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Building Initial Dynamic System Models for Digital Twins of the Cryogenic Moderator System at the ORNL Spallation Neutron Source

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April 2022

OAK RIDGE National Laboratory

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ABBREVIATIONS

CMS	cryogenic moderator system
EOS	equation of state
FMI	functional mock-up interface
FMU	functional mock-up unit
HFIR	High Flux Isotope Reactor
HIL	hardware in the loop
LDRD	Lab Directed Research and Development
LVDT	linear variable displacement transformer
MIL	model in the loop
ML	machine learning
MSDR	Molten Salt Demonstration Reactor
ORNL	Oak Ridge National Laboratory
ROM	reduced-order models
SIL	software in the loop
SNS	Spallation Neutron Source
STS	Secondary Target Station
TTF	Target Test Facility
TRANSFORM	Transient Simulation Framework of Reconfigurable Modules

ABSTRACT

This work describes the initial development of dynamic system models of the cryogenic moderator system (CMS) of the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) as a part of the ORNL Lab Directed Research and Development (LDRD)-funded project *Building TRANSFORM to Accelerate Digital Twin Applications for Nuclear Systems*, LOIS 10563. The goal of the work is to start the dynamic system modeling effort with the end goal of using the resulting models for real-time applications as digital twins. The CMS is a cryogenic liquid hydrogen flow loop that provides moderation of the neutrons generated by SNS. For optimal neutron production, the CMS must maintain a steady, controlled density of cryogenic hydrogen in the moderator section, thus requiring precise temperature and pressure control. Because of the varied time scales and system characteristics, system control is complex, and diagnostics are also difficult. Difficulty in accessing the flow loop during operations, limited instrumentation, and unknown equipment design details combine to make the case for developing sophisticated digital twin models of the system. Operationally, the CMS provides a strong use case for digital twins because of the constant need for optimization and for troubleshooting/diagnostics purposes. The large amount of data collected are freely available for use in building the model and verifying and validating the model. These data also make the CMS an exceptional candidate for a digital twins proof of concept. This project extends ORNL's capacity to develop and implement the open-source dynamic system modeling tool TRANSFORM (Transient Simulation Framework of Reconfigurable Modules) for engineering design and digital twin real-time applications. Specific system configuration data for the CMS have been gathered, and an initial dynamic model was created in the TRANSFORM library using Dymola as the solution platform. Models of increasing complexity are being created to demonstrate the need for a multilayered approach in digital twin modeling according to the scale and phenomena of interest. Dynamic modeling has been shown to bring the system's dynamic operational aspects to the design process, to serve as a digital twin to the hardware, and to allow for models to be tuned and compared against real-time operational data. These aims should help promote strategic goals for the application of digital twins and increase the impact of ORNL systems modeling capabilities with TRANSFORM/Modelica for advanced energy systems.

1. INTRODUCTION

1.1 MOTIVATION

1.1.1 Goals of this Project

The goal of this LDRD project, *Building TRANSFORM to Accelerate Digital Twin Applications for Nuclear Systems*, LOIS 10563, is to advance ORNL's capacity to develop and implement dynamic system modeling tools like ORNL's TRANSFORM (Transient Simulation Framework of Reconfigurable Modules) for engineering design and digital twin / real-time applications and to support edge utilization of high-fidelity instrumentations. This will be accomplished through deployment and demonstration in early adoption applications on existing and near-term ORNL infrastructure such as the Spallation Neutron Source (SNS) Target Test Facility (TTF) and the new Second Target Station (STS). Another objective is to broaden the user base of TRANSFORM into other energy sectors through implementation in oil and gas or subsurface energy applications. One major area of importance is the open-source nature of the TRANSFORM library, which allows access to a much broader user base.

There is an opportunity to help develop interfaces between lower order system models and physical models for use in real-time operation. Operational tuning will benefit though integration of scalable engineering tools that can be readily implemented in the operation and control of the final system. The concept is to integrate dynamic system models that can be connected as real-time embedded systems as hardware-in-the-Loop (HIL), software-in-the-loop (SIL), and model-in-the-loop (MIL), called *IL systems* in the remainder of this document. At this writing, there have been few demonstrations of IL implementations for thermal-fluid systems on the scale of energy systems. One way to proceed is to develop physics-based dynamic models that capture the essential behaviors of the physical system. The closure equations in these models can then be tuned using parameters gained from the actual operating parameters. Adding machine learning (ML) into the loop will allow for continuous learning of the system. This approach is similar to the approaches taken in the autonomous vehicle industry.

These new digital technologies for engineered system operation and control are becoming ubiquitous in all industry sectors. Development has accelerated in the autonomous vehicle and information technology industries. However, the nature of traditional nuclear power operations has caused digital technologies to remain in their infancy in the nuclear industry. Licensing and regulation have made the integration of digital systems into existing nuclear power plants virtually impossible. It is paramount that these technologies be integrated early into next-generation advanced nuclear power systems. Cutting edge concepts like digital twins have the potential to advance entire new paradigms in operations and maintenance and the processes used to assess system safety. Digital twins can create opportunities for increased economic benefits and safer operations in the nuclear industry.

To further develop these new technologies, it is paramount that carefully planned subscale tests and demonstrations be performed to allow for proper assessment and acceptance of the technology to proceed. This project establishes early adoption opportunities by making digital twins of existing and near-term laboratory systems here at ORNL and then working to implement the technology in existing industries such as oil and gas.

1.1.2 Dynamic Systems Modeling

Most engineering failures in newly designed systems result from unforeseen dynamic system behaviors. Dynamic system problems can also arise during off-normal operation of long-running systems and facilities. This off-normal operation can be caused by accidents, unintended operations, degradation, wear of the system, or changes to operational procedures and goals. The fundamental reason for these unforeseen failures lies in the nature of traditional engineering tools and education. Most of the focus in engineering design is placed on steady-state operational points, idealized accident scenario evaluation, and the objective to meet static safety margins. This "static mindset" prevents engineering analysis and design calculations from capturing important dynamic effects early enough to mitigate them. Early capture of dynamic effects results in dramatic cost savings for the overall project. Incorporating dynamic thinking into engineering design also adds enhanced safety performance through robustness.

The static mindset is exacerbated by a lack of flexible tools that allow for incorporating dynamic effects into the engineering design process. Historically, dynamic system modeling has been impeded by a lack of computational power and oversimplification of manual solution methods. Dynamic system modeling requires significant detail to capture key dynamic behaviors. However, recent improvements in dynamic modeling tools have emerged as a result of the need for more flexible methods to model complex dynamic systems such as those encountered in aerospace, autonomous machines, and data flow networks. Modelica is a tool that has gained tremendous momentum in open-source dynamic system modeling Greenwood [2017].

