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SOME THERMAL-HYDRAULIC CONSIDERATIONS IN THE CALCULATIONS OF LOADS IN A PRESSURIZED WATER REACTOR CONTAINMENT DURING A LOCA OR MSLB

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SOME THERMAL-HYDRAULIC CONSIDERATIONS IN THE CALCULATION OF LOADS IN A PRESSURIZED WATER REACTOR CONTAINMENT DURING A LOCA OR MSLB

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- *encouraging harmonisation of governments' regulatory policies and practices in the nuclear field, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;*
- *keeping under review the technical and economic characteristics of nuclear power growth and of the nuclear fuel cycle, and assessing demand and supply for the different phases of the nuclear fuel cycle and the potential future contribution of nuclear power to overall energy demand;*
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In these and related tasks, NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded a Co-operation Agreement, as well as with other international organisations in the nuclear field.

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1. INTRODUCTION

A nuclear reactor containment structure with its ancillary systems is the last line of defence before fission products become a possible general public hazard. Whilst it is designed to handle some well defined situations it is also expected to cope with the unforeseen and unexpected.

Nuclear reactor plants are designed with automatic protection systems and engineered safety features so that the reactor and steam raising plant should be kept in a safe condition and no damage should arise from:-

(i) normal operational transients, and

(ii) faults or transients which can be expected to occur during a reactor lifetime.

For less frequent events, but which nevertheless may occur during one generation of a nuclear power programme (typically 100 reactors for 30 years) there would be limited plant damage, but the off-site release of fission products would be controlled with a negligible health hazard to the public.

Events which come within the above categories or conditions are known as design basis accidents, since the safety and protective systems are designed to safeguard the public in the event that one of these accidents occurs. In practice, designers select certain limiting events against which the safety systems are designed and their performance analysed. They then aim to show that all other events within the design basis envelope will have less serious consequences than the selected limiting events.

As an illustration of this, safety studies on PWR's in the United States of America have identified the double-ended guillotine break of a reactor main coolant pipe as a limiting event. Federal regulations lay down the assumptions to be made and the criteria to be met in the evaluation of this event(1). In other studies, a main steam line break (MLSB) inside the containment has been shown to give rise to pressure loads as high, if not higher, than the primary circuit loss of coolant accident (LOCA). Even where a secondary side steamline break does not give the highest pressure, it will generally lead to higher containment temperatures. Such studies define the loadings, pressure and thermal, for the reactor containment structure. These loads originate from the following sources:-

- stored energy from the primary coolant system and from associated components of the secondary system (steam generator)
- nuclear transient energy from the core
- decay heat released from the core
- chemical reaction energy (eg, hydrogen combustion)
- energy from jets and missiles generated within the containment.

Full pressure containment systems are internally subdivided by structures according to the layout of the primary coolant system and the other necessary associated auxiliary equipment to operate reactors safely. This demands careful considerations with respect to the design of the containment system under all accident situations anticipated within the DBA-philosophy. It has to remain leaktight when all the energy has been released and the internal structure must be capable of withstanding the dynamic loading process during the energy release without serious damage. Some important equipment within the containment must still be operable after the accident demanding a knowledge of the post-accident conditions within the containment in terms of pressure and temperatures.

Except for a situation involving a steam line break inside the containment boundary, the containment structure is only loaded as a consequence of a loss of primary coolant. For such accident sequences the emergency core cooling systems have to continue to operate and reject the fission product decay heat from the core to the earth's atmosphere or other "infinite" heat sink. This generally involves recirculation of water from a containment sump through the reactor core. This water is, in turn, kept cool by a secondary cooling circuit, rejecting heat through the containment boundary to the outside world. In order to minimise the effect of any fission products released from the fuel during the course of the accident, wash down sprays are often installed inside the containment structure. These serve several purposes, but principally they ensure the containment atmosphere is kept cool and local over-heating of structure or equipment, due to deposited fission products, does not occur.

This review is concerned with the fluid dynamic and heat transfer effects that need to be studied in order to predict the pressure loads acting on a reactor containment and its internal components. The discussion is confined to problems associated with the full pressure dry containment concept for the pressurized water reactor (PWR). The additional problems associated with pressure suppression, eg, the water pool for a boiling water reactor (BWR) or an ice bed for a PWR, are not covered.

Whilst the main emphasis of this review is on the design basis situations, the same thermal-hydraulic considerations will apply to beyond design basis situations (the Class 9 accidents). Such situations arise if the emergency core cooling systems fail to function on demand and can lead to core damage and fuel melting. The probability of such situations arising is, of course, extremely small. Heat transfer and fluid flow conditions in the containment, whilst generally similar, do need to take into consideration aspects such as large scale generation of hydrogen from metal or fuel reactions with water and the possibility of rapid energy additions if a flammable atmosphere is obtained, and the possibility of sudden generation of large quantities of steam if molten material drops into a water pool.

Hydrogen generation and its distribution are outside the terms of reference of this study. So also is any discussion of rates of steam generation due to the quenching of hot debris, which is regarded as input data, mass and energy additions, to the appropriate containment volume. Also outside the terms of reference are consideration of material and hardware problems of the design and construction of a full pressure containment.

2. METHODS FOR THE DETERMINATION OF DESIGN LOADS

The basic tools for the determination of the design loads for a containment are computer codes describing various physical aspects of the accident involving fluid dynamics, heat conduction and heat transfer, structure-dynamics and to a certain extent chemical engineering (fission product behaviour). Various types of computer codes are available with different degrees of sophistication and experimental verification. These codes serve as the primary tool to determine local design requirements and structural dimensions before the containment can be built. A certain number of calculations have to be performed to cover the necessary spectrum of parameters such as size and location of anticipated breaks, primary system conditions, envisaged subdivision of the containment and associated flowpaths etc. The results of these calculations finally determine an envelope of loads for all important components of the structure serving as basis to fix the structural design. Normally a margin will be allowed between the computed loading and the value taken for structural design purposes, which reflects the confidence of designers and licencing authorities in the computer code calculations used to bound conditions in a containment volume.

