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ANALYSIS OF SGTR IN AP-600 BY RELAP5/MOD3.2 CODE

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Abstract

Five SGTR (Steam Generator Tube Rupture) sequences assumed to occur in the AP-600 system have been analysed in the present framework. These came from PSA (Probabilistic Safety Assessment) studies performed at ENEL in Rome; however, the bounding properties or the realism of the sequences are not discussed hereafter. Rather, the attention is focused toward the thermohydraulic performance of the system.

In all the considered sequences, the break is a double ended at the top bend of a single U-tube; this is done to maximise the I131 release to the environment. The break model in the code input deck consists of two pipes having the cross section area equal to that of a single U-tube. These are connected to the primary side in the position of the steam generator plena and to the secondary side at the bottom of the riser zone separating the U-tubes bundle from the steam separator.

1. INTRODUCTION

The design and the safety characteristics of innovative reactors, essentially based upon passive emergency core cooling systems, have been studied at Dipartimento di Costruzioni Meccaniche e Nucleari of the University of Pisa (DCMN) since 1986, i.e. soon after the Chernobyl accident. Experimental activities, code assessment activities and development of phenomenological models have been conducted and are in progress. Most of the researches in the area, have been supported, supervisioned or stimulated by ENEL (Ente Nazionale Energia Elettrica).

The present activity deals with an application of system codes finalised at the demonstration of safety and at the same time to the optimisation of the emergency procedures for the AP-600 plant. The study needs the availability of qualified code, nodalisation, code-user and computer-compiler installation. Basically, before achieving results of potential interest to the technology, like those foreseeable from the present code application, the above conditions must be proven.

The code qualification (first condition) stems from the use of an internationally recognised code version, the Relap5/mod3.2, ref.[1]. The quality of the code derives from the demonstration of capabilities in predicting suitable sets of experimental data. This can be achieved by considering the results of different groups of qualified code users (see below). Published papers in international Journals or Conferences, as well as conclusions or discussions from working Seminars (e.g. CAMP meetings or Relap5 Seminars), support the conclusion that the first condition is met. The specific activities carried out at DCMN finalised either to the identification and characterisation of phenomena expected to be important for new generation reactors, [2], and to the assessment of the code capabilities against the same phenomena, [3], constitute an independent confirmation of the same finding. A proposal for a comprehensive code qualification procedure, i.e. to demonstrate in a traceable and reproducible way code limits and capabilities, has also been recently proposed by DCMN, ref. [4]; the considered 'quality' criteria have basically been met.

The availability of a qualified code does not imply quality of results unless a qualified nodalisation is available (second condition). Nodalisation qualification criteria have been proposed dealing with the development, the "steady- state" and the "on-transient" acceptability of a nodalisation, ref. [5]. Those criteria are considered for the development and the qualification of the AP-600 noding scheme.

The availability of qualified code and nodalisation does not imply quality of results unless the code user, or better the group of code users, is qualified (third condition). The user may "interpret" boundary and initial conditions as well as code options available from the code manual, supplying wrong or inadequate information in the input deck; user effects upon predicted results are extensively discussed in ref. [6]. The problem of user qualification is a critical one to be solved or even to be addressed, e.g. ref. [7].

The last condition to be met is concerned with the availability of a qualified computer/compiler installation (fourth condition). The code released by developers can be used in different computers. The results may be largely affected by the computer/compiler, e.g. ref.. [8]. The solution to the problem is the execution of relevant 'benchmarks' showing that code developers results are "the same" as produced from the concerned installation.

A comprehensive description of conditions I to IV can be found in ref. [9]. All the conditions are supposed to have been met before starting the present investigation, e.g. refs. [2], [3] and [10] to [12]. This is focused toward the analysis of AP-600 performance during Steam Generator Tube Rupture (SGTR) transient; the results can be used to optimise Emergency Operating Procedures.

2. CODE AND INPUT DECK

The Relap5/mod3.2 is a well known code based upon 1-D thermalhydraulics and 0-D neutron kinetics equations. The adopted one is the latest version of a series of codes distributed since 1980. The code is widely used by several Organisations all over the world. Wide range assessment programs like CAMP (Code Assessment and Maintenance Programme) are in progress that may give an idea of the interest of the scientific community toward this code and, at the same time, of its capabilities.

Independent assessment activities have been carried out at DCMN as already mentioned (e.g. ref.. [9]); these also brought to the proposal for a methodology for the evaluation of the error made by a generic code calculation in predicting a transient scenario in a Nuclear Power Plant (NPP): uncertainty evaluation. With main reference to the area of advanced reactors, the code capabilities were characterised: basically, it was found that Relap5 performance is the same in case of applications to present generation and future generation NPP, provided the pressure is above 0.5 Mpa; however, areas for improvements connected with the simulation of components and systems introduced in advance reactors, have been identified, refs. [3] and [10]. Looking at the present application, it may be concluded that the adopted code is fully able to represent physical phenomena relevant in the case of SGTR scenarios here considered: the primary loop remains in nearly single phase condition at high pressure for the entire duration of the transients.

2.1 Nodalisation

A detailed nodalisation has been developed at DCMN for simulating the AP-600. This is described into detail in ref. [13]. It consists of more than 400 hydraulic nodes and 1200 meshes for conduction heat transfer. All the Engineered Safety Features of AP-600 design are part of the nodalisation including CMT (Core Make-up Tanks), PRHR (Pressurised Residual Heat Removal system), IRWST (In-Reactor Water Storage Tank), Accumulators, ADS 1 to 4 (Automatic Depressurisation System from 1 to 4), Pressuriser PORV (Pilot Operated Relief Valve), steam generator PORV and SRV (Steam Relief Valve) and SFW (Start-up Feedwater). In addition, systems for the nominal reactor operation like CVCS (Chemical and Volume Control System), MSIV (Main Steam Isolation Valves), turbine inlet and turbine bypass valves are included into the code model together with full control logic of operation of the various systems.

Special attention has been paid in modelling components like CMT and PRHR, specifically considering the experience gained in simulating the related phenomena measured in Spes-2 facility: CMT recirculation and draining phases controlled by thermal stratification of the fluid and pool side heat transfer in the case of PRHR, are examples of such phenomena.

The nodalisation underwent the qualification process at the steady state level as discussed in ref. [9]; the related results are given in ref. [13]; information suitable for the 'on-transient' qualification of the nodalisation can be derived from ref. [14]. The transformation from Relap5/mod2.5 to Relap5/mod3.2 was carried out utilising a standard procedure, basically considering the new capabilities of the Relap5/mod3.2 and the(slightly) different code input options. A new steady state was run; the related results demonstrated to be consistent with the requirements settled in ref. [9].

The nodalisation dimensions are given in Tab. 1; the related sketch and the utilised boundary and initial conditions can be seen in Fig. 1 and Tab. 2, respectively.

3. IMPOSED SEQUENCES OF EVENTS FOR SGTR

The imposed sequence of events for five SGTR sequences in the AP-600 can be deduced from Tab. 3, where the actuated systems are listed together with the relevant or adopted conditions for actuation. The sequences are identified with labels from SGT1 to SGT5.

Tab. 1 - AP-600 Nodalization dimensions

PARAMETER	VALUE
Number of volumes	416
Number of junctions	450
Number of heat structures	367
Number of mesh points	1214

Tab. 2 - Relevant boundary and initial conditions for the AP-600 SGTR calculations.

Quantity	Unit	Calculated value	Reference value
Reactor thermal power	Mw	1971.7	1971.7
PRZ pressure	MPa	15.51	15.51
Loop mass flowrate a	kg/s	4416.4	-
Loop mass flowrate b	kg/s	4450.1	-
Primary coolant mass	kg	150848	-
SGa exchanged power	Mw	985.83	985.85
SGb exchanged power	Mw	990.50	985.86
SG secondary side pressure	MPa	5.48	5.40
MFWa mass flowrate	kg/s	542	542
MFWb mass flowrate	kg/s	542	542
SGa secondary side coolant inventory	kg	52994.2	51397.8
SGb secondary side coolant inventory	kg	52909.6	51397.8
PRZ level	m	6.32	6.33
Core inlet mass flowrate	kg/s	8263.2	8549
Core bypass mass flowrate	kg/s	347.94	693
Core inlet fluid temperature	K	550.9	549
Core outlet fluid temperature	K	592.1	591
SGa DC level	m	13.46	13.46
SGb DC level	m	13.46	13.46
MFWa fluid temperature	K	499	499
MFWb fluid temperature	K	499	499

In all cases the break is a double ended at the top bend of a single U-tube. The break position has been chosen as the most critical one as far as iodine release is concerned. In the code input deck this is achieved by adding two pipes having the cross section of a single tube connected to the primary side in the position of the Steam Generator (SG) inlet and outlet plena and to secondary side at the bottom of the riser zone separating the U-tubes bundle from the steam separator.

Following the break occurrence in SGT1 at time t=0 s in the SG No. B (or b), pressure decrease in pressuriser is assumed to cause scram. Turbine isolation occurs followed by condenser bypass opening and main feedwater blockage. Primary pumps are also stopped and SFW comes into operation as scheduled. PRHR and CMT systems work as from the design. One CVCS pump is assumed to start following low level in pressuriser.

