# SELECTION OF TRANSIENT ANALYSIS SOFTWARE FOR PIPELINE DESIGN: TOWARDS A EUROPEAN STANDARD

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**ABSTRACT**

Studies of European and world standards have shown that those for pipeline design address the question of transient behaviour at best briefly, and in some cases not at all. Many of these standards originate from times when computer analysis was not commonplace in the design process, and none of them lay down guidance for the use of such tools.

The present paper describes part of the work currently in progress with the financial support of the European Commission to draw up guidelines for a future standard in this area. The main purpose of this work is to incorporate procedures for the consideration of pressure surges and other transient phenomena in a future pipeline design standard. These will use true maximum loads to select the appropriate components, rather than a notional factor of the mean operating pressure. This will lead to safer designs with less over-design, guaranteeing better system control and allowing unconventional solutions such as the omission of expensive protection devices. It will also reveal potential problems in the operation of the system at the design stage, at a much lower cost than during commissioning.

This paper presents two aspects of the evaluation of transient analysis software for use in pipeline design. It describes a "Classification Procedure" which will grade the suitability of a software package for the analysis of a variety of different types and configurations of pipeline system. It describes a method of benchmark testing against a set of known test cases, which verify the numerical accuracy of the software in analysing the various types of system. The emphasis of the paper is on a standardised method of qualifying and verifying pipe flow analysis software for use in pipe system design; it does not seek to discuss specific details of that design process.

Finally, the paper looks forward to the possible adoption of this standardised design procedure and its potential for improving the safe design and operation of industrial pipe systems.

**Key-words**: transient analysis, pipeline systems, hydraulic software classification

## 1- INTRODUCTION

Today, computer analyses are commonplace in the design process, but this is not governed by existing pipeline design standards (Ref.1). Hence, it is necessary to develop methods of qualifying transient analysis software, in order to ensure its suitability for transient hydraulic analysis of specific types of pressurised pipeline systems.

Methods of pipeline design, the prediction of surge and the selection of protection equipment are addressed in depth elsewhere (Refs. 2-7) and need not be elaborated here. It is not the purpose of this paper to deal with detailed considerations of design. It intends to present proposals for a method of qualifying software for conformity to the requirements of a proposed standard. This standard would formalise the choice of design method according to the nature of the planned pipeline system, but would allow the use of any software, provided it conformed to the acceptance procedure for the type of analysis required. Thus, the parties involved in the design remain free to choose the best available software for the application, while still adhering to the standard, provided that software passes the qualifying process for the intended application.

The purpose of work discussed in this paper is to develop methods of qualifying transient analysis software for use in the design process and to devise guidelines for when such analysis is necessary for water and wastewater systems. The work divides into two main tasks – the classification of software against certain criteria of suitability and the benchmark testing of that software against test data.

Initially it is necessary to define the basic constituent parts of an analysis scheme that will represent different components of the system. The modelling sophistication needed for the analysis capabilities depends on the types of event and phenomena encountered in a particular system. These factors depend upon the type and importance of the system, its characteristic and the stage the design has reached. The main factors to be defined in each project are:

- Definition of the most likely constraints imposed by different operational conditions
- Verification of correct safety levels
- Specification of operation rules to support system automation.

## 2- CLASSIFICATION PROCEDURE

Independent of the characteristics of each system, the steps involved in developing a classification procedure include the following:

- Categorise pressurised conduits into a limited number of clearly defined types;
- Identify events to be analysed and phenomena present in each type of system;
- Grade different levels of modelling detail by the class of analysis accuracy required;
- Identify essential components for each system type, analysis requirement and class of accuracy;
- Devise guidelines relating components and modelling techniques to type of system, event to be analysed and phenomena present;
- Define expected and permitted variances in results for each class of analysis accuracy.