Furthermore codes also must predict, to a certain extent, the post-accident pressures and temperatures within the containment to determine the conditions under which safety equipment (measurement devices, motors, valves etc.) must be operated reliably to prevent unfavourable consequences of accidents. Long-term behaviour of the containment system is therefore the second important predictive aspect expected from computer codes.

Several computer codes have been developed in various countries to describe the thermo-fluid dynamic phenomena involved in containment pressurization and to serve as a tool for the design of the containment system. In general, these codes are based on a lumped parameter concept averaging relevant thermo- and fluid-dynamic parameters for a prescribed arrangement of control volumes. One code concept - the BEACON-code(2) - attempts to solve a six-equation system as partial differential equations in order to more closely approach the physical reality of spatial distribution of governing parameters also taking into account nonequilibrium processes between involved phases and components. A list of codes (Table 1) applied by the participants of the second International Containment Standard Problems(3) gives an indication of the considerable number of available codes.

It should be noted that development of the BEACON code has now been stopped by the USNRC. The code COBRA originally developed for fast reactor studies is now being developed for LWR applications.

The lumped-parameter codes are used for the determination of local and time dependent distribution of pressure and temperature within full pressure containment systems after a loss-of-coolant-accident of a water cooled power reactor. Most of these codes may be used to compute short term (eg, formation of local pressure differences) as well as long term processes.

Common features of these codes are

- Subdivision of the net free volume of a containment into a suitable number of arbitrary control volumes, (generally one per sub-compartment)
- Thermodynamic equilibrium between phases and components (air/steam) within a particular control volume (this general characteristic feature is mostly corrected by empirical correlations, assumptions or constants to compensate for the heterogeneous nature of low-pressure two-phase flow).
- Mass- and energy-exchange between connected control volumes is either described by quasi-steady flow through idealized orifices as compressible, homogeneous two-phase/two-component flow or by non-steady-state one-dimensional momentum flow with friction and formloss-coefficients. In both cases empirical assumptions are required with regard to water droplet transportation (or slip between phases)
- Most codes take into account heat exchange between the fluid and solid structures
- Mass- and energy-release into the containment at the location of an anticipated failure is to be provided from primary system analysis (mostly as input to the containment codes).

Clearly, this kind of a treatment of the fluid dynamic problem includes several sources for inaccuracies and uncertainties and requires a considerable experience in using such codes. To warrant a safe design of the containment so-called "conservative assumptions" have to be made to influence calculated results into an overemphasising direction. It should be noted that the "conservative assumptions" used to bound the pressure loads on the containment structure do not necessarily bound the temperature effects. This is particularly true for small components, other heat transfer assumptions will generally be required to determine suitable equipment qualification conditions.

On the other hand the utilisation of "advanced codes" - like BEACON, which has been written to describe the complex processes of transient two-phase flow in a more detailed manner - is presently hampered by a considerable lack of knowledge about interfacial relationships universally applicable to two-phase/two-component flows. Furthermore such codes would also require better constitutive relationships describing in detail the interaction of confining structures with the fluid (eg, heat transfer between structures and each phase, or wall friction attributed to each phase).

Therefore in most countries the design of nuclear reactor containment systems is in fact based on the result of lumped parameter codes. A suitable choice of correlations, assumptions and constants offered to the user of these codes is of utmost importance to achieve an adequate treatment of the complex two-phase flow phenomena. An appropriate nodalisation of a system is of equal importance for the description of the fluid dynamics as for the description of the heat conduction processes within structures. The main thermal/hydraulic problems associated with the full pressure dry containment concept are

- modelling of flow resistances within a subcompartmented containment
- modelling of water deposition and carryover in containment calculations (nonequilibrium effects)
- treatment of "Heat Soakage" into structures (short term and long term considerations)
- appropriate nodalisation concepts and available numerical solution schemes.

The first three areas, covering the "physics" of the situation, will be discussed in more detail within the following section.

The problems of nodalisation will be briefly referred to in the treatment of heat soakage. This report does not deal with the problems of devising numerical solution schemes for computer codes.

3. IMPORTANT PHYSICAL PHENOMENA DETERMINING FLUID-DYNAMIC CODE CALCULATIONS

3.1 MODELLING OF FLOW RESISTANCES IN CONTAINMENT CALCULATIONS

Generally a reactor containment will consist of a series of interconnected volumes. Some volumes will contain parts of the primary circuit, other volumes contain necessary auxiliary equipment. A primary circuit breach in one sub-compartment will induce flows into adjoining volumes. The pressure differences induced by these flows will be dependent on the area of the openings available and the geometry of the opening which controls the effective flow area and loss pattern.

3.1.1 Single Phase Conditions

For single phase flow, a large body of experimental data with some backing theoretical analysis exists to give guidance on the choice of effective flow areas and flow resistance coefficients for steady state flow. In many countries codes of practice for flow measuring devices give relevant information and loss coefficients for many typical piping components may be obtained from handbooks, eg, Idelcik(4). For highly transient flow conditions, flow resistance coefficients may temporarily exceed the stationary values and this could lead to higher pressures in the upstream compartment. However no empirical data for evaluating resistance coefficients in transient flow exist.

Factors which have a major influence on the flow losses include the radius of the entry edge, the length to diameter ratio and changes in cross-sectional area of the passage involved. In normal flow conditions, a fluid separates from the passage wall when it passes round a sharp corner, with a low velocity eddy filling the space between the main flow lines and the wall. For flow from a large compartment into a vent of smaller cross section this formation of a reduced flow area is referred to as a "vena contracta". Because of the reduced effective flow area, local flow velocities are increased and the corresponding flow losses are also increased. Prediction of loss coefficients is therefore very dependent on the prediction of the size of the vena contracta. The extensive work on sharp-edge orifice flow measuring devices indicates that very close control has to be exercised on the size of the entry radius if the ideal vena contracta coefficient, of the order 0.6, is to be realised. For example, an entry radius of the order 3% of the opening radius increases the vena contracta coefficient to about 0.64. For an opening of about 1m diameter, an edge radius of 15 mm will have this effect.