At t=1800 s (30'), after scram, a planned 55 K/hr equivalent depressurisation rate is assumed for both steam generators.

The affected steam generator is isolated (isolation of SFW) following high level in SG No. B; an operator action is assumed for the isolation of the MSIV. CVCS is isolated on the basis of the same signal controlling SFW.

The calculation ends at 10000 s.

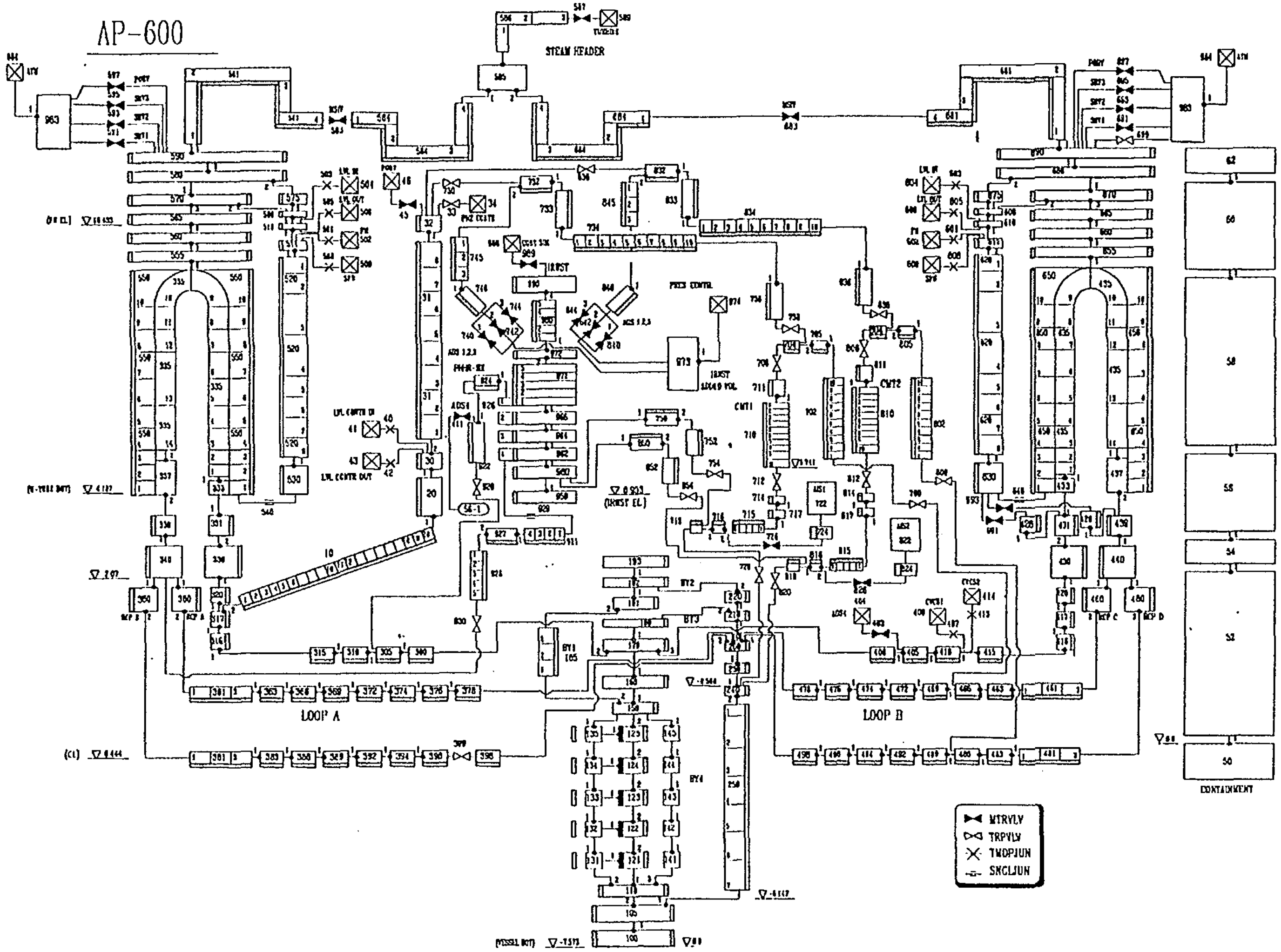

Fig. 1 - Nodalization for RELAP5/Mod2.5 code of the Westinghouse AP-600 plant

Tab. 3 - List of imposed events for AP-600 SGTR transients.

SYSTEM	TRIP	VALUE	DELAY	ACTION
RCP trip	scram time	-	17s	RCP coastdown table
CMT injection	scram time	-	22s	valve opening
PRHR actuation	CMT opening	-	60s	valve opening
SI signal	Low PRZ pressure Low SG pressure Low CL temperature	<11.7MPa <3.7MPa <554 K		
ADS actuation	-	-	-	not foreseen
Reactor trip	Low PRZ pressure	<12.41MPa	3.5s	
MSL isolation (only SGb)	manual closure	30 min after scam signal	-	
CVCS flow isolation	High narrow level in SGb	>14.97m	10s	valve closure
CVCS flow actuation	Low PRZ level	<0.823m	2s	valve opening
SFW activation	Low level in SGa or SGb Low FW flow	<12.57m	2s	flowrate 12.5 kg/s
SFW isolation (SGb only)	High level SGb	>14.97m	-	valve closure
Turbine trip	Scram time	-	5s	valve closure
Feedwater isolation	Scram time	-		complete valve closure in 15s
Steam dump to condenser actuation	turbine isolation time not actuated in SGT3	-	-	depres. rate corresponding to 55 K/hr

AP600 Plant - SGTR Transient - SGT1and SGT3 calculations : Trips List

SYSTEM	TRIP	VALUE	DELAY	ACTION
RCP trip	scram time	-	17s	RCP coastdown table
CMT injection	scram time	-	22s	valve opening
PRHR actuation	CMT opening	-	60s	valve opening
SI signal	Low PRZ pressure Low SG pressure Low CL temperature	<11.7MPa <3.7MPa <554 K		
ADS actuation	Low CMT level	<1.26m	120s	2 out of 4 stage four
Reactor trip	Low PRZ pressure	<12.41MPa	3.5s	
MSL isolation (only SGb)	manual closure	30 min after scam signal	-	NOT ACTUATED
CVCS flow isolation	High narrow level in Sgb Only for SGT2 case: after 6 hours from activation	>14.97m	10s	NOT ACTUATED (used for SGT2 case only)
CVCS flow actuation	Low PRZ level	<0.823m	2s	valve opening
SFW activation	Low level in SGa or SGb Low FW flow	<12.57m	2s	flowrate 12.5 kg/s
SFW isolation (SGb only)	High level SGb	>14.97m	-	NOT ACTUATED
Turbine trip	Scram time	-	5s	valve closure
Feedwater isolation	Scram time	-		complete valve closure in 15s
Steam dump to condenser actuation	turbine isolation time not actuated in SGT4	-	-	depres. rate corresponding to 55 K/hr
SRV stuck open	transient beginning	time = 0.0	-	actuated only in SGT5 case

AP600 Plant - SGTR Transient - SGT2, SGT4 and SGT5 calculations : Trips List

The SGT2 calculation proceeds in the same as SGT1. However, SFW and MSIV of the affected steam generator are not isolated. CVCS is isolated six hours following the scram.

The calculation ends at 30000 s (this is the only calculation allowed to reach 30000 s from the time of the break occurrence: this was done to evaluate the test scenario consequent to the failure of CVCS).

The SGT3 calculation is similar to the SGT1 with the only difference that the turbine bypass valves do not open. This is done to check the possibility that broken steam generator pressure reaches the SRV opening set point (this did not occur as the result of the calculation).

The SGT4 calculation is similar to the SGT2 with the only difference that the turbine bypass valves do not open. This is done, again, to check the possibility that broken steam generator pressure reaches the SRV opening set point (this did occur toward the end of the calculation).

The SGT5 calculation is similar to the SGT2 with the only difference that one SRV in the steam generator No. B remains stuck open starting from t=0 s. This is done to simulate a situation where the tube break is caused by the dynamic loads consequent the SRV opening. In such a situation, the lack of a qualified model for neutron kinetics, suggested to impose the scram at 200's into the transient (operator action).

In addition, in order to avoid back flow from the system controlling the steam generators pressure at 55 K/hr into the broken steam generator (in the present case, this attains a pressure much lower than in the case of SGT2), the MSIV of the broken steam generator has been assumed to close at t=0.

4. SUMMARY OF RESULTS

The resulting time sequences of events for steam generator tube rupture calculations in AP-600 identified as SGT1 to SGT5 are given in Tab. 3. Each transient scenario is documented and characterised by more than thirty time trends in ref. [16]. However, only four of these are shown hereafter per each calculation (Figs. 2 to 21). It can be premised that in all cases the CMT and the PRHR interventions were (as expected) successful: in other terms, the sum of the power exchanged through PRHR and used for CMT liquid heating up, was larger than core decay power. This basically prevented the possibility of steam generator SRV opening as mentioned before.

