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2400MWt Gas-Cooled Fast Reactor DHR Studies Status Update

Annual Report on GFR System Design and Safety

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1.0 Introduction

A topical report on demonstrating the efficacy of a proposed hybrid active/passive combination approach to the decay heat removal for an advanced 2400MWt GEN-IV gas-cooled fast reactor was published in March 2006 [1]. The analysis was performed with the system code RELAP5-3D (version 2.4.1.1a) and the model included the full complement of the power conversion unit (PCU): heat exchange components (recuperator, precooler, intercooler) and rotating machines (turbine, compressor).

A re-analysis of the success case in Ref [1] is presented in this report. The case was redone to correct unexpected changes in core heat structure temperatures when the PCU model was first integrated with the reactor model as documented in Ref [1].

Additional information on the modeling of the power conversion unit and the layout of the heat exchange components is provided in Appendix A.

2.0 Analysis of Depressurization Accident

This is a re-analysis of Case 32 as presented in Ref [1] with several modifications:

1. Reynolds number dependent spacer loss coefficients are implemented for the core coolant channels at time zero (versus for time > 1000s in Ref [1]).
2. Heat transfer area for the recuperator was reduced by a factor of 3.

The reduction in the recuperator heat transfer area was required because when the PCU model was integrated with the reactor model, the temperature of the helium gas coming out of the PCU went up by about 50 °C indicating too much heat transfer from the hot side to the cold side of the recuperator. This deficiency in the old analysis [1] has negligible effect on the outcome of the transient. The new Case 32 is still a success case whereby the combination of active (blower) and passive (natural circulation) decay heat removal approach was capable of maintaining the fuel temperature and the helium gas temperature below the success criteria of 1600 °C and 850 °C respectively, 24 hours after reactor shutdown.

The main purpose of this re-analysis is to provide the mass and energy flow to the guard containment for new CFD calculations with a new guard containment internals design from GA. In addition to helium loss through the 10 sq. inch break (0.00645 m^2), PCU and reactor vessel temperatures are needed for calculating the temperature and pressure responses of the guard containment (free volume = 20250 m^3). The timeline of the depressurization accident (designated as Case 05t32) is summarized in Table 1. The pressures of the reactor and the guard containment are shown in Figures 1 and 2 for the new (Case 05t32) and the old (Case 32) case respectively. The results are almost identical for the two cases. It is noted that the RELAP5 calculation assumed the guard containment was initially at cold shutdown condition with a temperature of 30 °C. The temperature and pressure of the guard containment for early part of the transient are shown in Figures 3 and 4 respectively.

Table 1 - Timing of Significant Events for Case 05t32

0 s	10 sq. in. break initiated.
169.3 s	Reactor tripped on low pressure. Generator tripped off line and turbine bypass is opened.
234.92 s	Turbine bypass re-closed when PCU flow dropped below 20% of rated value.
382.92 s	Compressors replaced by dummy volumes when PCU flow again dropped below 20% of rated value.
420 s	Blower turned on with a flow velocity of 3.5 m/s.
1250 s	Helium accumulator connected to guard containment to maintain pressure at 800kPa. Accumulator is modeled by a time-dependent volume of constant pressure (800kPa) and constant temperature (303.15K)
9000 s	Case restarted by defining reactor power as a function of time in the form of a table. Reactor power decayed linearly from 26.2589MW at t=9000s to 13.9748 MW at t=15000s. The later power level is equivalent to the decay power 24 hours after a shutdown.
9050 s	Trip valve located at the junction between the PCU outlet and the reactor downcomer was closed. This was used to simulate the action of a check valve that would have prevented flow from entering the PCU via the reactor downcomer.
15000 s	Blower speed reduced to zero in 5 seconds. Reactor power was maintained constant at the 24-hour decay heat level.
25000 s	Case ended.

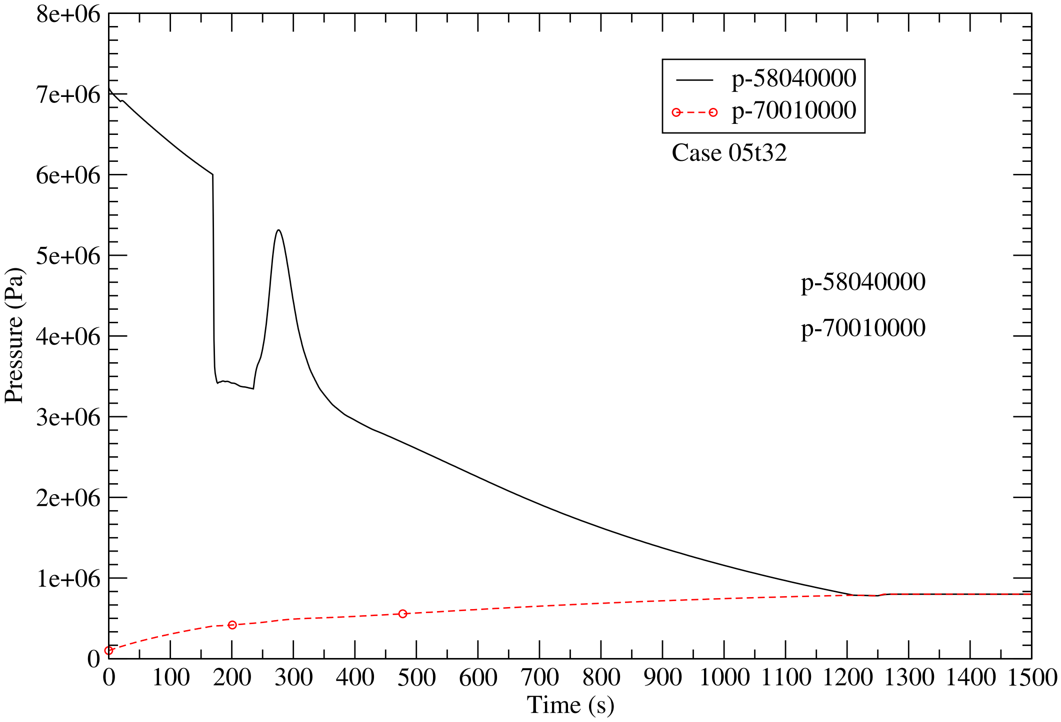


Figure 1. Reactor and guard containment pressures – new case.

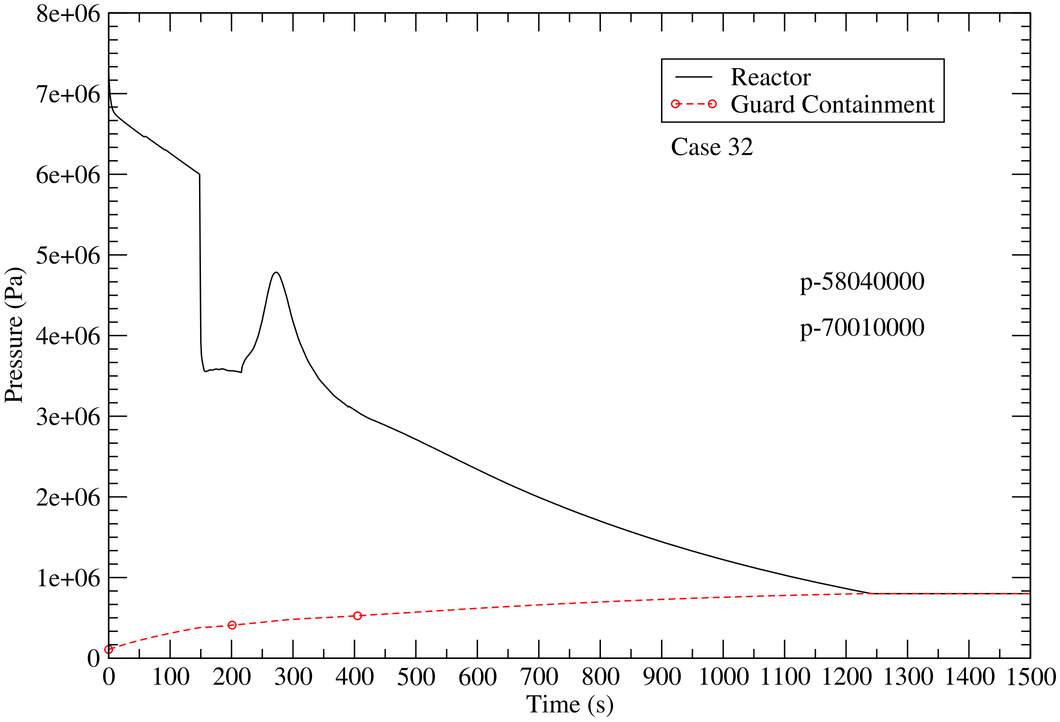


Figure 2. Reactor and guard containment pressures – old case.