Thus, a prototype structure for the classification procedure was developed, based on the set of models and analysis techniques needed in each case. The classification will be influenced by the modelling sophistication of the analysis capabilities required for different systems (potable or not), different types of event (pump trip, valve closure, turbine stoppage) and different phenomena (vapour and air release, trapped air, etc.).

Three levels of software capability are proposed, to meet different requirements:

- ***Class A*** – Final design by competent engineers.
- ***Class B*** – General design by experienced specialists in transient analysis and outline design or design optimisation by engineers.
- ***Class C*** – Preliminary design and assessment for tender.

It is not envisaged that one design organisation will have different software for each stage, because this leads to additional costs in transferring the models between software packages. However, there may be cases where an organisation is only involved in a limited part of the design process, and can therefore benefit from the simplicity of less sophisticated software. The multi-level approach also allows the use in accordance with the standard of some software that it would preclude, if it always demanded a comprehensive capability. Also, a single organisation may choose to use limited features of a software program at the early stages in order to obtain a rapid approximation or to accelerate the optimisation cycle. More advanced models in the same software would then be used, as required by the standard, at the final stage of design.

The level of accuracy and modelling requirements for each class were chosen from considerations that, if lower standards are set, then more present-day software will be graded as Class A, but this does not anticipate future developments. If higher standards are set, today's software will achieve few Class A grades, but it will extend the life of the proposed standard many years into the future. The original intention was to extend the requirements of the Classification Procedure to include stipulations of methods of solution (method of characteristics for pipes, solution optimisations schemes, etc.). This would create complexity in the classification process, and limit the use of the procedure to those conversant with all the intricacies introduced. It would have prevented anyone except the software authors and vendors from performing the qualifying process. The project partners therefore agreed to restrict the Classification Procedure to listing components and their models in general terms. The partners judged that the effects of solution methods would be covered by the Benchmarking Procedure also proposed as part of the qualifying process, and described later in this paper.

In order to define classes of software according to the level of modelling sophistication achieved, a common table (Table 1) to any System Type has been devised, listing the different models required to characterise each hydraulic variable, depending on the accuracy of software applied (i.e. Class). To classify a software package for a given System Type, the user may work through the common table, then through the appropriate table for that System Type, filling in the tick boxes for all the models which that software has. If all the tick boxes in one column, A, B or C for both tables are filled, then the software meets that classification and any lower ones for the System Type. Thus, if column A is filled the software meets all three Classes, and if column B is filled it meets both Class B and Class C.

**Table 1 – A general classification requirements for software**

| Components of each system | Type of model development | Class of software |
|---|---|---|
| **Pipes, accessories, boundaries and equipment** | **Description of modelling requirement for each class**<br>**Requirement for Class A**<br>**Requirement for Class B**<br>**Requirement for Class C** | **A B C**<br>☐<br>☐<br>☐ |

The software may have additional or alternative capabilities. For instance, a package may have multiple models for each component, but only if it has the most complete model will it qualify for Class A. It will be graded as Class B if it does not have this complete model, but does have a reasonable approximation model. In either case it meets the requirements for lower Classes than the highest for which it qualifies, so those boxes should also be ticked. If the software then fails the higher Class on other counts, it still may satisfy the lower Class or Classes.

The aim of this classification is to make the procedure as comprehensive as possible, so that it can be used to classify any appropriate software package in relation to the widest possible range of pressure pipeline systems. This will show whether it can be applied in practice to fit specific systems to the defined system types and to identify the class of use for a particular software package to perform various analyses.