After the vena contracta, viscous forces cause the flow streamline to diverge. If the flow is constrained within a passage then contact with the wall will be re-established. For circular pipes of constant cross sectional area, this occurs in the range $0.3 < L/D < 0.5$. Where discharge from the opening is into another large cross-sectional volume, whether or not flow contact has been re-established before the end of the communicating passage has an important influence on the flow losses, as discharge loss is proportional to the square of the exit velocity.

Similar effects are introduced by area changes along a communicating passage. Provided the angle of divergence is reasonably small, less than 10° - 15° included angle, the flow velocity at exit will be reduced, and lower overall losses will ensue as the kinetic energy wasted in the larger cross-section of the exit compartment is reduced.

Whilst it is important when analysing experimental tests to use the best possible representation of the flow passages to show that agreement of experimental and computed results is for the right reasons, in reactor safety calculations the assumption of a sharp-edged opening is "conservative" where the emphasis is on the peak pressure in the compartment where coolant discharge is taking place. Another aspect related to the full scale situation is that openings may be simple holes in concrete walls. During a loss of coolant accident blowdown situation, the edges of such a hole may get eroded by the fluid flow, changing the effective flow area. Whilst this effect will tend to increase the effective flow area and hence reduce the flow losses check calculations may need to be carried out to examine all the implications on the safety argument.

Because large pressure differences may be generated at early times in an accident, a further factor that may need to be taken into account is the effect of compressibility on the vena contracta. Measurements(5) for high speed flow indicate that the sharp-edged orifice coefficient will change from 0.6 to a maximum of 0.83 at down stream/upstream pressure ratio of 0.4. This pressure ratio is somewhat smaller than the conventional "choking" or Mach one ratio of 0.52 for air flows.

3.1.2 Two Component Two Phase Conditions

With two-phase flow, additional factors will influence the flow distribution and hence the pressure losses. One effect is slip between the phases, this will be exhibited as a velocity difference between the liquid and vapour phase both in magnitude and direction in the three-dimensional flow situations approaching vent openings. The importance of this effect depends on the flow regime and the size of liquid drops. In a two phase flow, the liquid drops will not turn corners so readily, so more of the dense phase appears in the middle of the flow channel than otherwise might be expected. Also during the general acceleration into a vent passage, the vapour phase responds faster so that its flow velocity nearly always exceeds that of the liquid phase. This fact should be acknowledged in the flow equations used to calculate mass flow and pressure loss between compartments.

A second effect that may be important is the evaporation of further liquid as the local pressure falls when the flow is accelerated into a vent passage. As the size of entrained droplets will be controlled by the differential flow velocity (ie, the "slip" velocity) and evaporation rate is surface area dependent, the rate of additional vapour formation will not follow simple geometric scaling laws. Assumptions suitable for the analysis of small scale experiments may not be relevant to a full size PWR containment conditions.

A third effect, which can be of importance in connecting passages a few diameters long, is that subsonic two-phase flows do not diverge so quickly after a vena-contracta region as a single phase flow. The angle of expansion is dependent on the flow quality and the point of re-attachment of the flow to the wall will change during a blowdown sequence. Depending on the containment layout, this effect may have to be allowed for in pressure loss calculations.

The addition of permanent gases to the flow considerations makes for some additional complexity. The gas will change the local void fractions and hence has an influence on the slip ratio. Depending on whether an assumption of thermal equilibrium is being made or not, it may be convenient to regard the gas as simply additional vapour or the vapour as additional gas.

Ideally, a computer code handling two- if not three-dimensional flows is needed to calculate these conditions. The major problem of such a code is that, even if the numerical difficulties were overcome, detailed information on the form and the magnitude of the inter-phase transfer of mass, momentum and energy are not known. It is only possible at this moment in time to speculate on the form of these relationships and to try various ideas to see if they produce sensible trends.

3.1.3 Containment Calculations for Safety Studies

A simplified approach has to be adopted particularly for safety studies. Development of elaborate computer codes, such as BEACON(2) to describe all aspects of two-component, two-phase flow have not been successful so far and even for the analysis of experimental work simplified assumptions have to be used to allow calculations to be carried out in a reasonable time.

In most cases the flow configuration between containment subcompartments may be approximated by an orifice of a suitable diameter. Generally, a frozen flow assumption is then used. In this situation the flow quality, allowing for the presence of permanent gases and liquid separation effects in the upstream compartment, is assessed and no further evaporation of the liquid is allowed to occur during the passage of the mixture through the hole. The kinetic energy of the flow is then assumed to be lose in mixing in the downstream compartment and thermal equilibrium attained. This type of approach has been shown to be adequate for the analysis of small scale experimental tests(3,6). Whilst there is every reason to believe the simple approach will be adequate for an analysis of a full sized PWR containment, additional confidence would be obtained if tests were performed on a larger containment structure.

3.1.4 Conclusions

Computer codes used for reactor safety calculations only treat flow resistances in a relatively crude way. In general, analysis of experimental work on quarter linear scale models(3,6) has shown that the approximations used are reasonable, and whilst they can be expected to apply to full sized containments it is currently unproven.

There is a need for data from much larger scale containment systems, backed by separate effects tests to develop a better understanding of the inter-play of various factors which may be important in calculating scaling factors and give increased confidence that the current approach is acceptable.

3.2 WATER DEPOSITION AND CARRYOVER IN CONTAINMENT CALCULATIONS

In reality water deposition and re-entrainment is a complex phenomena which is geometry and flow regime dependent. To try and compute what is happening in detail during a LOCA which is pressurizing the containment volume is extremely time consuming and subject to many uncertainties. Simplified calculation models have to be used to reduce the task to manageable proportions and the limitations introduced by this process need to be assessed.