Needless to say, the core remained covered during the entire duration of the different transients; so, the only safety concern remained the iodine release outside the secondary loop, and eventually that transferred from the primary to the secondary loop.

The main observations from the performed analyses as reported below.

- Only in the SGT1 calculation reverse flow is calculated at the break at about 5000 s into the transient; in the case SGT2, the heat sink constituted by the 55 K/hr system prevents pressure reversal between primary and secondary systems; in cases SGT3 and SGT4, SFW is sufficient to keep secondary pressure below primary pressure (in the case SGT3, an anticipation of the isolation of SFW would have been caused pressure reversal); in the case SGT5, the same effect is due to the SRV stuck open (Figs. 3, 7, 11, 15, 20).
- In SGT1 and SGT2 the primary pressure achieves low value to cause accumulator actuation, before the end of the calculated transient. The 4.2 MPa value is reached at about 4100 and 22000 s into the transient, respectively (Figs. 2, 6, 10, 14 and 18, see also Tab. 4).
- In both SGT2 and SGT4 calculations, solid condition occurs in the affected (broken) steam generator. This event occurs at a pressure below the SRV set-point in the SG No. B in the case SGT2; however, in both cases primary pressure at the time of this event is above 10 MPa causing the potential for failure of other tubes and/or opening of the SRV: this could be damaged by the crossing of liquid. It must be emphasised that no signal was assumed for SRV opening based on high downcomer level in the steam generator, if the pressure remained below the set-point. The flowrate delivered by CVCS is at the origin of such scenario.
- In the case SGT3, the pressure equalisation between primary and secondary system occurs earlier than in the case SGT1: this is due to the operation of the condenser dump, not available in SGT3.
- In the case SGT4, steam passes from steam generator No. A to No. B: this limits the overpressurisation in the steam generator No. B caused by the overfilling condition discussed above.
- In all cases, with the exception of the SGT5, the level in the steam generator No. B overpasses the break elevation soon after the scram (see also Tab. 3) and remains above that position for the entire duration of the transient.
- Related to CMT, a recirculation period can be observed in all cases: the recirculation rate decreases during the transient; however, only in the case SGT2, draining of CMT starts at about 25000 s into the transient following isolation of the CVCS.
- The integrals of mass lost from the primary into the secondary loop and of mass exiting from the steam line of the broken steam generator, are given in Tab. 4. These can be assumed as representative of iodine diffusion from primary to secondary system and of iodine lost from secondary system, respectively, though only in case SGT4 an actual release is calculated.