### 3- CLASSIFICATION BY SYSTEM TYPE

The Classification Procedure will be applied to a software program separately for each of the types of water and waste water pipeline, in the design of which the software is to be used. Having considered a range of options, the project team decided on a simple approach, using five basic configurations, of which Figure 1 gives examples:

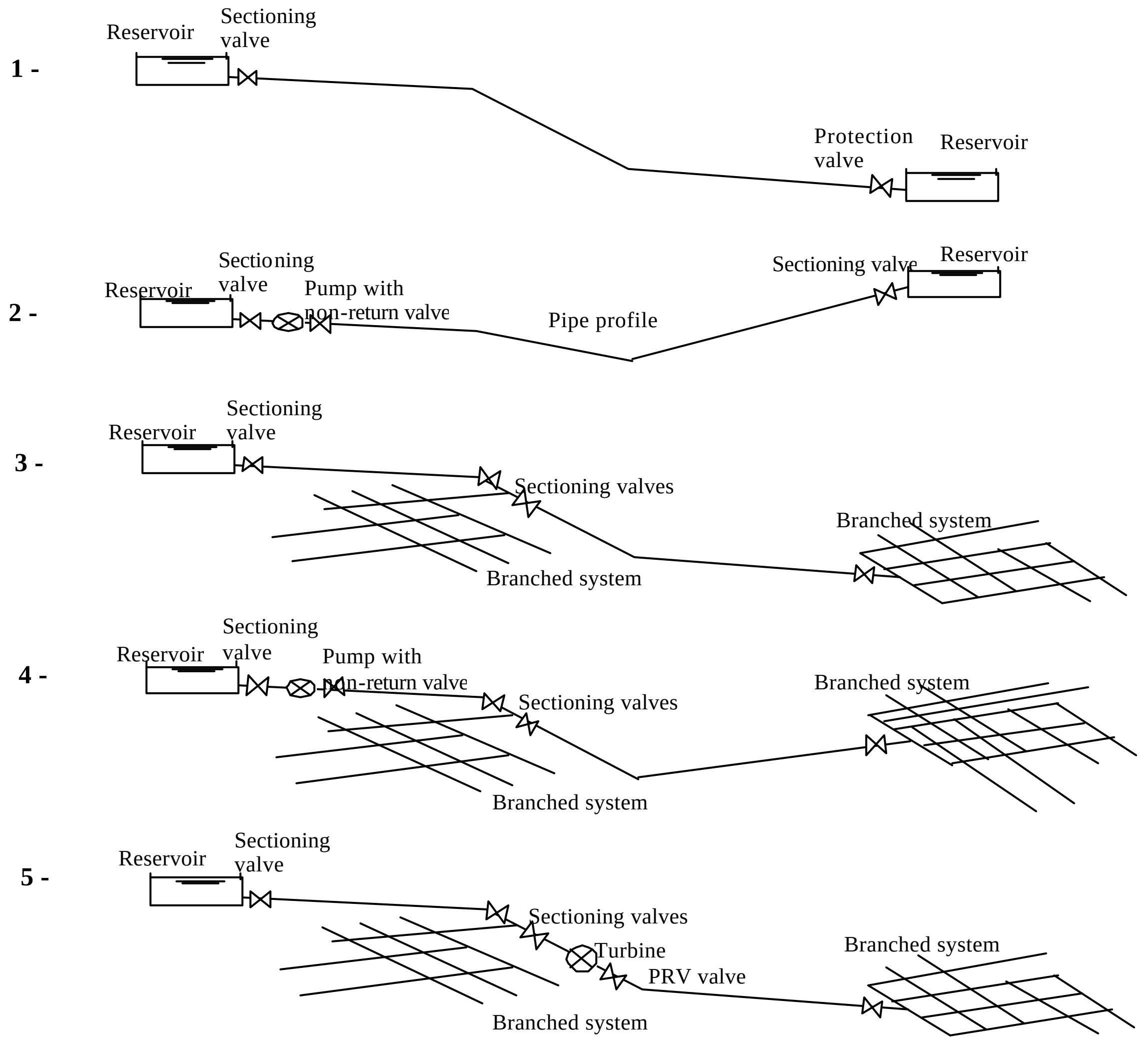


Fig. 1 – Scheme of System Types

The System Types must be defined in such a way that they can correctly be distinguished, using the basic properties of the system. The criteria must be objective, and may not be depend on the actual or anticipated outcome of any detailed design or analysis. Thus, the first stage consists in specifying all types of system into which to divide all pressurised conduits. A number of stages, in a "top down" approach, starting with an outline of the procedure in a simplified form led to the identification of the following types:

1 – **Single gravity main pipeline -** these are systems that consist of one pipeline from a tank or reservoir to another tank or reservoir at a lower elevation.