3.2.1 The Physical Problem

In the general situation, a two-phase, two component flow (that is liquid, vapour, and permanent gas) enters a subcompartment of the containment through a vent or door-way, flows round the equipment present and goes out through another vent to the adjoining subcompartment. The liquid in the incoming flow will probably not be homogeneously distributed, in that a liquid film may have formed on the wall of the first compartment and is being dragged in by viscous shear forces around the edges of the opening, whilst the main flow will contain droplets of various sizes. As this mixture enters the larger cross-section of the compartment, the flow velocity will decrease and larger liquid droplets will sink under gravity forces to be deposited on horizontal surfaces. Other droplets will impact on vertical surfaces, particularly the surfaces of equipment in that compartment. Only the small droplets of low inertia, which can follow the general air flow lines, escape from capture by direct impact. Naturally, unless the compartment is particularly full of equipment, some water droplets will traverse the compartment unimpeded and continue into the next volume.

In addition, because the compartment walls and possibly the equipment surfaces are cold compared to the incoming flow, heat transfer effects (described in the next section) will cool and condense some of the vapour content of the flow. The variations in the vapour concentration will induce a diffusion flow to the walls which can carry some droplets with it. The condensation process will, of course, add liquid to walls which then runs down to the floor of the compartment.

Depending on the way the compartment is shaped the liquid which accumulates on the floor may build up to such an extent that it may run through to an adjoining compartment. This might be forward to the next compartment in line with the flow direction or could be backwards in a counter flow direction. Another possibility is that liquid can accumulate in a region where the flow velocity is increasing, eg, near a vent or opening to another compartment, and the increased viscous forces may then whip up waves on the liquid surface which break up and water is re-entrained into the general fluid flow.

It is this complex situation that should ideally be described and calculated in the containment volume during the blowdown phase of the loss of coolant accident. Attempts to describe events in detail have been made, eg, the US code BEACON(2). However code development has now ceased as it was too demanding of computer time and many of the inter-phase transfer relationships were only arbitrary functions as detailed knowledge was lacking. Other studies of local phenomena have been made(7) in a rather inconclusive manner.

3.2.2 Containment Calculations for Safety Studies

A simplified approach has to be adopted in practical safety calculations. In general, the assumption of homogeneous subcompartment conditions is made as the basis of the calculation. This means that all the detail of the flow and temperature distribution inside the compartment is ignored, and an arbitrary multiplying factor introduced to cover the influence of liquid carryover fraction. Various definitions have been used for the carryover factor in computer codes. In some cases it is simply the fraction of the total liquid mass currently in a subcompartment. In other cases it has been expressed as a function of local void fraction or quality. In either case the correct dependence on local flow velocity will be lost.

Because the mechanisms involved are surface area, flow and droplet size dependent, scale model tests of containment structures cannot correctly reproduce all the relevant non-dimensional limitations. Care is needed, therefore, in the interpretation of small scale work when the results are being applied to larger sized systems.

In order to overcome some of the limitations of the homogeneous assumption, and to avoid the optimistic bias that this assumption can introduce at some times in the blowdown phase of a containment calculation, computer codes generally allow liquid to be separated out into a separate sump. If this option is being used, the way water carryover fraction is being computed in the particular code needs to be studied in detail to ensure incompatible conditions do not arise.

In general, it is possible to bias containment pressure calculations in the required direction by a choice of water carryover fraction. But this bias must be born in mind if any other aspect of water distribution, such as the time for a containment sump to fill, needs to be studied.

3.2.3 Liquid Drain-back to a sump

The total amount of water inside a typical PWR containment is limited. In extreme situations, if none of the pumped systems start to run, the water content is limited to that contained in the primary circuit, the emergency coolant accumulators and the hold-up in the secondary side of the steam generators. In many circumstances the secondary side interface remains intact and the available water is limited to just the primary circuit and accumulators. High and low pressure injection pumps will normally draw from a water store outside the containment boundary during the early stages of an accident and will considerably enhance the total water content of the reactor containment if they operate properly. At later stages in an accident sequence valves have to be operated to change the emergency pump suction arrangements to draw water from an internal containment sump and the total mass of water is then fixed.

The way water is held up in various subcompartments in a containment is important in determining whether there is sufficient water in the sump when the emergency pumps are switched to suck from it. This determines whether there is long term cooling capability for the reactor core and containment.

It is necessary to develop relationships for the thickness of water film running down walls and internal equipment, to study the drainage runs from one compartment to another and to determine how long it takes liquid to return to the containment sumps etc. Computer codes currently used for containment pressurization studies do not include the capability of studying this problem. It is normal to do separate studies of the water run-back to ensure suitable conditions exist at all times at entry to suction lines of all the emergency system pumps.

3.2.4 Conclusions

In general, a bias to give an overestimate of containment pressure can be introduced in the simple codes used for safety studies, but its magnitude is unquantified. When calculations are required for other aspects, eg, water accumulation in individual rooms, drain back to a containment sump, then the assumptions must be looked at critically and parameter sensitivity studies carried out to avoid bias in an unwanted direction.

There is a need for data from much larger scale containment experiments, backed by separate effects tests to study the local details of the flow. Such tests and the development of analytical methods will then give a better understanding of scaling factors.

3.3 FACTORS INFLUENCING "HEAT SOAKAGE" INTO STRUCTURES

Under accident situations in a containment six aspects have to be combined in the calculation of heat flows to and from structures either in or forming the containment boundary. These are:-

(a) Surface area involved;

(b) Underlying material providing the heat sink or source;

(c) presence of a surface thermal barrier, eg, paint or anti-corrosion treatment;

(d) condensation film resistance when surface is a heat sink;

(e) local boundary layer conditions controlling vapour diffusion to condensate layer;

(f) general conditions in a compartment, turbulence, non-homogeneous conditions, presence of water jets and droplets, etc.

The relative importance of each of these aspects will change depending on the accident sequence and the time elapse. Each item is discussed in more detail in the following sub-sections.

3.3.1 Available Surface Area

In the early stages of a reactor system containment design there will be considerable uncertainty in assessment of the surface areas which could be involved in heat soakage effects. In general, the main structure will be known reasonably accurately; although there may be some uncertainty in the extent of sub-dividing walls forming individual compartments. Much depends on whether a standardized design is being used. The major uncertainty will be in the available surface area of such items as stairways, handrails, ventilation ducting, unlagged piping, equipment boxes and other bare metal items. These items provide a readily available heat sink and can have a considerable influence on the total heat extracted from the containment atmosphere in the short term. Depending on which particular aspect of the safety argument is under consideration it will be necessary to bias the area to obtain upper and lower bounds to the heat removed. Upper and lower estimates of the heat removed may easily differ by factors of three or more.