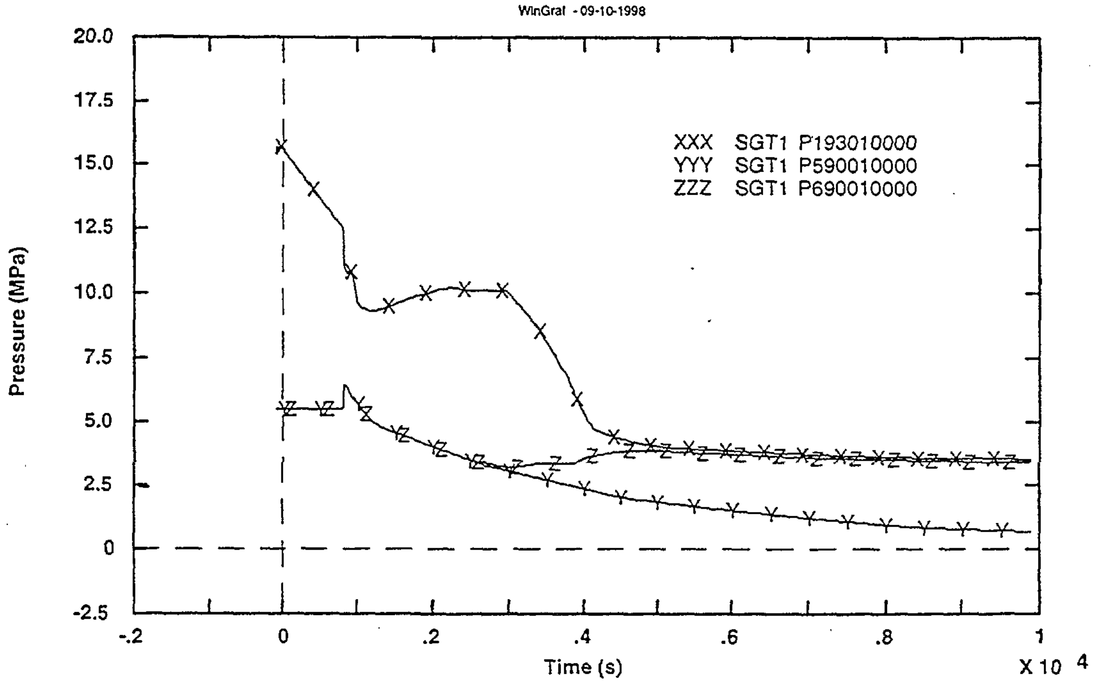

Fig. 2- Primary and secondary side pressures

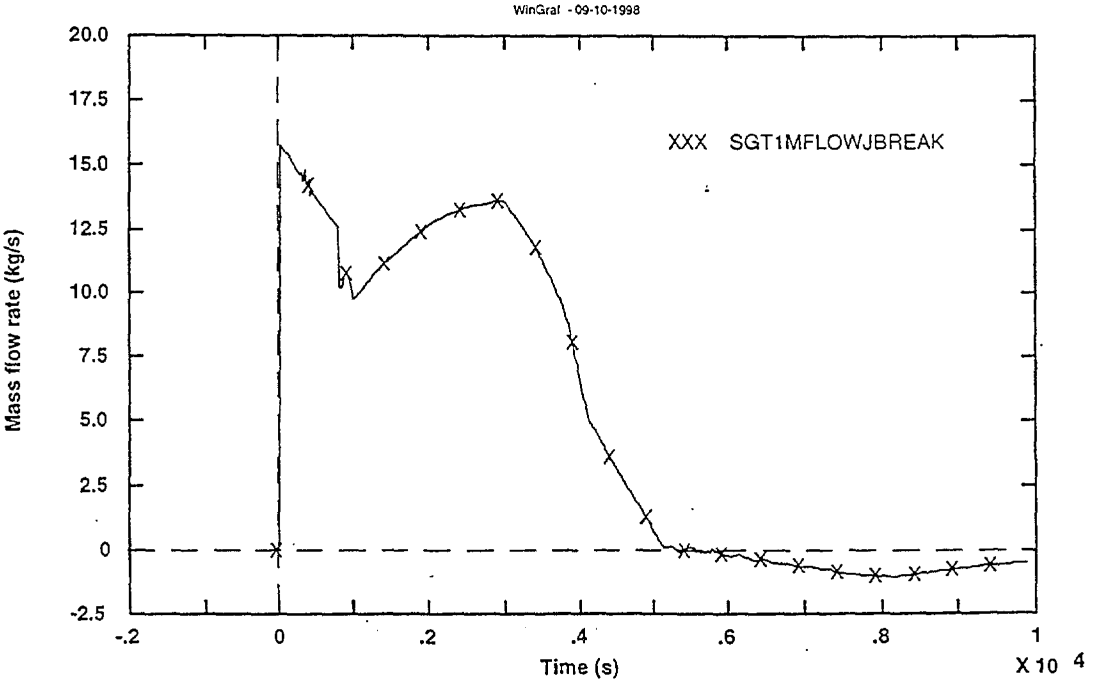

Fig. 3 - Break total mass flow rate

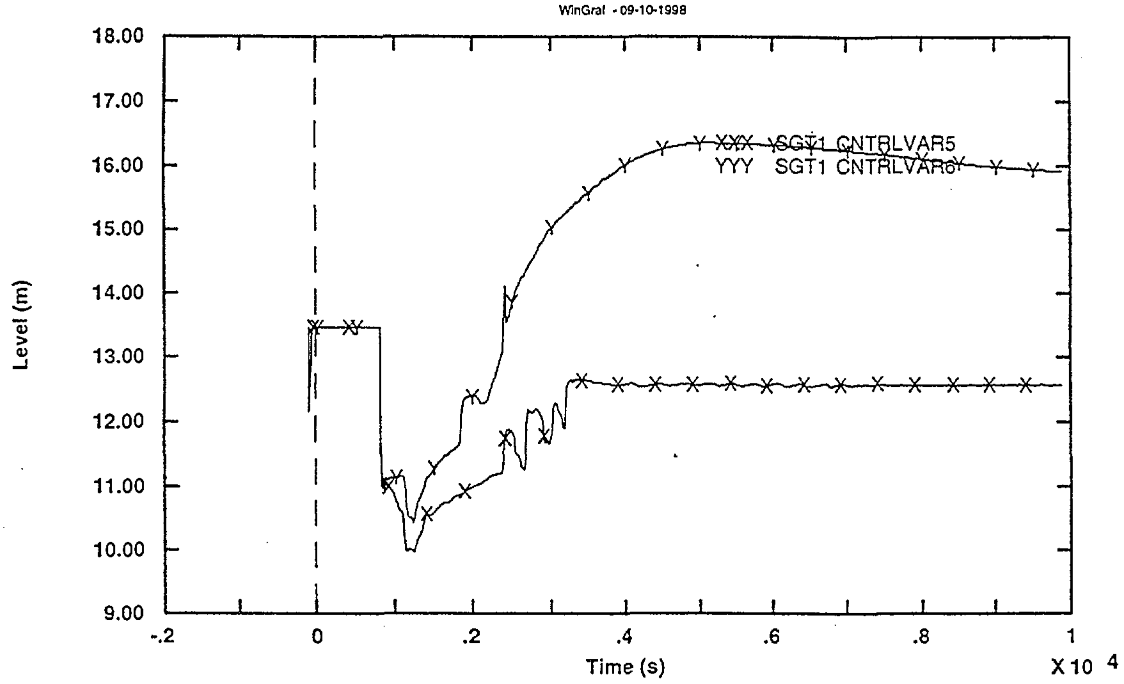

Fig. 4- Downcomer SGs collapsed level

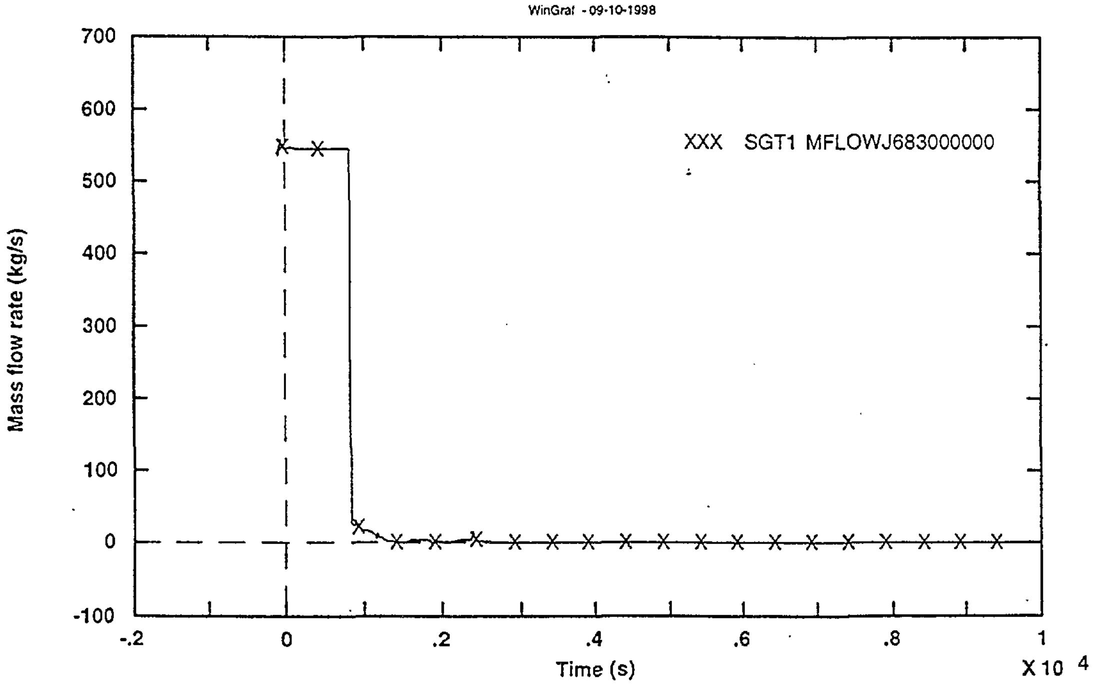

Fig. 5- Mass flow rate from SGB

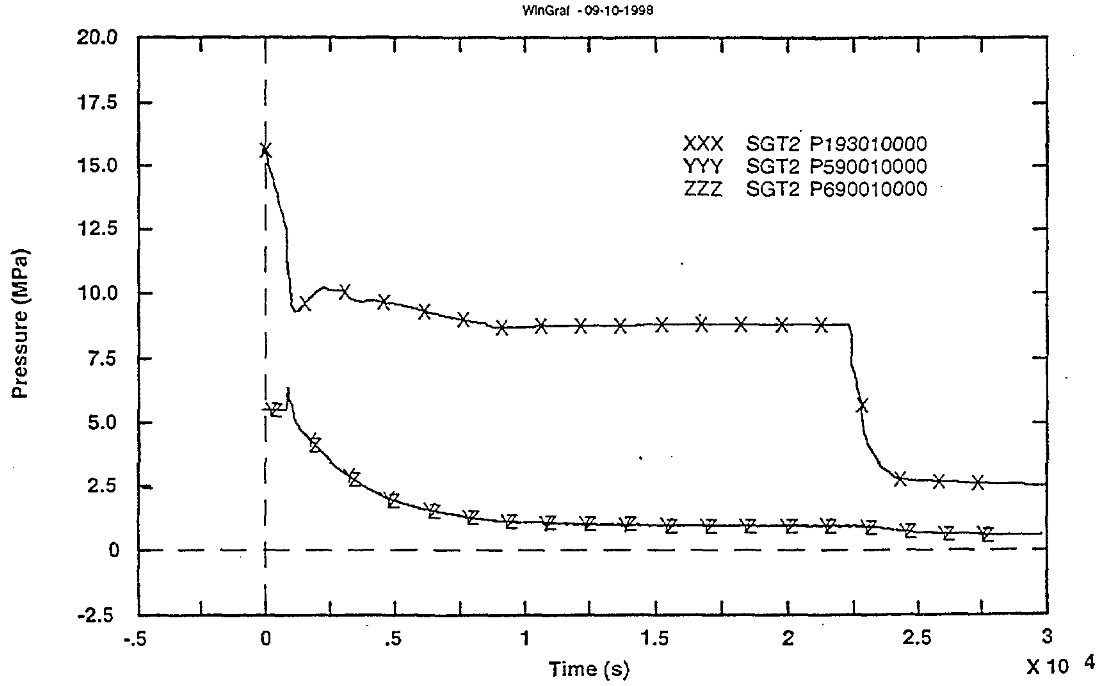

Fig. 6- Primary and secondary side pressure

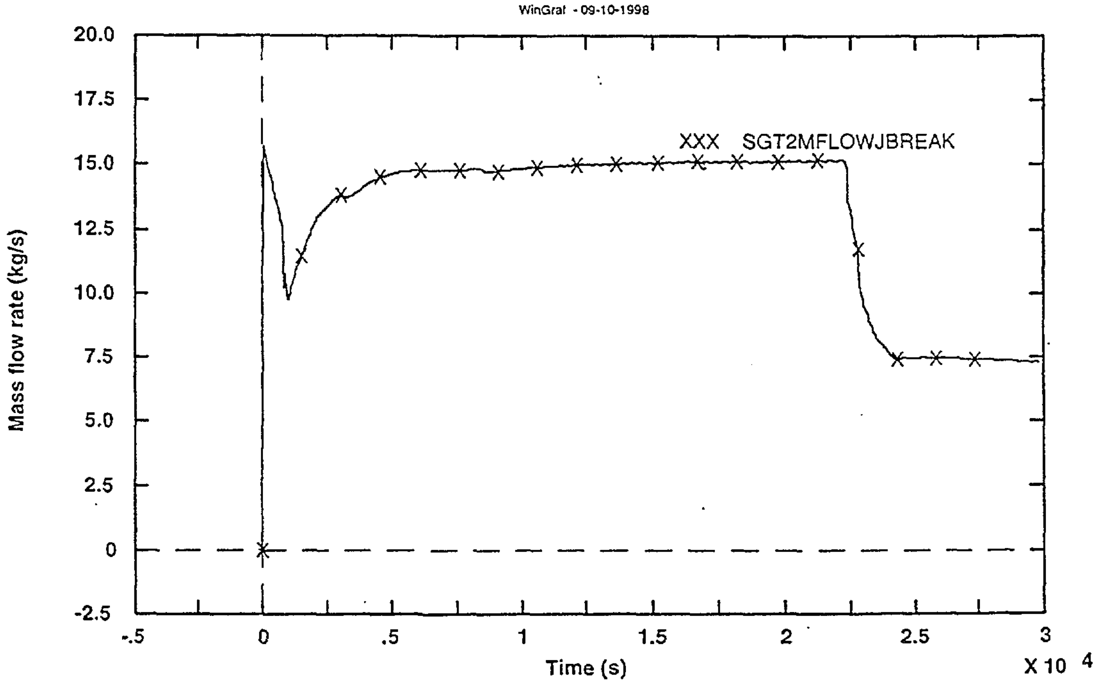

Fig. 7- Break total mass flow rate

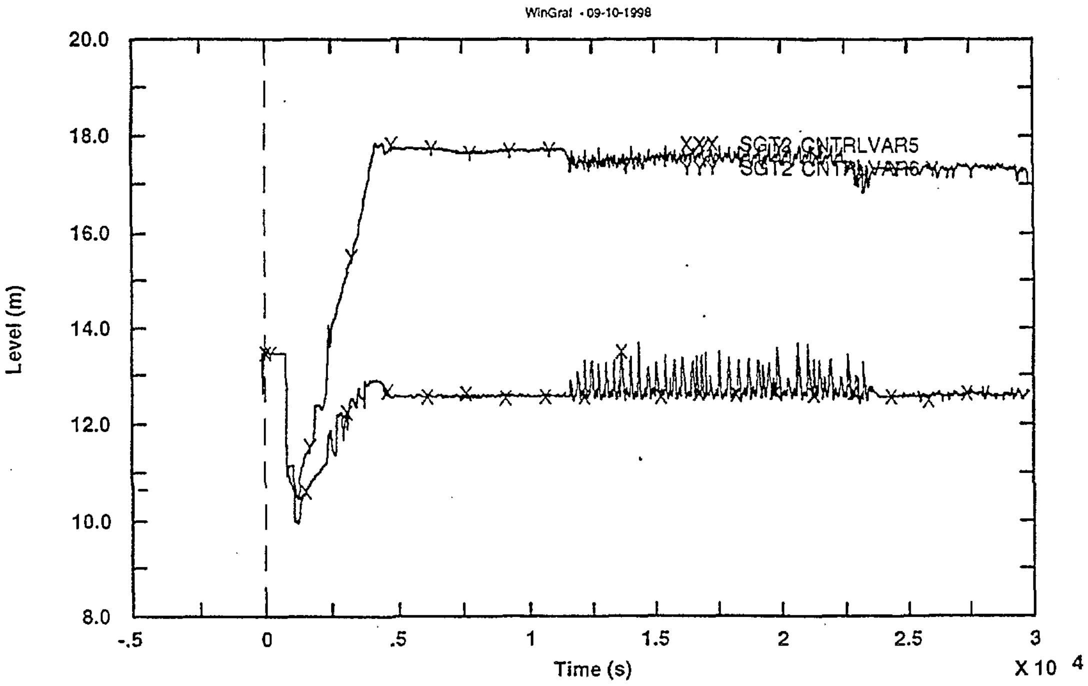

Fig. 8- Downcomer SGs collapsed level

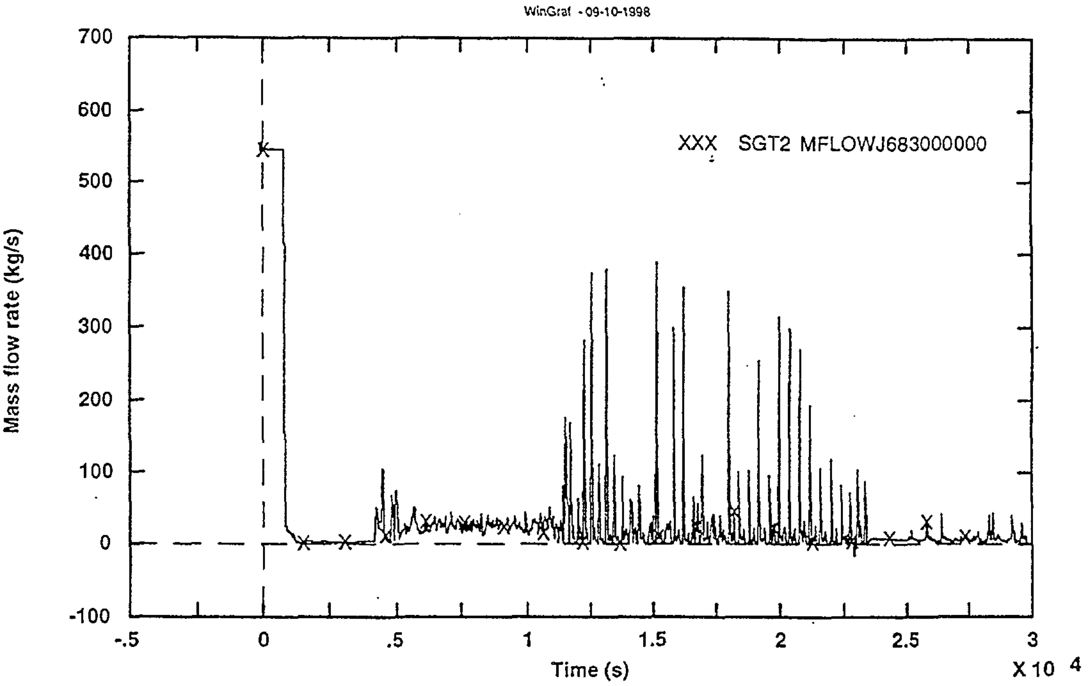

