressure drop oscillations, a compressible volume elsewhere in the loop interacts with the heated section to sustain rather low frequency oscillations.

Condensation induced instabilities (class 2.1, type 3) are currently rather poorly understood. This mechanism is known to influence the performance of heat exchangers (eg: regenerators, condensers)and has a dramatic effect during the bypass phase of a PWR LOCA. Since large impulse (ie, "water hammer") loads may result, it is obviously an area which needs further work.

We have added three catagories to Table-I. They are nonlinear effects (class 3), multidimensional effects (class 4), and transient effects (class 5).

We shall restrict our discussion of nonlinear effects to the case of quasilinear analysis, which pertains to the case when the system operating point is near the marginal stability boundary,that is, the system is either slightly stable or slightly unstable. If the near-by unstable region corresponds to a linear mode which grows without oscillation, there are many possibilities. The bifurcation may be supercritical, with a second equilibrium solution near the original one. In this case, the instability boundary may manifest itself by a slight shift in position. This case is often harmless when encountered. If, on the other hand, the bifurcation is subcritical, the situation is quite different. In this case, operation may be occurring with stable conditions, but a sufficiently large perturbation will cause a large flow excursion from the equilibrium solution. This may have disasterous consequences to the process equipment. In addition to these possibilities, there also exist cases when the instability manifests itself in relaxation oscillations to the new operating state.

On the other hand, if the nearby unstable region corresponds to a linear mode which oscillates as it grows, the main possibilities are a supercritical oscillation or a subcritical instability. The supercritical oscilation leads to a limit-cycle, i.e. a limited amplitude periodic solution near the steady-state. As in the case of bifurcation without oscillation, this supercritical case also occurs when the operating conditions are such that the steady-state is unstable. The instability may manifest itself as relatively gentle oscillations, which frequently do not create a hazard to the equipment. The subcritical instability, which is often called a finite amplitude instability occurs at stable conditions, for sufficiently large disturbances. Subcritical instabilities are quite dangerous since they occur unexpectedly (i.e. when the steady-state is linearly stable), and may grow to very large amplitudes, often causing process equipment damage.

Only one work on nonlinear effects in two-phase flow stability was found in the literature (Friedly and Krishnan, 1972). They assumed an extremely simple model, neglecting all frictional effects except the orifices at the inlet and outlet of the channel. Fortunately, a careful study of quasilinear instability analysis has been conducted by the authors and is being published as a separate Topical Report under NRC-03-78-128.

This analysis reveals several features of the linear stability of a heated channel which have escaped previous notice. Specifically, these studies show several "islands" of instability, which, according to the model, give rise to a subcritical instability. Moreover, the classical linearized stability boundary found by Ishii (1975), and others, is found to give rise to a supercritical instability.

A further area of study of interactions (nonlinearities) is suggested by Boure, Bergles and Tong (1973). Specifically, in some operating states, both acoustic and density-waves are possible. The effect of possible interactions on the stability criteria, and on the instability modes is not well known.

Multidimensional effects (class-4) have not been studied to any degree. The importance of possible multidimensional effects are eluded to in the paper by MacBeth (1974). He finds interesting results in rod bundles with an odd-or-even number of subchannels which indicate that within bundle subchannel-to-subchannel oscillations may be possible In addition to transverse hydrodynamic instabilities, one might expect subchannel-to-subchannel instability in the event that a local boiling transition occurs. In this case we may have the coupling of th l oscillations (class 2.2, type 1) with changes in subchannel pressure drop induced by the transition from nucleate boiling to film boiling, and back again.

To complete our discussion of multidimensional instability modes, we should note the cross-connected parallel channel experiments of Veziroglu and Lee (1971). They found that by cross-coupling the previously unventilated channels, the configuration was more stable than the individual channels would be alone. Thus it appears that multi-dimensional effects suppress density-wave oscillations in a parallel channel array, however, very little is known at this time about the possibility of lateral subchannel-to-subchannel oscillations.

Finally, we should mention the fluidized bed results of Murray (1965), Drew and Segel (1971) and Homsy (1979). In uniform fluidization, where the weight of the particles are supported by the drag exected by the upflow of a fluid, the flow is unstable for most cases of practical interest. This instability manifests itself either as traveling waves, or "bubbles" of low particle concentration moving upward through the mixture. The analogy with gas-liquid flows is not completely clear, however, these results may indicate that under some conditions, uniform bubbly flow in a plenum could undergo a flow regime change, perhaps to churn-turbulent flow, or slugging. It is also not clear how the flow geometry (subchannels, spacers, etc.) effect the multi-dimensional stability of two-phase gas-liquid flows. The area of multi-dimensional stability of gas-liquid flows is an important area where more analytical work is clearly needed.

The question of the effect of superimposed instability on transient flows (class-5) is one of potential importance during a hypothetical BWR LOCA. During depressurization, the flow rate through the heated channels changes, as does the power level. The rates of change are usually quite rapid, often on the scale of the period of the density-wave oscillation. For this reason, steady-state stability analyses cannot be directly applied. It may be possible to have superimposed flow oscillations within certain BWR channels even though the loop flow coast-down is monotonic. Such oscillations could cause a premature boiling transition, and thus lead to higher (than predicted) peak clad temperatures (PCT). This aspect of the problem seems serious enough to warrant further analytic study.

ANALYTICAL MODELS

Clearly, the results from stability studies can be no better than the models used to predict stability. It is probably inevitable in any complex situation that ad hoc models will be widely used. As summarized in Appendix-I, such models represent the current state-of-the-art.

Let us first examine the spatial description used in these models. Many studies use lumped models, where within each component, spatial variations are either ignored, or integrated out. These models can give good results when used in situations where the assumptions are not violated, such as in the interaction between a heated section, and a vessel with a compressible volume (ie: for pressure drop oscillations). They can give little insight in other situations where the same mechanism is operative, but the flow is distributed. Such an example occurs when the compressible volume is the steam in the downstream section of the heated channel. In this case, the interaction of the heated system pressure drop characteristics and compressibility can result in an oscillation which is not adequately predicted by a lumped mode.

The most popular spatial model to consider distributed effects is the one-dimensional one. This model uses conservation equations which have been cross-sectionally averaged, and is usually only employed with many other simplifying assumptions (typical assumptions will be discussed in more detail later).

There are no models in existence which consider the stability of a multi-dimensional flow situation. One model (Hancox and Nicoll, 1971) considers the effects of radial distribution (through the use of profile parameters), and finds the model sensitive to such effects. As noted previously, more work is clearly needed in this area.

Let us now discuss the various types of models which are used for LWR stability studies. Fundamental difficulties with current generation six-equation models (ie: two phasic equations for conservation of mass, axial momentum and energy) have forced all analyses to date to be done with less detailed models. The most sophisticated of these co-called drift-flux models assumes slip flow and boiling boundary dynamics (Ishii, 1971). Other models account for the effects of void-reactivity feedback (Lahey and Yadigaroglu 1974), radial heat conduction effects (Roy and Yadigaroglu, 1976), variation in the heat input distribution (Yadigaroglu and Chan 1979), and subcooled boiling (Saha, 1974). There exist few fundamental gaps in previous linearized models, however in general, the models currently used to support licensing (eg: Jones, 1961-65) are based on dated modelling of two-phase flow. It appears that more detailed slip flow models should be incorporated, and spatially distributed kinetics models (for void-reactivity feedback) should be used or improved.

A further shortcoming of current generation models, which are valid for density-wave analyses, is that they make assumptions which preclude the simultaneous analysis acoustic waves and the resultant coupling which may take place. Some models for acoustic waves are based on an assumed sonic velocity (Bergles, 1967; Krishnan, and Friedly 1974), thus compressibility effects are included in a very ad hoc way. We also mention here a number of models (Boure, 1966; Friedly & Krishnan, 1972), where an equation of "state" is used to relate the two-phase density to the "enthalpy" of the mixture, instead of the quality or void fraction. The validity of these models is subject to the interpretation of the mixture enthalpy, since the actual liquid temperature can not exceed the saturation temperature by very much.

Perhaps the most detailed model for acoustic waves is that of Christensen (1963), who uses linearized mass and momentum equations, plus an isothermal state equation. He shows that his model reduces to the well-known transmission line equation.

It is obvious that more work is needed in this important area of technology, however, one obvious shortcoming of the present state of understanding of the stability of boiling flows is the fragmented nature of the previous studies. There is no clear relation between, or separation of, the Ledinegg, density-wave and acoustic-wave instability mechanisms in the literature. Our own studies at RPI (reported in a separate Topical report) have shown that we can recover the Ledinegg results from the zero frequency limit of the density-wave model. Presumably, a more general model, including thermal and compressibility effects, would give the acoustic wave oscillations, when applied to the situation appropriate to this instability model. Such a model could then be used to study the relation between Ledinegg instability, density-wave oscillations, and acoustic wave oscillation in a systematic way, determining the correct dimensionless parameters and the various parameter ranges where each effect is important. While this is an ambitious task it is an important goal which one should strive to achieve.

DATA BASE

Let us now consider the experimental data base which exists in the area of interest to LWR instability mechanisms. Appendix-II summarizes much of the relevant data.

It can be seen that the data base is quite large, particularly for the inception of density-wave instability phenomena. Data on this important instability mechanism has been taken in rod bundles for forced and natural circulation conditions, and in many simplier geometry (ie: tubes and annuli) for single and parallel channel configurations. While most of these data are for uniform axial heat flux configurations, nonuniform axial and radial (rod bundles) heat flux data do exist. In addition, some steam generator instability data, in which the heat flux profile is not imposed, have also been reported.

The simple geometry, parallel channel density-wave data contains situations in which the hot channel's bypass ratio is less or greater, than a factor of ten, which is approximately the ratio required to decouple the hot channel (Carver, 1970). Unfortunately, both parallel channel and loop instability data has been previously concerned with the inception of instability rather than limit-cycle phenomena. There is a real need for good parametric density-wave instability limit-limit cycle data.

There has been considerable Japanese work associated with Ledenigg instability mechanisms in parallel channel arrays, however virtually no large scale data has been taken. Indeed, very little systematic work has been done to understand the effect of system compressibilities in single and parallel channel pressure drop oscillations.

There has been some significant stability data taken in various size BWRs. These data contain the information necessary to appraise the prediction capability of analytical models for nuclear-coupled density-wave oscillations. Unfortunately, only limited comparisons have been made with these data. Indeed the only comparisons reported are with the reactor vendor's proprietary codes, which did not agree too well with the data.

Another group of data in Appendix-II is concerned with the power-to-flow, power-to-void, flow-to-pressure and flow-to-void transfer functions. These are fundamental measurements which are of great importance in the evaluation of analytical models. While the data available appear to be of good quality, more measurements of this type are needed in various geometric configurations to provide a complete data base. In addition, more comparisons with the analytical models are needed.

There is obviously a large amount of data which is available for the qualification of analytical models for density-wave and nuclear-coupled density-wave instability phenomena. The data considered most relevant is so-marked in Appendix-II.

A careful study is needed in which existing and developmental analytical models are compared with these data. It is surprising to see how few such comparisons have been reported. It is apparently a reflection of the inactivity in this area during the last decade.

In contrast to the density-wave data base, very little data exists for flow-regime induced, and flow-pattern-transition instability data. The situation is much the same for condensation-induced instability, acoustic oscillations, and superimposed instability during system transients (eg: LOCA and/or flow coast down). Many of these phenomena are important in LWR safety technology and thus more work is clearly needed.

Since very little separate effects acoustic oscillations data exists it should not be surprising that no data exists with which to quantify the compound interaction between density-wave and acoustic modes of instability (ie: between dynamic and continuity waves). Moreover no data exists with which to quantify multidimensional effects, such as subchannel-to-subchannel instabilities within rod bundles. Data on multidimensional instabilities, and the interaction between dynamic and kinematic waves, is sorely needed since these mechanisms have potential safety significance in LWR technology.

It is well to repeat at this point that, while the data here concerning instabilities in two-phase systems is relatively large, only a limited comparison has been made between data and analysis, and many areas exist in which there are insufficient data.

RECOMMENDATIONS FOR FUTURE WORK

The literature survey discussed herein has been concerned with the identification of data needs and analytical weakness associated with instability mechanisms of relevance to LWR technology. The following recommendations are made for future analytical and experimental work:

ANALYTICAL MODEL DEVELOPMENT NEEDS

( ) A more complete analysis of non-linear phenomena is clearly needed. In particular, limit-cycle phenomena and subcritical bifurcation response (ie: finite amplitude-instability) is of potential LWR safety significance and should be more thoroughly investigated.

(2) The development of linear stability models which quantify the interaction between density-wave, acoustic and pressure-drop instability modes are needed to determine the effect of these superimposed phenomena on LWR thermal margins.

(3) Analysis is needed on the possibility of superimposed oscillations (on the hot channel) during LWR transients, and their effect on the time to the boiling transition and/or peak clad temperature (PCT).

(4) The development of a model to appraise the potential for, and significance of, subchannel-to-subchannel oscillations in fuel rod bundles is needed.

(5) The development of more detailed and numerically efficient ways to handle nuclear-coupled void-reactivity feedback effects (ie: axial and radial kinetics) is needed.

(6) The development of a generalized analysis for pressure-drop instability modes (in single and parallel channels) such that the effect of compressibility can be treated generically (ie: independent of whether the compressible volume is in the heated channel, at the outlet, etc.) is needed.

(7) Comparison of any, or all, of these and existing stability models to the current data base to appraise our ability to model these complex phenomena is sorely needed.

Finally,

(8) If advanced generation two-fluid codes (eg: TRAC) are to be used for future stability analyses, we need more fundamental information on interfacial transfer laws.

EXPERIMENTAL DATA NEEDS

(1) Well controlled and monitored limit-cycle phenomena experiments are needed in both single and parallel channel arrays is needed. While data of this type exists it was not properly recorded, and is thus not adequate for model verification.

(2) Comprehensive experiments which are designed to involve the interaction between density-wave, pressure-drop and acoustic instability modes are needed to support the analysis recommended in item (2).

(3) Blowdown/flow-coast-down experiments are needed to study the effect of possible superimposed flow instabilities on BWR fuel bundles. These experiments could be best conducted in prototypical geometries although simple geometry experiments would also be helpful.

(4) Experiments are needed to investigate the effect of possible subchannel-to-subchannel instability modes. These experiments should be performed in support of the analysis recommended in item (4).

(5) Data on flow-regime-induced and transition instabilities would be helpful for the understanding of LWR performance (eg: steam separator stand pipes) however are not likely to be of safety significance.

It is readily apparent from the literature that virtually all the existing large scale data is equipment specific, and thus most parametric experimencs have been conducted in small scale facilities. While such data is useful, it may be misleading if there are phenomena which are scale dependent, thus further recommendation is:

(6) Conduct selected pressure-drop and density-wave instability experiments at a scale of commercial interest. These experiments should be similar to (but of much larger scale) previous small scale experiments. The intent is to identify any scale dependent phenomena of safety significance.

(7) Systematic mechanistic data on condensation-induced and boiling-induced (eg: nucleation delay and rewet controlled) instabilities is needed to be able to realistically model such phenomena during LWR reflood.

SUMMARY AND CONCLUSIONS

During the course of this literature survey over 316 references were collected and reviewed. The entire list of these references is given in the Bibliography. A number of these references, which were considered to be of most relevance to LWR technology are summarized in Appendices I and II. The order of these references is arbitrary, although the references in Appendix-II, which contain data of particular value in the assessment of analytical models, is marked with an asterisk.

It was clear from the survey that considerable data exists which has not been thoroughly used. Moreover, common weaknesses have been identified in existing analytical models, and areas where more work is needed were discussed.

Table-II summarizes the needs which are relevant to LWR technology. The specific needs addressed are:

- Modelling needs - the need for the development of analytical models.
- Analysis needs - the need to use existing analytical models on a specific problem.
- Experimental needs - the need to take data to understand a particular instability mode.

Clearly a great deal of work remains to be done to achieve a satisfactory level of understanding of instability modes in LWR technology.

APPENDIX-I

A SUMMARY OF SELECTED ANALYSIS ON INSTABILITY MECHANISMS IN TWO-PHASE FLOWS

I.1) "Study on Distribution of Flow Rates and Flow Stabilities in Parallel Long Evaporators", K. Akagawa, T. Sakaguchi, M. Kono, and M. Nishimura, Bulletin Japan Soc. Mech. Eng. 14, 74, 837-848, 1971.

The modes of operation and the corresponding stability of a system of parallel channels is studied. A lumped model is used.

- Instability mode: compound relaxational (Ledinegg)
- Mathematical approach: linearized analysis in frequency domain of steady-state
- Simplifying assumptions: lumped model, pressure drop given by steady characteristics
- Application: parallel heated channels

I.2) "Theoretical Feedback Analysis in Boiling Water Reactors", A.Z. Akcasu, ANL6221, 1960.

Feedback concepts are used to consider the effects of void-reactivity and other power-reactivity relations on BWR stability.

- Instability mode: nuclear-coupled density-wave
- Mathematical approach: linear analysis in frequency domain
- Simplifying assumptions: one-dimensional Homogeneous flow
- Applications: BWR

I.3) "Prediction of Density-Wave Stability Limits for Evaporators - Sensitivity to Model Assumptions", P.O. Akinjiola, and J.C. Friedly, 2nd Multiphase Flow and Heat Transfer Symposium, Miami Beach, April 1979.

This paper considers the sensitivity of the density-wave models to the assumptions of homogeneous flow, thermal equilibrim, and uniform heat flux. Simplified models are used to include the effects of slip, subcooled boiling, and non-uniform heat flux.

- Instability mode: density-wave
- Mathematical approach: linear analysis in frequency domain
- Simplifying assumptions: one-dimensional slip flow, simplified models for slip, subcooled boiling and non-uniform heat flux
- Application: heated channels

I.4) "Stability Analysis and Optimization of By-Pass Controlled Heat Exchanger with Boiling", J.S.Ansari, J. of Dynamic Systems, Measurement and Control, June 1976.

This paper formulates a control model of boiling flow in a heat exchanger with bypass, where the amount of bypass is used to control the temperature of the fluid leaving the heated section. The paper shows that even though the desired goal can be reached, some intermediate variable, such as flow velocities in the heat exchanger,are subject to oscillations. Global stability is shown using a Liapunov function.

- Instability mode: density-wave
- Mathematical approach: optimal control, Liapunov (global) stability theory,one-dimensional,homegeneous
- Simplifying assumptions: incompressible flow, axial and radial heat conduction negligible, heat transfer to fluid is general function of temperature alone
- Application: heat exchanger

I.5) "Instabilities in Parallel Channel of Forced-Convection Boiling Upflow System.I, Mathematical Model", M. Aritome, S. Aoki, and A. Inoue, J. Nuclear Sci. and Tech. 14(1), pp. 22-30, January 1977.

This paper treats density wave oscillations by integrating along the characteristics of the hyperbolc partial differential equations describing drift-flux, equilibrium two-phase flow. The resulting lumped parameter system is integrated numerically in time. The authors attempt to apply the model to multiple channels with common plena, but their analysis is suspect, since they have an overdetermined system, and do not state what conditions are ignored.

- Instability modes: density-wave
- Mathematical approach: integration along characteristics, numerical solution of lumped parameter systems
- Simplifying assumptions: one-dimensional, uniform/constant heat flux, constant subcooling, drift-flux model
- Application: parallel heated channels

I.6) "Unsteady Processes Caused by Inlet Enthalpy Perturbation During Flow of a Boiling Liquid in a Heated Tube", A.A. Armand, and V.V. Krashenininkov, Heat Transfer-Soviet Research, 5, 6, 168-176, 1973.

This paper considers the response to step changes in the inlet enthalpy in the forced circulation (constant inlet flow) in a heated tube. No stability results can be obtained since the flow is not allowed to oscillate.