Modelica is a nonproprietary, object-oriented, equation-based programming language used to conveniently model complex physical and cyberphysical systems, to include systems containing mechanical, electrical, electronic, hydraulic, thermal, and control components. A key advantage of Modelica is its separation of physical models and the solvers of the models. This separation enables rapid generation of complex physical system models and control design in a single language without deep knowledge of numeric solvers, code generation, and other factors. A major homegrown ORNL initiative has been the development of TRANSFORM (Transient Simulation Framework of Reconfigurable Modules) inside the Modelica ecosystem Greenwood [2017]. TRANSFORM is an ORNL-developed component library created using the Modelica programming language for the investigation of dynamic thermal-hydraulic systems and other multiphysics systems. The TRANSFORM library allows for rapid development of energy systems models, enabling the modeler to customize the components for any application, including instrumentation and control design. The complexity of how a large-scale model of an advanced reactor design (in this case a molten salt reactor) can be easily captured inside TRANSFORM is illustrated in Figure 1.

TRANSFORM marks a much-needed departure from traditional static system licensing codes like RELAP. TRANSFORM allows models to be developed in a modular, open-code manner which can be progressively expanded with increasing amounts of complexity as needed. Flexibility and speed are essential to the cost-effective development of next-generation energy systems, especially advanced nuclear power systems. Traditional licensing system codes are not suitable for parameter sweeping or scoping design or for development of real-time digital twin applications (hardware/software/model-in-the-loop). For this reason, there is a great need for agile system analysis tools for the development of next-generation energy systems that can be integrated into hardware.

Another important key to building tools for advanced reactor development is to foster a community of users of these tools. To develop a community, tools should be easy to access, and efforts should be made to

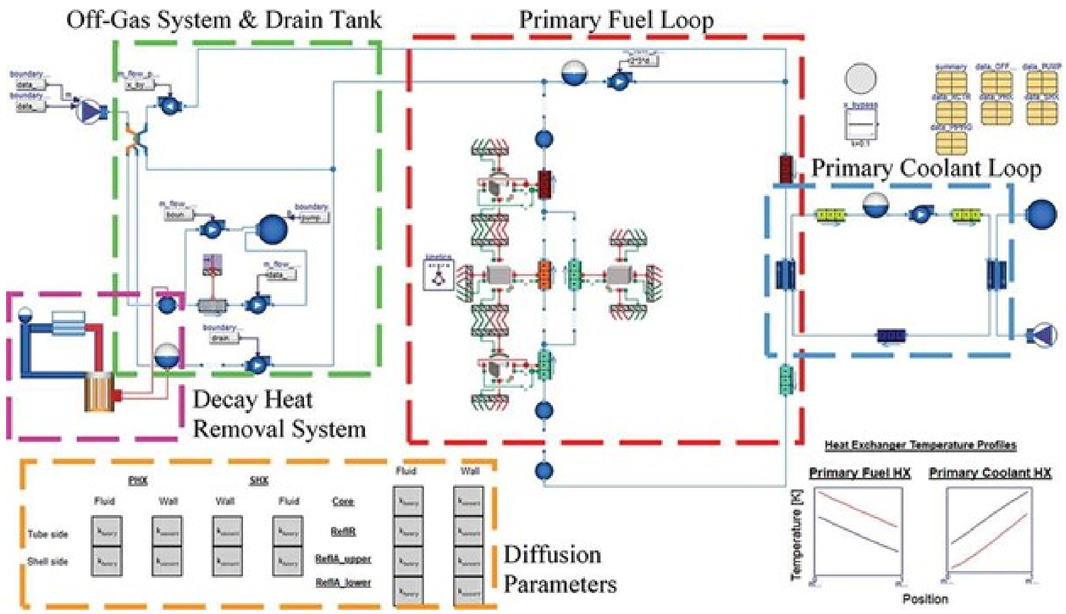

Figure 1. System model of a fluoride salt-fueled thermal reactor based on the Molten Salt Demonstration Reactor (MSDR). Colored box outlines represent corresponding systems between the MSDR flowsheet and the system model.

flatten the learning curve. Modern developments in software and cloud-based resources are opening up opportunities for modularity and scalability. Thge objective of this research effort is to build the Modelica/TRANSFORM user community in advanced reactor development and in other energy systems research and operations. The ability to quickly launch and come up to speed on system tools will directly impact their utilization. Modelica offers the opportunity to achieve this, but some growth in the user base is needed in thermal-fluid systems to achieve a critical mass.

1.1.3 Real Time Dynamic System Modeling, Reduced Order Modeling, and Control

Modelica also allows for compiled code as functional mock-up interface (FMI) / functional mock-up unit (FMU) interfaces. These can be coupled with other computational FMI/FMUs if higher fidelity is needed. The Modelica models can then be connected to real systems through simple or ML-based learning software that uses operational system data for learning and tuning the system or diagnosing/predicting the behavior of a dynamic system. There are opportunities to use mixtures of dynamic system models with ML and data to create reduced order models (ROMs) to produce faster solving systems. Current issues to be resolved include developing a way to properly interface these systems and a method for selecting the correct numerical solvers to capture the time-based dynamics of the system appropriately—both synchronously and asynchronously. In theory, the main structures of these technologies exist, but their integration can depend on the dynamicity of the system at hand. Opportunities for further research exist at all interfaces. This research may require refinement of numerical solvers and data flow techniques to properly capture the real-time synchronicities and/or asynchronicities.

Finally, it is envisioned that current increases in fidelity of instrumentation and sensing technologies will require more computational power at the edge to decipher complex and large data sets that may have strong qualitative natures. Simplified but descriptive dynamic system models (e.g. ROMs) operating at the edge can guide the collection and utilization of these data sets. This technology is already functioning in autonomous vehicles, where changing organic surroundings can be "understood" by ML in collaboration with physical models of the systems. This is an emerging field in which high-fidelity sensing can feed fast-learning, lower fidelity physics-based models through ML. This approach can help alleviate the need for human interpretation of qualitative high-fidelity signals while maintaining a base understanding and operating envelopes with physics-based models.

1.1.4 Use Case Selection

As mentioned above, finding ways to prove the concepts needed for application of digital twin models in nuclear systems will require knowledge that can only be practically gained from existing systems. ORNL has many opportunities to study the use of digital twins through scientific systems containing sophisticated, large support systems. The Spallation Neutron Source (SNS) provides one such unique opportunity. SNS has many dynamic support systems with extensive instrumentation and controls, not unlike advanced nuclear reactor systems. Large, openly available data stores from system operations provide details on many steady-state and transient system behaviors. The Cryogenic Moderator System (CMS), along with the supporting cryogenic vapor cycle system, is one of the most accessible and tractable systems. The CMS is a critical part of SNS operations, and it undergoes a wide range of operating conditions. The system dynamics and multiple scales provide an excellent opportunity for modeling and proving the use cases for digital twins. The system's general thermo-fluid components include characteristics suitable as a corollary to an advanced nuclear system. For this reason, the SNS CMS primary cryogenic hydrogen loop has been selected as a starting point for this work. A full description of the CMS follows.