2 – **Single pumped main pipeline -** these are systems that consist of one pipeline from a pumping station to a point of delivery. This may be a tank, or a reservoir or the atmosphere, to which the pipeline connects or discharges. The pump station may contain more than one pump, in parallel or in series, and these may be operated together or alternately.

3 – **Branched gravity system -** these are systems that consist of multiple pipelines without pumps. There may be multiple inlets each connected by a pipeline to a single point of delivery, a single inlet connected by multiple pipelines to a number of points of delivery, or both multiple inlets and multiple points of delivery.

4 – **Branched pumped system -** these are systems that consist of multiple pipelines. They may have multiple pumps or pumping stations, each connected by a pipeline to a single point of delivery. Multiple pipelines may connect a single pumping station connected by multiple pipelines to a number of points of delivery, or there may be both multiple inlets and multiple points of delivery. Water mains may be reticulated (cross-linked) forming loops, and certain parts may flow in opposite directions in different modes of operation. These systems may consist of multiple pipelines (with different characteristics) connected to each other and with other types of elements such as reservoirs, pumps, valves and all types of surge suppression equipment. They include typical water distribution systems, in which part of the system functions by gravity and part by pumping.

5 – **Systems with energy recovery or pressure control -** these systems include more complex elements, such as turbines, reversible pumps or pressure reduction valves. This allows the transient analysis of any pressurised system. This System Type will be subdivided corresponding to a number of different systems with specialised components, so that one subtype will deal with turbines, another with reversible pumps, another with pressure reduction, etc. Any design that contains more than one of these features will need software that is classified for use on all of the subtypes involved.

In order to refine and describe the system types by adding events and phenomena to analyse, the partners used their combined experience of current practice, consulted available literature and considered a range of existing implementations. In this way, the events and phenomena that will be necessary to model pressurised conduits were identified:

- **Valve operation** – the operation can occur in response to other events in a system – as a passive device, or it can be used to initiate an event – as an active device.
- **Pump shut-down (trip)** - is frequently the most violent event to be modelled in normal operation. This may be accompanied by the controlled closing of a valve. Where multiple pumps are operating concurrently at the time of a power failure, they all run down simultaneously, instead of the normal sequential shut-down.
- **Pump start-up** - while this event must necessarily precede any pump shut-down, it may be much less important in the design because it is always a planned event that can be anticipated and controlled and it causes much smaller disturbances.

- **Vapour cavity formation** - when the pressure at a point in a liquid fall to the local vapour pressure, a vapour cavity forms. Due to pressure variation in the pipe system the volume can reach to zero and consequently the cavity collapses, and the net inflow is instantaneously forced to zero. This frequently results in a large pressure rise, often to an unacceptable level.
- **Filling and drainage** - when a pipeline is started up for the first time, or restarted after shut-down for repair or maintenance, it is necessary to fill the line in a controlled manner. Thus the design must consider the safe expulsion of air as part of the initial start-up procedure.
- **Gas release in the fluid** - Rapid increases in pressure have little effect except to compress the free gas, causing some increase in wave speed. The effects of rapid pressure reduction are usually much greater, bringing dissolved gas out of solution and severely reducing the wave speed, which is fundamental to the behaviour of pipeline system.
- **Trapped gas pockets** - the presence of trapped gas pockets in a system has a major, and frequently undesirable, effect on its behaviour. There is a critical volume of gas between that large enough to cause long period pressure oscillations and that small enough to have a minor shock absorbing effect.
- **Surge suppression** - surge suppression techniques must be employed which the principal devices are: surge vessels and feed tanks; air vessels and accumulators; air admission and release valves; relief and by-pass valves; stand-pipes and flexible pipes; rupture (bursting) discs; pump flywheels;
- **Turbine stoppage (full-load rejection)** - is frequently the most violent event to be modelled in normal operation. This may be moderated by control and/or protection devices such as a flywheel, by-pass with synchronous valve; or relief-valve.
- **Turbine start-up** - is always a planned event that can be anticipated and controlled and it causes much smaller disturbances. Nevertheless, it may require a modification of the high points of the pipeline profile.