Fig. 9- Mass flow rate from SGB

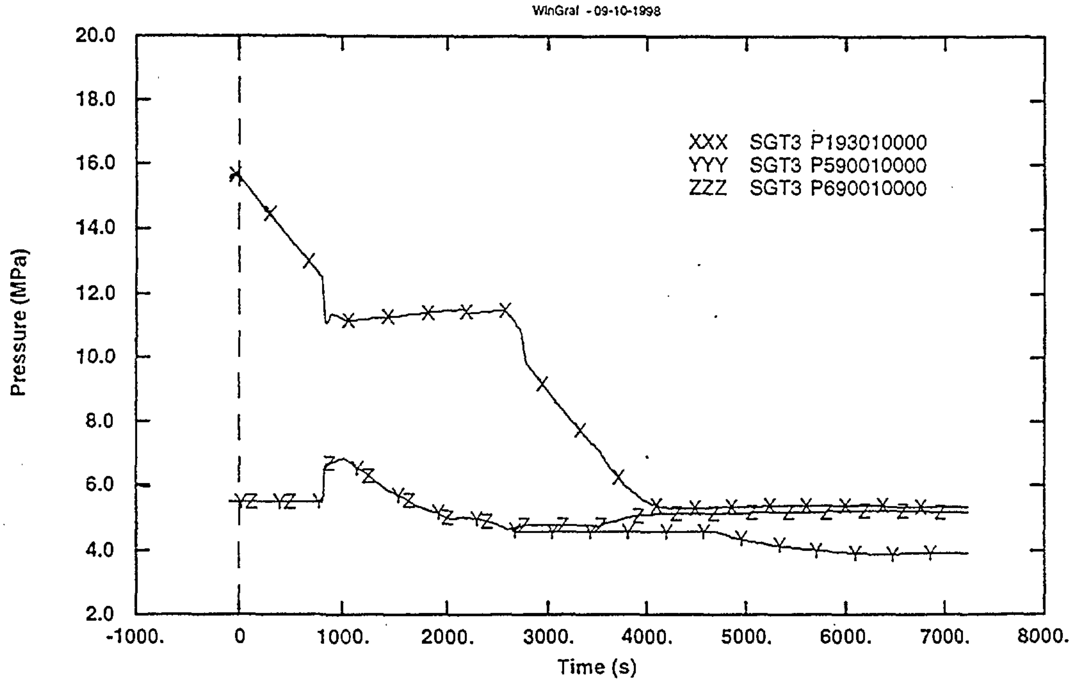

Fig. 10- Primary and secondary side pressure

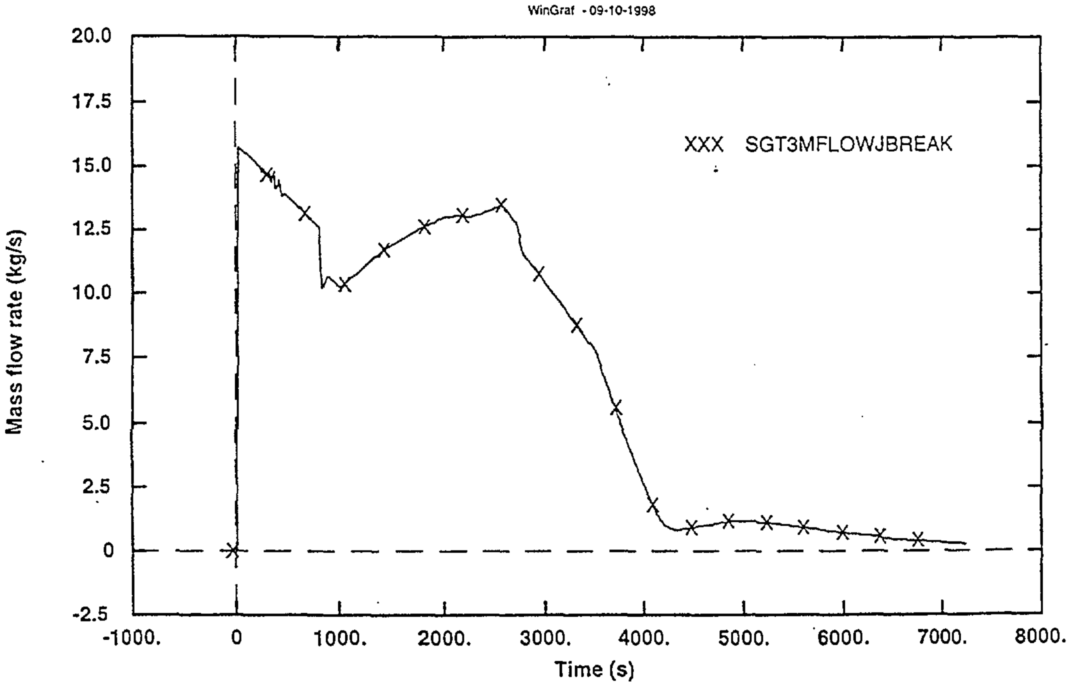

Fig. 11- Break total mass flow rate

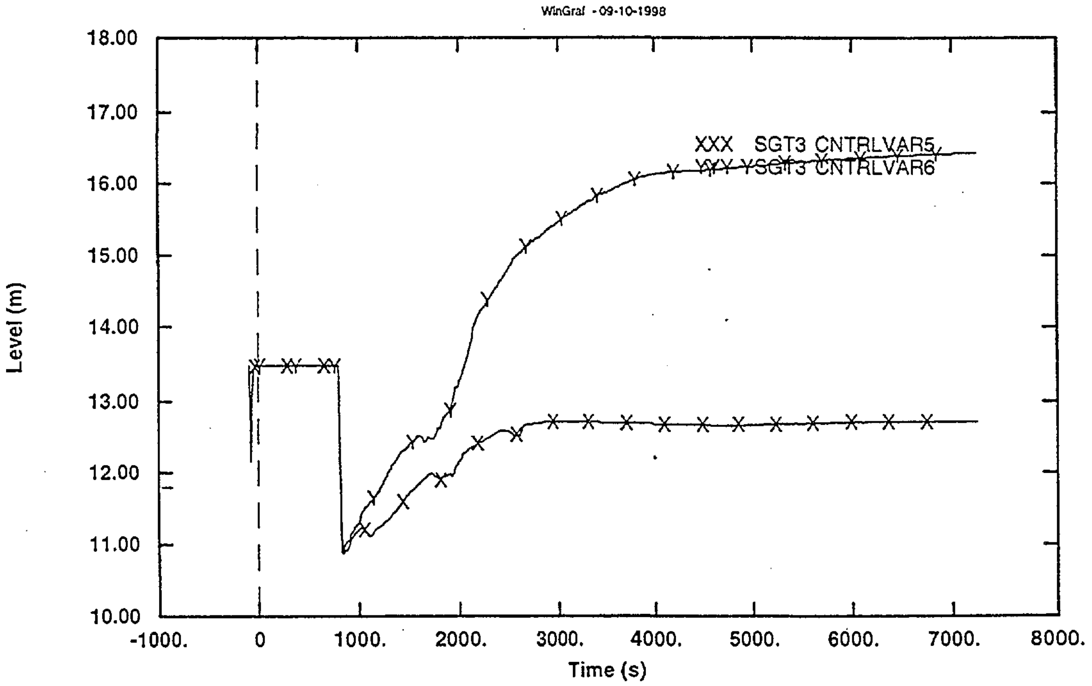

Fig. 12- Downcomer SGs collapsed level

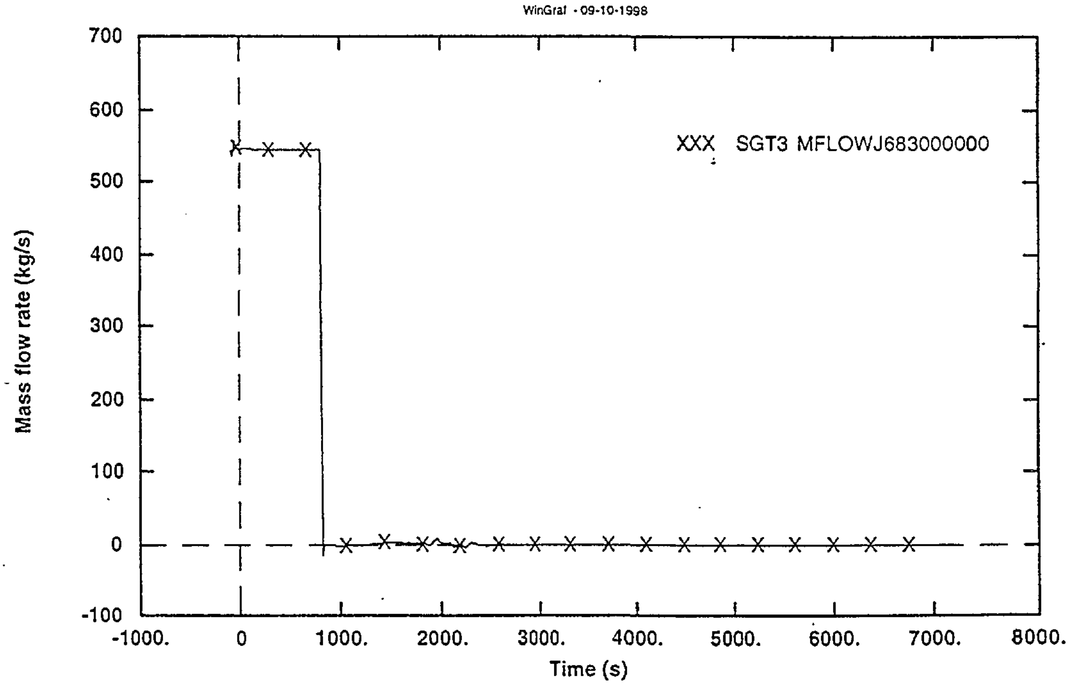

Fig. 13- Mass flow rate from SGB

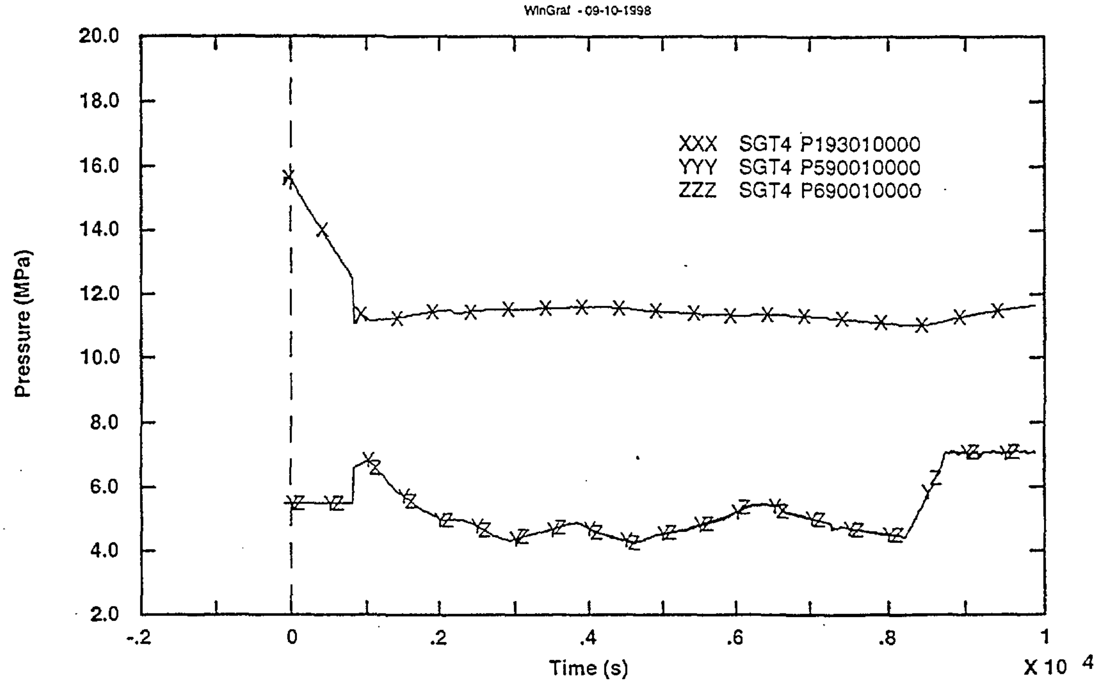

Fig. 14- Primary and secondary side pressure

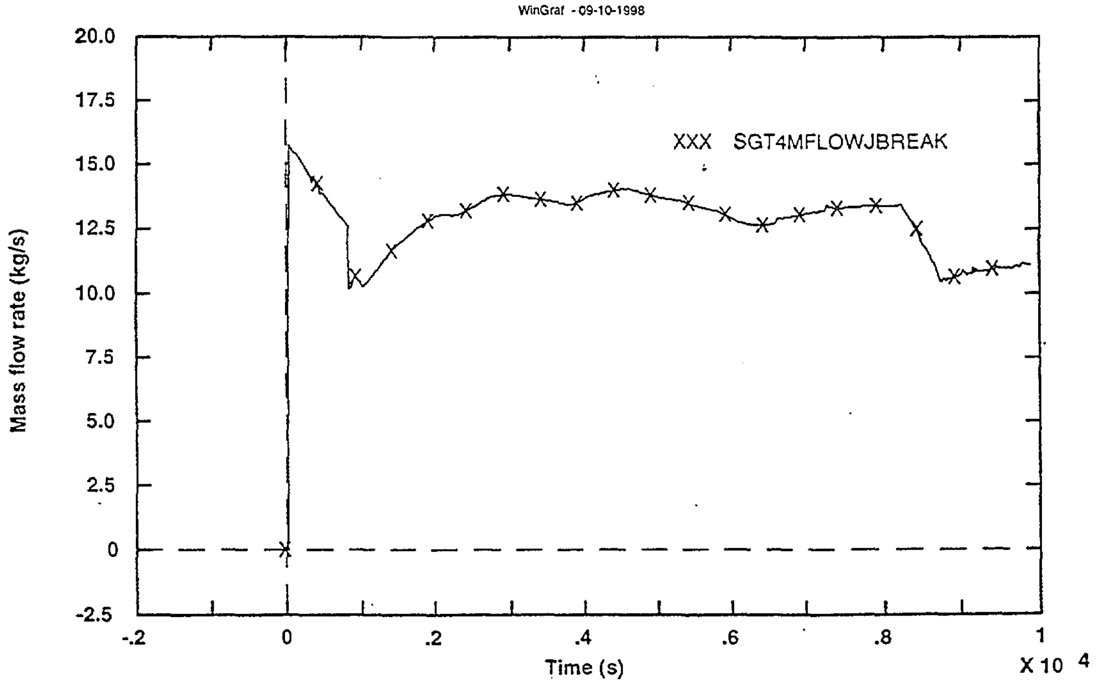

Fig. 15- Break total mass flow rate

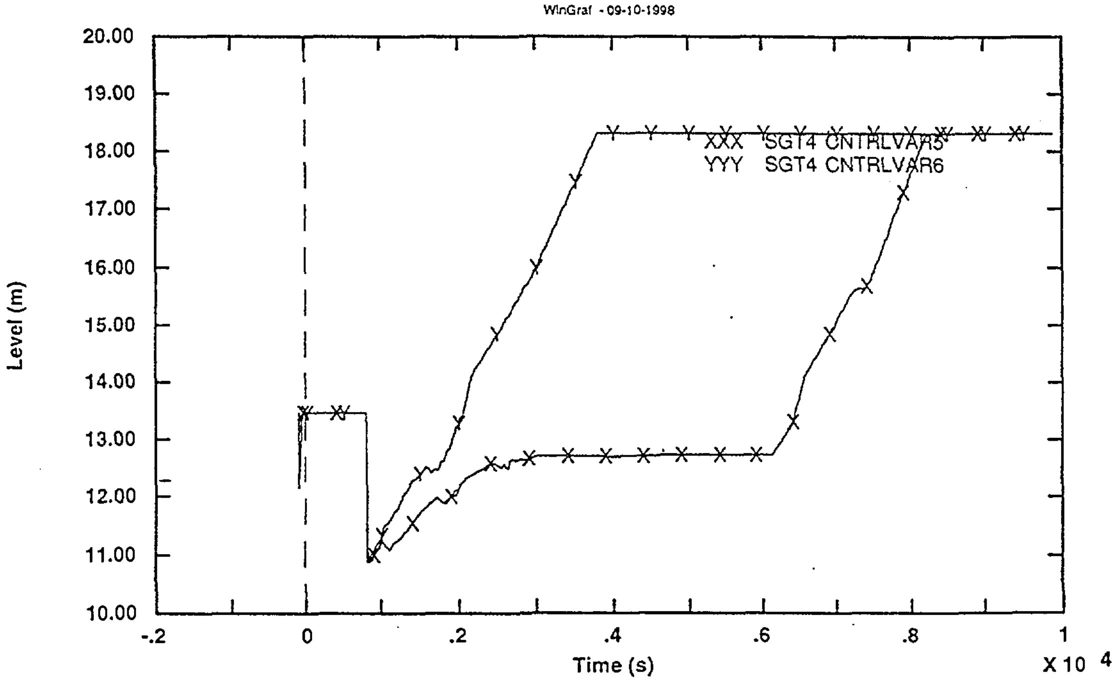

Fig. 16- Downcomer SGs collapsed level

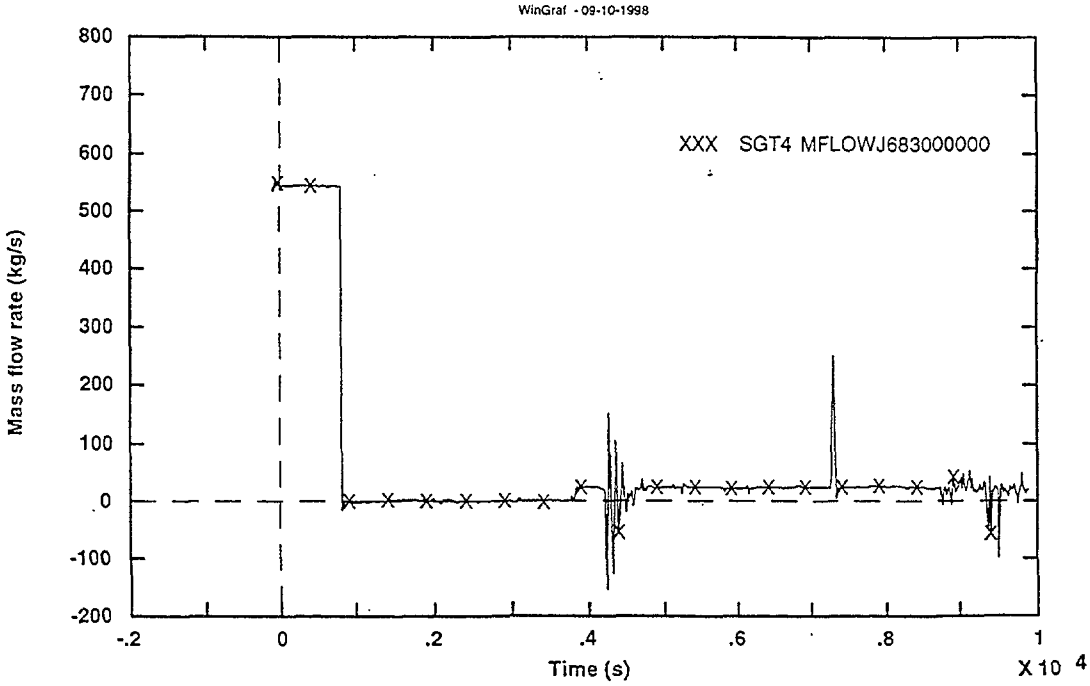