- Instability mode: density-wave
- Mathematical approach: exact analytical solution along characteristics
- Simplifying assumptions: one-dimensional homogeneous, equilibrium forced flow, constant subcooling, constant/uniform heat flux
- Applications: heated channels

I.7) "Hydraulic Impedance: A Tool for Predicting Boiling Loop Stability", T. T. Anderson, Nuc. Appl. and Tech. 9, 422-433, 1970.

The stability of a channel is determined from a linearized analysis of the one-dimensional thermal equilibrium model with a constant slip flow assumption.

- Instability mode: density-wave
- Mathematical approach: linear perturbations in frequency domain
- Simplifying assumptions: one-dimensional equilibrium, constant slip flow, constant inlet subcooling, constant uniform heat flux
- Application: heated channels

I.8) "A Model for the Dynamics of Nuclear Reactors with Boiling Coolant with a New Approach to the Vapour Generating Process", P. Bakstad, and K.O.Solbert, Symposium on Two-Phase Flow Dynamics, Eindhoven, Netherlands, 1967.

This paper describes the physics included in the code RAMONA, based on a thermal non-equilibrium, slip model.

- Instability mode: density wave, compound dynamics
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional drift-flux, incomplete thermal equilibrium
- Application: Loop, BWR

I.9) "Difference-Differential Approximations to a First Order Partial Differential Equation Describing the Hydraulics of Boiling Water Reactors, P. Bakstad, Kjeller Report, KR 54,1963.

This paper describes a numerical procedure used to integrate the one-dimensional homogeneous equilibrium partial differential equations.

I.10) "Thermodynamics of Liquid Diabatic Flow and Related Instabilities", G. Basso, Comitato Nagionale Energia Nucl. Report #CNEN RT/ING (67)2, 1967.

By considering conditions for critical flow in a channel, the author purports to have found stability criteria for boiling flow. His contention is not conclusively proved.

- Instability mode: acoustic
- Mathematical approach: critical flow analysis
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow
- Application: heated channels

I.11) "The Stability of Two-Phase Flow Loops and Response to Ship's Motion" E.S. Beckjord, GEAP 3493, 1960.

An analog computer program and linearized frequency domain analysis are used to predict stability.

- Instability mode: density-wave
- Mathematical approach: computerized (analog) linear analysis in frequency domain
- Simplifying assumptions: one-dimensional thermal equilibrium slip flow
- Application: heated channels

I.12) "Flow Stability and Dynamic Behavior of Nuclear Boilers", G. Beckman, K. Fritz, H. Lendl, and P.V. Gilli, Paper 15, Int. Conf. on Boiler Dynamics and Control in Nuclear Power Station, 1973.

Stability characteristics for boiler tubes are discussed, for both Ledinegg instability and dynamic instability. Numerical results are also mentioned.

- Instability mode: Ledinegg, dynamic (density-wave or pressure-wave)
- Mathematical approach: internal and external pressure drop characteristics, linear frequency domain analysis, numerical solution (TRANS code)
- Simplifying assumptions: one-dimensional homogeneous, equilibrium flow, constant subcooling, constant uniform heat flux
- Application: heated channels

I.13) "Single-Channel Flow Oscillations by Eigenvalue Stability Analysis", B.S. Bennett, and R.J. Watt, Symposium on Two-Phase Flow Dynamics, Eindhoven, 1967.

Temperature profiles were assumed to reduce the partial differential equations to ordinary differential equations, which are linearized and the eigenvalues are found. The approach is questionable.

- Instability mode: density-wave
- Mathematical approach: assumed profiles give ordinary differential equations, which are linearized, and a numerical procedure is used to find the eigenvalues
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow, constant inlet subcooling, constant uniform heat flux
- Application: heated channels

I.14) "Acoustic Oscillations in a High Pressure Single Channel Boiling System", A.E. Bergles, P. Goldberg and J.S. Maulbetsch, Symposium of Two-Phase Flow Dynamics, Eindhoven, 1967.

This paper discusses acoustic, ie: pressure-wave, oscillations. The theory involves the reinforcement of pressure perturbations by reflected waves. The results are qualitatively correct, but quite far off quantitatively.

- Instability mode: pressure-wave (acoustic)
- Mathematical approach: linear wave propagation and reflection
- Simplifying assumptions: one-dimensional homogeneous, equilibrium flow, linearized two-phase flow fluid properties
- Application: heated channel

I.15) "Thermal-Hydraulic Instability Most Recent Assessments", A.E. Bergles, Seminar on Two-Phase Flow Thermalhydraulics, Rome, Italy, June 1972.

This paper extends the review work of Boure, Bergles and Tong to describe instabilities observed in full-scale industrial equipment. Recent work on density-wave analysis is reported. Ishii's simplified criterion is shown to be incorrect for low pressure systems.

- Instability modes: density-wave oscillations; short discussion of others
- Mathematical approach: none
- Simplifying assumptions: one-dimensional, various other restrictions
- Application: BWR/PWR/Channels/Loops

I.16) "Application of a Boiling Water Loop Model to Boiling Sodium", M. Bogaart, and C.L. Spigt, Nuclear Eng. & Design 5, 465-476, 1967.

The stability of sodium loop is predicted from a code designed for water loop. A pump is added to the water loop. The sodium loop is found to be less stable, and to oscillate at a higher frequency than the corresponding water loop.

- Instability mode: density-wave, compound dynamic
- Mathematical approach: linear stability in frequency domain
- Simplifying assumptions: one-dimensional homogeneous, equilibrium flow, bubble number density equation with bubble formation, diffusion, demixing, interaction and growth effects, constant uniform heat flux
- Application: sodium loop

I.17) "The Oscillatory Behavior of Heated Channels - An Analysis of the Density Effect, I. The Mechanism (Non-Linear Analysis) II. The Oscillations Thresholds (Linearized Analyses)", J. Boure, CEA-R3049, 1966.

This paper derives the model for, and analyzes the stability of the flow in a heated channel.

- Instability mode: density wave
- Mathematical approach: derivation of lumped model by exact analytic solution;linear stability of lumped model in frequency domain
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow, "state" equation constant inlet subcooling, constant uniform heat flux
- Application: heated channels

I.18) "The Oscillatory Behavior of Heated Channels", J. Boure, and A. Mihaila, Symposium of Two-Phase Flow Dynamics, Eindhoven,1967.

A model using delay times is developed, and compared to experimental results:

He regards a heated channel as a kind of servo-mechanism.

Boure shows that the "density-effect" is most important in oscillating flow.

His model is scaled, and shows accuracy to experimental data (onset of instability) of 25%.

- Instability mode: density-wave
- Mathematical approach: linear stability in frequency domain
- Simplifying assimptions: one-dimensional homogeneous flow, thermal effects continued in steady-state internal characteristics, which is used for the pressure drop
- Application: heated channels

I.19) "Hydrodynamic Instabilities Limiting the Power of Boiling Water Reactors", J. Boure, EURAEC-1464, 1965.

This paper is a literature survey, predating Boure, Bergles and Tong. More details are given in the reference bel~ı (I.20).

I.20) "Two-Phase Flow Instabilities", J.A. Boure, Heat Transfer in Two-Phase Flows, Lecture Series 31" VonKarman Institute for Fluid Dynamics, January 1971.

This paper is a precursor to Boure, Bergles and Tong's paper, and gives a phenomenological discussion of the same mechanisms discussed there.

- Instability modes: all
- Simplifying assumptions: one-dimensional, homogeneous or drift-flux
- Application: heated channels & loops

I.21) "Review of Two-Phase Flow Instability", J.A. Boure, A.E. Bergles, and L.S. Tong, Nuc. Eng. and Design 25 (1973), pp. 165-192 (Revised and expanded version of ASME paper 71-HT-42).

This review paper classifies the types of instabilities, and discusses the mechanisms and evidences for each. The best understood mechanisms are the static mechanisms, the Ledinegg and Boiling Transition mechanisms,where the operating conditions are such that a small perturbation curves the system to move toward a new equilibrium, usually not close to the original conditions. The density-wave mechanisms are also quite well understood. On the other hand, acoustic or pressure-wave oscillations are not very well understood. Compound instabilities, both relaxational and dynamic, have been studied. These instabilities involve an interaction between the fluid in the heated channel and a mechanism external to the fluid, such as the thermal response of the wall, void-reactivity feedback, or interaction with other parts of the flow loop, including parallel channels. The so-called relaxational compound instabilities, where flow regime changes occur, have been studied empirically, but no analytical work exists. It is suggested that work is needed in regimes where two mechanisms might interact, for example, pressure-waves and density-waves. Analytical techniques for predicting thresholds are reviewed. Few results on nonlinear effects are mentioned. Also,although ventillated parallel channels are mentioned, little work has been done on multidimensional stability effects.

- Instability modes: all
- Mathematical approach: linear stability in frequency domain, numerical
- Simplifying assumption: mostly one-dimensional, homogeneous or drift-flux, various thermal-models (equilibrium, non-equilibrium)
- Application: BWR/PWR/Heated Channels & Loops

I.22) "Flow Oscillations in Fixed-Pressure-Drop Flow-Boiling Systems with Random Excitation", W. Brimley, W.B. Nicoll, and A.B. Strong, Int. J. Heat Mass Transfer, 19, 1379-1386, 1976.

The heat flux is assumed to have a random component, giving a random look to the output.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumption: quasi-one-dimensional slip flow with (uniform and random) heat flux
- Application: heated channel

I.23) "An Analytical Model for the Prediction of Hydrodynamic Instability in Parallel Heated Channels", M.B. Carver, AECL 2681, March 1967.

This paper gives the equations used in the code POISE, based on homogeneous, equilibrium thermodynamics, and a profile-fit of the mass flow.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional homogeneous, equilibrium flow, with assumed profile for the flow
- Application: heated channels

I.24) "Consumers Big Rock Point Nuclear Power Reactor Stability Analysis", J.M Case and L.K. Holland, GEAP 3795, 1961.

This paper describes the calculated stability characteristics of the Consumers Big Rock Point Reactor, done by evaluating the transfer functions for the actual components.

- Instability modes: nuclear-coupled density-wave
- Mathematical approach: linear analysis in frequency domain
- Simplifying assumptions: evaluated transfer functions assumed
- Application: Consumers Big Rock Point Reactor

I.25) "Two-Phase Flow Stability of Steam Generators", K.C. Chan, and G. Yadigaroglu, Japan-U.S. Seminar on Two-Phase Flow Dynamics, July-August 1979.

Stability of a steam generator is considered accounting for the primary-secondary coupling. The possibility of a Ledinegg instability is analyzed. The primary-secondary coupling is found to be stabilizing. Density-wave oscillations are considered using the code STMFREQ, which is a frequency-domain analysis of the linearized equations. It is found that the primary-secondary coupling has a substantial effect on the stability. The paper also discusses the oscillations of the dryout point, but gives no results or conclusions for the mechanism.

- Instability mode: density-wave, Ledinegg
- Mathematical approach: linear perturbation in frequency domain
- Simplifying assumptions: one-dimensional, drift flux equilibrium, with non-uniform heat flux determined by primary-secondary coupling, including tube wall dynamics.
- Applications: steam generators

I.26) "A Theoretical Study of Stability in Water Flow Through Heated Passages," H. Chilton, J. Nuclear Energy, 5, 273-284, 1957.

This paper derives the Ledinegg criterion for channels with various heat flux profiles.

- Instability mode: Ledinegg
- Mathematical approach: evaluate $\partial P/\partial G$ for various $q''(z)$
- Simplifying assumption: one-dimensional homogeneous equilibrium flow, constant inlet subcooling
- Application: Heated Channel

I.27) "Incomplete Thermal Equilibrium in Two-Phase Flow", H. Christensen and K.O. Solbert, Conference of Two-Phase Flow, University of Exeter, 1965.

This paper describes the improvements made in the RAMONA code, to include thermal non-equilibrium.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional homogeneous flow
- Application: heated loop

I.28) "Thermo-Hydraulic Stability of a System of Steam-Generating Channels with Super-Critical Pressure", Yu. G. Dashkiyev, and V.P. Rozhalin, Heat Transfer Soviet Research, 7, #5, 1975.

This paper looks at the stability of the flow in a system of parallel steam generating tubes. The stability mechanism is based on a type of flow excursion analysis based on an equation of incompatibility. It was difficult to assess the merits of this paper.

I.29) "Hydraulic Stability: An Analysis of the Causes of Unstable Flow in Parallel Channels", A.L. Davies and R. Potter. Symposium on Two-Phase Flow Dynamics, Eindhoven, 1967.

This paper describes the physics included in Harwell's LOOP code

- Instability mode: density-wave
- Mathematical approach: linear stability in the frequency domain
- Simplifying assumptions: one-dimensional homogeneous, equilibrium flow, constant uniform heat flux
- Applications: Heated Loop

I.30) "Analysis of Fluidized Beds and Foams Using Averaged Equations", D.A. Drew and L.A. Segal, Studies in Applied Mathematics, 50, 3, 1971.

This paper repeats the analyses of Murray (1965) on the stability of uniform fluidization, with a slightly different model. The results are the same.

- Instability mode: multidimensional
- Mathematical approach: linearized analysis in frequency domain
- Simplifying assumptions: two-fluid particle fluid model
- Application: fluidized bed

I.31) "Hydrodynamic Oscillation in Parallel-fed Heating Channels", S. Fabrega, European Two Phase Flow Meeting, Brussels, June 1973.

This paper shows the relation between the stability of a single heated channel and parallel channels. The stability of the parallel system can be computed from that of the single channel in a straightforward way.

- Instability mode: density-waves in parallel channels
- Mathematical approach: linear stability in frequency domain, assuming results for single channels
- Simplifying assumptions: one-dimensional flow, known stability characteristics of each heated channel, parallel coupling to common plena
- Application: parallel heated channels

I.32) "Hydrodynamic Stability Analysis", D.A. Feingold, KAPL-3027, 1964.

This report analyzes the stability of a boiling channel by a nodal digital computer-based analysis.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow, constant uniform heat flux, constant subcooling
- Application: heated channels

I.33) "The Influence of Pressure on Boiling Water Reactor Dynamic Behavior at Atmospheric Pressure", J.A. Fleck, Nuc. Sci. & Eng. 9, 271-280, 1961.

The most important influence of pressure changes on the dynamics of boiling flows seems to be in the resulting change in saturation temperature. No new instability modes were found.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: lumped model with assumed profiles
- Application: heated channel

I.34) "Prediction of Nonlinear Flow Oscillations in Boiling Channels", J.C. Friedly and V.S. Krishnan, AIChE Symposium Series, 68, 127-135, 1972.

This paper uses Poincaré's method (quasilinear) to compute the amplitude of the limit cycles for a simplified model of flow in a channel. Periodic solutions are found for heat fluxes slightly greater than the critical value predicted by linear theory. No attempt is made to determine the stability of these limit cycles.

- Instability mode: density-wave, nonlinear
- Mathematical approach: quasilinear stability analysis (Poincaré method). The necessary small parameter is not identified
- Simplifying assumptions: homogeneous, equilibrium flow, neglecting all pressure losses except at the orifices, simplified state equation
- Application: heated channels

I.35) "Estimation and Optimal Feedback Control Theory applied to a Nuclear Boiling Water Reactor", B. Frogner and L.M. Grossman, Nuclear Science and Engineering, 58, 265-277, 1975.

This paper applies optimal control theory to a lumped model of a nuclear reactor. No physics is discussed, but the authors conclude that the reactor can be controlled.

- Instability mode: compound dynamic (nuclear-coupled density-wave)
- Mathematical approach: linear stability, optimal control theory
- Simplifying assumptions: not discussed, lumped model
- Application: BWR

I.36) "Classification of Two-Phase Flow Instability by Density Wave Oscillation Model", K. Fukuda and T. Kobori, Journal of Nuclear Science and Technology, 16, 2, 95-108, 1979.

This paper breaks up the density-wave instability mechanism up into subclasses, based on which terms in the momentum equation cause the instability. Three "Ledinegg -like"modes are found, corresponding to transfer functions which are negative for $S \rightarrow 0$, and five "density-wave" modes.

- Instability mode: density-wave (Ledinegg as $S \rightarrow 0$)
- Mathematical approach: linear analysis in frequency domain
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow, constant subcooling, constant uniform heat flux
- Application: heated channels

I.37) "A Theoretical Study of the Transient Operation and Stability of Two-Phase Natural Circulation Loops", K. Gorlid, N.R. Amudson, and H.S. Isbin, ANL-6381, 1961.

A slip flow model is derived for pipe flow. The axial variation is treated by considering a discretization in the axial direction, assuming linear profiles in space.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional thermal equilibrium slip flow
- Application: natural circulation loop

I.38) "The Thermohydraulic Stability of Multi-Channel Steam-Generating Systems", V.A. Gerliga and R.A. Dulevskiy, Heat Transfer-Soviet Research, 2, 2, 63-72, 1970.

This paper couples the linear stability responses for individual channels in a multichannel flow device, and gives relations for the stability of the multichannel system from the individual channel transfer functions. The results give sufficient conditions for multichannel stability, which involves the condition that each channel be stable.

- Instability mode: density-wave, multichannel
- Mathematical approach: linear perturbations in frequency domain
- Simplifying assumptions: one-dimensional homogeneous, equilibrium flow, constant subcooling, constant uniform heat flux in each channel
- Application: multiple heated channels

I.39) "A Systematic Comparison of Different Hydrodynamics Models", R. Grumbach, Nuc. Sci. Eng., 36, 429-433, 1969.

Existing stability models are critiqued. Analytic predictions from "few-node" models are felt to be inadequate because of ficticious resonances.

- Instability mode: density-wave
- Mathematical approach: linear analyses of nodalized models
- Simplifying assumptions: various
- Application: heated loops

I.40) "A General Technique for the Prediction of Void Distributions in Non-Steady Two-Phase Forced Convection", W.D. Hancox and W.B. Nicoll, Int. J. Heat Mass Transfer, 14, 1377-1394, 1971.

This paper extends the analysis of Zuber and Staub to non-uniform, non-constant heat flux, and non-steady inlet velocity.

- Instability mode: density-wave
- Mathematical approach: exact analytical solution along characteristics
- Simplifying assumptions: one-dimensional, slip flow (drift-flux model) forced flow
- Applications: heated channels

I.41) "Hydraulic Stability of Single and Two-Phase Fluids Flowing in Parallel Channel and Loop Configurations", P.D. Hansen, GEK-1, Report 195, 1960.

A linearized analysis is performed based on a lumped parameter model, with assumed profiles.

- Instability mode: density-wave
- Mathematical approach: linear analysis in frequency domain/numerical
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow
- Application: heated channel/loop

I.42) "Linear Analytical Model Describing the Frequency Response and Stability Behavior of a Boiling Light Water Reactor", A. Höld, Nuc. Eng. and Design, 16, 103-136, 1971.

This paper gives a detailed derivation of the physics built into the stability code ADYSMO. The thermal model includes nuclear reactivity feedback, and wall-to-fluid heat transfer coefficients. Simple fluid assumptions are made, viz. drift-flux, equilibrium flow, and the pressure drops are due to friction. The total reactor is treated.

- Instability mode: compound dynamical
- Mathematical approach: linear perturbations in frequency domain
- Simplifying assumptions: one-dimensional equilibrium flow, simple pressure losses
- Application: BWR

I.43) "Response of a Boiling Channel to Power or Inlet Flow Modulation", J.L. Hudson, K.M. Atit, and S.G. Bankoff, <u>Chem. Eng. Sci.</u>, 19 387-402, 1964.

Boiling channel flow is studied using a spatial discretization based on a Taylor series expansion, followed by a linearization, and a Laplace Transform in time.