When the nuclear system has been built, a complete inventory of all items inside the containment should be made, listing the surface finish as well as surface area and material involved, so that the uncertainty may be minimised.

3.3.2 Modelling of Underlying Materials

Transient heat conduction into a solid slab is well understood and standard methods for numerical modelling of the process exist. The main requirement is for the code user to understand the limitations of the solution methods built into a particular code and their relevance to his particular problem.

The postulated accident sequence will influence the time periods when the containment pressure or internal compartment pressure differences are at their maximum values. The treatment of heat slabs needs to be different in different accident sequences if adequate accuracy is to be maintained without using excessive computer time. A large break LOCA will give maximum pressure differences between compartments on the time scale of seconds and a peak in the containment pressure in a few 10s of seconds. A second pressure peak may also occur towards the end of the reflood period, say between 100 and 200s. Correct modelling of the early heat flow into the surface layers of the structure is important, particularly if the aim is to obtain satisfactory comparisons with experimental work. A proper evaluation of the heat diffusion depth is required if metal masses of different thickness are to be lumped together in the interests of fast computing. The value for thermally affected mass may need to be different for structural integrity calculations than for ECCS performance calculations. Thirdly, there is the longer term heat soakage effects, with time scales ranging from hours to days or even months. In these circumstances the whole mass of the structure is involved and different approximations may be desirable to avoid excessive computational time with "pseudo steady state" conditions.

In general it can be stated that, when modelling a structure by dividing the thickness into a series of heat slabs linked by the appropriate thermal resistances, the heat flow into or out of the structure will always be over-estimated. The inaccuracy will depend on the speed of the transient, ie, the imposed rate of change of surface temperature, and the thermal diffusivity of the material in question which controls the depth of penetration of the temperature wave in a given time lapse. Table 2 lists the relevant properties of materials of interest in containment studies and indicates the depth to which a temperature wave will have penetrated in a given time. It can be seen that transient heat effects are important in concrete for many hours, whilst for metallic components, the initial transient effects are lost after the first few minutes of the accident. One other point to note regarding concrete structures, is that the influence of reinforcing steel on the temperature pattern will be felt in the time span of 10-60 secs. and may need to be allowed for in heavily reinforced structures.

Where the input to a computer program allows a variation in the thickness of the subdivisions to be used in the description of a solid structure, then a fine mesh for the surface layers with a coarse mesh for the bulk of the material, or better still a graded mesh through the thickness of the material, can give better accuracy without involving excessive computing time.

These considerations are of greater importance for heavy concrete than for thin metal structures, where the faster themal response and thinner sections involved, limit the inaccuracies in the calculation of the transient response after the first few seconds. Where the temperature wave has only penetrated one mesh space, it is possible for the calculated heat removed from the containment atmosphere to be in error by factors of 3 or more. It is only when the temperature wave is described by four or more mesh points that inaccuracies in the numerical methods become more reasonable and errors in the heat absorbed reduced below 50%. The magnitude of potential errors may be assessed for some situations, eg, step or ramp changes of surface temperature, by comparison with analytical results, eg, Carslaw & Jaeger(8). This aspect has been very successfully studied in a CSNI Containment Numerical Benchmark Problem(9).

Where stresses induced by the presence of a temperature gradient are believed to be important, then an adequate number of mesh points must be used to give a proper description of the progress of the temperature wave into the material. With a concrete structure, it may be necessary to allow for the presence of reinforcing steel under the surface layers, particularly if a localised heat load such as given by impact of a jet of hot water exists, and the radial spread of thermal effects is of concern.

3.3.3 Surface Coatings

Generally the surface of the majority of structural components and items of equipment have a protective coating to prevent corrosion in normal use, to aid in cleaning up after accidental spillage of contaminants, or to improve appearances. Typically these coatings are of paint or a plastic film with a low thermal conductivity compared to the underlying material. This thermal resistance can significantly change the heat soakage, particularly in the early stages of transient heating. Whilst there is some uncertainty in the value of thermal conductivity of such substances, the dominant uncertainty is in the thickness of the layer involved. Particularly where paint is used, factors of two or three may easily be involved in the thickness of paint on the parts of a structure, due to variations in the ease of application and accessibility, or in different workers being involved in painting different parts of the structure. Also over the life of a reactor installation, repainting of containment walls, etc., will take place and an appropriate allowance for this aspect is again subject to factors of two or three in uncertainty. Generally calculations using upper and lower bounds for thickness estimates will have to be performed to demonstrate whether the presence of paint, etc., is a significant factor in pressure or thermal stress calculations.

Where concrete is concerned, the influence on the heat flow may be less marked than for metals, as thermal conductivity values are generally of the same order of magnitude as paint and plastics. However, it is still necessary to check the influence on short term heat transfer before it can be concluded that it is unnecessary to allow for the effect in a numerical calculation.

The non-dimensional group which indicates the importance of a surface film is the Biot number (= h.b/k where b = ½ thickness and k the thermal conductivity of the underlying structural material, h the surface heat transfer coefficient). As the Biot number tends to infinity in the absence of a surface film 1/Bi = m is normally used, so m = 0 is the limit condition. Typically values for "h" for paint films will lie in the range 5000 - 2000 w/m^2k.

Table 3, based on data from McAdams(10) shows the general effect of a surface resistance due to a paint film, and has been based on the low end of the recommended range for the value of "h".

Despite the low value of 'm' for a typical situation with concrete, the influence of the paint film will be important in the short term (first 5 secs.) because of the limited penetration of the temperature wave. For metallic materials, generally the surface coating controls the heat flow at all times and a single point average temperature in the metal soon gives adequate accuracy. Care might still be needed in an experimental analysis when dealing with the short term heat flows during the first few seconds.