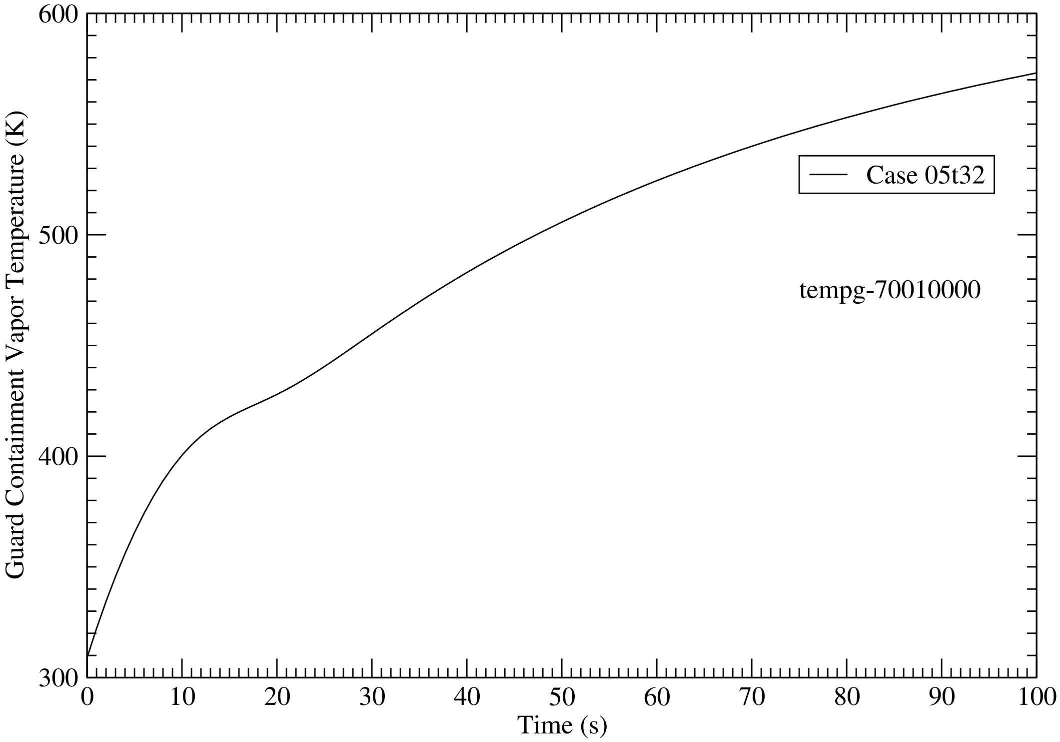


Figure 3. Guard containment temperature – new case.

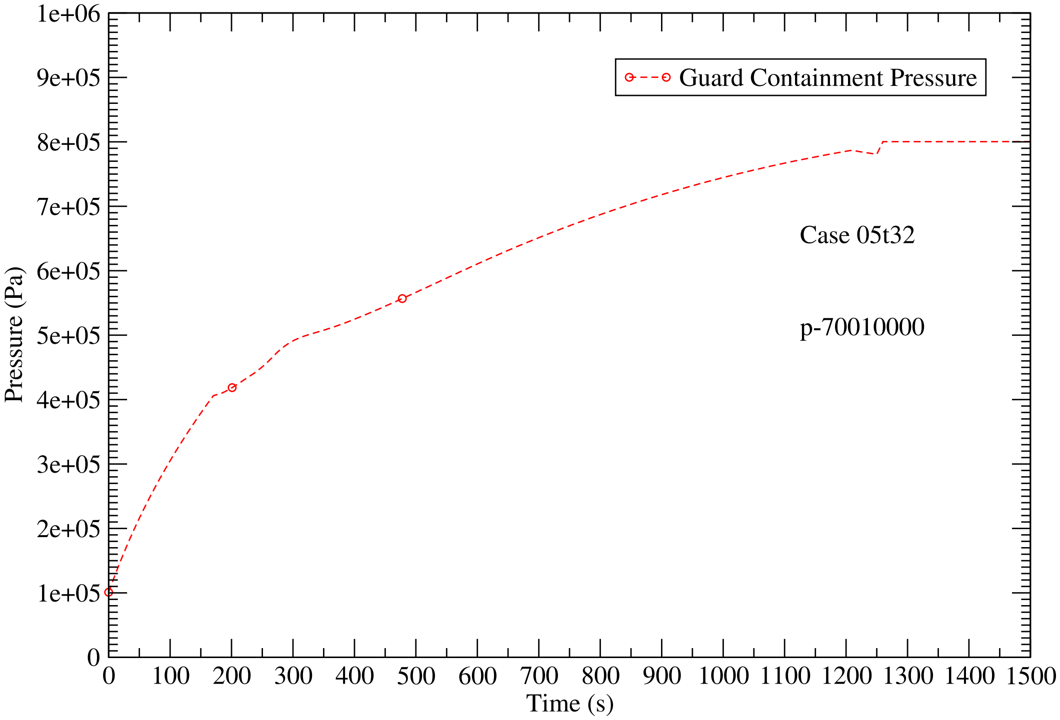


Figure 4. Guard containment pressure – new case.

The RELAP5 results that are to provide the boundary conditions for the CFD calculations are plotted in Appendix B as a function of time. The plots include the following outputs from Case 05t32:

Break flow, pressure, temperature, and junction internal energy.
ECS heat exchanger upper riser gas temperature.
ECS cold duct gas temperature.
Reactor vessel inner wall temperature at junction with PCU outlet.
Reactor vessel inner wall temperature at junction with ECS outlet.
Reactor vessel inner wall temperature at mid-core.
Precooler gas temperature.
Intercooler gas temperature.
Gas temperature on cold side of recuperator.
ECS cold duct inner wall temperature.
Flow across junction between guard containment and gas accumulator.
Accumulator junction internal energy.

It is noted that positive flow direction at the gas accumulator junction is from the guard containment to the gas accumulator. Also, the gas temperatures for the precooler, intercooler, and cold side of recuperator are taken from the mid-section of the respective volumes.

3.0 Reference

[1] Cheng, L. and Ludewig, H., “Combined Active/Passive Decay Heat Removal Approach for the 2400MWt Gas-Cooled Fast Reactor,” DOE GEN-IV program report, BNL-GFR-2006-001, March 31, 2006.

Appendix A – PCU Configuration

The purpose of this appendix is to provide additional information on the preparation of the RELAP5 input for the 600 MW power conversion unit (PCU). An overview of the RELAP5 model of the PCU was presented previously in Ref [1]. The current discussion will focus on the process of translating the basic geometric and operating conditions to RELAP5 inputs.

Geometric data for the various gas volumes in the PCU are from Ref. [2] and they are summarized in Table A-1.

Table A-1 - Geometric Data for a 600 MWt PCU

Component	Length (m)	Volume (m^3)	Area (m^2)	Orientation (Degree)	Hydraulic Diameter (m)
Hot Duct	7.4	11.885	1.606	0	1.43
Turbine	4.2	2.04	0.4857	90	0.7864
Turb - Recu	1.3848	0.6924	0.5	-90	0.7979
Recuperator-LP*	2.8152	30.91	10.98	-90	2.4384e-3
Recu - Prec	10.95	5.475	0.5	-90	0.7979
Precooler	4.73	134.48	28.431	-90	0.009924
LPC duct	4.9	11.786	2.405	90	1.75
LPC inlet	2.38	14.239	5.983	90	2.76
LPC	4.2	2	0.4762	90	0.7787
LPC outlet	4.9	21.3	4.347	-90	2.353
Intercooler	4.73	134.08	28.346	-90	0.009924
Intc - HPC	9.63	4.815	0.5	90	0.7979
HPC	4.2	2	0.4762	90	0.7787
HPC-Recu	2	1	0.5	0	0.7979
Recuperator-HP**	2.8152	20.61	7.32	90	1.067e-3
Recu - Cduct	2.8152	1.4076	0.5	-90	0.7979
Cold Duct	7.4	13.949	1.8850	0	0.6
Total Volume		412.7			

*   LP = low pressure side of recuperator.
** HP = high pressure side of recuperator.

It is noted that the flow area and the hydraulic diameter for the low pressure and high pressure side of the recuperator are actually copied from a RELAP5 input deck that was used for the RELAP5 calculations presented in Ref [3]. This was done to achieve consistency between the hydraulic and heat structure models of the plate-fin heat exchanger assumed for the recuperator. The hydraulic and heat structure models were similar to the GA model [3] and the heat transfer area was adjusted until the desired steady-state helium temperatures were reached at the outlet of the low and high pressure side of the recuperator.