- Instability mode: density-wave
- Mathematical approach: discretization in space, Laplace transform in time
- Simplifying assumptions: one-dimensional homogeneous slip flow, saturated feed water, constant/uniform heat flux
- Application: heated channels

I.44) "A Study on the Hydrodynamic Instability in Boiling Channels (2nd Report, The Instability in Two Parallel Boiling Channels)", S. Hyama, Bulletin, Japan Society of Mechanical Engineers, 7, 25, 129-135 (1964).

This paper studies the response of two parallel channels using a lumped model which uses the steady-state pressure drop-flow rate characteristic for each channel. Multiple steady-states are found, when the characterstics have negative slope regions. Both in-phase and out-of phase modes of oscillation are found.

- Instability mode: multiple channel compound relaxational
- Mathematical approach: steady-state pressure-drop-flow-rate analysis
- Simplifying assumptions: one-dimensional lumped model, using steady-state characteristics
- Application: parallel heated channels

I.45) "A Study on the Hydrodynamic Instability in Boiling Channels (3rd Report, The Modes of Vibration in Multi-Channel System and the Reverse Flow)", S. Hayama, Bull. Japan. Soc. Mech. Eng., 10, 8, 308-327, 1967.

The N normal modes of vibration in a system of N parallel boiling channels is studied. One model is an in-phase oscillation of all the channels, while the others are oscillations due to interactions between channels. For systems with a large number of channels, the in-phase oscillation is hard to generate. Moreover, no orificing external to the system can stabilize the mutual oscillations. The stability is decreased,(i) by increasing the flow resistance in the downcomer, (ii) by increasing the subcooling or the power level, and (iii) by increasing the number of channels.

- Instability mode: compound relaxational (static) and dynamic
- Mathematical approach: linearization of lumped model, also nonlinear analysis of steady-states
- Simplifying assumptions: lumped model, assuming all channels have static pressure drop characteristics
- Application: multi-channels

I.46) "A Study on the Hydrodynamic Instability in Boiling Channels (1st Report, The Instability in a Single Boiling Channel)", S. Hayama, Bull. JSME, 6, 23, 549-556, 1963.

A lumped model is derived for the flow in a channel with uniform heat flux. Simplifying assuptions are made about the friction and the mass in the channel. The resulting ordinary differential equations are solved in the phase plane (time-domain), and the possibility of limit cycles is discussed. Because of the simplifying assumptions, the results should be viewed as qualitative.

- Instability mode: density-wave
- Mathematical approach: lumped system, exact analytical (qualitative) solutions
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow, constant subcooling, constant uniform axial heat flux;ad hoc assumption about friction, mass
- Application: Heated Channels

I.47) "Study on Flow Instabilities in Two-Phase Mixtures", M. Ishii, ANL Report 76-23, Argonne National Laboratory, Argonne, Ill.

Excellent parametric study of density-wave oscillation using homogeneous flow and drift-flux models. The effects of heat flux, inlet subcooling, system pressure, inlet velocity, and inlet and exit orificing have been parametrically studied. The inlet velocity and inlet restrictions are stabilizing. The heat flux, and exit restriction are destabilizing. The inlet sub-cooling may be stabilizing or destabilizing, but is found to be generally stabilizing if sufficiently large, and destabilizing if sufficiently small. Ishii's results are plotted in the N_{sub}-N_{pch} plane. Ishii also gives a simplified criterion for stability. This simplified criterion is restricted in its utility for $N_{sub} \leq \pi$, and for oscillations occuring at a period near the density wave propagation time.

- Instability mode: density-wave
- Mathematical approach: linear stability in the frequency domain
- Simplifying assumptions: homogeneous/drift flux, thermal equilibrium, constant phasic densities, constant inlet sub-cooling, constant, uniform heat flux
- Application: Heated channels

I.48) "Hydrodynamic Stability of a Boiling Channel", A.B. Jones, KAPL-2170, 1961; Part II, A.B. Jones and D.G. Dight, KAPL-2208, 1962, A.B. Jones, June 8, 1962.

These papers describe the physics included in the code STABLE.*

- Instability mode: density-wave
- Mathematical approach: linearized analysis in frequency domain. Numerical nodal evaluations.
- Simplifying assumptions: one-dimensional slip flow, sub-cooling boiling considered using a subcooled boiling heat transfer coefficient. All correlations are dated.
- Application: heated channels

I.49) "Prediction of Flow Oscillation in Reactor Core Channel", H.S. Kao, C.D. Morgan, and M.B. Parker, Trans ANS, 16, 212-213, 1973.

The computer code HYTRAN is used to find the threshold values of heat flux for oscillations at high pressures.

- Instability mode: density-waves
- Mathematical approach: numerical solution in time domain
- Simplifying assumptions: not discussed
- Application: Heated channel, high pressure

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*The basis for the G.E. BWR design code FABLE

I.50) "An Integrated Analytical Model for the Evaluation of Two-Phase Flow Stability", N. Kjaer-Pedersen, Nuc. Sci. and Eng., 35, 200-210, 1969.

The linearized stability analysis for the one-dimensional homogeneous, equilibrium flow in a heated channel is carried out, with attention paid to whether the instability is oscillatory (incorrectly termed "limit cycle" by the author), or not.

- Instability mode: density-wave
- Mathematical approach: linearized perturbations in time domain
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow, constant inlet subcooling, constant uniform heat flux
- Application: heated channels

I.51) "Stability of Steady-state Boiling Heat Transfer with Perturbations", S.A. Kovalev, G.B. Rybchinskaya, and V.G. Vil'ke Teplofizika Vysokikh Temperatur, 11, 4, 805-809, 1973.

This paper considers the stability of the axial heat conduction with the heat flow to the fluid being assumed to be a function of wall temperature only. A function of temperature is calculated for given conditions, from which the final thermal state can be ascertained.

- Instability mode: compound relaxational (heat flux regime transition)
- Mathematical approach: "energy" method, exact analytical (qualitative) analysis
- Simplifying assumptions: heat flux to fluid a given function of temperature, no fluid effects
- Applications: heated rods

I.52) "Pressure Oscillations in Forced Convection Heating of Gases", V.S. Krishnan and J.C. Friedly, Heat Transfer FC9.5, 358-362, 1974.

This paper treats the acoustic wave propagation as the limiting case of high frequency wave propagation, which allows the use of the characteristics to solve the equations for pulse propagation. The authors also claim that the model is valid for density-waves which is questionable, since the frequency of density-wave oscillations is of the same order as the system propagation time.

- Instability mode: acoustic (pressure) wave, density-wave (authors' claim)
- Mathematical approach: propagation of pulses along characteristics
- Simplifying assumptions: single-phase (gas) flow
- Application: gaseous heaters

I.53) "Thermal Stability of Circulation in Steam - Generating Loops", R.S. Kuznetskiy and M.K. Likht, Heat Transfer - Soviet Research, 7, #5, 1975.

The stability of a steam generating loop to an increase in the heat flux is derived. The analysis is highly simplified, and linear. The definition of marginal stability is not motivated at all.

- Instability mode: density-wave
- Mathematical approach: unknown
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow, tube wall dynamics ignored, uniform heat flux, constant subcooling, assumed linear profiles
- Application: heated channels

I.54) "The Thermal-Hydraulics of a Boiling Water Nuclear Reactor", R.T. Lahey, Jr. and F.J. Moody, ANS Monograph 1977.

This book gives a thorough background in the mechanics needed to study the stability of boiling flows. A discussion of the Ledinegg instability and density-wave oscillations is given, with some information on the code NUFREQ.

- Instability mode: Ledinegg, density-wave
- Mathematical approach: linearized analysis in frequency domain
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow, constant inlet subcooling, uniform heat flux
- Application: heated channels & loops

I.55) "NUFREQ, A Computer Program to Investigate Thermo-Hydraulic Stability", R.T. Lahey, Jr. and G. Yadigaroglu, NEDO 13344 July 1973.

This report documents the model and results from the code NUFREQ. The code considers nuclear coupling to the homogeneous equilibrium one-dimensional two-phase flow. The basic mechanism is that of density wave oscillations. The analysis involves the perturbation, linearization and Laplace transform of the system, followed by a Nyquist plot in the frequency domain to determine stability.

- Instability mode: density-wave
- Mathematical approach: linearized analysis in frequency domain
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow, constant subcooling, constant uniform heat flux, nuclear coupling through point kinetics
- Application: BWRs & Heated channels

I.56) "Odds and Evens, a Formula for Enhancing the Dry-Out Power in Boiling Water Reactor Fuel Channels", R.V. MacBeth, Atomic Energy Establishment, Winfreth, AEEW-R954, 1974.

A multidimensional instability mechanism is proposed and qualitatively analyzed. An effect of within-bundle (subchannel-to-subchannel) oscillations on CHF is discussed.

- Instability mode: multidimensional
- Mathematical approach: none
- Simplifying assumptions: N.A.
- Application: Rod bundles

I.57) "A Dynamic Programming Approach to Stabilize Forced-Convection Two-Phase Flow Systems with 'Pressure-Drop' Oscillations", C.J. Madoy, Trans. ASME, J. Heat Transfer, 69-HT-43, 1969.

This paper considers the control of a forced two-phase flow through a heater, with the heat flux used as a control variable. A mathematical programming approach is used at each time.

- Instability mode: density-wave
- Mathematical approach: mathematical programming
- Simplifying assumptions: lumped momentum and energy equations
- Applications: heated channels with controlled heat source

I.58) "Dynamic Behavior of Hydraulic Channels", D. Malnes and H. Bøen, European Two-Phase Flow Group, Milano, 1970.

The stability results in this paper consist of the application of the dynamic code RAMONA to flow in a heated channel.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: slip flow, subcooled boiling, constant inlet subcooling, and constant uniform heat flux
- Application: heated channel

I.59) "SINOD - A Nonlinear Lumped-Parameter Model for Steady-State, Transient and Stability Analysis of Two-Phase Flow in Natural Circulation Boiling-Water Loops", M.P. Matausek, Nuc. Sci, and Eng. 53, 440-457, 1974.

This paper derives and applies a lumped parameter model for the numerical computation of density-wave phenomena. The model is also used to predict the stability boundary in boiling channels. The validity is limited to very short channels by the assumption of linear profiles in the two-phase region.

- Instability mode: density-wave
- Mathematical approach: numerical integration of lumped model
- Simplifying assumptions: one-dimensional flow, ad hoc assumptions about profiles in two-phase section
- Application: heated channels & loops

I.60) "A Study of System-Induced Instabilities in Forced Convection Flows with Subcooled Boiling", J.S. Maulbetsch and P. Griffith, MIT Report No. 5382-35, 1965.

This report investigates the pressure drop instability using a lumped analysis, with the channel assumed to behave according to the static pressure drop-flow characteristic. Parallel channels are also considered.

- Instability mode: pressure drop oscillations
- Mathematical approach: linearized analysis in time domain
- Simplifying assumptions: lumped model, channel governed by static pressure drop-flow characteristic
- Application: heated loops

I.61) "Application of a Momentum Integral Model to the Study of Parallel Channel Boiling Flow Oscillations", J.E. Meyer and R.P. Rose, <u>J. Heat Transfer</u>, 1963.

A numerical method is used to study parallel channel oscillations.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional thermal equilibrium slip flow, with a wall heat conduction model
- Application: heated channels

I.62) "Analysis of Flow Oscillations in a Boiling Channel", F.M. Mitenkov, B.I. Motorov and I.N. Romanov, Heat Transfer - Soviet Research, 2, 2, 34-40, 1970.

A lumped model for two-phase flow in a heated channel is derived using a simplified momentum balance, and a linearized version was studied. It was found that limit cycle solutions were unrealizable.

- Instability mode: density-wave
- Mathematical approach: exact analytical solution along the characteristics, linear and quasi-linear analyses
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow, simplified momentum equations (inlet and outlet frictional pressure drops only)
- Application: heated channels

I.63) "Stability of Once-Through Steam Generators", D. Moxon, ASME 73-WA/HT-24, 1973.

The stability and transient response of a steam generator is studied using a stability code (LOOP-20) and a transient code (HEDYN), using the equations of Davies and Potter.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: see Davies and Potter (1967)
- Application: heated channels

I.64) "On the Mathematics of Fluidization", J.D. Murray, J. Fluid Mech. 21, 3, 465-493, 1965.

This paper reports on a multidimensional instability mechanism found in fluidized beds (solid particles in a fluid). The flow is found to be unstable for all possible states of uniform fluidization.

- Instability mode: multidimensional
- Mathematical approach: linearized analysis in frequency domain
- Simplifying assumptions: two-fluid particle/fluid model
- Application: fluidized bed

I.65) "A Space-Dependent Dynamic Analysis of Boiling Water Reactor Systems", A.N. Nahavandi and R.F. von Hollen, Nuc. Sci. and Eng. 20, 392-413, 1964.

This paper describes the physics included in a numerical scheme. A space-dependent neutron kinetics equation is used.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional homogeneous flow
- Application: BWR

I.66) "Analytical Investigation of Density-Wave Oscillations", S. Nakanishi, S. Ishigai, M. Ozawa, and Y. Mizuta, Technology Reports of the Osaka University, 28, 1421, 243-251, 1978.

The density-wave oscillation theory is modified to account for wall heat storage. The wall heat storage is found to have a large effect.

- Instability mode: density-wave
- Mathematical approach: linear perturbations in frequency domain
- Simplifying assumptions: one-dimensional constant properties, constant subcooling, constant uniform heat flux, no subcooled boiling, drift-flux model
- Application: heated channels

I.67) "The Stability of Boiling-Water Reactors and Loops", L.G. Neal and S.M. Zivi, Nuclear Science and Eng. 30, 25-38, 1967.

This is a complete (through 1966) review of the state of stability studies in Boiling Channels. The physical mechanisms are discussed, a relatively complete one-dimensional model is derived and a discussion of solution methods (numerical and linearized) is given.

- Instability mode: density-wave, Ledinegg
- Mathematical approach: numerical/linear analysis in frequency domain
- Simplifying assumptions: one-dimensional flow, various slip and thermal assumptions
- Application: heated channels & loops

I.68) "The Mechanisms of Hydrodynamic Instabilities in Boiling Systems", L.G. Neal, S.M. Zivi, and R.W. Wright, Symposium on Two-Phase Flow Dymamics, Eindhoven, 1967.

The stability of a channel is considered using a slip model. Some results are given and compared with experiments. Effects of wall heat capacity, wall friction and system pressure are also discussed.

- Instability mode: density-wave
- Mathematical approach: linear stability in frequency domain
- Simplifying assumptions: one-dimensional equilibrium slip flow, constant subcooling, constant uniform heat flux
- Application: heated channels

I.69) "A Review of Two-Phase Flow Instability Aspects of Boiler Dynamics", R. Potter, Paper 13, Int Conf on Boiler Dynamics and Control in Nuclear Power Stations, 1973.

This paper reviews some of the instability mechanisms in boiling. The author suggests a more careful examination of the data.

I.70) "Analysis and Measurement of Flow Oscillations", E.R. Quandt, Chem. Eng. Progress Symposium,

This is a pioneering paper in the study of two-phase flow oscillations. The work has now been superceded by numerous authors.

- Instability mode: density-wave
- Mathematical approach: linearized stability in the S-plane
- Simplifying assumptions: homogeneous equilibrium model, constant inlet subcooling,constant
- Application: heated channels

71 "Kinetics of Boiling Hydraulic Loops", J. Randles, UKAEA Report No. AEE W R87, August 1961.

This report summarizes the physics in an early dymanic code, and the application to instability results of Levy and Beckjord.

- ' ..ability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow, constant inlet subcooling
- Application: heated channels

I.72) "Description of a Mathematical Model for Two-Dimensional Analysis of Boiling Water Reactor Transients", J. Rasmussen and A.O. Waagbǿ, Symposium on Two-Phase Flow Dynamics, EURATOM, 1967.

This paper describes a code designed to study the behavior of a marine reactor to ship motions. In the results shown, there is no evidence of an instability.

I.73) "Analytical Study of the Dynamic Behavior of the self-controlled Marviken Boiling Heavy-Water Reactor", F. Reisch and T. Spanne, Nuclear Applications, 3, 590-598, 1967.

A combination analog-digital computation was used to predict the transient behavior of the Marviken BHWR. Nuclear coupling was included, but the hydrodynamical model was crude. Certain combinations of fuel characteristics showed that an instability was possible as the inlet subcooling increased.

- Instability mode: compound dynamical, density-wave
- Mathematical approach: analog/digital computation
- Simplifying assumptions: lumped hydraulics
- Application: BHWR

I.74) "A Non-Linear Digital Computer Model Requiring Short Computation Time for Studies Concerning the Hydrodynamics of Boiling Water Reactors", F. Reisch and G. Vayssier, Nuc. Eng. and Design 9, 196-210, 1969.

The equations of mass, energy and momentum are discretized in space, assuming linear profiles between mesh points for the void. The resulting equations are integrated numerically using the language CSMP. A discussion of the difference between numerical and system instabilities is given.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional homogeneous, equilibrium flow, constant inlet subcooling, constant uniform heat flux
- Application: heated channels

I.75) "Thermally Induced Two-Phase Flow Instabilities, Including the Effect of Thermal Non-Equilibrium Between the Phases", P. Saha, Ph.D. Thesis, Georgia Institute of Technology, June 1974.

The analytical point of this work is to study the effect of thermal non-equilibrium on the stability of flow in a heated channel. A correlation is derived for the point of net vapor generation, and a model based on an assumed profile for the liquid enthalpy past the point of net vapor generation is formulated. The analysis is done using the linearized equations of motion, in the frequency domain. The non-equilibrium effects are shown to be stabilizing up to a certain subcooling, and destabilizing after that.

- Instability mode: density-wave
- Mathematical approach: linear stability in frequency domain
- Simplifying assumptions: one-dimensional drift-flux, thermal non-equilibrium
- Application: heated channels

I.76) "An Analytical Study of the Thermally Induced Two-Phase Flow Instabilities Including the Effect of Thermal Non-Equilibrium" P. Saha and N. Zuber, Int. J. Heat Mass Transfer, 21, 415-426, 1978.

This is the journal article summarizing Saha's Ph.D. Thesis.

I.77) "Dynamic Analysis of Coolant Circulation in Boiling-Water Nuclear Reactors, I and II", C.R. Sanathanan, J.C. Carter, and F. Miraldi, Nuc. Sci. and Eng. 23, 119-137, 1965.

This paper describes a numerical procedure to study natural circulation. The model includes void-reactivity feedback and slip.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional thermal equilibrium slip flow, non-uniform non-constant heat flux
- Application: heated channels & loops

I.78) "Theoretical Investigations on Sodium Boiling in Fast Reactors", E.G. Schlechtendahl, Nuc. Sci. and Eng. 41, 99-114, 1970.

This paper uses a bubble propagation model, together with equations for the heat transfer to the fliud to treat boiling in sodium. The equations are solved numerically by a finite difference technique. Effects of reactivity feedback and thermodynamic non-equilibrium are included.

- Instability mode: density-wave
- Mathematical approach: finite differences
- Simplifying assumptions: single bubble propagation model
- Application: sodium boiling in a channel

I.79) "Variation of the Vapor Volumetric Fraction During Flow and Power Transients", B.S. Shiralkar, L.E. Schnebly, and R.T. Lahey, Jr., Nuc. Eng. and Design,25, 350-368, 1973.

This paper describes the variation of the void in a boiling channel during exponential flow and power transients. The void-drift, thermal equilibrium partial differential equations are solved by intergrating along characteristics. Since the flow is forced, the implications on stability calculations are unclear.

- Instability mode: density-waves
- Mathematical approach: exact analytical solutions (in time domain)
- Simplifying assumptions: uniform heat flux, constant subcooling, forced flow
- application: heated channels

I.80a) "The Flow of Boiling Water in Heated Pipes", L.M. Shotkin, Nuc. Sci. and Eng. 26, 293-304, 1966.

I.80b) "Stability Considerations in Two-Phase Flow", L.M. Shotkin, Nuc. Sci. and Eng. 28, 317-324, 1967.