1.2 SNS CRYOGENIC MODERATOR SYSTEM

1.2.1 General Description of the System

The Cryogenic Moderator System (CMS) is an essential part of the production of neutrons at SNS. The CMS provides a flow of controlled density cryogenic hydrogen which acts to moderate—or slow down—the neutrons produced by the SNS beam hitting the target. The system dynamics are driven by the need to accommodate heat generated by the beam energy while maintaining constant hydrogen density. The flow of constant density hydrogen is controlled by a steady flow of hydrogen in a loop containing a heat exchanger to remove the heat generated in the moderator while the beam is on and an accumulator that acts as a volume expansion tank is effectively maintaining constant pressure in the system. The loop contains a fixed mass of hydrogen which is circulated through the heat exchanger and the connecting piping by a centrifugal circulator/pump: a general schematic is shown in Figure 2. The system is insulated with cryogenic helium, which also provides pressure to the accumulator bellows and cooling on the cold side of the heat exchanger. The helium system and its accompanying refrigeration cycle are not considered in detail in this work, but they present many opportunities to expand of the digital twin concept. The helium refrigeration cycle serves three similarly specified hydrogen loops, similar to that shown in Figure 2.

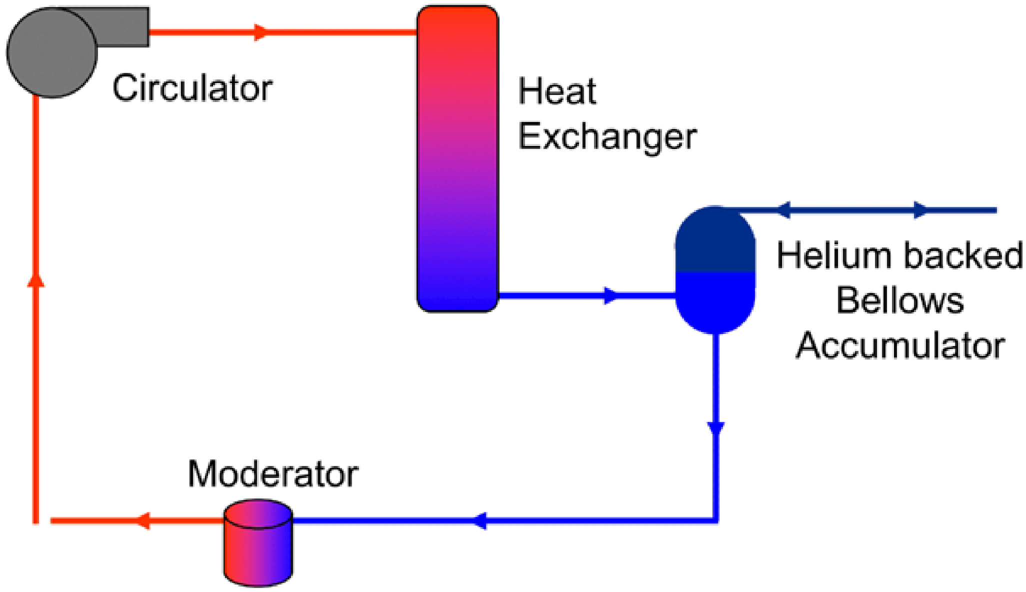

Figure 2. Schematic of CMS hydrogen loop.

1.2.2 CMS Normal Operating Conditions

The hydrogen operates as a supercritical fluid at all times to avoid phase changes. The hydrogen should be maintained at 20 K. Minimum loop pressure is maintained above 14 bars to provide a 1 bar margin above critical pressure. Because of the constant mass of hydrogen, the system must accommodate pressure/temperature fluctuations created by changes in the beam energy. Beam-off pressures range from 14 to 15 bars, and beam-on pressure ranges from 15 to 16 bars. The hydrogen supply temperature is controlled to maintain an average moderator temperature of 20 K, so the hydrogen throughout the loop is between 17.5 and 22.5 K. The heat exchangers are designed with a tight approach of 0.5 K. The circulator provides approximately 1 L/s of flow and is capable of 1 bar differential pressure development. The CMS is controlled without a compensation heater, so the beam trip effects on heat generation are handled by secondary helium heat exchange bypass.

1.2.3 Circulator

The circulator is designed to nominally provide 1 L/s of hydrogen at 1 bar of differential pressure. A picture of the circulator is shown in Figure 3. It is a fan-type impeller mounted on a diffuser that can move gas or liquid. It can circulate at up to 17,000 RPM and approximately 1 L/s. A performance curve is shown in Figure 4.

1.2.4 Heat Exchanger

The heat exchanger is one of the most vital and dynamic components of the system. The heat generated in hydrogen in the moderator section is removed by a stream of helium. Unfortunately, the design of the heat

Figure 3. Hydrogen circulator.

exchanger is proprietary, so the exact details of the geometry are not known at the present time. The overall large dimensions of the heat exchanger are known, as seen in Figure 5. The heat exchanger is like a plate-type heat exchanger with stacked sheets of corrugated metal. Helium supply temperatures are kept at 16.5 K and are maintained by a control system of valves that are used to split the flows between 3 separate heat exchangers for the three different CMS loops. Further geometric details of the system are described in the ATHENA/RELAP Model section.

1.2.5 Moderator Section

The moderator section has a special custom geometry which allows for a flow stagnation point in the section that encounters the neutrons generated by the beam/target system. There are three separate moderators, each of which has its own geometry. The outside of the moderator vessel is shown in Figure 6. It is arranged around the target system vessel inside a pocket, as shown in Figure 7.