The state points of the helium gas inside the PCU are summarized in Table A-2 [2, 4]. Also shown in the table is the power rating of the various heat exchange components and turbomachines. The power ratings are based on information from Ref. [5].

Table A-2 – Helium State Points

Component	Inlet Conditions	Outlet Conditions	Power Rating
Turbine	848 °C 7.07 MPa	508 °C 2.61 MPa	558.5 MW
Recuperator (Low Pressure)	508 °C 2.61 MPa	130.3 °C 2.58 MPa	639 MW
Precooler	130.3 °C 2.58 MPa	26.4 °C 2.55 MPa	173 MW
Low Pressure Compressor	26.4 °C 2.55 MPa	107.5 °C 4.31 MPa	132.3 MW
Intercooler	107.5 °C 4.31 MPa	26 °C 4.28 MPa	130.2 MW
High Pressure Compressor	26 °C 4.28 MPa	110.3 °C 7.24 MPa	134.5 MW
Recuperator (High Pressure)	110.3 °C 7.24 MPa	488 °C 7.16 MPa	639 MW

The heat transfer areas of the precooler and intercooler were determined as follows:

1. Define the cooling water flow rate and inlet temperature from Ref [4].
2. Adjust heat transfer area until the energy removed by cooling water on the tube side is equal to the power rating shown in Table A-2.

The above process of adjusting the heat transfer area was done while the helium flow was maintained at its nominal conditions at the inlet to the precooler and the intercooler on the shell side. The nominal helium flow rate used in the calculation was 312 kg/s.

In the RELAP5 model of the PCU the arrangement of heat exchange components is shown in Figure A-1. This is the same arrangement as described in the GA report [3]. Also noted on Figure A-1 are the external dimensions of the components taken from Ref [2]. It appears that the arrangement of heat exchange components has undergone some modification in the latest design for the GT-MHR that is being developed by GA and its Russian partner. The new arrangement [5, 6] is shown in Figure A-2 and the two main changes are:

1. The recuperator modules are arranged to operate in parallel with equal number of modules supported above and below the hot duct axis.
2. The precooler and intercooler modules are placed at the bottom of the PCU and they alternate with each other around the circumference of the PCU.

It is noted that dimensions of the precooler/intercooler heat exchange tubes as documented in [2] are in agreement with the description in [5]. The height of the recuperator listed in [2] seems to be too short for the arrangement as shown in Figure A-1. The RELAP5 model of the PCU needs to be updated if there is any change in the arrangement of the heat exchange components.

REFERENCES

[1] Cheng, L., Ludewig, H.., “Modeling of the Power Conversion Unit (PCU),” BNL report submitted to the DOE GEN-IV Program, July 15 2005.

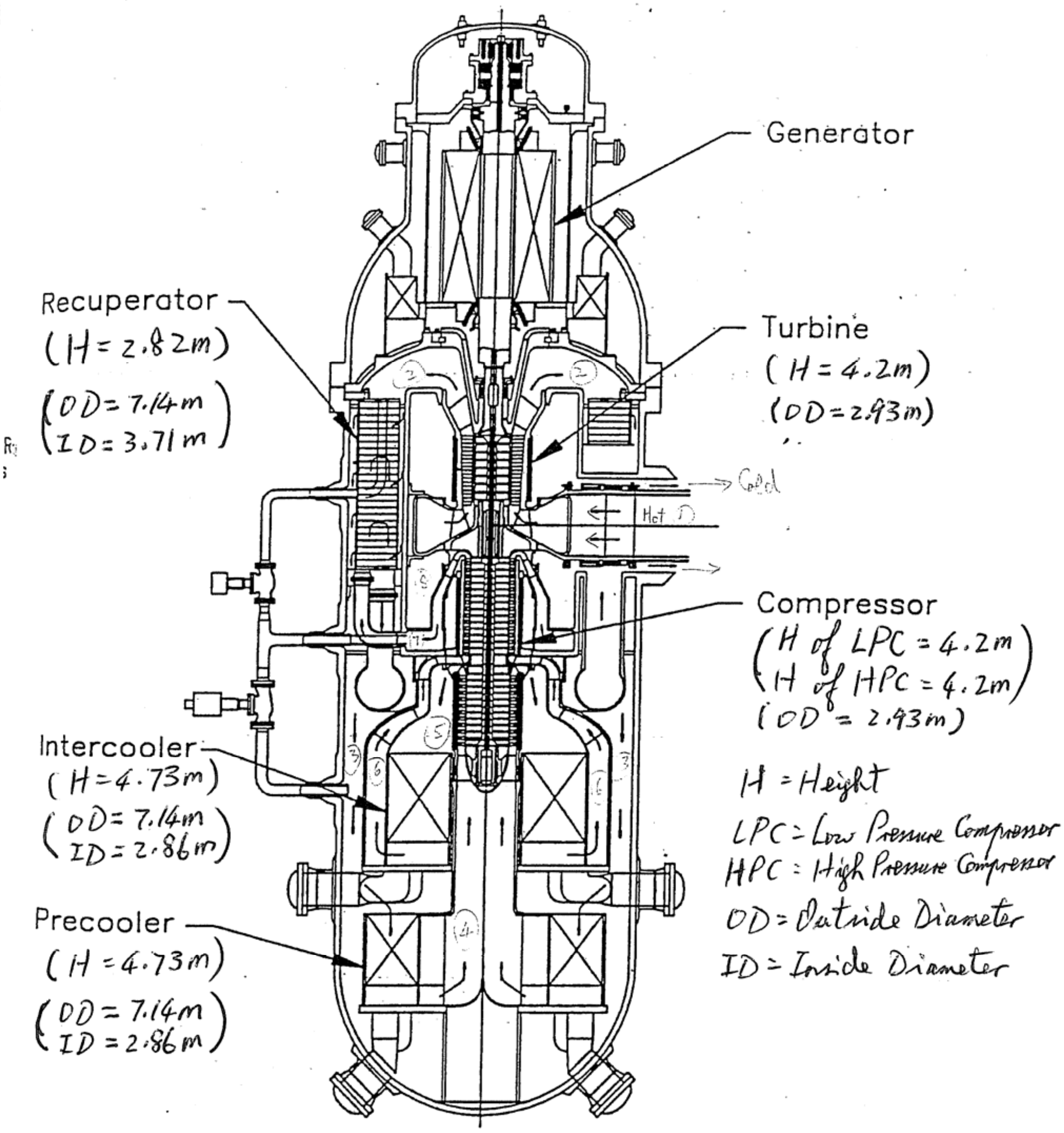
[2] Personal communication with D. Carosella of GA, Mathcad worksheet, PCUVOL.mcd, December 1, 2004.

[3] “Gas Turbine-Modular Helium Reactor (GT-MHR) Conceptual Design Description Report,” General Atomics Report 910720 Revision 1, GA Project No. 7658, July 1996.

[4] Golovko, V.F., et. al., “Features of Adapting Gas Turbine Cycle and Heat Exchangers for HTGRs,” Gas Turbine Power Conversion Systems for Modular HTGRs, IAEA-TECDOC-1238, p. 63-74, August 2001.

[5] Kostin, V.I., et. al., “Power Conversion Unit with Direct Gas-Turbine Cycle for Electric Power Generation as a Part of GT-MHR Reactor Plant,” Proceedings of the Conference on High Temperature Reactors, #Paper D21, IAEA HTR-2004, Beijing, China, September 22-24, 2004.

[6] “Review of the Gas Turbine-Modular Helium Reactor (GT-MHR) Plant,” Current Status and Future Development of Modular High Temperature Gas Cooled Reactor Technology, IAEA-TECDOC-1198, Chapter 4, February 2001.