These papers study the linear stability using a model based on steady-state profiles. The effect of slip is included.

- Instability mode: density-wave
- Mathematical approach: linear stability
- Simplifying assumptions: one-dimensional equilibrium slip flow, steady-state profiles used, constant subcooling, constant uniform heat flux
- Application: heated channels

I.81) "The 'Kjeller Model' for the Dynamics of Coolant Channels in Boiling Water Reactors, Part 1, Theory," K.O. Solberg, KR-51, 1966.

This paper describes the physics used in the computer code RAMONA. The code includes provisions for subcooled boiling and slip.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional slip flow
- Application: heated loops

I.82) "A Comparison between the Computer Codes OWEN and TOSCLE in a Calculation of Two-Phase Flow Stability", N. Spinks, Australian Atomic Energy Comission AAEC/TM 621, August 1972.

The purpose of this paper is to qualify the predictions of the code TOSCLE, based on closed form solution of the space-dependent linearized, Laplace transformed equations of conservation of mass, momentum and energy.

- Instability mode: density-wave
- Mathematical approach: comparison of linearized exact solutions with (time domain) numerical solutions
- Simplifying assumptions: one-dimensional homogeneous, equilibrium flow, constant sub-cooling, constant uniform heat flux
- Application: heated loop

I.83) "Analysis of Flow Stability in Boiling Systems with the TOSCLE code", N. Spinks, Australian Atomic Energy Commission AAEC/E217, May 1971.

This paper summarizes the physics included in the TOSCLE code.

- Instability mode: density-wave
- Mathematical approach: linear perturbation in frequency domain
- Simplifying assumptions: one-dimensional equilibrium model using simple slip flow, constant inlet subcooling, constant uniform heat flux
- Application: heated channels

I.84) "Response of a Boiling Water Channel to Power Modulation", C.C. St. Pierre, M. Petrich, and S.G. Bankoff, Conference on Two-Phase Flow, University of Exeter 1965.

The analytical part of this paper develops a numerical model, based on steady-state profiles.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional, slip flow, with steady-state profiles
- Application: heated channels

I.85) "Void Response to Flow and Power Oscillations in a Forced-Convection Boiling System with Axially Non-Uniform Power Input", F.W. Staub and N. Zuber, Nuc. Sci. and Eng. 30, 296-303, 1967

The effects of oscillations of flow rate and power are considered, with a non-uniform heat flux. If the oscillations are in-phase, then the void oscillations are lower than those due to either oscillation alone, while if the oscillations are out-of-phase, the void oscillations are essentially the sum of the void oscillations due to each input oscillation alone.

- Instability mode: density-wave
- Mathematical approach: exact analytical solution of hyperbolic system (in time domain)
- Simplifying assumptions: one-dimensional thermal equilibrium slip flow
- Application: heated channels

I. 86) "Instabilities in the Flow of a Boiling Liquid", A.H. Stenning, J. Basic Eng, 1964.

A very simple model for boiling flow is used. A lumped model is used for short pipes (constant profiles), and a numerical approach is used for longer pipes.

- Instability mode: density-wave
- Mathematical approach: linearization, also discretization for long pipes; numerical
- Simplifying assumptions: one-dimensional homogeneous equilibrium flow with a simple friction model for the pressure drop
- Application: heated channels

I.87) "'Pressure-Drop' oscillations in Forced Convection Flow with Boiling", A.H. Stenning, T.N. Veziroglu, and G.M. Callahan, Symposium on Two-Phase Flow Dynamics, Eindhoven, 1967.

Pressure drop oscillations occur on the negative sloping portion of the Δp-flow rate curve, with (in this case) a compressible volume upstream.

- Instability mode: pressure drop (compound dynamic)
- Mathematical approach: linearization of lumped model/ analog computation with nonlinear model
- Simplifying assumptions: lumped model, thermal equilibrium, empirical relation between heat transfer coefficient and flow
- Application: channel/surge tank systems

I.88) "Theoretical Study of Two-Phase Flow Oscillation in a Hot Channel", R. Takahaski and M. Shindo, I. Theoretical Study for Interpreting the Mechanism of Hydrodynamic Instability, J. Nuc. Sci. and Tech. 8[11], 637-643, 1971; II. Influence of Heat Transfer Characteristics on the Flow Stability, J. Nuc. Sci. and Tech. 8[12], 690-695, 1971.

A one-dimensional slip flow thermal equilibrium model is discussed in I as a basis for a finite difference model for flow in a heated channel. In II, the model is linearized and Laplace transformed, and the effects of the heat transfer coefficient are studied.

- Instability mode: density-wave
- Mathematical approach: numerical (I);linear perturbation in frequency domain (II)
- Simplifying assumptions: one-dimensional slip flow
- Application: heated channel

I.89) "Theoretical Study of Flow Instability of a Sodium-Heated Steam Generator", R. Takahashi and T. Futami, Nuc. Eng. and Design 41, 193-204, 1977.

This paper treats the stability of a steam generator by both numerical and an Eigenvalue analysis of the linearized equations. The model consists of a homogeneous **fluid** model with a linear void fraction profile in the two-phase region, and a non-convecting model for the sodium (heated) side. The linearized equations were integrated numerically, and a linearized stability analysis was performed.

- Instability mode: density-wave
- Mathematical approaches: numerical, linearized stability via Eigenvalues
- Simplifying assumptions: one-dimensional constant inlet subcooling wall effects neglected, linear profile assumed for temperature and void
- Application: steam generators

I.90) "Investigations on the Thermohydraulics of Parallel Boiling Water Tubes", C.W.J. van Koppen, F.J.M. Schelleman and J.W.G.M. Schellens, European Two-Phase Flow Meeting, Haifa, June 1975.

The homogeneous, equilibrium fluid equations are integrated numerically for four parallel boiler tubes. The coupling conditions are not discussed.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional homogeneous, equilibrium flow, constant uniform heat flux, constant inlet subcooling
- Application: water tube boilers

I.91) "A Non-Linear Model Describing the Hydrodynamics of Three Parallel Boiling Channels", A.C.M. van Vonderen and M.C. Sluiter, European Two-Phase Flow Group Meeting Milan, Paper A6, 1970.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional slip flow
- Application: parallel heated channels

I.92) "On the Hydrodynamic Behavior of Parallel Boiling Water Channels", A.C.M. van Vonderen, Ph.D. Thesis Eindhoven U. Technology, Netherlands, March 1971.

A numerical procedure is used to solve the nonlinear equations of conservation of total mass, total momentum and energy for each phase, along with a void-quality relation and a correlation for the fraction of heat used for steam generation.

- Instability mode: density-wave
- Mathematical approach: numerical
- Simplifying assumptions: one-dimensional, slip flow, phasic energy equations with a correlation to partition the heat added
- Application: heated channels

I.93) "A Nonlinear Analog Model for Boiling Loop Dynamics and its Application in Reactor Stability", G. Vayssier, Symposium on Two-Phase Flow Dynamics, Eindhoven, 1967.

An analog model has been formulated to calculate the behavior of a boiling loop. The thermo-hydrodynamics are quite crude, but nuclear coupling has been included.

- Instability mode: compound dynamic/relaxational
- Mathematical approach: analog computation
- Simplifying assumptions: hydrodynamic correlations
- Application: heated loop

I.94) "Oscillations in Two-Phase Flow Systems", G.B. Wallis and J.H. Heasley, J. Heat Transfer, Trans. ASME, C, 83, 1961.

This paper discusses the physics and simple models for three different instabilities. These concepts became some of the classical ideas in the two-phase flow theory. First they studied flow regime induced instability, due to an interaction between the heated section and the riser. They then consider force flow density wave oscillations in the heated section alone. They also consider parallel channel oscillations, where the pressure drop acrcss the heated section is assumed to be constant.

- Instability mode: (i) flow regime induced
  (ii) density-wave (forced)
  (iii) density-wave (parallel channel)
- Mathematical approach: (i) lumped model
  (ii) & (iii) exact analytic solution of the hyperbolic p.d.e.'s. Followed by analysis in frequency domain
- Simplifying assumptions: (i) lumped model, steady-state pressure drop in heated section
  (ii) & (iii) one-dimensional homogeneous equilibrium flow, constant inlet subcooling, constant
- Application: (i) heated loop
  (ii) & (iii) heated channel

I.95) "Theoretical Model of the Mixture-Vapor Transition Point Oscillations Associated with Two-Phase Evaporating Flow Instabilities", G.L. Wedekind and B.T. Beck, J. Heat Transfer, Paper 74-HT-T, 1974.

This paper treats the position of the mixture-vapor transition point as a random variable, and calculates the effect of this randomness on the void-quality relation. The implications on stability are not discussed.

- Instability mode: oscillation of dryout point
- Mathematical approach: applied statistics
- Simplifying assumptions: void-quality relation, linear realtion between perturbation of transition point and quality perturbations, and Rayleigh statistics for the quality perturbations
- Application: horizontal heated channels

I.96) "A Model for Predicting the Onset of Oscillatory Instability Occuring with the Intermixing of High-Velocity Vapor with its Subcooled Liquid in Cocurrent Streams", W.H. Westendorf, Heat Transfer, V, 1970.

This paper proposes a simple model for jet penetration, and predicts a stability boundary from observing the 'knee' of the condensing length versus subcooling temperature.

- Instability mode: condensation-induced
- Mathematical approach: none
- Simplifying assumptions: simple energy balance
- Applications: submerged steam jets

I.97) "Fundamental and Higher-Mode Density Wave Oscillations in Two-Phase Flow; the importance of the Single-Phase Region", G. Yadigaroglu and A.E. Bergles, ASME Paper 71-HT-13, 1971.

Stability of flow in a heated channel is studied accounting for non-uniform axial heat flux, wall heat capacity, and the effect of the pressure variation on the movement of the boiling boundary. The authors also cited higher mode oscillations.

- Instability mode: density-wave
- Mathematical approach: linear perturbation in frequency domain
- Simplifying assumptions: one-dimensional homogeneous flow constant inlet subcooling, constant, but non-uniform, axial heat flux
- Application: heated channels

I.98) "Two-Phase Flo Instabilities and Propagation Phenomena", G. Yadigaroglu, Two-Phase Flows in Nuclear Reactors, Von Karman Institute for Fluid Dynamics, Lecture Series 1978-5, 1978.

This paper gives a dynamical interpretation of the static Ledinegg instability, based on a balance between the channel inertia and the internal and external pressure-flow rate characteristics. The compound instability mechanisms of parallel channel effects and pressure drop oscillations are briefly discussed. A detailed discussion of density-wave oscillations is given. The method used involves integration along the characteristics of the hyperbolic partial differential equations governing the homogeneous equilibrium two-phase flow, perturbing, and Laplace transforming. The use of the Nyquist diagram in determining the marginal stability is discussed. Some discussion of computer codes is included and Ishii's results are reviewed. Mechanisms for the compound relaxational instabilities of chugging and geysering, and flow regime instabilities are discussed. Acoustic (pressure wave) oscillations are mentioned. Condensation induced instabilities are discussed. Implications of these instability mechanisms, to Nuclear Reactor Systems are discussed. The discussion includes reference to steam/water mixing and condensation phenomena occuring in vapor supression pools, and a discussion of the oscillations occuring during ECCS injection. A discussion of some instability mechanisms in steam generators is given.

- Instability mode: all
- Mathematical approaches: linear stability in frequency domain
- Simplifying assumptions: one-dimensional, homogeneous equilibrium flow
- Application: BWR, heated channels, BWR containments

I.99) "Analyses of Flow Instabilities", G. Yadigaroglu and K.C. Chan, Japan - U.S. Seminar on Two-Phase Flow Dynamics, July-August 1979.

This paper summarizes the improvements in the modeling of the heat storage and release of the wall and the assumption of non-uniform heat flux distributions. The results are obtained using the code SOFREQ, which uses a drift-flux model. The linearized analysis is done in the frequency domain. The authors also discuss current instability concerns in reactors. Several condensation-related instabilities, such as the "water hammer" problem in BWR supression pool inlet pipes, and the ECCS oscillations, are discussed. The oscillations observed in PWR bottom reflooding are discussed.

- Instability mechanisms: density-waves, condensation induced, and compound dynamic instabilities in a PWR
- Mathematical approaches: linear perturbations in frequency domain
- Simplifying assumptions: one-dimensional drift-flux, thermal equilibrium wall heat storage and non-uniform heat flux considerations
- Application: heated channels, BWR, PWR

I.100) "Prediction of Instability in Sodium Heated Steam Generator", M. Yamakawa, Tsuchiya, Two-Phase Flow Dynamics, The Japan-U.S. Seminar on Two-Phase Flow Dynamics, 1979.

The effects of the heat transfer on the flow stability is studied with the emphasis on the differences between sodium heated, and other steam generators.

- Instability mode: density-wave
- Mathematical approach: numerical; linear analysis in frequency domain and in time domain
- Simplifying assumption: one-dimensional thermal equilibrium slip flow, heater dynamics for sodium, others.
- Application: sodium steam generators

I.101) "Stability Analysis of a Boiling Loop in Low-Pressure Operation", O. Yokomigo, I. Sumida, K. Fukuda, T. Kobori and S. Hirao, Trans ANS, 468, 1974.

Fundamental and higher modes of oscillation are predicted, however The frequencies predicted do not agree with experiments.

- Instability mode: density-wave
- Mathematical approach: linear analysis in frequency domain; finite differences in space
- Simplifying assumptions: one-dimensional separated flow
- Application: heated loops

I.102) "The Propagation and the Wave Form of the Vapor Volumetric Concentration in Boiling, Forced Convection Systems under Oscillatory Conditions", N. Zuber and F.W. Staub, Int. J. Heat Mass Transfer, 9, 871-895, 1966.

This paper computes density-waves under the conditions of certain oscillatory input conditions. The fluid flow is forced, and therefore, natural circulation instabilities do not arise. This paper has only indirect consequences on flow stability.

- Instability mechanism: density-wave
- Mathematical approach: exact time-domain solutions, integrated along characteristics
- Simplifying assumptions: one-dimensional drift-flux, forced inlet conditions, uniform, but oscillatory power
- Application: heated channels

I.103) "An Analytical Investigation of the Transient Response of the Volumetric Concentration in a Boiling Forced-Flow System", N. Zuber, F.W. Staub, Nuc. Sci. and Eng. 30, 268-278, 1967.

This paper derives the void propagation equation. The results are given in a subsequent paper.

I.104) "Approximate Criterion for Prediction of Flow Oscillations in Supercritical Fluid Heat Exchangers", J.C. Friedly, J.L. Manganaro, and P.G. Kroeger, Advances in Cryogenic Engineering, Vol. 14, Plenum Press, 1969.

This paper proposes a simplified model for the stability threshold. The criterion is based on the assumption that the ratio of stabilizing to destabilizing pressure drops must be greater than an expansion factor.

- Instability mode: density-wave
- Mathematical approach: linearized stability in frequency domain
- Simplifying assumptions: one-dimensional homogeneous, equilibrium flow, simplified state equation
- Application: heated channel

I.105) "Thermohydraulic Stability Analysis of Steam Generators", K.C. Chan, Ph.D. Thesis, Department of Nuclear Engineering, U.C., Berkeley, 1979.

A study of density-wave oscillations using linearized analysis in the frequency domain. The effects of wall heat transfer and subcooled boiling are considered. Good agreement with some steam generation data is obtained.

- Instability mode: density-wave
- Mathematical approach: linearized analysis in the frequency domain
- Simplifying assumptions: one-dimensional slip flow
- Application: steam generator instabilities

I.106) "Acoustical Oscillation in Steam Systems, H. Christensen, Nukleonik, 5, 1963.

This paper treats acoustic vibrations by analogy with a transmission line theory. Gravity and convection are neglected.

- Instability mode: acoustic
- Mathematical approach: linearization (analogy with transmission line) model/numerical
- Simplifying assumptions: one-dimensional homogeneous flow, with an assumed sound speed
- Application: heated channel

I.107) "Flow and Stability Problems in Multiple-Channel Natural Convection Systems", J.C. Chato, Trans. ANS, Vol-5, No. 1, 1962.

A multiple channel model based on steady-state concepts is studied.

- Instability mode: compound relaxational (static)
- Mathematical approach: steady-state solutions
- Simplifying assumptions: static empirical model
- Application: multichannel flow system

I.108) "A Study of System-Induced Instabilities in Forced-Convection Flows with Subcooled Boiling", J.S. Maulbetsch and P. Griffith, Report 5382-35, MIT Dept. of Mech. Eng. 1965.

This paper describes the analyses and experiments describing the "pressure drop" oscillations which results from the interaction between the heated section and another energy storage device in the loop, usually a compressible volume. The steady-state pressure drop-flow rate characteristic is used for the heated section, and a lumped model is used for the compressible volume.

Both "parallel channel" and forced flow conditions were used. It is necessary to have channel conditions corresponding to a region of negative slope in the pressure drop-flow rate characteristic.

- Instability mode: pressure drop oscillations
- Mathematical approach: linearized analysis of a lumped parameter model
- Simplifying assumptions: Lumped compressible volume, quasi-steady-state channel operation
- Application: Heated loops and parallel channels

I.109) "Analytical and Experimental Study of the Dynamics of a Single-Tube Counterflow Boiler", H.L. Hess, J.R. Hooper, S.L. Organ, NASA Contract Report, NASA CR-1230, 1969.

This paper contains a simplified model for density-wave oscillations in a heated tube. Subcooled boiling is considered, as is thermal coupling with the wall.

- Instability mode: density-wave
- Mathematical approach: linearized analysis in frequency domain
- Simplifying assumptions: various, including homogeneous flow, and constant resident times for fluid particles in the boiling regions
- Application: heated channels

I.110) "Studies of Thermal-Hydrodynamic Flow Instability", A. Suzuoki and M. Yamakawa, Bull. JSME, 19, 1976.

This paper describes the results of a numerical solution for the eigenvalues of a model for flow in a heated channel which includes the effects of compressibility and wall heat capacity. Even though the possibility of acoustic oscillations exists, they are not found. Details of the model are not given.

- Instability modes: density-wave acoustic
- Mathematical approach: linearized analysis in frequency domain
- Simplifying assumptions: one-dimensional homogeneous flow (other details not given)
- Applications: steam generator

I.111) "Oscillatory Behavior of a Two-Phase Natural-Circulation Loop", E.H. Wissler, H.S. Isbin and N.R. Amundson, A.I.Ch.E. J., 2, 1956.

A discretized-in-space analog computer calculation for density-wave oscillations is reported in this classic study.

- Instability mode: density-wave
- Mathematical approach: analog computation from discretized model
- Simplifying assumptions: one-dimensi nal homcgeneous equilibrium flow
- Application: heated loop

APPENDIX II

A SUMMARY OF SELECTED DATA ON INSTABILITY MECHANISMS IN TWO-PHASE FLOWS

II.1) "An Experimental Study of Thermally-Induced Flow Oscillations in Supercritical Helium", D.E. Daney, P.R. Ludtke, M.C. Jones, Journal of Heat Transfer, 101, 1979.

This paper presents experimental data on density-wave oscillations in supercritical helium, a coolant in superconducting power transmission lines. A stability boundary is determined from the data provided.

- no. of data points: 28
- heat flux profile: uniform axial
- test section configuration: single tube, circular cross-section D_H = 3.99mm, L_H = 185m
- range of parameters:

  $0.32 \leq w \leq 0.58$ kg/sec

  $2.7 \leq p \leq 15$ bar

  $4.6 \leq T_{IN} \leq 6.0$ °K

  $9.6 \leq q \leq 41.8$ W
- oscillation modes studied: density-wave oscillations
- test fluid: Helium

II.2) *"Transient and Stability Tests at Peach Bottom Atomic Power Station Unit-2 at End of Cycle 2", L.A. Carmichael, R.O. Niemi, EPRI Topical Report, EPRI NP-564, 1978.