Fig. 17- Mass flow rate from SGB

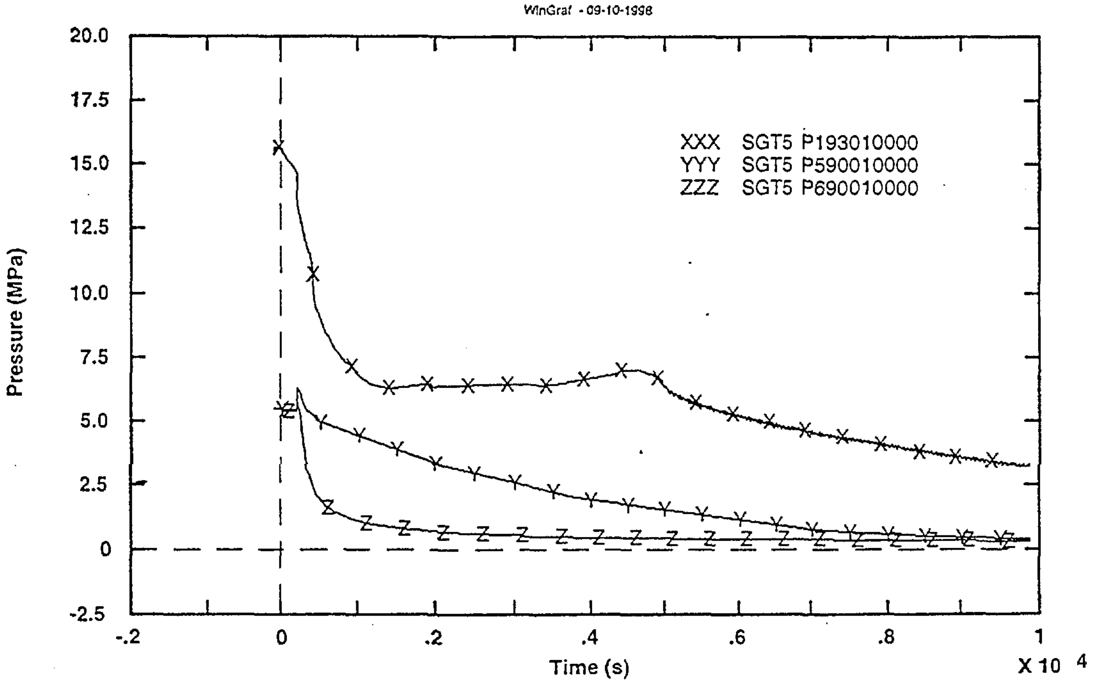

Fig. 18- Primary and secondary side pressure

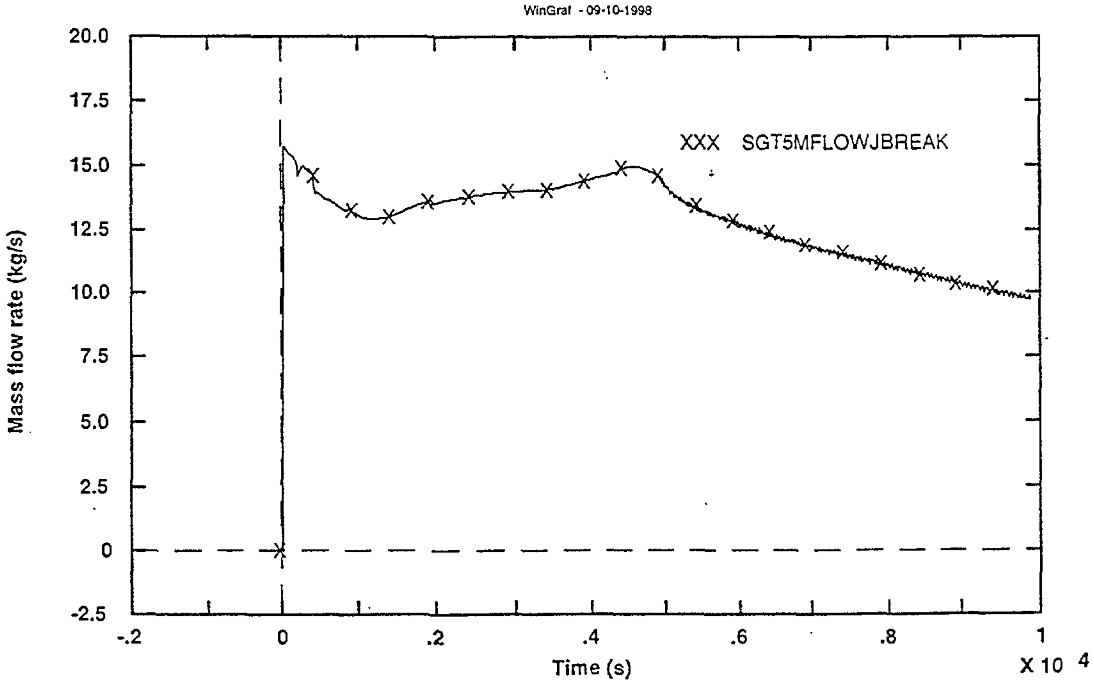

Fig. 19- Break total mass flow rate

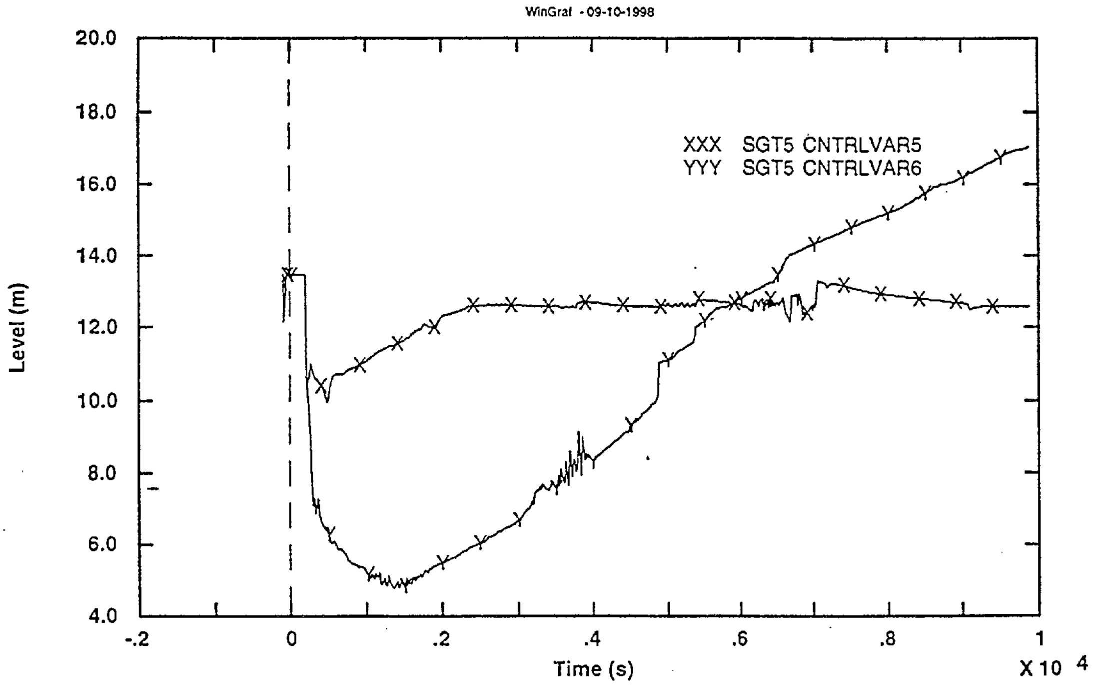

Fig. 20- Downcomer SGs collapsed level

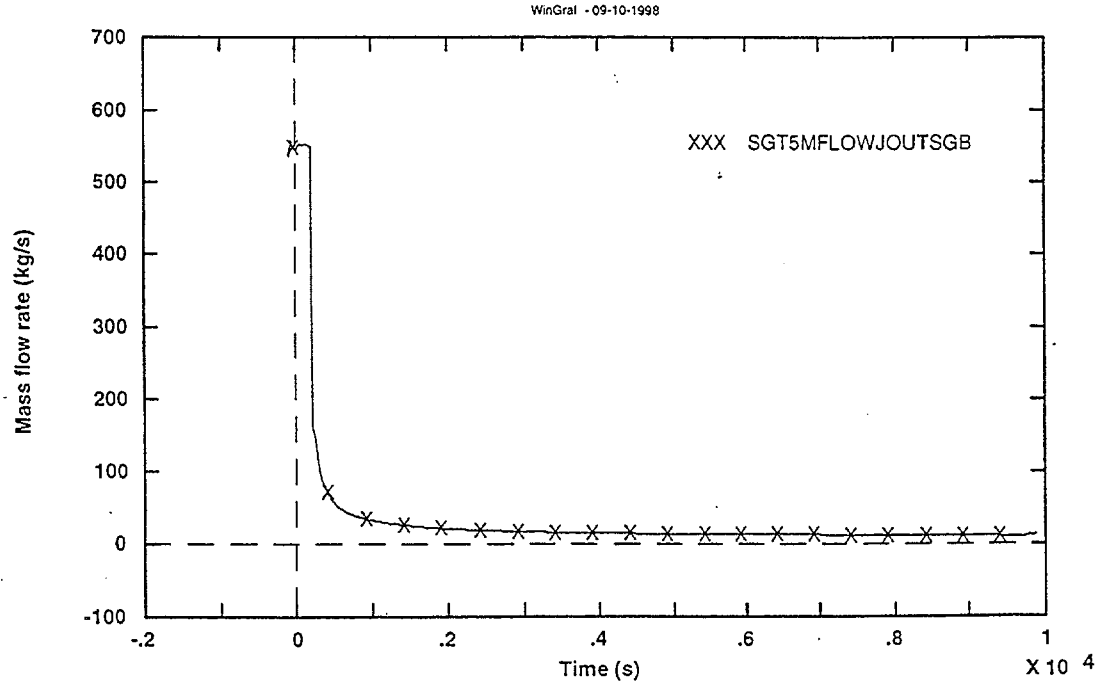

Fig. 21- Mass flow rate from SGB

Tab. 4 - Break and MSIV mass flow rate integrals

QUANTITY	SGT1	SGT2	SGT3	SGT4	SGT5
Break integral (Mg)	52.2	139.9/384.9*	47.4	127.1	126.4
MSIV integral from SG No. B (Kg)	443.5	593.6/1005.6*	435.2	572.5**	86.3/197.5***

* value at 30000 s into the transient

** some mass is lost from the SRV (cycling)

*** value from the SRV stuck open

5. CONCLUSIONS

A qualified AP-600 nodalisation has been adopted for performing scoping calculations concerned with steam generator tube rupture transient in AP-600. The analysis confirmed the quality of the AP-600 safeguards during this kind of transient: mainly CMT and PRHR system design parameters are concerned in this case. In particular, core level remains above the top of active fuel at each time during any of the calculated transient scenarios.

In relation to iodine release from primary to secondary side and across the MSIV of the broken steam generator, the following can be noted:

1. The closure of the MSIV of the affected steam generator is essential for limiting primary coolant mass leakage; clearly, this result must be evaluated considering the status of the primary and secondary loops at the end of the calculated transients.
2. The occurrence of 'solid condition' should be avoided with improved design of Emergency Operating Procedures;

Only in one calculation, i.e. SGT4, SRV cycling (i.e. direct release of iodine to the atmosphere) has been calculated toward the end of the transient.

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