HELIUM FLOW PATH IN POWER CONVERSION VESSEL

Figure A-1

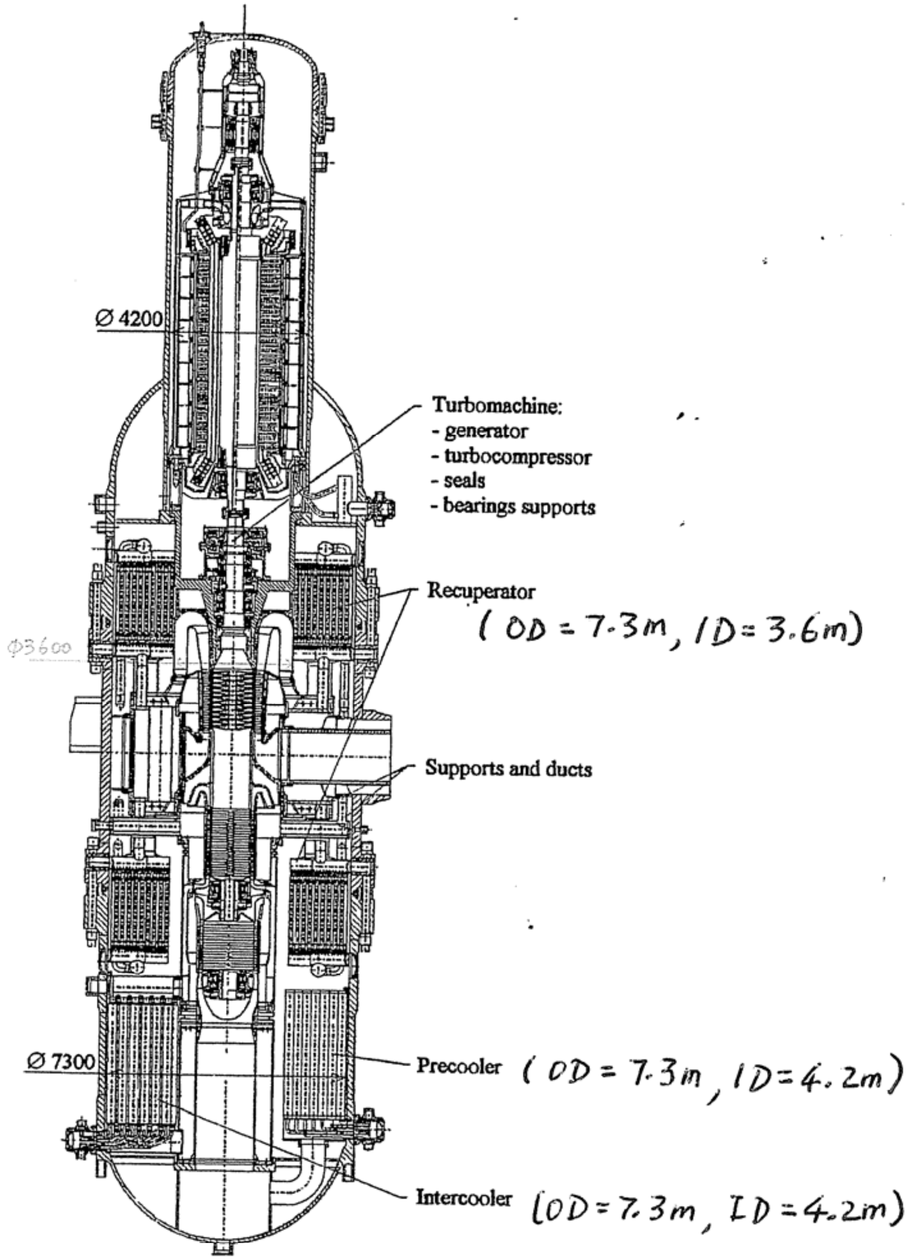


FIG. 4.10. PCS arrangement. (IAEA-TECDOC-1198)

Figure A-2

Appendix B – RELAP5-3D outputs for Case 05t32

A set of RELAP5 results for Case 05t32 was provided to ANL for use as boundary conditions for CFD calculations. These RELAP5 results are shown in the following figures.

Figure B-1. Break flow rate.
Figure B-2. Break pressure (upstream).
Figure B-3. Break temperature (upstream).
Figure B-4. Break junction internal energy.
Figure B-5. ECS heat exchanger upper riser gas temperature.
Figure B-6. ECS cold duct gas temperature.
Figure B-7. Reactor vessel inner wall temperature at junction with PCU outlet.
Figure B-8. Reactor vessel inner wall temperature at junction with ECS outlet.
Figure B-9. Reactor vessel inner wall temperature at mid-core.
Figure B-10. Precooler gas temperature (mid-volume).
Figure B-11. Intercooler gas temperature (mid-volume).
Figure B-12. Gas temperature on cold side of recuperator (mid-volume).
Figure B-13. ECS cold duct inner wall temperature.
Figure B-14. Gas accumulator flow.
Figure B-15. Gas accumulator junction internal energy.

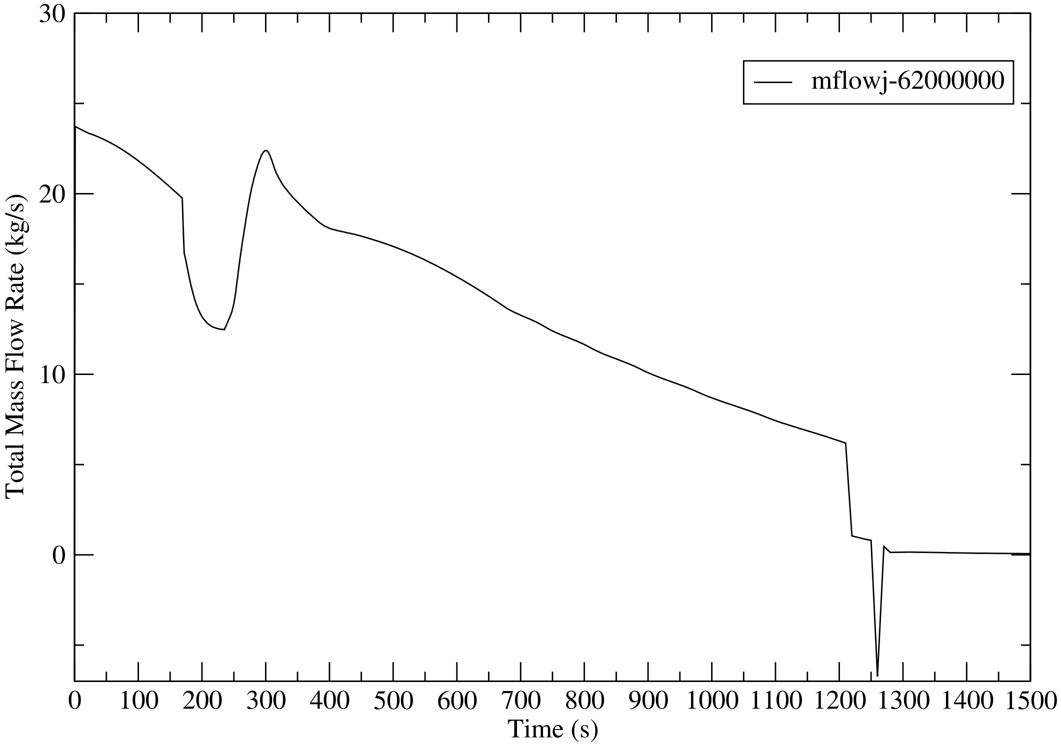


Figure B-1. Break flow rate.

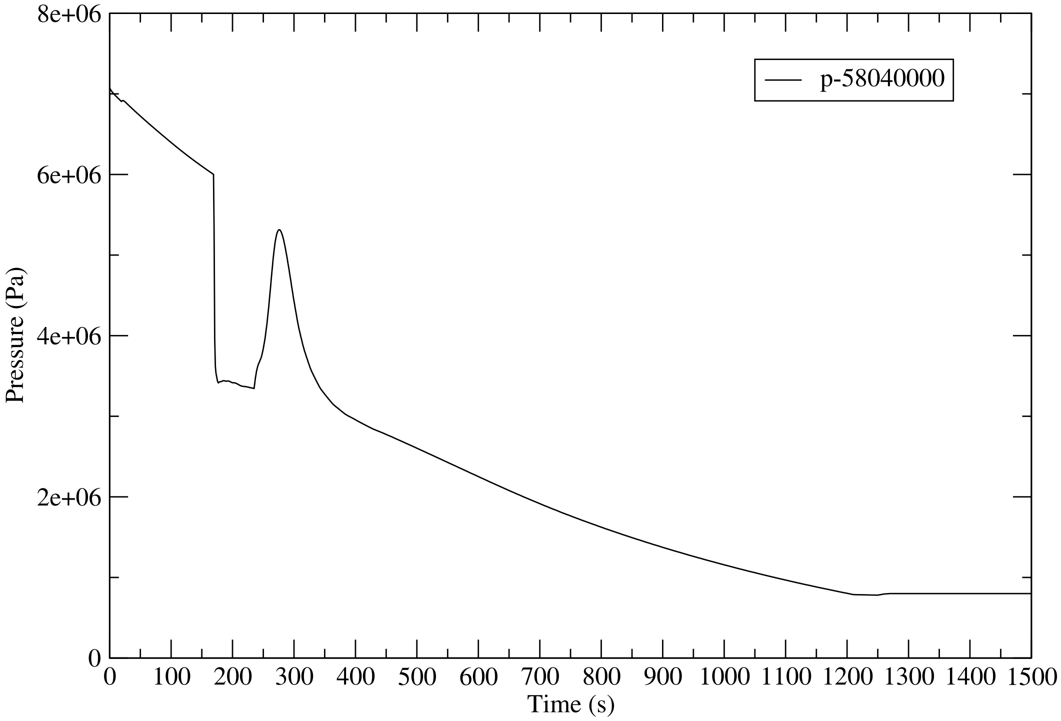


Figure B-2. Break pressure (upstream).