3.3.4 Condensate Layer

Whether or not the thermal resistance of a layer of liquid on the wall surface has an important influence on the rate of heat soakage is impossible to decide without careful study of a given problem, as conditions in a reactor containment vary so widely both in space and time.

In general, one can say that in compartments remote from the primary circuit breach little or no water is present in the short term so the effect is not present. Later on, the thermal lags induced by either the underlying material, if of concrete, or the surface finish on metal, are sufficient to dominate the heat flows. Hence condensate layers can be neglected.

In the compartment where the discharge is occurring, in the short term the thickness of the liquid layer can be an important influence. Its effect will be different when considering the floor, walls, and ceiling surfaces and ideally should be accounted for individually, particularly when assessing experimental evidence. Reactor safety calculations can obviously be biased to be conservative for a particular accident situation by a suitable choice of average values, if speed of calculation is important, as in parameter sensitivity studies.

Ideally for a roof surface a study should be made of the stability of a liquid film on the surface. The tendency for drops to form and fall off needs to be known, so that an average film thickness can be assessed. Similarly for vertical surfaces, the average thickness depends on how the liquid runs down the walls. Whilst some information exists for steady state situations in these circumstances(11) it is not known whether the information would be relevant to a highly transient situation. One aspect which needs to be accounted for in rapid transients is the thermal capacity of the water film. When the containment atmospheric pressure and temperature are rising the water film acts as a temporary heat sink. When temperatures start to fall, water films will release their stored heat.

In addition to the liquid formed from steam condensation there will be additional water droplets impacting the walls and floor of containment compartments. These arise from the fact that expansion of the reactor primary coolant will leave 60 - 65% of the water in the liquid phase. Depending on the initial event and the compartment concerned this liquid fraction may outweight the condensate formed.

Where simplified calculations, using one representative temperature for the condensate layer, are being performed it is necessary to check whether the condensate is being subcooled in some regions. Subcooling the liquid does not result in the containment pressure being reduced. This effect is an obvious violation of the simple homogeneous assumption used in most computer codes and will result in too low an estimate of containment temperature and pressure.

Typical heat transfer coefficients for water film on vertical surfaces in the absence of a non-condensible gas lie in the range 10,000 - 30,000 w/m^2k(11). Values for upward heat flow into a horizontal surface are likely to be lower may be by an order of magnitude as the water film cannot drain away so effectively. Generally, the surface coating and condensate layer are important at the same time.

3.3.5 Vapour Diffusion and Condensation

As soon as a release of primary circuit water occurs, the problem is one of simultaneous heat and mass transfer with condensation. Instead of the water vapour being freely available at the cold surface and the condensate film being the controlling factor, the vapour has to diffuse through the non-condensible gas to reach the cold surfaces and counter diffusion of the air reduces the rate of heat transfer by orders of magnitude. The theory of similarity shows that mass and heat transfer are related and that if the flow pattern in the compartment is known, eg, natural or forced convection conditions, an estimate of the condensation rate can be made(12).

A review of condensation heat transfer was carried out by Slaughterbeck(13) and forms the basis for the US NRC requirements(14). A more recent review of available data and the development of a simplified analytical model has been carried out by Whitley(15).

For simple flow situations, the theory of similarity(12) gives acceptable agreement with the limited data from controlled experiments carried out by Uchida(16). Fig 1 shows that as soon as the mass ratio of air/steam is greater than 2 the condensation effect is quite small and heat transfer coefficients are of the same order as those for gas alone (50 - 100 w/m^2k). Heat transfer coefficients of the order 500 - 1000 w/m^2k apply when the mass ratio is below 1. Higher values can occur locally in regions where the blowdown phenomena induce large turbulence or strip a small compartment of air. It is the wide variation of heat transfer with flow conditions that introduces the major uncertainty in reactor accident studies as the flow conditions can cover a very wide spectrum. For example, during blowdown of the primary circuit, particularly with a large break situation, the turbulence generated will greatly enhance heat transfer. This is allowed for in the US NRC regulations by the use of the Tagumi correlation in codes such as CONTEMPT(17). As the turbulence dies down after the end of blowdown, a different recipe has to be used and the Uchida correlation has been accepted by the USNRC for most purposes. It has, however, been recently pointed out(18) that the Uchida correlation is inappropriate for MSLB situations when superheated steam conditions arise and also that the correlation does have some forced convection component built into it, hence overestimates heat transfer coefficients for pure natural convection conditions. In primary circuit LOCA situations this does not normally matter, but it can be important in the MSLB accident calculations.

There will always be a problem of the most appropriate way to represent a spatial variation of heat transfer coefficient in a large containment volume by the single value needed in the simplified lumped volume code approach.

Similarly flow distribution effects are a dominant factor in the variation and uncertainty of local heat transfer rates in experimental work. The availability of better data for specific flow situations could help to limit the range of uncertainty. But it will be difficult to ensure all flow patterns which might develop under transient blowdown can be adequately covered except for a few very well defined situations. The correct representation of the first few seconds of a transient, particularly in an experimental test, can be of major importance in obtaining good comparisons between code calculations and experimental measurements.

3.3.6 General Conditions in a Compartment

To a great extent conditions in a compartment cannot be separated from the considerations of the local boundary layers which are controlling condensation. However, it is easier to appreciate the factors involved if, at least initially, this separation is imagined to be possible.

The factors and effects which may be important will change according to the time elapse and the compartment under consideration. If a large discharge is taking place in a relatively confined space, the issuing jet will rapidly mix with the air. Jet impact on the walls will rapidly ensure wetting of all surfaces. Also, assuming an adequate vent area to an adjoining compartment to prevent excessive pressure differentials building up, the reactor coolant discharge will rapidly sweep the majority of air out of the first compartment. All these factors combine to give very high local heat transfer conditions in the first compartment, although there could still be significant non-uniformity of heat transfer coefficients, depending on the direction of the jet discharge in relation to the vent apertures. The jet discharging straight through a vent would be a particular situation needing separate treatment.