1.2.6 Accumulator

The CMS is operated as a closed mass system. The hydrogen is loaded until the desired pressure is met (14/15 bar). The generation of heat in the control mass would cause an increase in the volume of the cryogen. If the volume is not allowed to expand, then the system pressure would rise drastically, and the

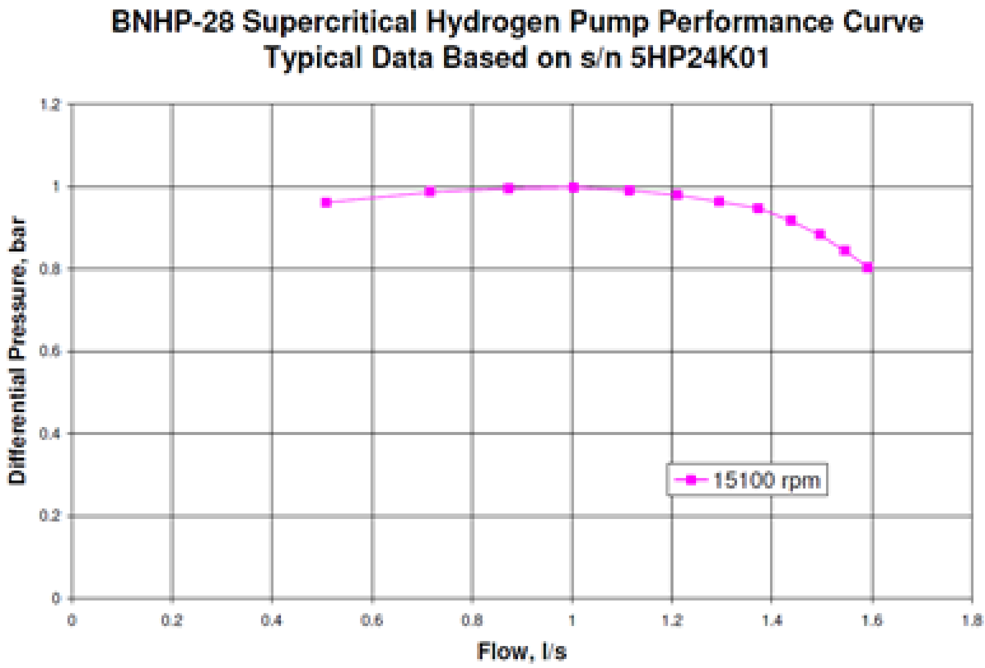

Figure 4. Hydrogen circulator performance.

system would be over-pressurized. To allow for this expansion, a constant pressure metal bellows accumulator is added to the CMS loop as shown in Figure 8 and 9. The accumulator is a flow-through type accumulator, meaning the hydrogen enters the top of the outer vessel. The hydrogen flows down the sides of the annular space around the vessel, thus cooling the volume. The hydrogen then enters the bottom chamber, where it fills the inside of the metal expansion bellows. If the system is heated, then the bellows will expand, but if it is cooled, the the bellows will contract, thus maintaining the constant pressure of the helium supply charge on the back side of the metal bellows, as shown in Figure 10. The helium is also a control volume and is charged to the desired operating pressure of approximately 15 bar. The accumulator also has a linear variable displacement transformer (LVDT) which is used to measure the location of the bellows to provide further information regarding the change of system volume.

1.2.7 Transfer Lines

The hydrogen transfer lines move the fluids from the circulator and heat exchanger to the moderator section. The design provides multiple concentric tubes for insulating the system and to ensure hydrogen containment in case of a leak. Pictures of the transfer lines' flexible and hard piping are shown in Figure 11 and 12. A schematic of the layout is shown in Figure 13. The supply tubing is within the innermost tubing and is surrounded by an intermediate annulus at vacuum. This annulus is surrounded by the hydrogen return annulus, and finally, the entire assembly is surrounded by vacuum. Vacuum insulation is required to maintain the desired cryogenic temperature of the system. However, the system does leak some heat from the ambient air into the system.

Figure 5. Heat exchanger module (showing all three loops).

1.3 PREVIOUS ATHENA/RELAP MODEL

The CMS system was previously modeled in ATHENA/RELAP as a part of the design review process. ATHENA/RELAP has also been used to model the cold source system at the High Flux Isotope Reactor (HFIR). The input deck for the model is used here to determine the existing geometry and some other key system parameters. A nodalization for the ATHENA/RELAP model is shown in Figure 14 and 15. Detailed nodalization of the transfer lines is included, because historically there were issues requiring detailed modeling. Additional information was taken from data collected as a part of the previous ATHENA/RELAP modeling. The entire input deck is provided in Appendix A. More information was found in drawings to support this model creation.

Figure 6. Moderator.

Figure 7. Moderator vessel pockets (one inserted, one removed).

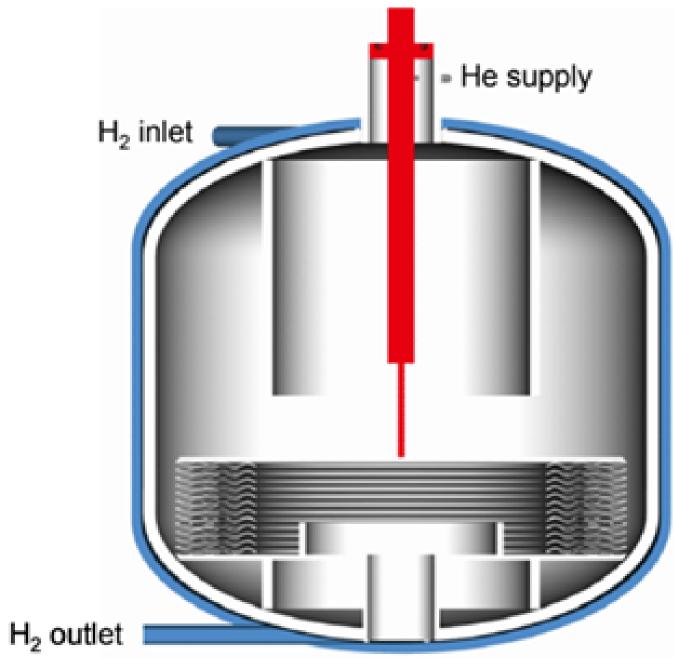

Figure 8. Schematic of accumulator.