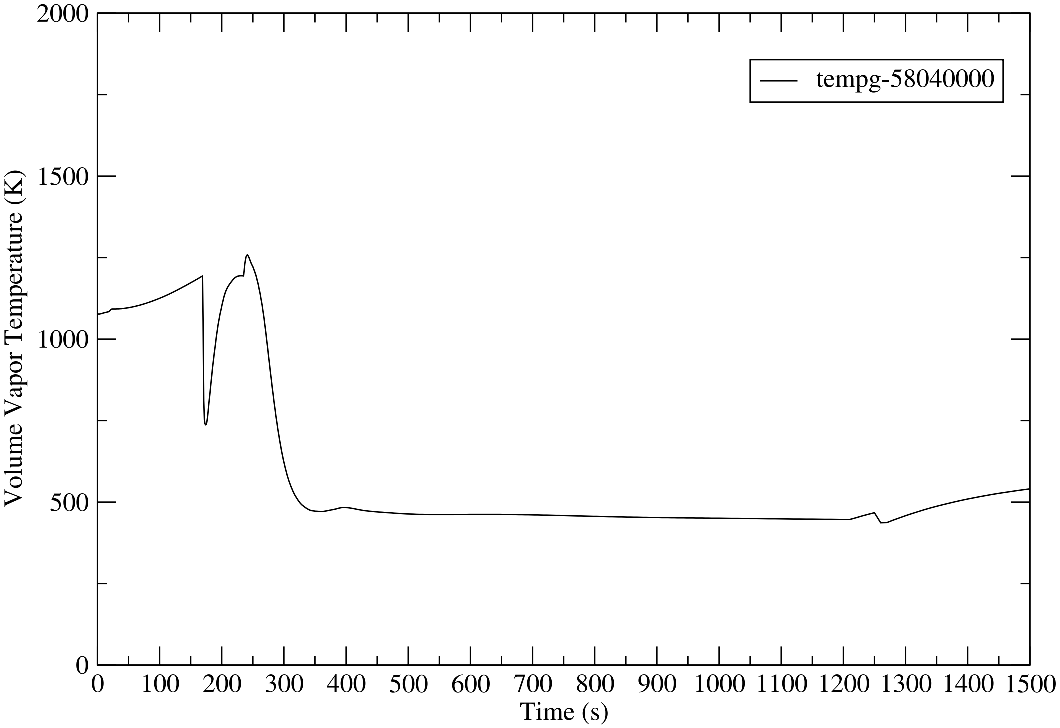


Figure B-3. Break temperature (upstream).

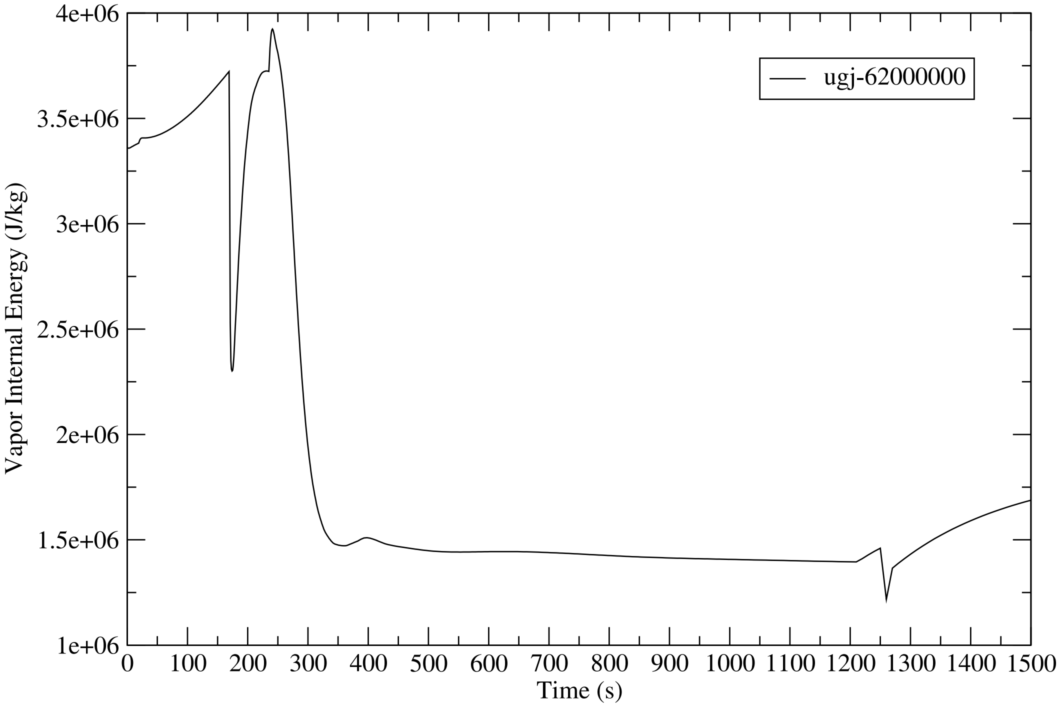


Figure B-4. Break junction internal energy.

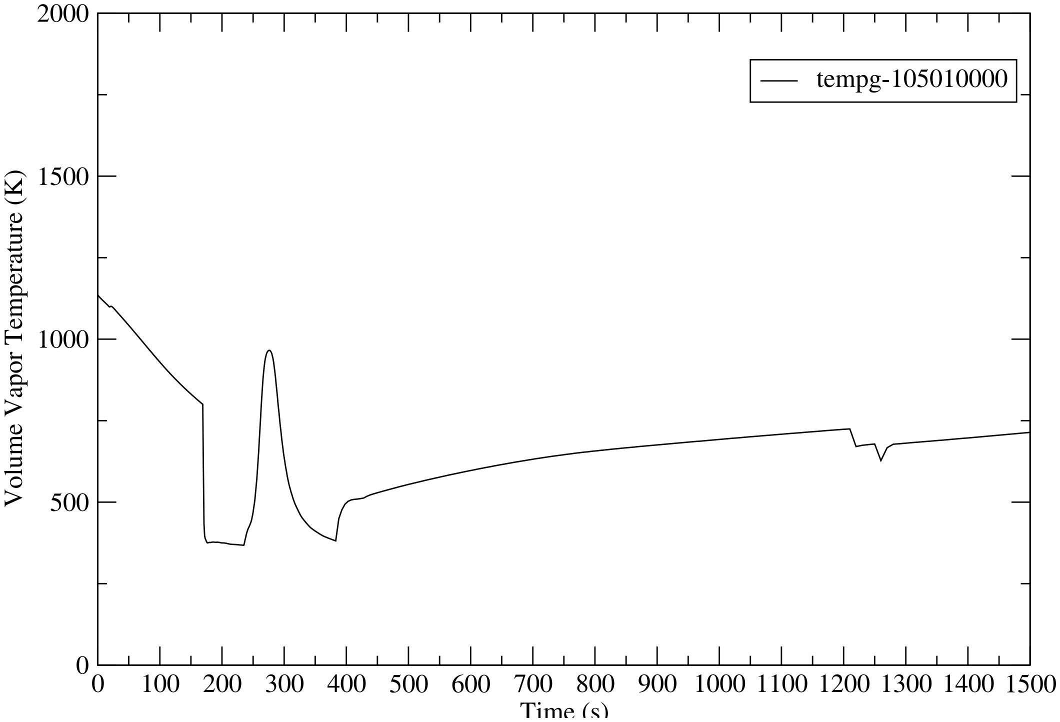


Figure B-5. ECS heat exchanger upper riser gas temperature.