In other compartments more remote from the discharging reactor coolant, conditions could be less uniform. A low velocity discharge into a large compartment can give rise to non-homogeneous conditions leading to stratification if the vents are high in the walls and the density differences appropriate. The circulation induced by the discharge plays a dominant part in controlling convection patterns and hence the boundary layer thickness which, in turn, controls the heat transfer and condensation rate to the compartment walls.

If water sprays are used, they will also influence the convection pattern present in that compartment and the change in wall heat transfer needs to be assessed in addition to the direct effect of the spray water on the heat balance.

When the heat balance for a compartment is being considered in order to evaluate the compartment pressure the uniformity of the temperature of the contents is of importance. Non-uniformity can arise from a number of causes. Incomplete mixing of the flow of water/steam with the air in a compartment can lead to large temperature differences, but generally, because of the low heat capacity of the air, little difference to the computed pressures. More important is whether water discharge at different times in a blowdown sequence mixes to give a uniform temperature in equilibrium with the steam/air mixture. Temperature stratification can lead to an increase in pressure of the order 10%. Most containment codes have a facility to extract water from a compartment and place it in a sump volume to deal with this effect. Currently the problem of over-cooling the water running down a wall referred to in subsection 3.3.4 is not allowed for in computer code calculations. The magnitude of this effect may need to be assessed if pressure reduction due to significant condensation is an important aspect in a safety argument.

When a containment spray first starts operating it is likely that the water used will be colder than the compartment temperature. Ideally, information on the rate of heat transfer to a droplet cloud should be used if available to assess the heat pick-up. The assumption of instantaneous thermal equilibrium may bias calculations in an unwanted direction.

To calculate the effect of operation of the containment coolers to assist pressure reduction demands information on the performance of a multiple bank of water cooled tubes when condensing from a vapour/gas mixture. In general this can only be obtained experimentally as the mean effective temperature of the coolant varies with the flow conditions on both sides of the system.

3.3.7 Conclusions

Six aspects have to be taken into account in the calculation of heat flow from the containment atmosphere into structures or equipment. The importance of some of these aspects varies during the course of an accident and on the accident sequence under consideration.

(1) Surface area available:- Very uncertain at early stages of a new design study. Need for accurate tabulation of final plant as built. Factors of three or greater in uncertainty applying directly to preliminary heat loss calculation.

(2) Underlying material:- Major uncertainty arising from inappropriate use of a numerical method in a computer code. Code users must be aware of the limitations of particular methods. Care needed in early stages of a transient when large temperature gradients exist. Factors of two or three in the heat flow estimate possible by wrong choice of input data and methods.

(3) Surface coatings:- Major uncertainty arises from a lack of detailed knowledge of coating thickness. This is dependent on materials used and on how many times repainting takes place during the life of the plant.

(4) Condensation film resistance:- Uncertainties in estimating thickness in different situations, but unlikely to dominate any situation.

(5) Condensation Rate:- Very sensitive to presence of air in compartment. Relationships exist which allow value to be obtained if flow conditions known.

(6) General conditions in a compartment:- Non-homogeneous effects can be important in influencing condensation rate and possible thermal stresses in structures.

4. CONCLUDING REMARKS

A survey of the current state of knowledge of thermal-hydraulic effects which help to determine the loads imposed on a PWR containment structure has been made. The physical situations that can exist in the containment during a loss of coolant accident have been described and simplifications needed to allow safety calculations to be carried out have been outlined.

Generally there is a choice between rapid approximate calculations with a bias or more detailed specific studies of particular accident sequences which can take a long time to compute. As is usually the case, far more care over detail is necessary when making comparisons between code calculations and experimental work to ensure that the real reason for discrepancies is properly understood.

The physical situations involved in two-component two-phase flow through connecting passages are reasonably well understood but a description of the detail of the phenomena cannot be included in present day computer codes because of a lack of knowledge of interphase transfer relationships. A simplistic approach has to be used, combined with a sensitivity study.

Factors affecting water separation are not well defined or understood. This effect can only be treated in a very simplistic manner in current computer codes and sensitivity studies are normally carried out to ensure that any adverse combination of effects is being adequately recognised.

Most heat transfer aspects can be adequately described and computed if the flow regime is known. The flow regime is break position and accident sequence specific, so care is needed in defining input data for calculations. Some uncertainty arises from the applications of steady state data to transient conditions. Data on transient two-component condensation will help to limit the uncertainties in the interpretation of containment experiments, but it is unlikely to significantly change the assessment of containment in reactor safety studies.

Experimental data from large scale containment tests and from suitable separate effects tests are needed to give a better understanding of scale effects, and to allow the margins of conservatism to be assessed in present day safety calculations. In all cases code users must thoroughly understand the limitations of the solution methods built into a computer code to avoid introducing calculational errors that may not be readily apparent.

Apart from uncertainties introduced by scale effects the standard problems completed to date under the auspices of the CSNI indicate that an adequate understanding of containment thermal-hydraulics exists at this time. In general, the bias introduced by various simplifying assumptions is adequately understood, although it is difficult to quantify its magnitude. The general aspects that need to be described in computer codes to give more accurate representations of particular pressure time histories can be written down, but it is not obvious that the increased cost of computing will result in any saving of containment construction costs.

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Country (Organization)	Contributor	Computer Code
Australia (AAEC)	P G Holland J Marshall	ZOCO V
Belgium (Tractionel)	E J Stubbe	TRAP-SCO TRAP-CON
Canada (AECL-EC)	W M Collins	PRESCON-2
Finland (VTT)	E Pekkarinen	RELAP/MOD6 CONTEMPT-LT/026
France (CEA/EDF)	A Sonnet A Mattei/ F Herber	GRUYER
F R Germany (GRS)	W Erdmann M Tiltmann	COFLOW CONDRU
Italy (CNEN/Pisa Univ)	R Romanacci/ F Cassano A M Gorlandi M Marchi M Mazzini F Orialo	ARIANNA-0 CONTEMPT-LT-26
Italy (NIRA)	B Chiantere R Monti A Pennase	PACO
Japan (JAERI)	K Namatame I Takeshita Y Kukita	RELAP4/MOD5
Netherlands (ECN)	J P A Van den Bogaard A Woudstra	ZOCO-V/MOD
Sweden (Studsvik)	J E Marklund	COPTA-6
United Kingdom (UKAEA, AEEW)	W H L Porter	CLAPTRAP II CLAPTRAP I
United States (USNRC/EG&G)	S Fabic/ C R Broadus	BEACON/MOD3