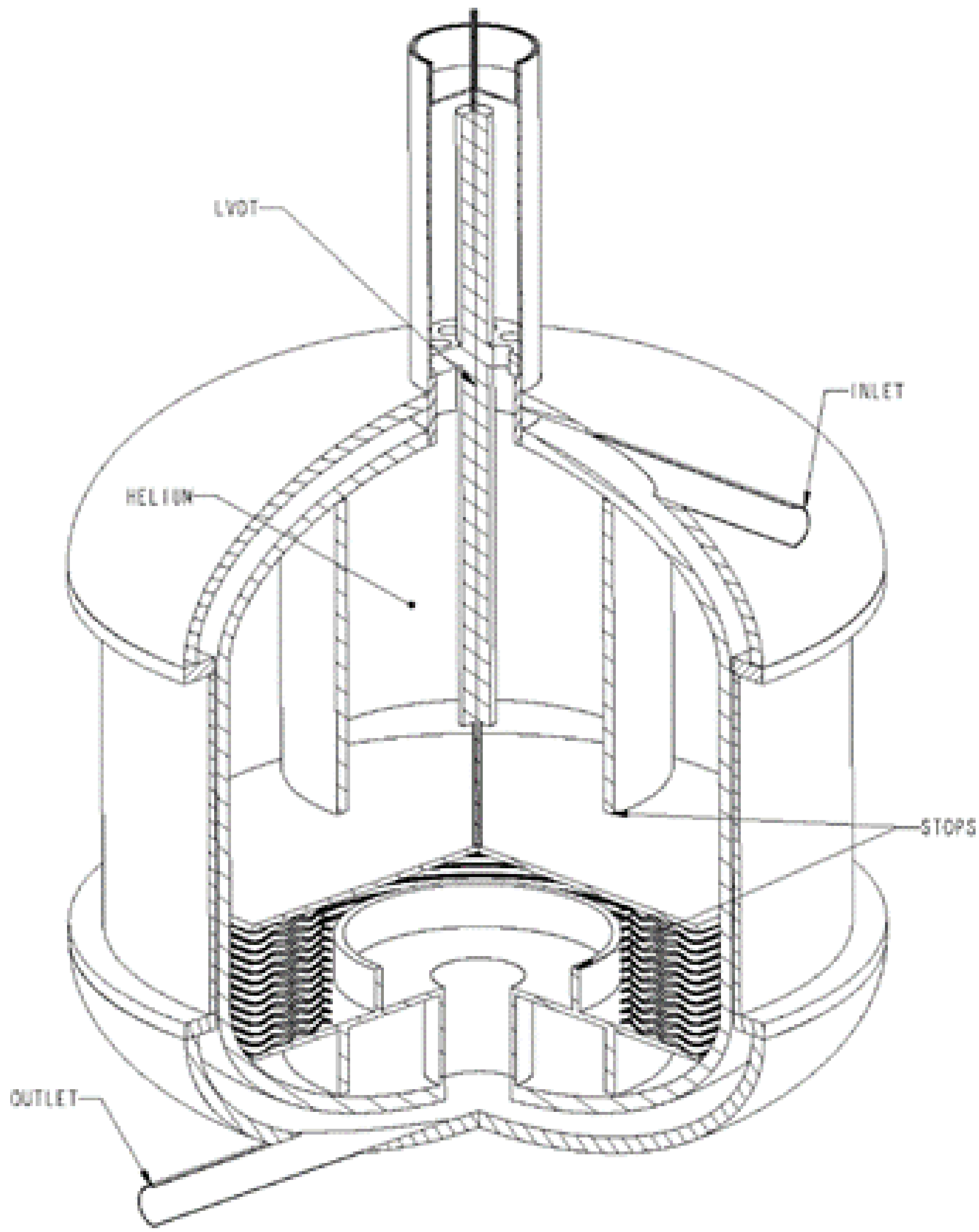

Figure 9. 3D schematic of accumulator cutaway.

Figure 10. Metal bellows of the accumulator.

Figure 11. Flexible section of transfer lines.

Figure 12. Hard pipe transfer lines.

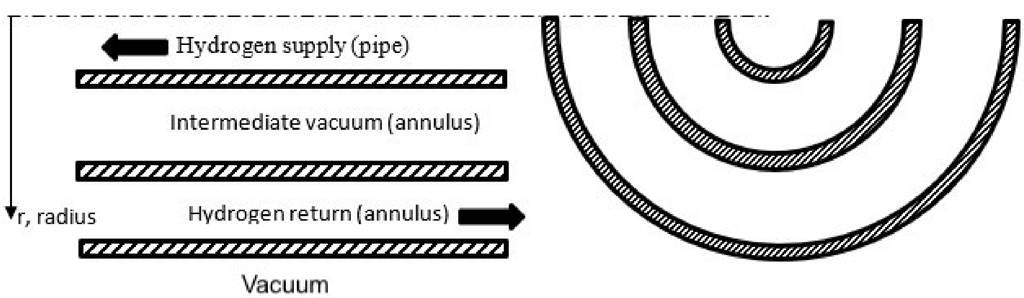

Figure 13. Section view of transfer line tubing (r is the radial distance from the centerline of the flow).

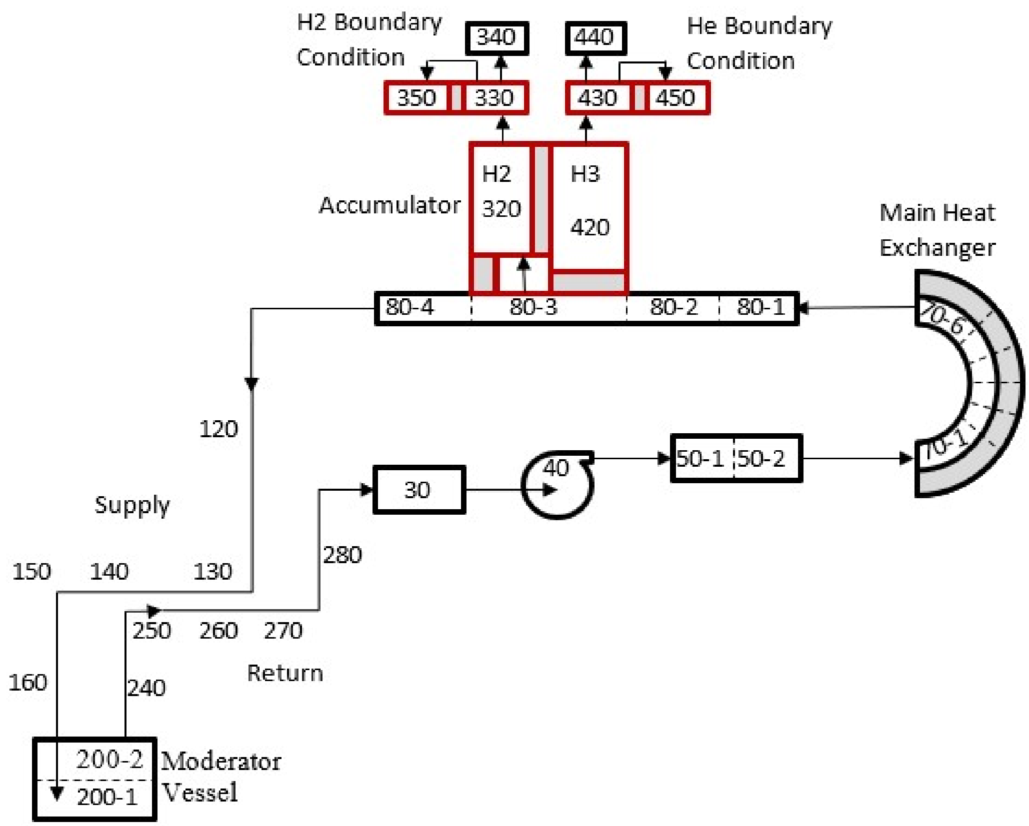

Figure 14. ATHENA/RELAP nodalization schematic.