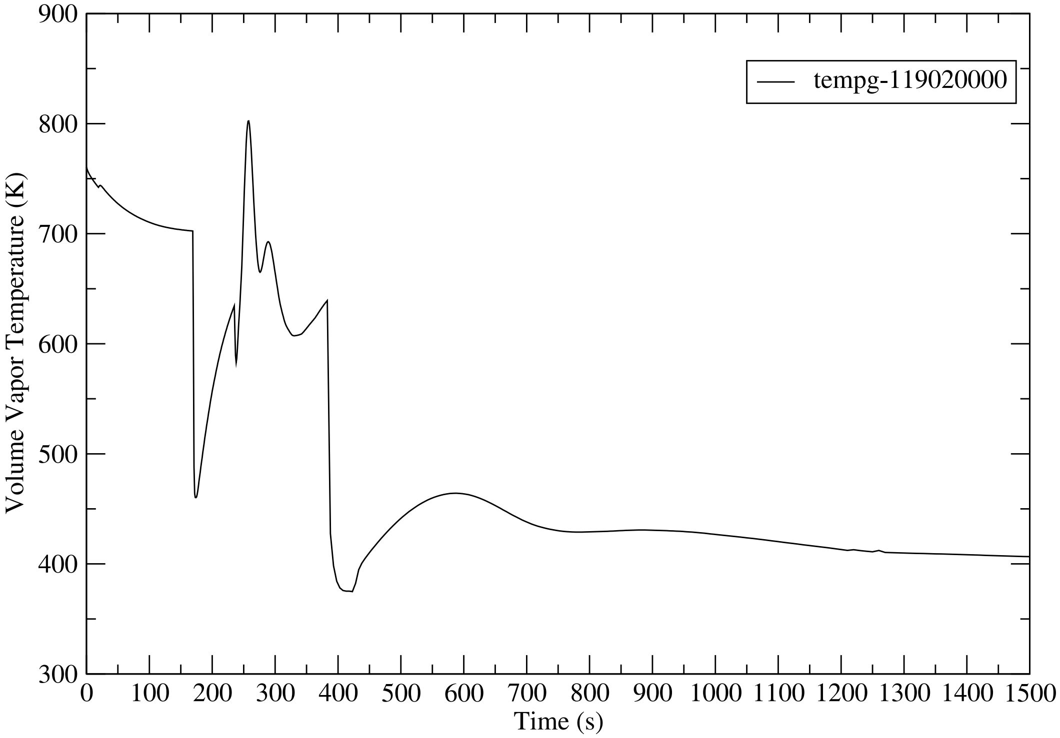


Figure B-6. ECS cold duct gas temperature.

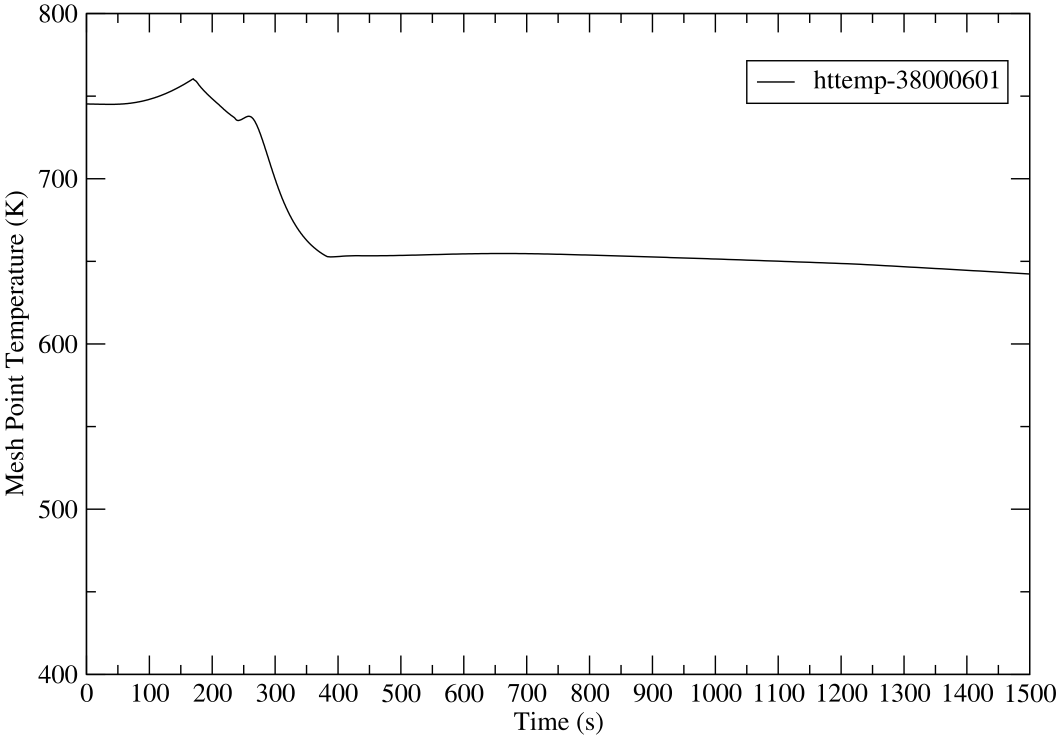


Figure B-7. **Reactor vessel inner wall temperature at junction with PCU outlet.**

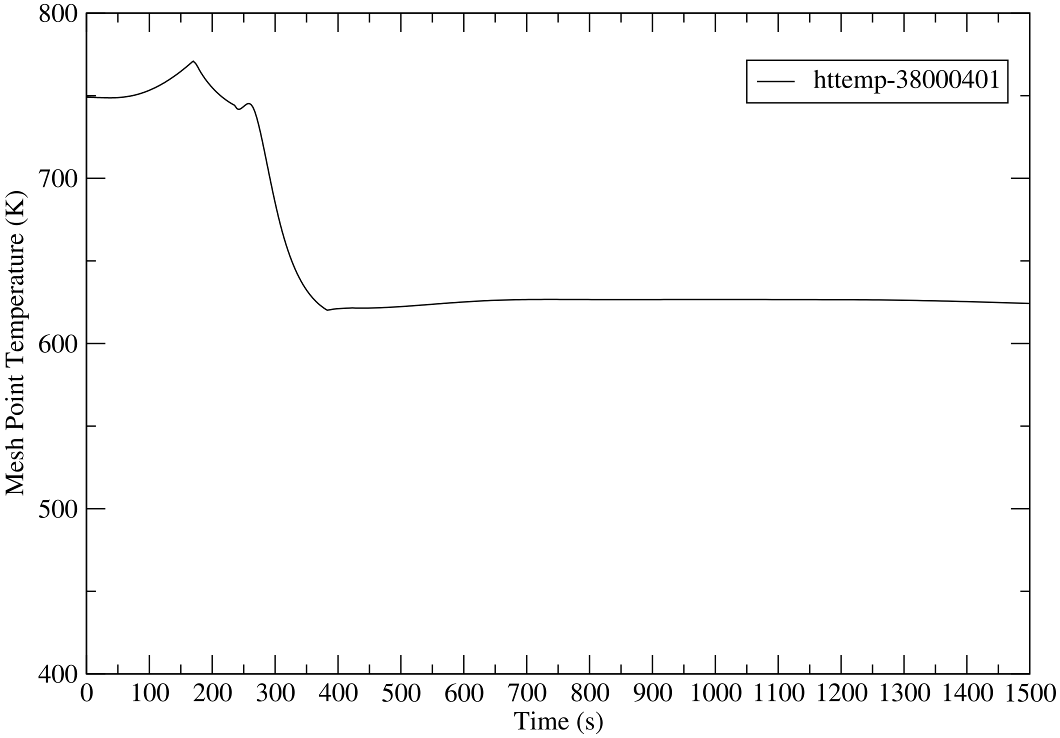


Figure B-8. **Reactor vessel inner wall temperature at junction with ECS outlet.**