Some events will not occur in all types of system, and some phenomena either may not occur or may be unimportant in certain types of system. These differences will not be addressed in detail, but will be described when defining the models required for each system type.

## 4- MODELLING REQUIREMENTS OF THE CLASSIFICATION PROCEDURE

The models and modelling techniques required for any transient analysis of each System Type are characterised as a function of accuracy level in the results obtained for each variable simulated. The Classification Procedure lists the main components of each system, though not all are required for any one System Type. In fact the majority of them appear in a common list required by all System Types; the remainder are listed according to the specific requirements of each System Type.

The main components and a selection of their modelling requirements are:

**Pipes –** Models for friction, elevation and wave speed are specified.

Friction – A fixed Friction Factor is acceptable for Class C, while Class B requires Reynolds Number-dependent, roughness-based friction and Class A stipulates unsteady friction modelling.

Wave speed – Wave propagation at a constant speed is adequate for Class C, while Class B indicates that a rigid column model must also be available for short pipes. Class A provides for a range of models including wave speed dependent on air content, an inertia-less model for very short pipes, and wave propagation incorporation the response of the pipe support structure.

**Tanks and reservoirs –** Models are specified for constant pressure on a free surface, with or without inlet and outlet losses and liquid level either constant or varying as a function of vessel geometry. Some models have liquid inertia and the Feed Tank may have a simple or dynamic non-return valve connecting it to the system.

**Free discharges –** This model is based on a tank or reservoir, representing a pipe end that normally runs full, but which empties on flow reversal.

**Enclosed vessels** – These operate in steady conditions with a pre-determined pressure or liquid level. During a transient event the gas will change in volume, which will lead to a change in pressure based on P ~ V relationship of the gas properties.

**Air vent** – Models are required for air release through a single orifice, for admission and release with a single symmetric orifice and for an asymmetric loss in the main orifice with or without an auxiliary bleed orifice.

**Virtual boundaries** – It may not be appropriate to model the complete physical system, because that would make the simulation too large, complex or slow to analyse. In such cases, non-physical component models are required to represent the response of that part of the physical system omitted from the simulation model.

**Passive valve** – Non-return and relief valves may be modelled in a number of ways: instantaneous response, with no time lag; fixed response time; typical response time, factored by the acting pressure difference; effective mass, stiffness and damping.

**Active valves** – Models are required for direct control valves, that may have a fixed position (opening) throughout the analysis or may vary as a user-defined function of time. Models are also required for feedback control valves, that may be a simple user-defined function of the measured variable, or a Proportional-Integral-Derivative device. This device may be used to simulate pressure reduction valves.

**Pumps –** These model the conversion of rotating energy into potential energy through the head or pressure generated and to predict the torque absorbed for a range of flow rates and different shaft speeds. They may run at constant or variable speed.

Rotodynamic – a single relationship for head torque, typically based on Suter parameters.

Positive displacement – defined as a flow boundary component.

**Turbines** –These model the conversion of hydropower energy as head or pressure into rotating mechanical energy, and predict the torque for a range of flow rates and shaft speeds at a given opening of the guide vane.

Impulse – consists of a runner and nozzles with movable needles to control the discharge together with behaviour of the valve control system.