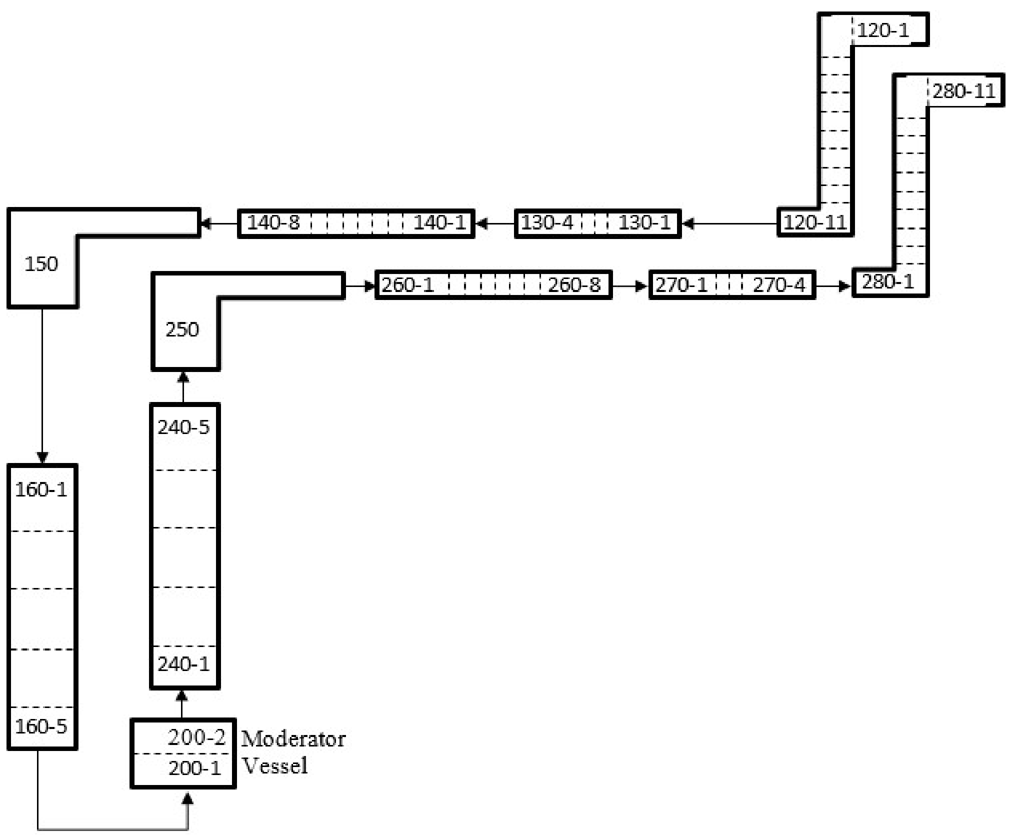

Figure 15. ATHENA/RELAP nodalization transfer line schematic.

2. MODELING AND SIMULATION SETUP

2.1 HYDROGEN PROPERTIES

Essential to this model is the ability to implement cryogenic hydrogen properties. TRANSFORM utilizes the *ExternalMedia* package to access CoolProp fluid properties package by Bell et al. [2014]. The hydrogen properties in CoolProp implement the fundamental equations of state (EOSs), which capture parahydrogen, normal, and orthohydrogen properties down to 14 K, the triple point by Leachman et al. [2009]. Properties around the nominal pressure and temperature (15 bars and 20 K) of the system are shown in Table 1. The importance of capturing the temperature dependence of the fluid properties is evident, the most important being the viscosity, which can vary by nearly 60%.

Table 1. Hydrogen properties around system nominal pressure and temperature

Temperature (K)	Pressure (bar)	Density (kg/L)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Thermal conductivity (mW/m-K)	Viscosity (μ Pa-s)
17.000	14.000	0.075572	-15.121	-1.7592	97.844	19.873
20.000	14.000	0.072763	9.9827	-0.40218	103.20	15.198
23.000	14.000	0.069409	39.516	0.97102	104.75	12.035
17.000	15.000	0.075665	-14.053	-1.7742	97.962	20.002
20.000	15.000	0.072877	10.973	-0.42132	103.40	15.302
23.000	15.000	0.069557	40.374	0.94574	105.04	12.127
17.000	16.000	0.075757	-12.984	-1.7890	98.080	20.131
20.000	16.000	0.072990	11.966	-0.44023	103.60	15.405
23.000	16.000	0.069703	41.238	0.92085	105.34	12.219

2.2 TRANSFORM DESCRIPTION

The Transient Simulation Framework of Reconfigurable Modules (TRANSFORM) is an ORNL-developed component library created using the Modelica programming language to investigate dynamic thermal-hydraulic systems and other multiphysics systems by Greenwood [2017]. The TRANSFORM library of components, built in the Dymola environment, is used here. Modelica is a nonproprietary object-oriented, equation-based programming language used to conveniently model complex physical and cyberphysical systems, to include systems containing mechanical, electrical, electronic, hydraulic, thermal, and control components, for example. Modelica provides for separation of physical models and the solvers of the models, enabling rapid generation of complex physical systems and control design in a single language without requiring deep knowledge of numeric solvers, code generation, and other factors. TRANSFORM has standard thermal-fluid models built in to components in a drag-and-drop schematic environment. Components for pumps, heat exchangers and piping are included. Conjugate heat transfer and fluid flow can be solved in a dynamic transient. Events can also be captured.

2.3 GEOMETRY

As stated above, ATHENA/RELAP modeling has been performed, so many of the design parameters were copied from the previous input deck. The system was divided into component categories similar to that of the original model. The schematic is shown in Figure 16, and the detailed input deck is provided in Appendix B.