Low flow stability testing was performed in the Peach Bottom Unit-2 BWR/4 to determine the stability margin of a modern jet pump BWR/4.

The forcing function was small pseudo-random and regular spaced pressure perturbations. The result demonstrated that this method is a good way of measuring core stability margins in operating BWRs. In addition, turbine trip transient tests were conducted to determine system response.

The data provided are excellent for thermal-hydraulic stability code evaluation. For full geometric data, see the companion report NP-563, "Core Design and Operating Data for Cycles 1 and 2 of Peach Bottom-2".

- no. of data points: 4, the test conditions given below:
  1. $w = 52.6 \times 10^6$ lb/h

     $p = 1000$ psia

     $q = 1995\ MW_t$

     $H_{inlet} = 508.9$ Btu/lb
  2. $w = 43.0 \times 10^6$ lb/h

     $p = 992$ psia

     $q = 1702\ MW_t$

     $H_{inlet} = 505.0$ Btu/lb

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* On this, and subsequent pages, a single asterisk denotes references of significant value in the assessment of analytical models.

3. $w = 38.9 \times 10^6$ lb/h

   $p = 1005$ psia

   $q = 1948$ MW_t

   $H_{inlet} = 528.4$ Btu/lb

4. $w = 38.9 \times 10^6$ lb/h

   $p = 999$ psia

   $q = 1434$ MW_t

   $H_{inlet} = 507.2$ Btu/lb

- heat flux profile: non-uniform axial
- test section configuration: BWR/4 core
- range of parameters: see above
- oscillation modes studied: density-wave oscillations
- test fluid: water

II.3) "Dynamic Instabilities in Tubes of a Large Capacity, Straight-Tube, Once-Through Sodium Heated Steam Generator, H.C. Unal, M.L.G. VanGasselt, Int. J. Heat Mass Transfer, Vol 20, pp. 1389-1399, Pergamon Press, 1977.

Data dealing with dynamic instabilities in a long, straight-tube, once-through, sodium heated steam generator are provided. Also given are data and correlations for oscillation periods and inception conditions of the dynamic instabilities. It is noted that the inception conditions can be predicted with simple equations. A hot channel factor is also developed, relating conditions in the first tube to go unstable to the average conditions of the steam generator.

- no. of data points: 25
- heat flux profile: non-uniform axial (counter-flow sodium/water)
- test section configuration: 139 tube bundle

  D_H = 0.0126 m, L_H= 18.64

  Equitriangular pattern of 0.0275m pitch
- range of parameters:

  (steam/water side)

  $2.5 \leq w \leq 13.9$ kg/s

  $5.3 \leq p \leq 16.8$ MN/M^2

  $6.6 \leq q \leq 22.3$ MW

  $214 \leq T_{inlet} \leq 302$ °C

  $305 \leq T_{outlet} \leq 422$ °C

  (sodium side)

  $62 \leq w \leq 186$ kg/s

  $351 \leq T_{inlet} \leq 452$ °C
- oscillation modes studied: density-wave oscillations
- test fluid: water

II.4) **"An Investigation of Heat Transport In Oscillatory Turbulent Subcooled Flow", R.P. Roy, G. Yadigaroglu, Journal of Heat Transfer, pp. 630-637, Nov. 1976.

This experimental work shows that to bring quantitative as well as qualitative accuracy to analytical investigations of the threshold of stability, effects such as subcooled boiling and radial heat transport mechanisms must be accounted for. This paper provides data on radial heat transport in oscillatory flow, and indicates that it may not be possible to predict the point of net vapor generated (NVG) using a 1-D thermal-hydraulic analysis.

- no. of data points: data for 6 velocities;perturbation frequencies at 4 axial locations. Velocity perturbation frequencies of 0.1, 0.2, 0.3, 0.5, 0.7, and 0.9 Hz
- heat flux profile: uniform axial
- test section configuration: single tube in vertical downflow, circular cross-section $D_H = 24.4$
  $L_H = 1.638m$
- range of parameters:
  $v_{inlet} = 0.637$ m/s
  $p = 2.5 \times 10^5$ N/m^2
  $q' = 814$ w/m
  $T_{inlet} = 20°C$
- test fluid: freon-113

** On this, and subsequent pages, a double asterisk denotes data which provides insights useful in model development.

II.5) *"Comparison of a Two-Phase Flow Instability Analytical Model (NUFREQ) Against Experimental Data", W.Y. Lyon. M.S. Thesis, Dept. Mech. Eng., Univ. of Calif.-Berkeley, 1976.

This paper presents a good comparison of the thermal-hydraulic computer code NUFREQ with data obtained by Paul and Riedle, Christensen, and Krejsa, Goodykoontz, and Stevens, (see references below). These data include inlet flow-to-inlet pressure, inlet flow-to-exit void fraction and volumetric-heat-generation-to-exit void fraction transfer fractions. It is demonstrated that NUFREQ compares well with data obtained under conditions of uniform axial heat flux and low subcooling.

- no. of data points: 14 runs
- test section configurations: see references on individual data sets
- range of parameters: see references on individual data sets
- oscillation modes studied: density-wave oscillations
- test fluid: see references on individual data sets

II.6) "Boiling Flow Instabilities in a Multichannel Upflow System", S. Kakac, Proceedings of the NATO Advanced Study Inst., Two-Phase Flows Heat Transfer, Instanbul, Turkey, Aug. 1976.

A four-parallel channel system using Freon-11 was experimentally investigated for sustained (ie: limit cycle) and transient boiling flow instabilities. Density-wave and pressure-drop oscillations are considered in 4 parralel channels with and without cross-connections. Stability maps are developed for the various systems. It is shown that the cross-connected system is more stable than the non-cross-connected systems.

- no. of data points: approximately 100
- heat flux profile: uniform axial;equal and unequal powers on 4-tube system
- test section configuration: 4-tube, vertical upflow, circular-cross-section system, with and without cross-connection

  D_H = 3.75mm L_H = 69 cm
- range of parameters:

  $2.95\ \frac{kg}{cm^2} \leq p_{inlet}\ \ 7.7\ \frac{kg}{cm^2}$

  - (cross-connection)

  $600 \leq q \leq 800$ W

  $0.1359 \leq w \leq 0.4304$ kg/min

  - (no cross connection, equal heating)

  $360 \leq q \leq 800$ W

  $0.1268 \leq w \leq 0.5436$ kg/min

  - (no cross connection unequal heating)

  $300 \leq q \leq 600$ W

  $0.0906 \leq w \leq 0.6795$ kg/min
- oscillation modes studied:density-wave oscillations,pressure drop oscillations
- test fluid: Freon-11

II.7) "Boiling Flow Instabilities in a Four Parallel-Channel Upflow System", S. Kakac, T.N. Veziroglu, H.B. Aksu, Y. Alp, Proceedings of Int. Meeting on Reactor Heat Transfer, Karlsrhue, Germany 1973.

Freon-11 was used in a 4 parallel channel boiling system to investigate flow instabilities. Density-wave oscillations and pressure drop oscillations were noted in the investigation of sustained instabilities, and transient oscillations were detected as a result of step changes in power. Heat was uniformly applied to the four channels, and subcooling effects on system instability were not investigated. A stability map of pressure drop vs. flow rate for a 4 channel system is provided.

- no. of data points: 20 runs of sustained oscillation
  23 runs of transient instability data
- heat flux profile: uniform axial
- test section configuration: 4 circular cross section tubes in parallel. Flow is upward and vertical
  $D_H = 0.125$ inch $L_H = 75$ cm
- range of parameters:
  $413 \leq q \leq 868$ W
  $0.136 \leq w \leq 0.589$ Kg/min
- oscillation modes studied: density-wave oscillations, pressure drop oscillations
- test fluid: Freon-11

II.8) "An Experimental Investigation of Flow Instability in Freon-12 and Comparison with Water Data", J.D. Harvie, Proceedings of Symposium on Multiphase Flow Systems, University of Strathclyde, 1974.

The major purpose of this investigation was to determine whether Freon-12 is an effective substitute for water in the modeling of two-phase flow instability in steam-water systems and to determine the scaling between Freon-12 and water data.

The steam-water data of D'Arcy are compared to Freon-12 data obtained in this investigation. Both sets of data were found to exhibit similar trends.

An empirical mass flux scaling factor was derived, but not enough data was obtained to fully define scaling relations between Freon-12 and water.

- no. of data points: threshold maps for Freon-data (six mass fluxes) and water (four mass fluxes). Also, stability map for low quality oscillations are provided
- heat flux profile: uniform axial
- test section configuration: 3 parallel annular tubes ($20.83 \geq D_H \geq 15.24$mm) connected to common inlet and exit headers, $L_H = 2.03$m
- range of parameters:

  $4 = \Delta T_{sub} \leq 33$ °K

  $220 \leq G \leq 960$ Kg/m^2-s

  system pressure - 6.89 MN/m^2

- oscillation modes studied: density-wave oscillations, low quality oscillations (note: the three channel system can have various modes of oscillation among tubes in test section; eg: two channels oscillating together 180° out-of-phase with third channel, which has twice the amplitude)

- test fluid: Freon-12

II.9)**"Sust ined and Transient Boiling Flow Instabilities in a Cross-Connected Four-Parallel Channel Upflow System", S. Kakac, T.N. Veziroglu, K.A. Kyuzlu, O. Berkol, Heat Transfer, Vol. 4, Scripta Book Co., 1974.

An investigation was made of the instabilities in a four-channel cross-connected system. A pressure-drop vs. flow rate map was given, showing the areas of density-wave oscillation and pressure-drop oscillation. It was determined that density-wave oscillations start at a higher heat flux with a four-channel system that is cross-connected as opposed to a non-cross-connected system. Also, the four-channel cross-connected system oscillates in phase, in contrast with two parallel channels which oscillate 180° out of phase, and it is noted that the four parallel channel system is more stable than a single channel, a two channel, and a four channel non-cross connected system.

The surge tank in the experimental system provided significant upstream compressible volume to promote pressure-drop oscillations.

- no. of data points: 23 sustained oscillation points
  24 transient instability points
- heat flux profile: uniform axial
- test section configuration: 4 parallel channels in a vertical, upflow system, circular cross-section
  $D_H = 0.125"$ $L_H = 75cm$

- range of parameters: $360 \leq q \leq 850$ W

  $0.091 \leq w \leq 0.772$ kg/min

  system pressure: 3 kg/cm^2
- oscillation modes studied: density-wave oscillations, pressure drop oscillations
- test fluid: Freon-11

II.10) "Pressure Oscillation in Forced Convection Heating of Gases", V.S. Krishnan, J.C. Friedly, Proceedings of the 5th International Heat Transfer Conference, Vol. 2, paper FC9.5, 1974.

Instability data was taken in a horizontal test section with nitrogen as the test fluid. Density-wave oscillations as well as acoustic oscillations were considered. A stability plot was constructed along with a plot of calculated vs. experimental oscillation frequencies. Data was not plentiful and not well documented.

- no. of data points: 1 stability plot
- heat flux profile: uniform axial
- test section configuration: single, horizontal circular cross-section tube $D_H = 0.397$cm, $L_H = 1.07$m
- range of parameters:

  $1.86 \leq p \leq 5.05 \times 10^{-5}$ N/m^2 (other parameters were not available)
- oscillation modes studied: acoustic and density-wave oscillations
- test fluid: nitrogen

II.11) "Thermally Induced Two-Phase Flow Instabilities, Including the Effect of Thermal Non-equilibrium Between the Phases", P. Saha, Phd.Thesis, Georgia Inst. Tech., U. Microfilms Order No. 74-21, 580, 1974.

The onset of thermally induced flow oscillations in a uniformly heated boiling channel was presented. The working fluid was Freon-113. The onset of oscillation was determined by plotting the average amplitude of the flow fluctuations against the power supplied to the test section. Seven sets of experiments were done to see the effects on stability of pressure, inlet restriction, outlet restriction, and subcooling. Data repeatability was demonstrated.

- no. of data points: 69 data points for various conditions
- heat flux profile: uniform axial
- test section configuration: single-tube in vertical upflow†

  $D_H = 0.402$ in $L_H = 9$ ft
- range of parameters:

  $150 \leq p \leq 200$ psia

  $2.37 \leq v_{inlet} \leq 4.88$ ft/sec

  $3.1 \leq \Delta H_{sub} \leq 27.7$ Btu/lb_m

  $3.465 \leq q \leq 14.375$ Btu/sec
- oscillation modes studied: density-wave oscillations
- test fluid: Freon-113

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† In parallel with a large unheated bypass

II.12) "Hydrodynamic Stability and Thermal Performance Test of a 1-MW_t Sodium Heated Once-Through Steam Generator Model", R.P. Waszink, L.E. Efferding, ASME Journal of Engineering for Power, pp. 189-200, July, 1974.

This test program was undertaken to examine water-side instabilities in sodium-heated heat exchangers. Although the test model employed straight tubes, the resulting instability data adequately predicts instability in serpentine-tube circuits owing to the weak dependence of density-wave oscillations on circuit configuration. Experimental and predicted data are compared. A static stability index is developed (related to Ledinegg cirterion).

- no. of data points: stability plots for five values of load are presented (not all data taken is presented)
- heat flux profile: non-uniform axial (Sodium/water heat exchanger)
- test section configuration: 3 active 130 ft. long surpentine tubes; upward water flow
  $D_H = 0.37$ in, $L_H = 1561.5$ in
- range of parameters: (steam/water side)
  $260 \leq w \leq 3615$ lb/hr
  $359 \leq T_{inlet} \leq 573$ °F
  $622 \leq T_{out} \leq 950$ °F
  $1805 \leq p \leq 2400$ psia
  $0.085\ q \leq 1\ MW_t$
  (sodium side)
  $2600 \leq w \leq 42{,}060$ lb/hr
- oscillation modes studied: density-wave oscillations
- test fluid: water

II.13) "Prediction of Flow Oscillation in Reactor Core Channel", H.S. Koo, C.D. Morgan, M.B. Parker, Trans. Amer. Nucl. Soc., Vol. 16, pp 212-213, June, 1973.

A short table of density-wave oscillation data is presented. These data are unique since pressures above 1600 psia were studied for a 12-foot test section in the B & W test loop.

- no. of data points: 16
- heat flux profile: uniform axial
- test section configuration: vertical tube: $D_H = 0.55$ in., $L_H = 12$ ft
- range of parameters:

  $760 \leq p \leq 2197$ psia

  $0.66 \leq G/10^6 \leq 1.814$ $lb_m/hr\text{-}ft^2$

  $28.7 \leq \Delta T_{sub} \leq 146.1$ °F

  $0.20 \leq q''/10^6 \leq 0.406$ $Btu/ft^2\text{-}hr$

- oscillation modes studied: density-wave oscillations
- test fluid: water

II.14) *Dresden-3 Rod Oscillator Tests", R.O. Neimi, General Electric Report, NEDM-13357, Class I.

Control rod oscillator tests were conducted by G.E. and Commonwealth Edison at the Dresden Nuclear Power Station, Unit-3. One control rod was oscillated to determine the neutron flux responses to the reactivity perturbation produced by the oscillated control rod. The tests were designed to check trends with parameters such as shifting of power profile, changing inlet subcooling,and employing either natural or forced circulation. It was claimed that G.E.'s stability design code (FABLE) is conservative for evaluation of BWR stability margins, but is able to predict oscillation frequency rather well. This data is of interest since it was taken in a large jet pump BWR. Gross core data was provided, but paper lacks information on channel geometry.

- no. of data points: five sets of transfer functions are provided, related to five core conditions (see below)
- heat flux profile: non-uniform axial
- test section configuration: BWR core
- range of parameters:

  5 sets of test conditions

  1. $p = 946$ psia

     $q = 906.3$ MW

     $w = 30 \times 10^6$ lb/hr

     $\Delta H_{sub} = 30.84$ Btu/lb

2. $p = 946$ psia

   $q = 921.4$ MW

   $w = 29.5 \times 10^6$ lb/hr

   $\Delta H_{sub} = 31.82$ Btu/lb

3. $p = 946$ psia

   $q = 1033.0$ MW

   $w = 30 \times 10^6$ lb/hr

   $\Delta H_{sub} = 41.39$ Btu/lb

4. $p = 977$ psi

   $q = 1786.9$ MW

   $w = 53.6 \times 10^6$ lb/hr

   $\Delta H_{sub} = 30.67$ Btu/lb

5. $p = 1002$ psi

   $q = 2235.6$ MW

   $w = 83.5 \times 10^6$ lb/hr

   $\Delta H_{sub} = 24.07$ Btu/lb

- oscillation modes studied: nuclear-coupled density-wave oscillations
- test fluid: water

II.15) "Two-Phase Instability in a Low Pressure Natural Circulation Loop", V.K. Chexal, A.E. Bergles, AIchE preprint #19, 13th NHTC, Denver, 1972.

Data was presented from a single-channel, natural circulation loop that is a model of a thermosiphon reboiler. Seven flow modes are characterized, and stability maps are constructed showing the location of these modes for both water and Freon-113. The effects of inlet restriction and liquid level are demonstrated. Also, a comparison of the data is made with the simplified stability criterion of Ishii and Zuber which was found to be conservative for Freon-113 but non-conservative for water.

- no. of data points: 10 stability maps are developed (2 for Freon-113, 8 for water). All runs were in natural circulation.
- heat flux profile: uniform axial
- test section configuration: single tube, vertical upflow system, circular cross-section:
  D_H = 0.43 in, L_H = 30"
- range of parameters:
  $q'' \lesssim 27{,}000$ Btu/hr-ft^2
  $p \simeq 15.4$ psi
  $0 \lesssim \Delta T_{sub_{(water)}} \lesssim 110°F$
  $0 \lesssim \Delta T_{sub_{(Freon)}} \lesssim 40°F$
- oscillation modes studied: density-wave oscillations
- test fluids: water and Freon-113

II.16) "An Experimental Study of Flow Instability in Boiling Channel Systems", G. Matsui, Heat Transfer-Japanese Research, Vol. 1, No. 1, pp. 46-57, 1972.

A single-channel experiment using n-pentane was described in this paper. The fluid, n-pentane, was chosen for its low boiling temperature, but similar thermal and hydrodynamic properties with that of water. The experiment was concerned with flow regime instabilities, however, the instability mechanism was not clear in this study.

- no. of data points: 9 stability maps are provided for various conditions of heat input, subcooling, inlet resistance, and inlet velocity.
- heat flux profile: uniform axial (heater element in center of flow tube)
- test section configuration: single-channel, circular cross-section vertical upflow test section
  D_H = 22mm, L_H = 0.2m
- range of parameters: not available
- oscillation modes studied: not clear
- test fluid: n-pentane

II.17)*"Void Fraction and Stability of Natural Circulation Water Boiling in a Vertical Annulus Heated Internally, F.J.M. Kijkman, Nuclear Engineering and Design, 15, 1971.

A single-channel, uniform axial heat flux test section was used in this experiment. It was shown that the threshold of oscillatory behavior cannot be determined from an examination of the voids, (ie: amplitude of oscillation of void) since curves representing phase differences between axially distributed voids and the inlet velocity do not show a discontinuity as the region of instability is entered.

Also, the effect of a cosine-shaped heat flux was examined, and it was noted that results on the onset of instability with uniform heat flux must be used with care, since the chopped-cosine axial heat flux case was more stable.

- no. of data points: 8 stability curves for 2 pressures and several subcoolings along with axial void distribution for uniform heat flux with the cosine-shaped heat flux; 5 stability curves are given with associated axial void distributions
- heat flux profiles: uniform and chopped-cosine axial
- test section configuration: internal heated annular test section, vertical upflow, single-tube, natural circulation, D_{ROD} = 33.8 mm, D_{TUBE} = 50 mm, L_H = 2.4
- range of parameters:

  $1.6 \leq \Delta H_{sub} \leq 30.0$ °C
  $45.0 \leq q \leq 180.0$ KW
  T_{sat} = 200°C, 234°C
- oscillation modes studied: density-wave oscillations
- test fluid: water

II.18)*"On the Hydrodynamic Behavior of Parallel Boiling Water Channels", A.C.M. VanVonderen, Ph.D. Thesis, Eindhoven U. Technol., Netherlands, 1971.