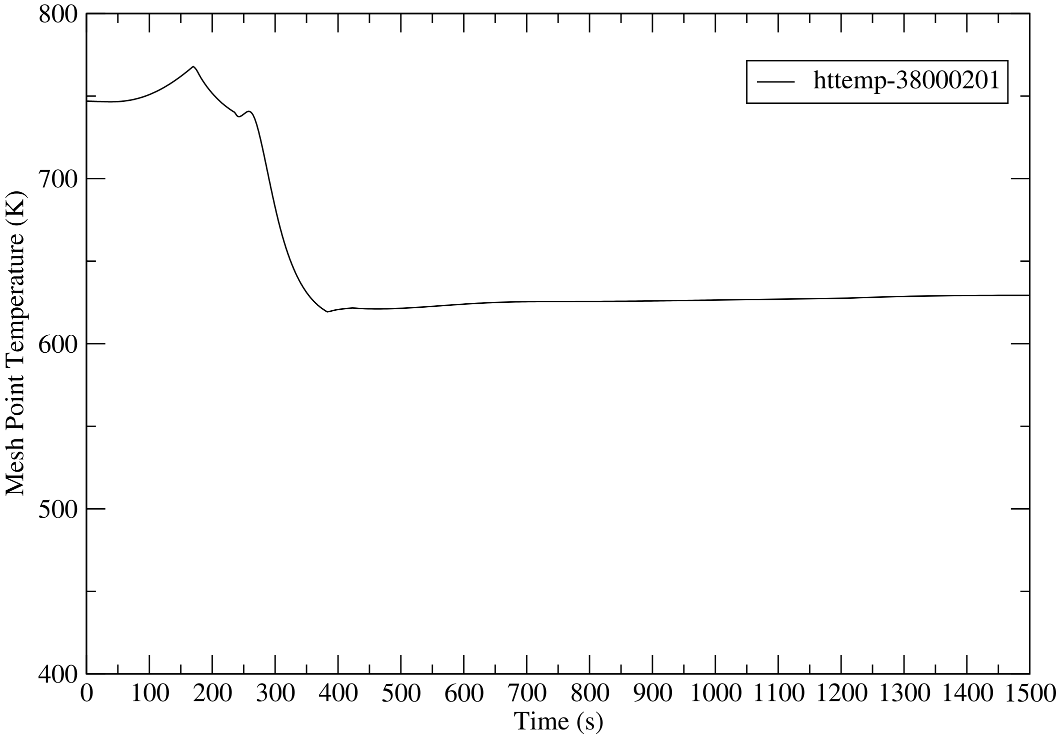


Figure B-9. **Reactor vessel inner wall temperature at mid-core.**

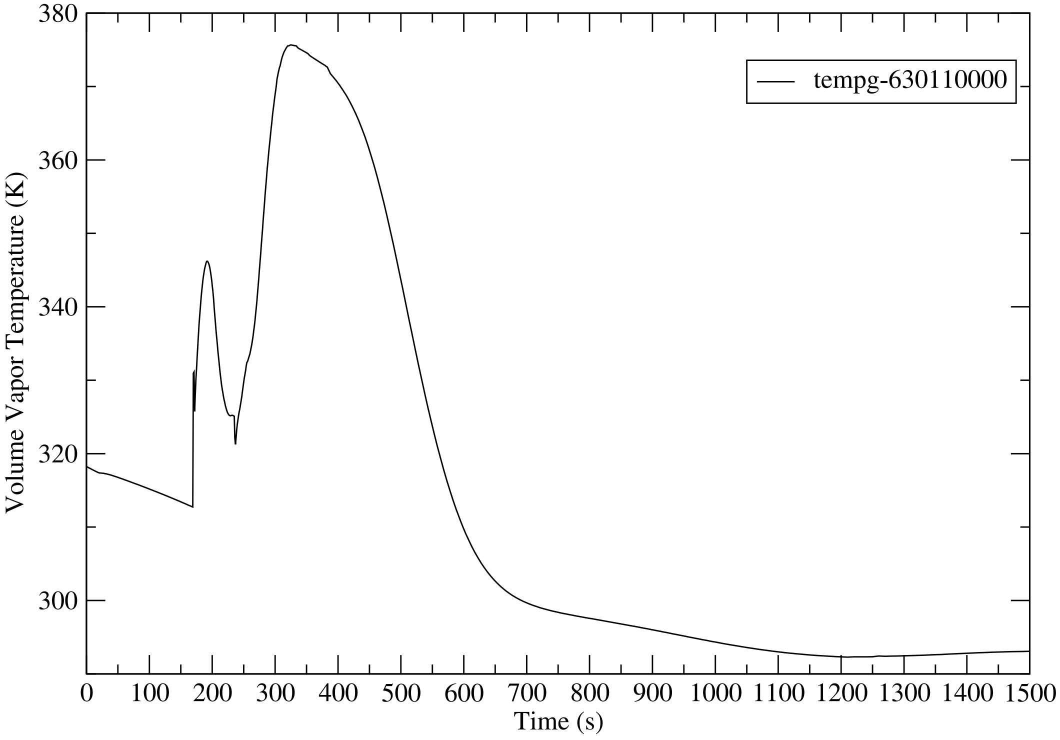


Figure B-10. **Precooler gas temperature (mid-volume).**

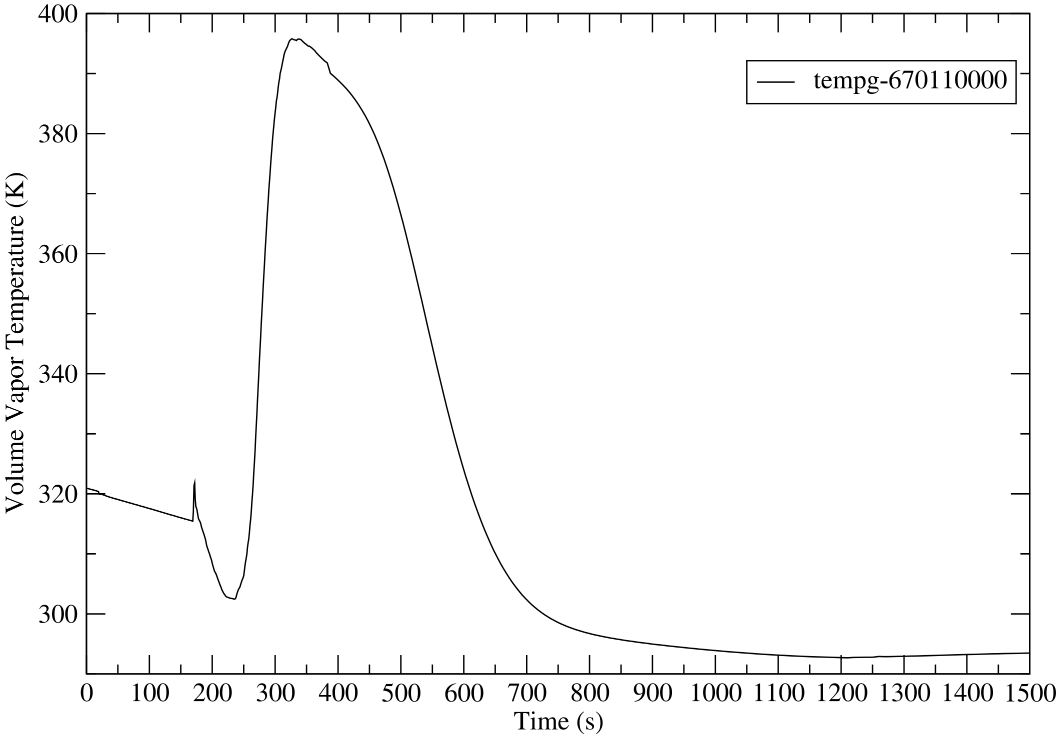


Figure B-11. Intercooler gas temperature (mid-volume).

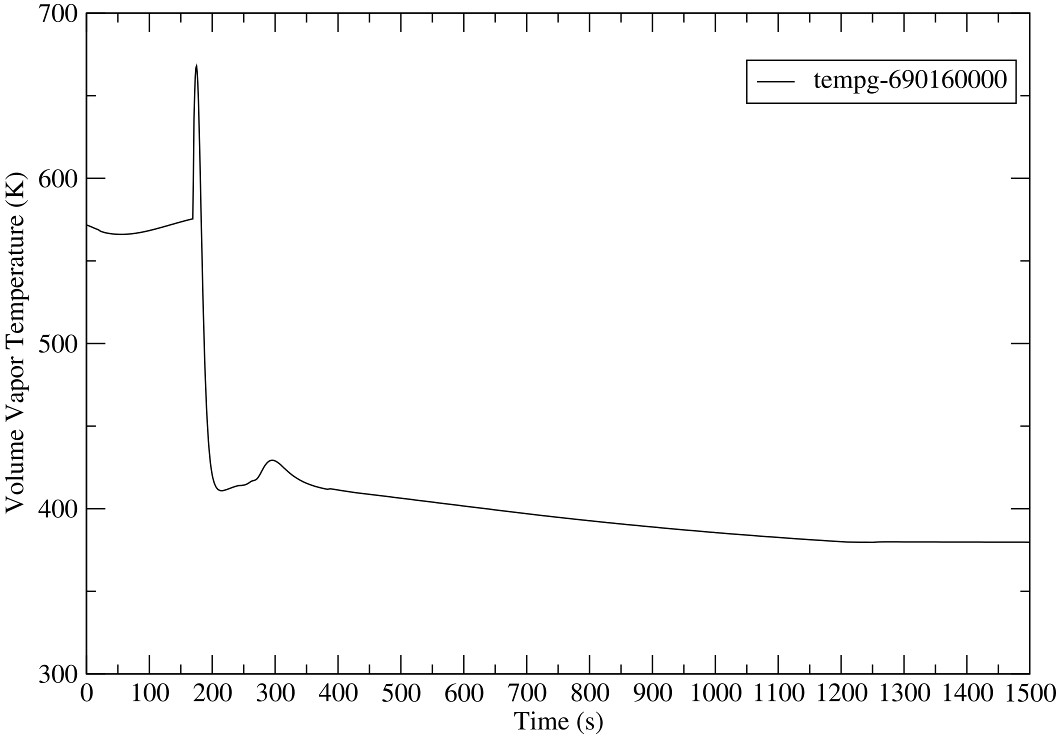


Figure B-12. Gas temperature on cold side of recuperator (mid-volume).