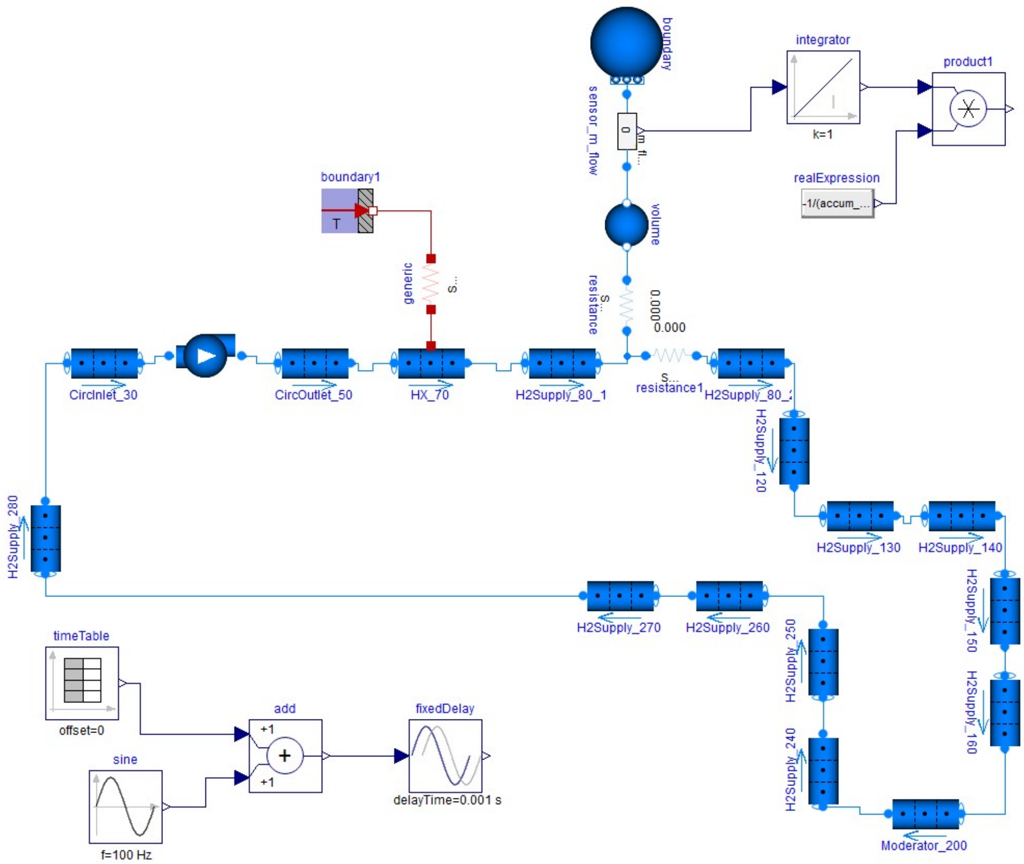

Figure 16. Schematic of TRANSFORM model.

2.3.1 Circulator Inlet (CircInlet_30)

The inlet to the circulator is a section of tubing inside the cold box that contains the circulator and heat exchangers. It is modeled as a *GenericPipe_MultiTransferSurface*. For now, it is assumed as a fully insulated pipe, and therefore it does not transfer heat. The basic geometry is shown in Table 2.

Table 2. Circulator inlet geometry

Parameter	Value	Unit
Hydraulic diameter	0.02301	m
Length	1	m
Roughness	2e-6	m
Number of volumes	2	

2.3.2 Circulator (Circulator_40)

The circulator is contained inside the cold box (containing the circulator and heat exchangers). It is modeled as *TRANSFORM.Fluid.Machines.Pump_SimpleMassFlow*. For now, it is assumed as a fully insulated pipe, and therefore it does not transfer heat. The circulator does not contain any specific geometry, and for now it is assumed as a constant nominal mass flow rate of 0.025487 kg/s.

2.3.3 Circulator Outlet (CircOutlet_50)

The outlet to the circulator is a section of tubing inside the cold box (containing the circulator and heat exchangers). It is modeled as *GenericPipe_MultiTransferSurface*. For now, it is assumed as a fully insulated pipe, and therefore it does not transfer heat. The basic geometry is shown in Table 3.

Table 3. Circulator outlet geometry

Parameter	Value	Unit
Hydraulic diameter	0.02301	m
Length	2	m
Roughness	2e-6	m
Number of volumes	1	

2.3.4 Heat Exchanger (HX_70)

The heat exchanger is located inside the cold box (containing the circulator and heat exchangers). As a simplification, it is modeled as *GenericPipe_MultiTransferSurface*, but the actual exchanger is more of a corrugated plate design. Inside the flow, is modeled as 175 identical channels. For now, it is modeled as a heat transfer component with a constant wall temperature simulating the helium cold side of the heat exchanger. The constant wall temperature is set at 19 K. The heat transfer coefficient is a calculated value using a fixed Nusselt number model in the component. The basic geometry is shown in Table 4.

Table 4. Heat exchanger geometry

Parameter	Value	Unit
Hydraulic diameter	0.004	m
Length	0.89124	m
Roughness	2e-6	m
Number of volumes	2	

2.3.5 H2 Supply Line 1 (H2Supply_80_1)

This component is the first part of the coaxial tubing outside the cold box. It is modeled as a *GenericPipe_MultiTransferSurface*. For now, it is modeled as completely insulated, so there is no heat transfer. The basic geometry is shown in Table 5.

Table 5. H2 supply line 1 geometry

Parameter	Value	Unit
Hydraulic diameter	0.02301	m
Length	2	m
Roughness	2e-6	m
Number of volumes	2	

2.3.6 H2 Supply Line 2 (H2Supply_80_2)

This component is the first part of the coaxial tubing outside the cold box. It is modeled as a *GenericPipe_MultiTransferSurface*. For now, it is modeled as completely insulated, so there is no heat transfer. The basic geometry is shown in Table 6.

Table 6. H2 supply line 2 geometry

Parameter	Value	Unit
Hydraulic diameter	0.02301	m
Length	1.88371	m
Roughness	2e-6	m
Number of volumes	1	

2.3.7 H2 Supply Line 3 (H2Supply_120)

This component is the coaxial tubing outside the cold box. It is modeled as a *GenericPipe_MultiTransferSurface*. For now, it is modeled as completely insulated, so there is no heat transfer. The major geometry is shown in Table 7.

Table 7. H2 supply line 3 geometry

Parameter	Value	Unit
Hydraulic diameter	0.02301	m
Length	9.295	m
Roughness	2e-6	m
Number of volumes	1	
Change in vertical	9.295	m

2.3.8 H2 Supply Line 4 (H2Supply_130)

This component is the coaxial flexible tubing outside the cold box. It is modeled as a *GenericPipe_MultiTransferSurface*. For now, it is modeled as completely insulated, so there is no heat transfer. The major geometry is shown in Table 8.

2.3.9 H2 Supply Line 5 (H2Supply_140)

This component is the coaxial flexible tubing outside the cold box. It is modeled as a *GenericPipe_MultiTransferSurface*. For now, it is modeled as completely insulated, so there is no heat

Table 8. H2 supply line 4 geometry

Parameter	Value	Unit
Hydraulic diameter	0.01566	m
Length	3.7122	m
Roughness	2e-4	m
Number of volumes	1	

transfer. The basic geometry is shown in Table 9.

Table 9. H2 supply line 5 geometry

Parameter	Value	Unit
Hydraulic diameter	0.02301	m
Length	6.49936	m
Roughness	2e-6	m
Number of volumes	1	

2.3.10 H2 Supply Line 6 (H2Supply_150)

This component is the coaxial tubing outside the cold box. It is modeled as a *GenericPipe_MultiTransferSurface*. For now, it is modeled as completely insulated, so there is no heat transfer. The basic geometry is shown in Table 10.