The test section used in this thesis consisted of a three parallel channel, uniformly heated, inside cooled, system. The influence on stability of parameters such as pressure, inlet subcooling, channel orifices, and pump characteristics was investigated. Three modes of oscillation were noted: each channel oscillating 120° out-of-phase with the other with the same amplitude, two channels oscillating 180° out-of-phase with the same amplitude while the third was stable, and two channels oscillating in phase with equal amplitude with the third channel oscillating 180° out of phase with the other two and with twice the amplitude.

In comparison of the data with a single-channel model, it was noted that the single channel model appeared to work only when the number of parallel channels is large or the downcomer cross-section is large compared to the sum of the cross-sections of the boiling channels.

- no. of data points: 6 sets of data, with 4 or 5 values of subcooling (pressure, restrictions, and pumping varied over the sets)
- heat flux profile: uniform axial
- test section configuration: three parallel vertical heated tubes: $D_H = 20$ mm, $L_H = 2.55$ m
- Range of parameters: $1 \leq \Delta T_{sub} \leq 35°C$

  $30 \leq q_{total} \leq 340$ kw

  $15.5 \leq p \leq 30$ bar

  $0.52 \leq v_{in} \leq 1.3$ m/s
- Oscillation mode studied: density-wave oscillations
- Test fluid: water

II.19) Study on Distribution of Flow Rates and Flow Stabilities in Parallel Long Evaporators, K. Akagawa, T. Sakaguchi, M. Kono, M. Nishimura, Bulletin J.S.M.E., Vol. 14, No. 74, pp. 837-848, 1971.

This experiment used a three parallel, vertical channel evaporator tube system charged with Freon-113. This data had a high ratio of length-to-diameter for the test section. While emphasis was on excursive instabilities, thermal (denisty-wave) instabilities were also observed at low flow rates.

- no. of data points: not tabulated (graphical display)
- heat flux profile: not available
- test section configuration: three coiled copper tubes connected in parallel. The coil diameter was 20mm and pitch was 12mm. D_H = 4mm and L_H = 40m
- range of parameters:

  $1 \leq p \leq 41$ atmospheres
- oscillation mode studied: Ledinegg instability
- test fluid: Freon-113

II.20) *"Frigg Loop Project - Hydrodynamic and Heat Transfer Measurements on a Full-scale Simulated 36-Rod BHWR Fuel Element with Non-uniform Axial and Radial Heat Flux Distribution", O. Nylund, et.al. FRIGG-4, R4-502/RL-1253, 1970.

Data was taken in a 36-rod cluster that has both an axial as well as radial power peaking pattern which is typical of a reactor. This report is the last of a series of loop experiments that were part of the test program for the Marviken BHWR project. These data are some of the best available to check various analytical models of two-phase flow instability in rod bundle arrays. Measurements are performed with various axial and radial void distributions for: single-and two-phase pressure drop, natural circulation mass flux, stability limits as well as detailed dynamic and burnout characteristics in natural and forced circulation. It was noted that the stability limit, as a function of inlet subcooling was significantly affected by the axial heat flux distribution.

- no. of data points: approximately 350 data sets are provided for various loop conditions
- heat flux profile: axially and radially non-uniform
- test section configuration: 36 rod test section with prototype reactor spacers (unheated center rod), $L_H = 4.365$m
- range of parameters:

$10 \leq p \leq 70$ bars	(natural circulation)
$30 \leq p \leq 70$ bars	(forced circulation)
$4 \leq \Delta T_{sub} \leq 16°C$	(natural circulation)
$5 \leq \Delta T_{sub} \leq 16°C$	(forced circulation)
$G \simeq 790$ kg/m^{2}s	
$3 \leq q \leq 5$ MW	(natural circulation)
$q = 3$ MW	(forced circulation)

- method of data generation: introduction of pseudo-random perturbations and steps in heat input
- test fluid: water

II.21) "Inception of Pulsations Using a Model of Vertical Water-wall Tubes", I.I. Koshelev, A.V. Surnov, L.V. Nikitina, Heat Transfer-Soviet Research, Vol. 2, No. 3, pp. 111-115, May 1970.

Experimental data are provided for the onset of flow instability in a 3 to 4 parallel tube system. Parameters varied are the coolant flow rate, heat flux and inlet subcooling. The system pressure was 100 atm.

- no. of data points: 4 plots of stability data (uniform and non-uniform heat flux, variable subcooling)
- heat flux profile: uniform and non-uniform
- test section configuration: 3 or 4 tubes in vertical upflow
  $L_H = 12m \quad D_H = 25mm$
- range of parameters:

  $p = 100$ atms

  $230 \leq G \leq 1250$ Kg/m^2-sec

  $5 \leq H_{sub} \leq 170$ Kcal/Kg

  $100 \leq q'' \leq 420 \times 10^3$ Kcal/m^2-hr
- oscillation mode studied: typical phase shifts for three tube case indicated density-wave oscillations
- test fluid: water

II.22 *"Frigg Loop Project - Hydrodynamic and Heat Transfer Measurements on a Full-Scale Simulated 36-rod Marviken Fuel Element with Non-uniform Radial Heat Flux Distribution", O. Nylund, et.al., FRIGG-3, R4-494/RL-1154, 1969.

Data was taken in a 36-rod cluster that had an imposed radial heat flux distribution. This paper is third in a series of four on this project. No large influence of the radial heat flux was detected.

- no. of data points: approximately 400 data sets are provided for various loop conditions
- heat flux profile: radially non-uniform, uniform axial
- test section configuration: 36-rod test section with prototype reactor spacers (unheated center rod), $L_H = 4.365$ m
- range of parameters:

  $30 \leq p \leq 50$ bars (natural circulation)

  $p \leq 50$ bars (forced circulation)

  $2 \leq T_{sub} \leq 23°C$ (natural circulation)

  $3 \leq T_{sub} \leq 25°C$ (forced circulation)

  $3 \leq q \leq 5$ MW (forced circulation)

  $G \simeq 810$ Kg/m^{2}5

  $G_{nat} \simeq 900$ Kg/m^{2}s (natural circulation)
- method of data generation: introduction of pseudo-random perturbations and steps in heat input
- test fluid: water

II.23) "Hydraulic Instabilities in Parallel Spiral Steam Generator Tubes", G. Hernborg, B. Ohlsson, J. Flinta, Arbetsrapport, AE-RTL-1107, 1969.

Long, parallel, spiral steam generator tubes were examined for hydraulic instability. The system pressure used was 10 bars and the power input was the parameter varied. This experiment provides data on 2 more realistic geometries for some steam generators. The data agreed rather well with a model proposed by Flinta.

- no. of data points: 109 data points provided for various flow conditions
- heat flux profile: uniform axial
- test section configuration: two parallel, spiral tubes: $D_H = 14mm$, $L_H = 5.4m$
- range of parameters:

  $p = 10$ bars

  $300 \leq G \leq 1500$ Kg/m^2-sec

  $40 \leq \Delta T_{sub} \leq 100$ °C

  $8.1 \leq q'' \leq 71.2$ W/cm^2
- oscillation modes studied: density-wave oscillations
- test fluid: water

II.24) "Experimental Investigation of the Dynamics of a Pressure Drop Controlled Heated Channel and Comparison with HYKAMO - Calculations", R. Schöneberg, Paper VII-2 of the European Two-Phase Flow Group Meeting, Karlsruhe, Germany, 1969.

A constant imposed pressure drop experiment was performed to simulate a "hot" channel in a reactor core, surrounded by many "cold" channels. A four rod bundle was used. Insufficient geometrical data make it difficult to use this data for code verification.

- no. of data points: 12 transfer function plots are provided (heat flux-void fraction, heat flux-pressure drop, heat flux-mass flow, etc)
- heat flux profile: uniform axial
- test section configuration: 4 rod (electrically-heated) bundle
- range of parameters:

  $p = 71$ atms

  $v_{in} \simeq 1.0$ m/sec

  $10.16 \leq \Delta T_{sub} \leq 10.88$ °C

  $137.2 \leq q \leq 173.3$ KW
- oscillation mode studied: density-wave oscillations
- test fluid: water

II.25) *"Frigg Loop Project - Hydrodynamic and Heat Transfer Measurements on a Full-Scale Simulated 36-Rod Marviken Full Element with Uniform Heat Flux Distribution", O. Nylund, et.al. FRIGG-2, R4-447/RTL-100, 1968.

Data were taken in a 36-rod Marviken fuel rod bundle having a uniform axial heat flux distribution. This report was second in a series of four on this project.

- no. of data points: 200 sets of data are presented along with 3 plots of the power-to-mass-flux transfer functions
- heat flux profile: uniform axial and radial
- test section configuration: 36-rod test section with prototype reactor spacers (unheated center rod)

  $L_H = 4.4$ m
- range of parameters: p = 50 bars

  $\Delta T_{sub} = 4°C$

  $1470 \leq q \leq 3600$ KW

  $500 \leq G \leq 2000$ Kg/m^2s
- method of data generation: introduction of pseudo-random perturbations and steps in heat input
- test fluid: water

II.26) "Flow Pulsations in the Horizontal Elements of Steam Generators", O.M. Baldina, R.I. Kalinin, R.I. Saburova, Ts. M. Baitina, <u>Teploenergetika</u>, pp. 52-57, 1968.

Flow pulsations in horizontal evaporative tubes were studied under high pressure. The data are poorly presented, and the geometric data is sparse.

- no. of data provided: 1 stability map
- heat flux profile: uniform axial
- test section configuration: 3 bundles of straight horizontal tubes, and horizontal tube coils
- range of parameters: $20 \leq p \leq 240$ atm
  $300 \leq G \leq 2000$ Kg/m^2-sec
  $5 \leq \Delta H_{sub} \leq 100$ Kcal/Kg
  $40 \leq q'' \leq 600 \times 10^3$ Kcal/m^2-hr
- oscillation mode studied: probably density-wave oscillations
- test fluid: water

II.27) "Flow Instability Thresholds in Parallel Heated Channels", G. Masini, G. Possa, F.A. Tacconi, Energia Nucl., 15, 1968.

A heated two-parallel channel circuit operating in the forced convection mode provided data on parallel channel flow instability thresholds. It was noted that the period of the flow oscillations is in most cases proportional to the transit time in the heated elements, indicating density-wave oscillations.

- no. of data points: more than 200 flow instability threshold conditions are provided for various values of pressure, mass flow rate, valve position, and inlet steam quality (subcooling)
- heat flux profile: uniform axial
- test section configuration: two individually heated parallel, vertical annular channels
  inner radius = 1.35cm, outer radius =2.10cm,
  L_H = 300 cm
- range of parameters:
  $10 \leq p \leq 50$ Kg/cm^2
  $133 \leq w \leq 266$ Kg/hr
  $-30 \leq X_{in} \leq 20$ % (steam quality)
  $10.5 \leq q \leq 103.9$ Kw
- oscillation mode studied: density-wave oscillations
- test fluid: water

II.28) "Full Scale Loop Studies of the Hydrodynamic Behavior of BHWR Fuel Elements", O. Nylund, O. Gelius, Z. Rouhani, European Two-Phase Group Meeting, Oslo, June 18-20, 1968.

This paper is a summary of the results obtained from the first three reports of the Frigg Loop Project (FRIGG-1, FRIGG-2, and FRIGG-3). The pressure range of interest in the Marviken reactor was considered (30 to 90 bars). See other reports (FRIGG-1, FRIGG-2, FRIGG-3) for comprehensive data. In this report, 18 transfer function plots (power-to-mass-flux, power-to-exit-void-fraction) and three stability plots (power vs pressure, subcooling, and inlet throttling) are given.

For test parameters, see: FRIGG-1, FRIGG-2, FRIGG-3 reports.

II.29) "Flow Instabilities with a Natural-Circulation Loop", G. DelTin, S. DiFrancesco, C. Merlini, 1968

Natural circulation instability was investigated in a single-channel test section. The pressure range was 1 to 3 atmospheres. It was confirmed that flow oscillations can occur for conditions of outlet subcooling (due to the effect of subcooled voids) and that oscillation periods decreased as the power supplied increased.

- no. of data provided: 5 instability threshold plots showing the effects of subcooling are provided (at three pressures) and 2 plots demonstrating the effect of power level on the oscillation period
- heat flux profile: uniform axial
- test section configuration: single, vertical, central rod heated tube, D_{rod} = 12mm

  D_H = 15mm, L_H = 350mm
- range of parameters:

  $1 \gtrsim p \gtrsim 3$ atm

  $1 \gtrsim q \gtrsim 3.5$ Kw

  $25 \gtrsim \Delta T_{sub} \gtrsim 75$ °C
- oscillation mode studied: density-wave oscillations
- test fluid: water

II.30)*"Frigg Loop Project - Measurements of Hydrodynamic Characteristics, Instability Thresholds, and Burnout Limits for 6-Rod Clusters in Natural and Forced Circulation", O. Nylund, et. al. FRIGG-1, R4-442/RTL-91, 1967.

A Series of Experiments were performed in the 2.5 MW Fröja loop with a 6-rod cluster. This 6-rod assembly simulated the central region of a boiler channel for the Marviken BHWR. The heat flux was radial and axially uniform in this series of runs. This was the first in a series of four reports on the FRIGG Loop Project. The four reports together comprise an excellent basis for testing analytic models of hydrodynamic stability.

- no of data points: 300 data points are provided along with 16 transfer function plots.
- heat flux profile: uniform axial and radial
- test section configuration: 6-rod cluster
  rod OD = 13.8mm, L_H = 4.4m
- range of parameters:
  - $30 \leq p \leq 50$ bars (natural circulation)
  - $p = 50$ bars (forced circulation)
  - $2 \leq \Delta T_{sub} \leq 40$ °C (natural circulation)
  - $6 \leq \Delta T_{sub} \leq 21$ °C (forced circulation)
  - $350 \leq q \leq 800$ Kw (natural circulation)
  - $500 \leq q \leq 800$ Kw (forced circulation)
  - $500 \leq G \leq 2000$ Kg/m^{2}s
- method of data generation: introduction of pseudo-random perturbations and steps in heat input
- test fluid: water

II.31) "Frequency Response of Forced-Flow, Single Tube Boiler", E.A. Krejsa, J.H. Goodykoontz, and G.H. Stevens, NASA-TN-D-5023, 1967.

Hydraulic impedance (pressure-drop vs. flow transfer function) data were taken in a shell and tube heat exchanger test section. Freon-113 was the test fluid and water flowed counter-current to the test fluid.

- no of data points: approximately 275 data points are presented
- heat flux profile: non-uniform axial (water flows counter-currently through heat exchanger - see data in report).
- test section configuration: vertical, upward flow through a water heated shell and tube counter-current heat exchanger

  D_H = 0.315 in (8.0mm)

  L_H = 36 in (0.91m)

  shell I.D. = 0.620 in (15.7mm)
- range of parameters:

  $17.7 \leq p_{inlet} \leq 32.4$ lb/in^2

  $175 \leq w \leq 656$ lb/hr

  $67 \leq T_{inlet} \leq 78°F$ (Freon)

  $117 \leq T_{outlet} \leq 139°F$ (Freon)

  $208 \leq T_{inlet} \leq 250°F$ (Water)

  $191 \leq T_{outlet} \leq 229°F$ (Water)
- oscillation mode studied: density-wave oscillations
- test fluid: Freon-113

II.32**"Experimental Investigation of the Transient Response of the Volumetric Concentration in a Boiling Forced-Flow System", F.W. Staub, N. Zuber, G. Bijwaard, Nuclear Science and Engineering, Vol. 30, pp. 279-295, 1967.

The power input to an electrically heated circular tube was sinusoidally oscillated to obtain data on the transient response of the vapor volumetric concentration. The tube contained Refrigerant-22 in forced upward flow. It was shown that the void distrubance and its propagation up the channel can be predicted by kinematic wave theory.

- no.of data points: three runs, and the corresponding power-to-void frequency response data are given
- heat flux profile: uniform axial
- test section configuration: two parallel tubes; one steel (304SS) and one metallized pyrex

  L_H = 60.6 inches

  D_H = 0.44inches
- range of parameters: $p/p_{crit} = 0.22$ *

  $220 \leq G/10^3 \leq 340$ ($lb_m/hr\text{-}ft^2$)

  $1.1 \leq \Delta T_{sub} \leq 1.6$ (°F)

  $3270 \leq q'' \leq 8400$ ($Btu/hr\text{-}ft^2$)
- test fluid: Freon-22

II.33) "Acoustic Oscillations in a High Pressure Single-Channel Boiling System", A.E. Bergles, P. Goldberg, J.S. Maulbetsch, Proceedings: Symposium on Two-Phase Flow Dynamics, Eindhoven U.,The Netherlands, 1967.

Acoustic oscillatory behavior was noted during an investigation of two-phase flow regimes at high pressures. It was determined that the frequency of oscillations is greater than 35Hz, and induced by the collapse of subcooled voids.

- no. of data points: 2 plots of the frequency characteristics of the oscillations
- heat flux profile: uniform axial
- test section configuration: single tube, vertical upflow with bypass. $0.4 \leq D_H \leq 0.82$ in
  $2 \leq L_H \leq 8$ ft
- range parameters
  $500 \leq p \leq 1000$ psia
  $0.2 \leq G \leq 1.2\ lb_m/ft^2\text{-}hr\ (X10^6)$
  $0.5 \leq q/10^6 \leq 4.5\ Btu/ft^2\text{-}hr$
- oscillation mode studied: acoustic oscillations
- test fluid: water

II.34) "Pressure-Drop" Oscillations in Forced Convection Flow with Boiling, A.H. Stenning, T.N. Veziroglu, G.M. Callahan, Symposium on Two-Phase Flow Dynamics, Eindhoven, Netherlands, Sept. 1967.

Data is taken of the oscillations in a tube filled with Freon-11. It is noted that a negative slope in the heater pressure-drop - flow curve is required for pressure drop oscillations to occur. Very little data was presented.

- no. of data points: 1 plot of limit cycle phenomena in the pressure drop vs. mass flow rate plane
- heat flux profile: uniform axial
- test section configuration: single tube, horizontal orientation, $D_H = 0.1475$ in, $L_H = 37.5$ in
- range of parameters: q = 1170 Btu/hr, w = 2.35 lbm/min
- oscillation mode studied: pressure drop oscillations
- test fluid: Freon-11

II.35) "Two-Phase Flow Oscillations in Vertical, Parallel, Heated Channels", J.D. Crowley, C. Deane, S.W. Gouse, Jr., MIT Summer Course, "Two-Phase Liquid Flow and Heat Transfer", 1968.

A natural and forced convection Freon-113 loop having three parallel vertical uniform axially heated channels, and a large bypass to provide constant pressure drop maintained across the channels, was used in the experiment.

Data are provided on the regions of stable and oscillating flow using the following as parameters: system pressure, subcooling, mass flow rate, and heat flux.

Besides the data, it was determined that the results of one, two, or three test sections in parallel are identical and that changes in channel length that do not effect the heated sections transit time, do not effect the period or amplitude of oscillation, but do effect the stability of the channel.