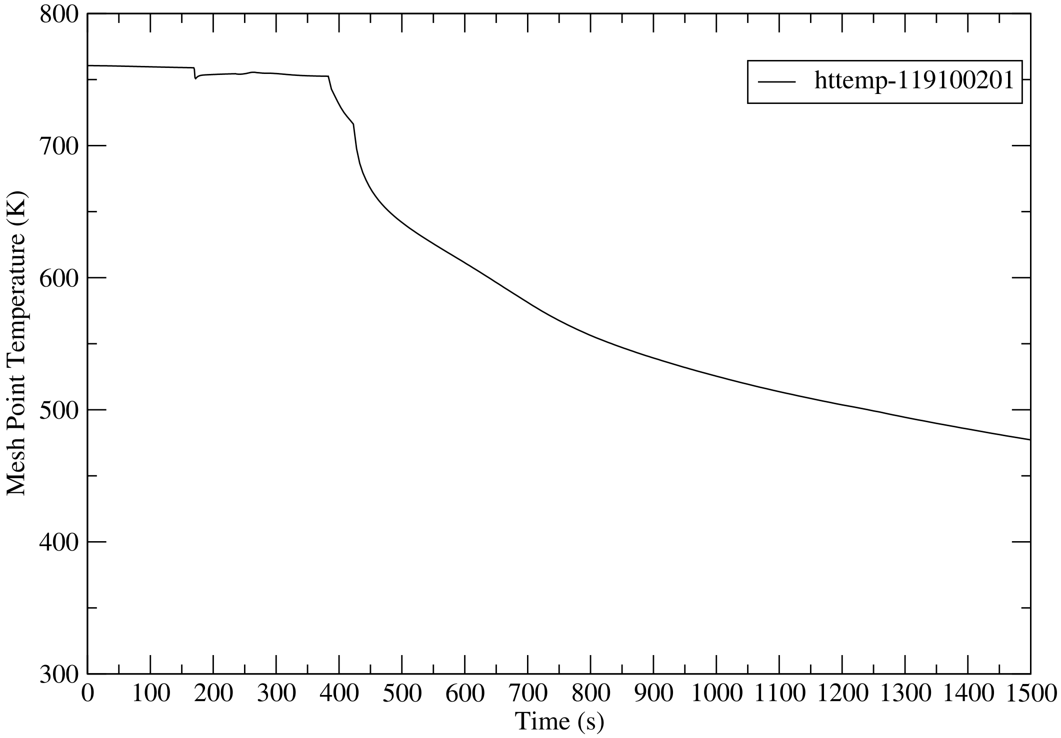


Figure B-13. ECS cold duct inner wall temperature.

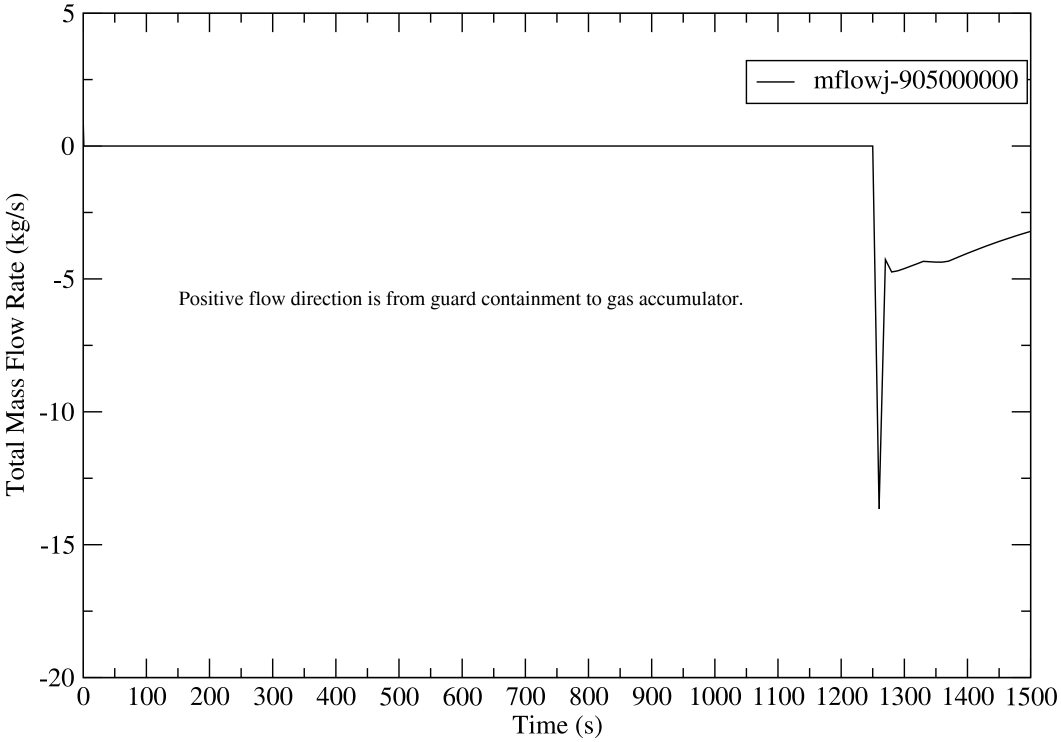


Figure B-14. Gas accumulator flow.

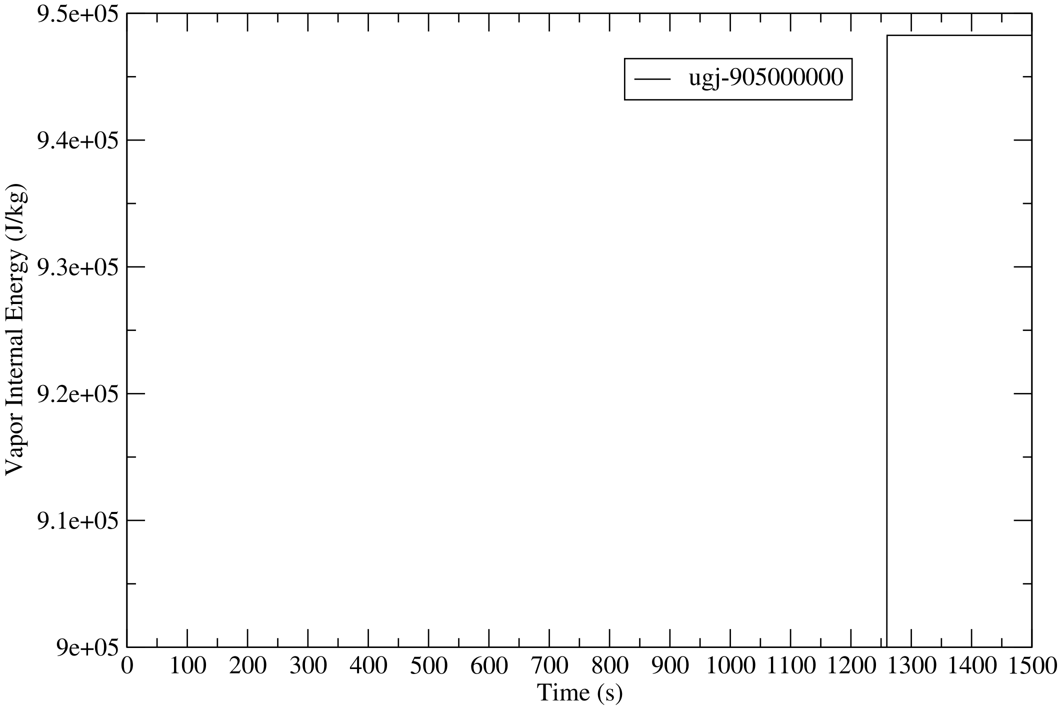


Figure B-15. Gas accumulator junction internal energy.