Reaction – is composed by a spiral case, a movable guide vane that controls the flow inside the runner presenting special problems due to overspeed effect in low specific speed turbines.

**Bends** – The effect of bends on transient analyses is generally small but can be modelled knowing the number and position of each bend with its angle and radius/diameter ratio.

**Junctions** – The effect of tees and wyes on transient analyses is generally small, but they may be present in models that are also used to calculate steady state conditions when high accuracy is required.

**Minor losses** –Their effect on transient analyses is generally small, but they may be present in models that are also used to calculate steady state conditions when high accuracy is required.

**Orifices** – These may be modelled using the loss coefficient appropriate to their geometry, or using a pressure loss versus flow rate relationship.

**Transitions** – There are two types of transition: gradual reducers or diffusers and abrupt reducer or expansion, reducing collar or stepped flange which are characterised by loss coefficient as a function of geometry.

**Filters and strainers** – These may be modelled by a specific component or they may be represented by a general loss component depending on the type of flow (i.e. laminar or turbulent).

**Other losses** – These may be based on pressure loss versus flow rate, pressure loss versus velocity, a fixed loss coefficient, loss coefficient versus Reynolds Number, or a combination of these to model a general loss component.

## 5- BENCHMARKING ANALYSIS

It is clear from the two preceding sections that the Classification Procedure is both detailed and comprehensive. However, it cannot be sufficiently detailed to prescribe the exact requirements of analysis software without becoming too complex to use in the context of a standard. We have therefore used the approach of combining the Classification Procedure (as a basic "check-list") with a series of Benchmark Tests. These will verify the actual accuracy achieved by the software to be qualified, in a series of realistic cases. One or more systems with verified transient results will be associated with each System Type (and with each of the sub-types of Type 5).

The Benchmark Test procedure has yet to be developed in detail, but the general approach adopted is to pilot a series of tests. These will use the software available to the Partners, and test data drawn from that produced in the project and other data procured by the Partners. In order to formalise and streamline the process of preparing the input data for a number of different software packages, a Standard Input Data Definition (SIDD) was devised. For each modelling requirement identified in the Classification Procedure, this lists the data items that may be used to define the models. It provides a range of alternative inputs, to cater for differences in modelling approach between programs, which will inevitably occur with software from different authors.

Based on the SIDD, BHR Group has developed an Access database, to store data that will be selected for use in the Benchmark Tests. It will then be a relatively simple matter to extract the data required by each software package, and enter it in the Benchmark Analysis. This database could then become the repository of standard test cases to be used in a formal Benchmark Test procedure.

Different system types and models are required for this benchmark analysis, making possible the identification of quality, quantity and capability of results which can therefore be used as a standard with which other systems or expected dynamic behaviour can be compared. However, the depth of analysis should not exceed the reliability of the input data. Thus, an important part of the transient analysis is to specify physical parameters of the system that allow operation as required.

## 6- CONCLUSIONS

In order to integrate the use of transient analysis software in pipeline designs that conform to a formal standard, it is necessary for that standard to lay down a method to qualify the suitability of the software. This paper describes a proposed method consisting of two complementary components. One is a sophisticated check-list of the features required in the software, for it to analyse systems of specified types. The other is a procedure for benchmarking the software against known data representative of the appropriate type of system. Much remains to be done to create a simple and practical method, which is reliable in permitting the use of software that is capable of giving solutions of the required accuracy for the particular application, while excluding any software that does not meet those requirements.

Based on several real cases, problems and accidents that have occurred, it is now possible to have a large number of techniques to deal with hydraulic transients and the global dynamic behaviour of the hydrosystems. Transient state prototype test data will be used to verify the mathematical model accuracy by the comparison of computed and measured results.

The work described in this paper is continuing. The authors invite comment on the work to date, and any suggestions as to how their approach might be improved. They also welcome contributions concerning omissions and additional items that they should consider.

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