- no. of data provided: 4 plots are provided for each of five heat fluxes. The four plots are a stability map, period of oscillations vs. subcooling, magnitude of bulk fluid temperature oscillation vs. subcooling.
- heat flux profile: uniform axial
- test section configuration: three parallel, vertical, transparent, heated channels under natural and forced convection with bypass:
  $D_H = 0.430$ in, $L_H = 108$ in
- range of parameters: $10 \le p_{inlet} \le 20$ psig
  $\Delta T_{sub} \le 90°F$
  $w \le 1{,}200\ lb_m/hr$
  $q'' \le 14{,}000\ Btu/ft^2/hr$
- oscillation mode studied: density-wave oscillations
- test fluid: Freon-113

II.36)**"An Experimental Investigation of Boiling Channel Flow Instability", D.F. A'Arcy, AECL-2733, 1967.

A test section composed of three internally heated annular flow channels connected to inlet and outlet plena were used to examine the nature and threshold of flow oscillations. The most common modes of oscillation observed were as follows: if Q_1, Q_2 & Q_3 are the amplitudes of the oscillations in each of three channels(1, 2, 3),and $\underline{Q}_1$, $\underline{Q}_2$, $\underline{Q}_3$ are their respective phase angle, then the modes are: i) $Q_1=Q_2$, $\underline{Q}_1=180°+\underline{Q}_2$, $Q_3=0$

ii) $Q_1=Q_2$, $\underline{Q}_1=\underline{Q}_2$, $Q_3=2Q_1$, $\underline{Q}_3+180°=\underline{Q}_1$

iii) $Q_1=Q_2=Q_3$, $\underline{Q}_1=\underline{Q}_2+120°=\underline{Q}_3+240°$

- no. of data points: 5 basic series of data are shown, along with 5 series of dryout data
- heat flux profile: uniform axial
- test section configuration: annular tube, parallel, vertical, upward flow channels:

  D_H = 0.220 or 0.161 inches

  L_H = 120 or 80 inches
- range of parameters: $15 \leq \Delta T_{sub} \leq 150°F$

  $550 \leq p \leq 1200$ psia

  $w \leq 5{,}000$ lb/hr

  $q' \leq 15$ Kw/ft (for each tube)
- oscillation mode studied: density-wave oscillations
- test fluid: water

II.37)**"BWR Stability Considerations Resulting From Garigliano Research and Development Program", J.A. Hodde, C.L. Howard, R.T. Lahey, R.O. Niemi, Symposium on Two-Phase Flow Dynamics, Eindhoven, Netherlands, Sept. 1967.

This test program provided stability data on a large BWR/1 (SENN) at various operating conditions. It is pointed out in the report that the notion of a specific stability limit for a BWR is not really appropriate. The authors state that BWR systems can be expected to have nonlinearities which make the instability threshold a diffuse item, with increasingly more severe operating conditions during which progressively larger limit cycle oscillations are expected.

Provided are reactivity-to-power transfer functions taken from experiments at Garigliano. Open loop Nyquist diagrams are also provided from the data.

- no. of data points: 7 sets of plant operating parameters provided the transfer function data in the paper
- heat flux profile: non-uniform axial
- test section configuration: a BWR/1 core 81 rods/bundle, positioned vertically, $L_H = 2.76$m
- range of parameters:

  $18.2 \leq \Delta H_{sub} \leq 33.3$ Kcal/Kg

  $p \simeq 69$ atm

  $13.5 \leq q'' \leq 25.8$ W/cm^2

  $260 \leq q \leq 498$ Mw
- method of data generation: sinusoidal oscillation of central control rod
- test fluid: water

II.38) "Dynamic Coupling Experiments Conducted In-Pile Using Adjacent Boiling Channels", T.J. Bjørb, R. Grumbach, V. Tosi, Symp. on Two-Phase Flow Dynamics, Eindhoven, Netherlands, Sept. 1967.

Experiments to determine the degree of coupling between adjacent tubular fuel assemblies in natural circulation in the Halden Boiling Heavy Water Reactor were conducted. Transfer function data were taken, and the absence of coupling was demonstrated.

- no. of data points: 8 transfer function plots are reported
- heat flux profile: non-uniform axial power distribution
- test section configuration: HBWR core (adjacent tubular fuel assemblies in natural circulation)

  $D_H = 8.9 \times 10^{-3}$ m

  $L_H = 1.70$ m
- range of parameters:

  $p = 15$ bar

  $\Delta H_{sub} = 7$ & 11 Kw

  $q = 65$ & 90 Kw
- method of data generation: perturbation of flow in one channel
- test fluid: water

II.39) "Self-Sustained Hydrodynamic Oscillations in a Natural-Circulation Boiling Water Loop", K.C. Jain, M. Petrick, D. Miller, and S.S. Bankoff, Nuclear Engineering and Design, Vol. 4, 1966.

A variable geometry test section using water provided data on flow and pressure oscillations in a natural-circulation system. It was noted that the inception point of oscillations is generally not a clearcut threshold.

- no. of data points: 4 flow oscillation envelopes, 12 plots demonstrating the effects of inlet subcooling
- heat flux profile: uniform axial
- test section configuration: a single vertical tube.

  D_H = 0.8125 inches

  L_H = 96 inches
- range of parameters:

  $199 \leq p \leq 1502$ psia

  $0 \leq \Delta T_{sub} \leq 64$ °F

  $10 \leq q \leq 83$ Kw
- oscillation modes studied: density-wave oscillations
- test fluid: water

II.40)**"Control Rod Oscillator Tests - Garigliano Nuclear Reactor" Parts I & II, R.T. Lahey, Jr., J.A. Hodde, et.al., GEAP-5534, 1967.

This two volume set documents the data taken during control rod oscillator tests performed at the Garigliano BWR/1 in Italy, and provides interpretation and conclusions from that data. In Volume I, the reduced data and Bode plots are given. Seven sets of test conditions were achieved during the experimental sequence.

Since the core is large, spatial effects were readily apparent.

Volume II explains some of the qualitative aspects of the data, and provides the results of the noise analysis performed as part of the experiments.

- no. of data points: 114 pages of transfer functions and 114 pages of raw data, with a table of stability margin results. Note that experiments were performed under forced circulation, natural circulation with one recirculation loop and natrual circulation with two recirculation loops.
- heat flux profile: non-uniform axial distribution
- test section geometry: a BWR/1 core (81 rods/bundle positioned vertically), L_H = 2.76m
- range of parameters:

$965 \leq p \leq 988$ psia

$326 \leq \Delta H_{sub} \leq 56.5$ Btu/lb_m

$2775 \leq w \leq 9719$ MT/hr

$330.8 \leq q \leq 497.6$ Mw

- method of data generation: rod oscillator tests
- test fluid: water

II.41a)"Density-wave Oscillations in Boiling Freon-11 Flow", A.H. Stenning and T.N. Veziroglu, NASA Report NSG-424, #9, 1966.

II.41b)"Flow Oscillation Modes in Forced-Convection Boiling", A.H. Stenning and T.N. Veziroglu, Proceedings of 1965 Heat Transfer and Fluid Mechanics Institute, Stanford University Press, 1965.

Freon-11 in a single-tube forced convection system was used to determine parametric effects on stability. Three instability modes were noted: density-wave, pressure-drop and thermal. The latter (thermal) being related to beyond B.T. phenomena.

Reference (II.41a) presented data while (II.41b) gave only trends.

- no. of data points: 278 tabulated points
- heat flux profile: uniform axial
- test section configuration: single-tube, forced convection:

  $D_H = 0.1475$ in, $L_H = 37.5$ in
- range of parameters:

  $0.2 \leq w \leq 1.7$ lb/min

  $5000 \leq q'' \leq 36{,}000$ Btu/ft^2-hr

  $0 \leq p \leq 60$ psig

  $70 \leq T_{inlet} \leq 140$ °F
- oscillation mode studied: density-wave oscillations
- test fluid: Freon-11

II.42) "Onset of Flow Oscillations in Force-Flow Subcooled Boiling", F.A. Jeglic, T.M. Grace, NASA Technical Note, NASA-TN D-2821, Wash. D.C., May, 1965.

A single-tube boiler was examined under forced-flow conditions. The study of the onset of instability was made over a pressure range of 3 to 100 psia. A model predicting the onset of oscillations was developed, and agreement with data was good.

- no. of data points: 26
- heat flux profile: uniform axial
- test section configuration: a single vertical Inconel-X tube:
  $D_H = 0.29$ inches, $L_H = 21$ inches
- range of parameters:
  $2.2 \leq v_{in} \leq 8.25$ ft/sec
  $3.0 \leq p \leq 40.0$ psia
  $61 \leq T_{in} \leq 183°F$
  $34.1 \leq q'' \leq 201$ Btu/ft^{2}sec
- oscillation mode studied: density-wave oscillations
- test fluid: water

II.43) *"Experimental Measurement of Design Parameter Effects on Void-Power Transfer Function", R.O. Niemi, J.C. Rawlings, GECR-4940, 1965.

Power-to-void transfer functions were measured in high pressure steam/water in an electrically treated test retangular section. The test section power was oscillated sinusoidally and an X-ray machine was used to determine the transient void fraction. It was found that the modulus and phase lag of the transfer fractions were a strong function of inlet subcooling and velocity (and thus void transport time).

- no. of data points: 8 experiments
- heat flux profile: uniform axial
- test section configuration: a single rectangular test section (0.188" X 1.560"), vertical: $A_{x-s} = 0.293\ in^2$, $L_H = 76.2$ inches
- range of parameters:

$$0.32 \leq G/10^5 \leq 0.92 \quad lb_m/hr\text{-}ft^2$$

$$11.0 \leq H_{sub} \leq 37.9 \quad Btu/lb_m$$

$$0.479 \leq q''/10^5 \leq 0.966 \quad Btu/ft^2hr$$

$$p = 1000\ psia$$

- oscillation mode studied: density-wave oscillations
- test fluid: water

II.44) *"Power-To-Void Transfer Functions", H. Christensen, ANL-6385, 1961.

This report gives an excellent discussion of the harmonic excitation experiment which was performed and presents a good compilation of the power-to-void transfer functions taken in an electrically heated rectangular test section containing high pressure steam/water. Both Bode plots and tabular data are given.

- no. of data points: 7 runs
- heat flux profile: uniform axial
- test section configuration: a single rectangular vertical test section (1.11 cm X 4.44 cm), L_H = 127 cm
- range of parameters:

  $76.7 \leq v_{in} \leq 115.2$ cm/sec

  $27 \leq p \leq 68$ atms

  $2.5 \leq \Delta T_{sub} \leq 14.4$ °C

  $47.85 \leq q \leq 111.7$ Kw/liter
- oscillation modes studied: density-wave oscillations
- test fluid: water

II.45) "Effects of Upstream Compressibility on Subcooled Critical Heat Flux", R.S. Daleas and A.E. Bergles, ASME Preprint 65-HT-67, 1965.

This study investigated the effect of the compressibility of upstream volumes of subcooled water on system instability. It was found that Ledenigg-type instability interacted with the compressible volume to cause oscillations which triggered a premature CHF in the heated test section.

- no. of data points: N.A.(not available)
- heat flux profile: uniform axial
- test section configuration: single horizontal tube.

  $0.047 \leq D_H \leq 0.246$ inches,

  $1.22 \leq L_H \leq 6.7$ inches
- range of parameters:

  $1.12 \leq G/10^6 \leq 10.15 \ lb_m/hr\text{-}ft^2$

  $p \leq 30$ psia

  $0 \leq h_{sub} \leq 100 \ Btu/lb_m$

  $1.0 \leq q''/10^6 \leq 10.0 \ Btu/ft^2\text{-}hr$
- oscillation mode studied: pressure-drop instabilities
- test fluid: water

II.46)**"A Study of System-Induced Instabilities in Forced-Convection Flows With Subcooled Boiling", J.S. Maulbetsch and P. Griffith, MIT Report # 5382-35, 1965.

This report documents the details of a subsequent† study concerned with the interaction of upstream compressible volumes with the inherent pressure-drop/flow rate curves of the heated system. The instability modes noted were excursive (ie: Ledenigg) instabilities, which when coupled with system compressibility effects, led to oscillations. Instability modes of this type have become known as "pressure drop" instabilities. Since this study was directed toward understanding instability mechanisms in the cooling system of high density magnets, only small diameter conduits were tested. The onset of instability was deduced from CHF in the test section.

- no. of data points: N.A.
- heat flux profile: uniform axial
- test section configuration: single horizontal tubes

  $0.0465 \leq D_H \leq 0.1805$ inches

  $25 \leq L_H/D_H \leq 250$

- range of parameters:

  $5.0 \leq v_{in} \leq 50$ ft/sec

  $p \leq 80$ psia

  $T_{in} \leq 70°F$

  $0.5 \leq q''/10^6 \leq 5.0$ Btu/hr-ft^2

- oscillation mode studied: pressure drop instabilities
- test fluid: water

†Subsequent to the study in Ref.(II.45)

II.47a) *"Analytical and Experimental Study of the Dynamics of a Single-tube Counterflow Boiler", H. L. Hess, J. R. Hooper, S. E. Organ, Pratt & Whitney / NASA Report, PWA-3175, 1967.

II.47b) *Analytical and Experimental Study of the Dynamics of a Single-tube Counterflow Boiler", H. L. Hess, J. R. Hooper, S. E. Organ, Pratt & Whitney / NASA Report, NASA CR-1230, 1969.

An extensive experimental and analytical program is documented. This program supported the development of a Nuclear Rankine-cycle space power plant (e.g.: SNAP-8). Step charge and sinusodial perturbation experiments were conducted in a horizontal counter-current flow heat exchanger, in which the secondary fluid exited as superheated vapor.

- No. of data points: 21
- Heat flux profile: Nonuniform axial from primary to secondary side
- Test section configuration: two concentric horizontal tubes (secondary fluid in inner tube).

  $D_{H_{(secondary)}} = 0.59$ inches,

  $D_{H_{(primary)}} = 0.201$ inches

  $L_H = 10$ ft.

- Range of parameters:

  $400 \leq w_{primary} \leq 1{,}000.$ lbm/hr

  $35 \leq w_{secondary} \leq 65$ lbm/hr

  $50 \leq p_{secondary} \leq 130$ psia

  $360 \leq T_{in_{(primary)}} \leq 430°F$

  $95 \leq T_{in_{(secondary)}} \leq 185°F$

- Oscillation mode studied: Density-wave oscillations
- Test fluid: water (primary and secondary sides)

I.48) "An Experimental Study of the Limit of Flow Stability in Steam-Generating Tubes Connected in Parallel with Non-Uniform Heating of the Surface", E.P. Serov, O.K. Smirnov and L.A. Zykov, (UDC 532.5.001.5) Teploenergelika, 11, 1964.

This paper presents the data taken in two horizontal heated tubes connected in parallel. The power level on each tube was parametrically varied. The data was displayed in terms of stability maps.

- no.of data points: 33
- heat flux profiles: uniform axial
- test section configuration: two horizontal tubes connected in parallel:

  $D_H = 0.55\text{mm}, \quad L_H = 7.25\text{m}$
- range of parameters:

  $G = 376 \text{ kg/m}^2\text{-sec}$

  $30 \leq p \leq 100$ atms

  $\Delta H_{sub} = 100$ kcal/kg

  $150 \leq q''/10^3 \leq 450 \text{ kcal/m}^2\text{-hr}$

  $q''/10^3 = 100 \text{ kcal/m}^2\text{hr}$
- oscillation modes studied: density-wave and "flow pulsations"
- test fluid: water

II.49 "The Influence of Certain Design Variables on the Hydrodynamic Stability of a Heated Channel- A Digital Computer Code Supported by Experimental Data", M.B. Carver, AECL-2976, 1967.

This paper summarizes some of the data taken in the AECL FLARE experimental program, and compares these data with the AECL POISE code. The FLARE loop consists of three vertical heated annular test sections connected in parallel.

- no. of data points: 6 runs presented
- heat flux profiles: uniform axial
- test section configurations: three vertical annular test sections connected in parallel
  D_H = 0.16 & 0.22 inches, and, L_H = 10ft
- range of parameters:

  $80 \leq G \leq 300\ lb_m/ft^2\text{-sec}$

  $500 \leq p \leq 1100$ psi

  $20 \leq \Delta T_{sub} \leq 125$ °F

  $30 \leq q \leq 106$ Kw
- oscillation modes studied: density-wave oscillations
- test fluid: water

II.50) "An Experimental Study on the Instability Induced by Voiding from a Horizontal Pipe Line", I. Nakajima, A. Kawada, K. Fukuda and T. Kobori, ASME preprint 75-WA/HT-20, 1975.

This paper describes work in support of the Japanese ATR reactor. This reactor has pressure tubes and subsequent to a SCRAM, relys on natural circulation for decay heat removal. Full scale experiments were performed in PNC's 14Mw HTL loop. The data indicated flow regime induced instabilities in the horizontal riser-to-steam-drain piping. The data was presented in graphical form.

- no of data points: N.A.
- heat flux profile: uniform axial, non-uniform radial
- test section configuration: a 28-rod bundle mounted vertically:

  D_{rod} = 16.46mm, D_H = 9.7mm

  L_H = 3.7m, A_{x-s} = 46.85 cm^2

- range of parameters:

  G = N.A. (natural circulation)

  $1.0 \leq p \leq 70$ atms

  $20 \leq \Delta T_{sub} \leq 100°C$

  $1 \leq q''/10^4 \leq 15$ w/m^2

- oscillation modes studied: flow regime induced instabilities
- test fluid: water

II.51) "Two-Phase Flow Instability in Parallel Channels", K. Fukuda and T. Kobori, Paper FB-17, Proceedings of the Sixth International Heat Transfer Conference, 1978.

This paper summarizes full scale data taken in two vertical electrically heated rod bundles connected in parallel in the 14Mw HTL loop at O-aroi. These data indicated that pressure drop instabilities occurred at low (or negative) exit qualities while density-wave oscillations occurred at high exit qualities. All data was taken with the same power on both bundles, and all data trends were presented graphically.

- no. of data points: N.A.
- heat flux profile: uniform axial, non-uniform radial
- test section configuration: two 28-rod bundles connected in parallel:

  D_{rod} = 16.46mm, D_H = 9.7mm

  L_H = 3.7m, A_{x-s} = 46.85 cm^2
- range of parameters:

  $0 \leq w_T \leq 15$ kg/sec

  $0.1 \leq p \leq 7$ Mpa

  $0 \leq \Delta T_{sub} \leq 50$ K

  $0 \leq q \leq 3.2$ Mw (per channel)
- oscillation modes studied: Ledinegg and density-wave oscillations
- test fluid: water

II.52) **"Flow Instabilities in Multi-Channel Boiling Systems", M. Ozawa, S. Nakanishi, S. Ishigai, ASME Preprint 79-WA/HT-55, 1979.

This paper summarizes the results of small scale experiments involving instabilities in one, two and three heated parallel channels. These data indicate that instability in a parallel channel array can be deduced from data on a single channel.

Tubes of two different sizes were tested. The smaller size was used to insure substantial frictional drop, and thus a negative position in the Δp-w curve. All data is presented in graphical form.

- no. of data points: N.A.
- heat flux profile: uniform axial
- test section configuration: vertical electrically heat tubes connected in parallel
  D_H = 6.03mm & 3.58mm, L_H = 2.8m
- range of parameters:

  $w \leq$ 28-38 kg/hr

  $0.2 \leq p \leq 0.4$ Mpa

  $20 \leq \Delta T_{sub} \leq 83$ K

  $0 \leq q \leq 1.8$ Kw (each tube)

II.53) **"A Study on the Hydrodynamic Instability in Boiling Channels (4th Report, Experimental Results)", S. Hayama, Bulletin of JSME, Vol.-10, No.38, 1967.

This paper summarizes the results of a series of experiments conducted with from two to ten parallel boiling channels. These experiments were done for natural circulation in a thermosyphon reboiler configuration. The data showed that both in-phase and out-of-phase oscillations were possible, although as the number of parallel channels increased it was difficult to get all of them to oscillate in-phase. In addition, for conditions of high inlet subcooling and high resistance in the downcomer some of the parallel channels operated in reverse flow.