TABLE 1: Containment Codes

TABLE 2

Thermal Properties and Temperature Wave Penetrations Depths for Typical Materials Found in Reactor Containments

	Concrete	Steel		Aluminium	Copper	Plastic or Paint
		M/S	S/S			
Density (ρ) (kg/m^3)	2300	7800	7800	2720	8800)	1.6 10^6 (J/m^3)
Specific Heat (Cp) (J/Kg.K)	890	480	510	860	400)	
Conductivity (k) (w/m.k.)	1.5	50	15	236	403	0.3
Thermal Diffusivity (α) (m^2/s)	7.33 10^{-7}	1.34 10^{-5}	3.76 10^{-6}	1.01 10^{-4}	1.15 10^{-4}	2. 10^{-7}
Depth of Penetration of Temperature Wave (mm)						
Lapse Time 1 sec	3	15	8	40	43	2
10 sec	11	46	25	128	136	
1 min	27	113	60			
1 hr	206	878	466			
Typical half thickness encountered (mm)	250	10	2 → 10	1	1	0.5

TABLE 3

Approximate Effect of Surface Resistance on the Time for a Given Change in the Average Temp of a Slab

m	0	0.05	0.2	0.5	1	2
rel. time req						
Tave = 0.9 ΔTchange	1	1.1	1.5	2.3	3.6	6.4
Tave = 0.2 ΔTchange	1	1.5	2.7	5.0	9.3	17.7

Approximate m for a "thick" coat of paint (0.5 mm) on various materials

	Concrete	M.S.	S.S.		Al	Cu
typical ½ thickness (mm)	250	10	2	10	1	1
m	.001	.85	1.25/.25		40	67

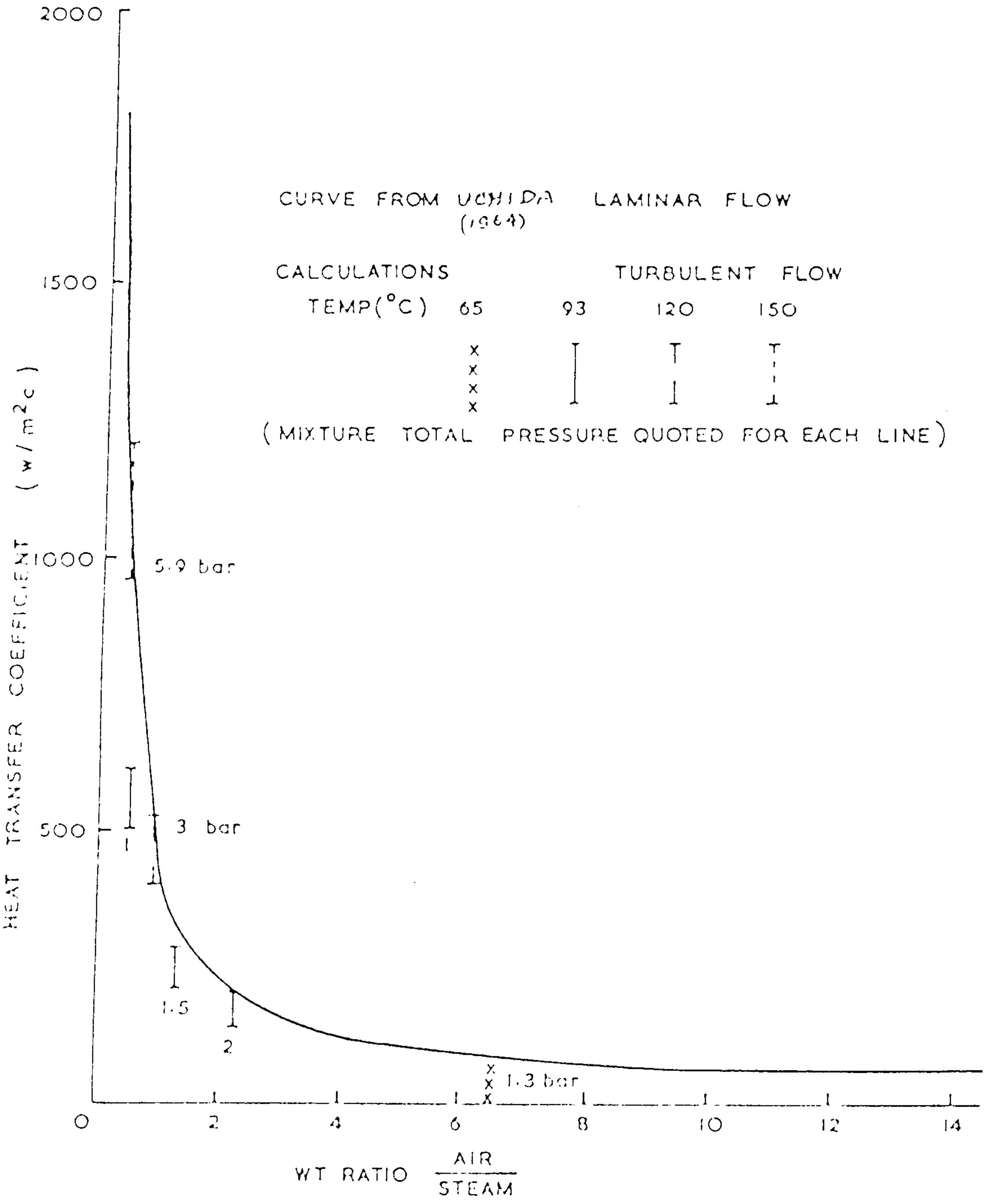

FIG. 1 HEAT TRANSFER WITH CONDENSATION FROM STEAM-AIR MIXTURES, VERTICAL SURFACES