- no. of data points: N.A.
- heat flux profile: uniform axial
- test section configuration: vertical electrically heated annuli connected in parallel:

  D_{rod} = 12mm, D_H = 10mm, L_H = 320mm
- range of parameters

  w = N.A. (natural circulation)

  p = 1 Atms

  $85 \leq T_{in} \leq 99$ °C

  $0.2 \leq q_{rod} \leq 1.0$ Kw
- oscillation modes studied: density-wave oscillations
- test fluid: water

II.54) "Flow Instability in Boiling Channel Systems", G. Matsui, International Chemical Engineering, Vol. 11, No. 3, 1971.

This paper presents the results of the study of instabilities in a single heated channel and riser for both forced and natural circulation. The inlet resistance was varied to appraise the effect on instability. It was found that in the natrual circulation mode, increased inlet resistance reduced the flow rate and thus destabilized the system. Little data is given but a valuable comparison between the properties of n-pentane (the boiling fluid) and water is presented.

- no. of data points: N.A.
- heat flux profile: uniform axial
- test section configuration: a single vertical glass tube with a Nichrone wire along the centerline.
  $D_{tube} = 22mm$, $L_H = 0.2m$
- rante of parameters: w = N.A.
  p = 1 Atms
  $0 \leq \Delta T_{sub} \leq 15$ °C
  $0 \leq q'' \leq 1500$ kcal/m^3-sec
- oscillation modes studied: flow regime induced instabilities and density-wave oscillations
- test fluid: n-pentane

II.55a)"Instabilities in Parallel Channel of Forced-Convection Boiling Upflow System, (II) - Experimental Results", M. Aritomi, S. Aoki and A. Inoue, (Japanese) Journal of Nuclear Science and Technology, Vol. 14, No.2, 1977.

II.55b)"Instabilities in Parallel Channel of Forced-Convection Upflow System, III - System with Different Flow Conditions Between Two Channels", M. Aritomi, S. Aoki, & A. Inoue, (Japanese) Journal of Nuclear Science and Technology, Vol. 16, No. 5, 1979.

These papers present the results of a study of instability mechanisms in a two parallel channel array. System thermal-hydraulic parameters, heated length and inlet resistance were parametrically varied. It was found that system stability improved when one had different conditions in the two channels. All data is presented in graphical form.

- no. of data points: N.A.
- heat flux profile: uniform axial
- test section configuration: two vertical electrically heated annuli connected in parallel: D_{rod} = 5mm, D_H = 6.8mm, L_H = 0.4m
- range of parameters:

  $0 \leq v_{in} \leq 0.8$ m/sec

  p = 1 atms

  $80 \leq T_{in} \leq 95$°C

  $0.1 \leq q''/10^6 \leq 1.0$ kcal/m^2-hr
- oscillation modes studied: density-wave oscillations
- test fluid: water

II.56) *"An Experimental Study of Natural Circulation in a Loop With Parallel Flow Test Sections",Conference on Two-Phase Flow, University of Exeter, R.P. Mathisen, 1965.

This paper presents the results of an instability study using two parallel tubes connected in parallel. The inlet and outlet resistances were varied parametrically. A ! data is tabulated and plotted.

- no. of data points: 33 runs tabulated
- heat flux profiles: uniform axial
- test section configuration: two vertical heated tubes connected in parallel; D_H = 20mm, L_H = 4.3m
- range of parameters:

$$560 \leq G \leq 1120 \text{ kg/m}^2\text{-sec}$$

$$p = 50 \text{ bars}$$

$$6 \leq \Delta T_{sub} \leq 40°C$$

$$10 \leq q'' \leq 179 \text{ Kw/liter}$$

- oscillation mode studied: density-wave oscillations
- test fluid: water

II.57) "Critical-Heat Flux and Flow - Pattern Observations for Low-Pressure Water Flowing in Tubes", A.E. Bergles, R.F. Lopina and M.P. Fiori, Journal of Heat Transfer, Feb. 1967.

This paper summarizes the results of experiments conducted in single heated tubes. Flow regime and CHF data was taken. The effect of flow regime-induced instability on CHF was discussed. All data was presented in graphical form.

- no. of data points: 200
- heat flux profile: uniform axial
- test section configuration: a single heated tube:

  $D_H = 0.079 - 0.242$ inches

  $L_H/D_H = 15\text{-}200$
- range of parameters:

  $0.2 \leq G/10^6 \leq 2.0\ lb_m/hr\text{-}ft^2$

  $25 \leq p \leq 125$ psia

  $100 \leq T_{in} \leq 200$ °F

  $0.8 \leq q''/10^6 \leq 2.8$
- oscillation modes studied: flow regime induced instabilities
- test fluid: water

II.58) "The Incipience of Flow Oscillations in Forced-Flow Subcooled Boiling", F.A. Jeglic and K.T. Yang, Proceedings of the 1965 Heat and Mass Transfer Institute, 1965.

This paper presents the results of a study of the mechanism of flow oscillations in subcooled boiling. Analysis of the data indicated that the onset of oscillations was related to bubble dynamic phenomena. The data are tabulated and presented in graphical (ie: time trace) form.

- no. of data points: 32 runs
- heat flux profile: uniform axial
- test section configuration: a single vertical heated tube:

  D_H = 0.21 inches

  L_H = 4.0 - 21 inches
- range of parameters:

  $2.2 \leq v_{in} \leq 8.25$ ft/sec

  $3.0 \leq p \leq 100$ psia

  $61 \leq T_{in} \leq 183$ °F

  $34.1 \leq q'' \leq 234$ Btu/ft^2-sec
- oscillation modes studied: boiling induced instabilities
- test fluid: water

II.59) "Flow Instability and Critical Heat Flux in Heater Parallel Channels", J.E. Casterline, D.M. Lee, Columbia University Topical Report (Task XIII of Contract AT (30-3) -187), 1964.

This memo presents the results of an AEC sponsored instability & CHF program in which three parallel vertical heated tubes,were employed. These data indicated the tendency toward instability was greatest at low pressures & mass fluxes and with flow restriction in the two-phase region. All data is tabulated.

- no. of data points: 31 runs
- heat flux profile: uniform axial
- test section configurations: three vertical heated tubes connected in parallel: D_H = 0.5 inches, L_H = 76 inches
- range of parameters:

  $0.75 \leq G/10^6 \leq 2.5$ lb$_m$/hr-ft^2

  $500 \leq p \leq 1500$ psia

  $15 \leq \Delta T_{sub} \leq 195°F$

  $0.25 \leq q''/10^6 \leq 1.0$ Btu/hr-ft^2
- oscillation modes studied: density-wave oscillations
- test fluid: water

II.60) "Measurements of Hydrodynamic Instabilities, Flow Oscillations and, Burnout in a National Circulation Loop", K.M. Becker, R.P. Mathisen, O. Eklind and B. Norman, AB Atom Report No. S-316, 1963.

This report presents data on an investigation into hydrodynamic instabilities in a single vertical heated tube being operated in natural circulation. The data indicated system stability increased at elevated pressures. All data is presented in graphical form.

- no. of data points: N.A.
- heat flux profile: uniform axial
- test section configuration: a single vertical tube:

  D_H = 20mm, L_H = 4.89m
- range of parameters:

  $100 \leq G \leq 1{,}500$ kg/m^2-sec

  $10 \leq p \leq 60$ atms

  $2 \leq \Delta T_{sub} \leq 16$ °C

  $20 \leq q'' \leq 80$ W/cm^2
- oscillation modes studied: density-wave oscillations
- test fluid: water

II.61) "Instabilities in Two-Phase Flow", D.J. Pulling and J.G. Collier, AERE-M 1105, 1963.

This report presents the results of some preliminary experiments on flow instability in two vertical heated tubes. These tubes were enclosed in a steam jacket (where they were heated by condensing steam), and connected in parallel. Both subcooled and two-phase inlet conditions were studied. It was found that two-phase inlet conditions was stabilizing. All data is presented in graphical form.

- no. of data points: N.A.
- heat flux profile. N.A.
- test section configuration: 2 vertical tubes: D_H=1 inch, L_H=8 ft.
- range of parameters:

  $550 \leq w \leq 1{,}100\ lb_m/hr$

  $20 \leq p \leq 50$ psia

  $60°F \leq \Delta T_{sub} - X_{inlet} - 11\%$

  $3.0 \leq q''/10^4 \leq 25\ Btu/hr\text{-}ft^2$

- oscillation modes studied: density-wave oscillations
- test fluid: water

II.62) "Hydraulic Instability in a Natural Circulation Loop with Wet Steam Generation at 1000 PSIA", S. Levy, E.S. Beckjord, ASME, preprint 60-HT-27, 1960.

This paper presents the results of a high pressure hydraulic instability experiment conducted in a vertical single-rod heated annulus.

- no. of data points: 58 points
- heat flux profile: uniform axial
- test section configuration: vertical single-rod annulus

  $D_{ROD} = 0.875$ inch

  $D_H = 0.375\text{-}0.540$ inches

  $L_H = 8.5\text{-}9.0$ ft

- range of parameters:

  $0.495 \leq G/10^6 \leq 0.804\ lb_m/hr\text{-}ft^2$

  $p = 1000$ PSIA

  $8.1 \leq \Delta H_{SUB} \leq 125.5\ Btu/lb_m$

  $207 \leq q''/10^3 \leq 445\ Btu/hr\text{-}ft^2$

- oscillation modes studied: density-wave oscillations
- test fluid: water

II.63) "Further Experimental Results on Natural Circulation Loop Performance at 1000 PSIA under Periodic Accelerations", E.P. Quinn, GEAI-3397 Addendum, 1960.

This report documents the results of a marine application study into the effect of ship's motion on system stability and CHF. A vertical single-rod annulus was rocked at period from 1.5 to 6.5 seconds and accelerations as high as 2g. It was found that CHF was not decreased by ship's motion and that natural circulation instability threshold could be increased. All data is presented in tabular form.

- no. of data points: 110 runs
- heat flux profile: uniform axial
- test section configuration: a single vertical heated annulus.

  $D_{ROD} = 0.375 - 0.438$ inches

  $D_H = 0.081 - 0.112$ inches

  $L_H = 23\text{-}33$ inches
- range of parameters;

  $0.36 \leq v_{IN} \leq 2.4$ ft/sec

  $p = 1000$ PSIA

  $55 \leq \Delta H_{SUB} \leq 235$ Btu/lb$_m$

  $107 \leq q''/10^3 \leq 470$ Btu/hr-ft^2
- oscillation modes studied: density-wave oscillations
- test fluid: water

II.64) "Pressure Oscillations Induced by Forced Convection Heating of Dense Hydrogen", R.S. Thuston and J.D. Rogers, Cryogenic Engineering Conference, CONF-660605-4, Bolder, Col., 1966.

This paper presents the results of a study of cryogenic instability mechanisms which may occur during horizontal flow. The data indicated that thermal-acoustic oscillations can occur. All data is presented in graphical form.

- no. of data points: N.A.
- heat flux profile: uniform axial
- test section configuration: a single horizontal heat tube.

  D_H = 0.25 inches, L_H = 10 feet
- range of parameters:

  $0.0022 \leq w \leq 0.0537$ lb_m/sec

  $112 \leq p \leq 265$ psia

  $45 \leq T_{IN} \leq 63$ R

  $1.44 \leq q \leq 56.5$ Kw
- oscillation modes studied: acoustic, flow regime induced (ie: Helmholtz instability induced wave formation in stratified flow) and probable density-wave oscillations
- test fluid: Hydrogen

II.65) "Flow Oscillations in Two-Phase Flow, Their Characteristics and Effects on Burnout", D. Barmann, D. Hein, F. Mayinger, O. Schad and E. Weiss, Proceedings of Symposium of Two-Phase Flow Dynamics, Eindhoven, Paper 3.2, 1967.

This paper is concerned with the effect of flow instability on CHF. The data taken indicated a coupling effect. Only limited data was presented.

- no. of data points: N.A.
- heat flux profile: uniform axial
- test section configuration: vertical heated tubes.

  D_H = 7-15mm, L_H/D_H = 10-80
- range of parameters:

  $50 \leq G \leq 400$ gm/cm^2-sec

  $1 \leq p \leq 100$ atms

  T_{IN} = N.A.

  $100 \leq q'' \leq 1{,}100$ Watts/cm^2
- oscillation modes studied: pressure drop and density-wave oscillations
- test fluid: water

II.66) *"An Experimental and Theoretical Study of Density-Wave Oscillations in Two-Phase Flow", G. Yadigaroglu, A.E. Bergles, MIT Report Number DSR 74629-3, 1969.

This excellent report presents the Ph.D. thesis of G. Yadigaroglu. The data he took was concerned with density-wave oscillations in a three vertical channel array, in which electrically conducting (coated) glass tubes were used. Uniform and nonuniform axial data was taken. These data indicated that a cosine axial heat flux profile was more stable than a uniform profile.

Higher-order (ie: higher frequency) instability modes were observed in these experiments. All data is tabulated and plotted.

- No. of data points: 21 runs
- Heat flux profile: uniform, cosine and "rooftop"
- Test section configuration: 3 three vertical electrically heated (glass) tubes

  D_H = 0.430 inches

  L_H = 13 inches
- Range of parameters: $0.5 \leq v_{in} \leq 10$ ft/s

  $95 \leq T_{in} \leq 115$°F

  $4,700 \leq q'' \leq 14,100$ Btu/h-ft^2

  p = Atmospheric
- Oscillation modes studied: density-wave oscillations
- Test fluid: Freon-113

TABLE I

Classification of Flow Instabilities

Class	Type	Mechanism	Characteristics
1. Static instabilities			
1.1 Fundamental (or pure) static instabilities	1. Flow excursion or Ledinegg instability	$\left.\frac{\partial \Delta p}{\partial G}\right\|_{system} < \left.\frac{\partial \Delta p}{\partial G}\right\|_{ext}$	Flow undergoes a sudden, large amplitude excursion to a new, stable operating condition
	2. Boiling transition	Ineffective removal of heat from heated surface	Wall temperature excursion and flow oscillation
1.2 Flow regime instability	1. Flow pattern transition instability	Bubbly flow has higher Δp than that of slug flow for the same void fraction	Cyclic flow pattern transitions and flow rate variations
	2. Flow regime induced instability	Periodic Δp in slug flow regime	Possible excitation of system at slug flow frequency
1.3 Thermal relaxation instability	1. Bumping, geysering, or chugging	Periodic adjustment of metastable condition, usually due to lack of nucleation sites	Periodic process of superheat and violent evaporation with possible expulsion and refilling
2. Dynamic instabilities			
2.1 Fundamental (or pure) dynamic instabilities	1. Acoustic oscillations	Resonance of pressure waves	High frequencies (10-100 Hz) related to time required for pressure wave propagation in system
	2. Density-wave oscillations	Delay and feedback effects in relationship between flow rate, density, and pressure	Low frequencies ($\sim$1Hz) related to transit time of a continuity wave
	3. Condensation induced instabilities	Condensation driven instabilities	Large impulsive ("water hammer") loads may result

TABLE I (cont'd)

Classification of flow instability

Class	Type	Mechanism	Characteristics
2.2 Compound dynamic instabilities	1. Thermal oscillations	Interaction of variable heat transfer coefficient with flow dynamics	Occurs in film boiling
	2. Nuclear-coupled instability	Interaction of void reactivity coupling with flow dynamics and heat transfer	Strong only for a small fuel time constant and at low pressures
	3. Parallel-channel instability	Interaction among small number of parallel channels	Various modes of flow redistribution
2.3 Compound dynamic instability as secondary phenomena	1. Pressure drop oscillations	Flow excursion initiates dynamic interaction between channel and compressible volume	Very low frequency periodic process (~0.1 Hz)
3. Nonlinear effects	1. Subcritical instabilities	Nonlinear interaction reinforces nearby instability	Sufficiently large disturbance destabilizes linearly stable flow
	2. Supercritical instabilities	Nonlinear interaction limits growth	Limit cycles
4. Multidimensional effects	1. Wave-induced instabilities	Two-dimensional disturbances interacting	Waves of particle motion sweep apparatus (fluidized beds)
	2. Plenum voidage instabilities	Three-dimensional disturbances interacting	Regions of high void form and propagate
	3. Subchannel instabilities	Transverse Δp fluctuation induces periodic transverse flow fluctuations	Subchannel-to-subchannel instability

TABLE I (cont'd)

Classification of flow instability

Class	Type	Mechanism	Characteristics
5. Transient effects	1. Superimposed instability (during system transients)	Changing flow conditions excite instability	Coast-down with superimposed oscillations
	2. Oscillatory (loop) flow	Imposed oscillation triggers or delays existing instability mode	Oscillations grow

TABLE II

SUMMARY OF RECOMMENDED WORK

TYPES OF INSTABILITIES	MODELLING NEEDS	ANALYSIS NEEDS	EXPERIMENTAL NEEDS
(1) Density-Wave Oscillations	• Description of Nonlinear Limit Cycle and Finite Amplitude (Sub-critical) Phenomena • Non-equilibrium Laws: · Thermal-Interfacial Mass and Energy Transfer · Mechanical-Interfacial Momentum Transfer • More Detailled Void-Reactivity Feedback Models	• Finite Amplitude (Non-linear) Stability Maps are Needed • A Compilation of World's Data (in non-dimensional form) and a comparison of selected data with state-of-the-art analytical models • Analysis of Superimposed Instability During System Transients	• Data on Limit Cylcle Phenomena • Data on the Individual Transfer Functions in Linear Analysis • Data on Superimposed Instability During Transients
(2) Pressure Drop Instabilities	• Generalize Models for Δp Instabilities	• Generalization of Effect of Compressible Volumes • Generalized Stability Maps	• Data on the Effect of Location and Composition of Compressible Volumes

TABLE II (cont'd)

TYPES OF INSTABILITIES	MODELLING NEEDS	ANALYSIS NEEDS	EXPERIMENTAL NEEDS
(3) Heat Transfer Controlled Instabilities		• BWR Parallel Channel Effects	• Interfacial Area Density Measurements • Instability Data on Various Heat Exchangers (e.g. Regenerators)
• Condensation-Induced Instabilities	• Interfacial Heat Transfer Model (Steam/Water Mixing) • Realistic "Water Hammer" Models		• Systematic "Water Hammer" Type Data • Well Controlled Wall Nucleation Data on Chugging, Bumping & Gysering • Data on Transient Wall Heat Transfer to Fluid (eg: Rewet)
• Boiling-Induced Instabilities	• Global Nucleation and Rewet Models • Transient Wall Heat Transfer Laws	• LWR Reflood Oscillations	

TABLE II (cont'd.)

TYPES OF INSTABILITIES	MODELLING NEEDS	ANALYSIS NEEDS	EXPERIMENTAL NEEDS
(4) Flow Regime Induced Instabilities • Flow Regime Excitation • Flow Regime Relaxation	• Instability Threshold and Forcing Function • The Interaction Between Flow Regime Induced and Density-Wave Modes	• Generalized Instability Maps Needed	• Flow Regime Excitation and Relaxation Data on Instability Threshold
(5) Multidimensional Effects	• "Subchannel-to-Subchannel" Instabilities	• Instability Analyses (Using Existing Subchannel Techniques)	• Rod Bundle Instability Data
(6) Acoustic Driven Instabilities	• Sonic Velocity in Two-Phase Flow • Generalized Mechanistic Models • The Interaction Between Acoustic, Pressure Drop and Density-Wave Models	• Appraisal of Instability Thresholds	• Data on Acoustic Driven Instability in Various Geometries

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16. ABSTRACT *(200 words or less)*

The purpose of this Topical Report is to present the results of an extensive literature survey on instability modes of relevance to LWR technology. The current understanding of relevant thermal-hydraulic and nuclear-coupled instability modes is summarized and specific recommendations are made for future work.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

LWR Instability
- Density-Wave Oscillations
- Flow Excursion
- Limit Cycle Phenomena

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT

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