Table 10. H2 supply line 6 geometry

Parameter	Value	Unit
Hydraulic diameter	0.01566	m
Length	0.8382	m
Roughness	2e-4	m
Number of volumes	1	
Change in vertical	-0.5588	m

2.3.11 H2 Supply Line 7 (H2Supply_160)

This component is the coaxial tubing outside the cold box. It is modeled as a *GenericPipe_MultiTransferSurface*. For now, it is modeled as completely insulated, so there is no heat transfer. The basic geometry is shown in Table 11.

2.3.12 Moderator (Moderator_200)

This component is the moderator cell. It is modeled as a *GenericPipe_MultiTransferSurface*. It is modeled as an internal heat generating system; the heat is described later in the simulation parameters section. The basic geometry is shown in Table 12.

Table 11. H2 supply line 7 geometry

Parameter	Value	Unit
Hydraulic diameter	0.02301	m
Length	5.23396	m
Roughness	2e-6	m
Number of volumes	1	
Change in vertical	-3.95683	m

Table 12. Moderator geometry

Parameter	Value	Unit
Hydraulic diameter	0.03004	m
Length	0.16256	m
Roughness	2e-6	m
Number of volumes	8	
Change in vertical	0.00016256	m

2.3.13 H2 Supply Line 8 (H2Supply_240)

This component is the coaxial tubing outside the cold box. It is modeled as a *GenericPipe_MultiTransferSurface* with 7 parallel pipes. For now, it is modeled as completely insulated, so there is no heat transfer. The major geometry is shown in Table 13.

Table 13. H2 Supply line 8 geometry

Parameter	Value	Unit
Hydraulic diameter	0.009933	m
Length	5.0714	m
Roughness	2e-6	m
Number of volumes	1	
Change in vertical	3.79427	m

2.3.14 H2 supply line 9 (H2Supply_250)

This component is the coaxial tubing outside the cold box. It is modeled as a *GenericPipe_MultiTransferSurface*. For now it is modeled as completely insulated, so there is no heat transfer. The major geometry is shown in Table 14.

2.3.15 H2 supply line 10 (H2Supply_260)

This component is the coaxial flexible tubing outside the cold box. It is modeled as a *GenericPipe_MultiTransferSurface*, with 7 parallel pipes. For now, it is modeled as completely insulated, so there is no heat transfer. The basic geometry is shown in Table 15.

Table 14. H2 supply line 9 geometry

Parameter	Value	Unit
Hydraulic diameter	0.006	m
Length	0.8382	m
Roughness	2e-4	m
Number of volumes	1	
Change in vertical	0.5588	m

Table 15. H2 supply line 10 geometry

Parameter	Value	Unit
Hydraulic diameter	0.009933	m
Length	6.49936	m
Roughness	2e-6	m
Number of volumes	1	

2.3.16 H2 Supply Line 11 (H2Supply_270)

This component is the coaxial tubing outside the cold box. It is modeled as a *GenericPipe_MultiTransferSurface*. For now, it is modeled as completely insulated, so there is no heat transfer. The basic geometry is shown in Table 16.

Table 16. H2 supply line 11 geometry

Parameter	Value	Unit
Hydraulic diameter	0.006	m
Length	3.7122	m
Roughness	2e-4	m
Number of volumes	1	

2.3.17 H2 supply line 12 (H2Supply_280)

This component is the coaxial tubing outside the cold box. It is modeled as a *GenericPipe_MultiTransferSurface* with 7 parallel pipes. For now, it is modeled as completely insulated, so there is no heat transfer. The basic geometry is shown in Table 17.

2.3.18 Accumulator (boundary)

This component is modeled as a constant pressure boundary. It is modeled as *TRANSFORM.Fluid.BoundaryConditions.Boundary_pT*. For now, it is modeled as completely insulated, so there is no heat transfer. It is also assumed to be a fixed pressure and temperature. These are fixed at 14.5 bar and 21 K. This boundary has no geometrical values.

Table 17. H2 supply line 12 geometry

Parameter	Value	Unit
Hydraulic diameter	0.009933	m
Length	9.295	m
Roughness	2e-6	m
Number of volumes	1	
Change in vertical	7.0359	m

2.3.19 Resistances (resistance and resistance1

These additional resistances are needed to branch between the H2Supply_80_1 and H2Supply_80_2 and the accumulator. These negligible small resistances are needed to allow for closure and stability of the model. They are set to be a nominal value of 0.0001 Pa/(kg/s).

2.4 SIMULATION PARAMETERS

2.4.1 Thermal Loads

To capture the transient effects of interest, the ability to address thermal and pressure loads that can change with time is important. In this current model, there are two thermal processes that are directly captured and one that is indirectly captured. The heat exchanger is an obvious heat load that is directly captured. The constant temperature boundary condition is set to 19 K to match the data from the experimental runs that will be used to validate the model. The Nusselt number is set to be 400, which also helps match the data from the experimental runs. The actual heat flux is calculated from these parameters.

The heat addition to the system is inside the moderator component. The ability to have a transient internal heat generation term is set in the component. This is tied to a signal generation component which can generate the heat generation value from tabular and continuous function sources. To benchmark against the existing data, real values of the beam power load are brought into the model in the form of a tabular time table. The values of the power are linearly interpolated between the values given in the table vs. time. This is complemented with a small amplitude sine wave generator at 100 Hz. This signal is added to help smooth the signal from having sharp discontinuities and to therefore provide some numerical assistance to the solvers. This value is finally delayed by a small fraction of a second to allow for the numerical solution to be less stiff.

Finally, the indirect heat load of the compression and expansion of the accumulator is captured as a boundary condition. It is assumed that the accumulator maintains a constant temperature of 19 K during the simulation. It is also assumed that it maintains a constant boundary pressure. The effects of flow into and out of the accumulator can be monitored by integrating the flow rate through the connecting piping. This value is captured to be able to correlate with real system data.

2.4.2 Numerical Solver Simulation Settings

The Dymola environment provides a host of numerical solvers that can be set, and it also provides the ability to set the tolerance of the simulation. The standard solver is a *DASSL* solver. However, this solver can struggle when the model has significant nonlinear components/behaviors, as is the case with this model. For this simulation, the *Sdirk34hw - order 4 stiff* model has been selected. This is a Runga-Kutta type 4th order solver that has the ability to handle stiff systems. Because of the various system scales of this model, stiffness is certainly an issue. The solver was able to handle this stiffness and provided a timely solution. The tolerance of the model was set to 1e-5 for all simulations. The time step is variable and automatically adapts to maintain the desired tolerances during integration.

3. SIMULATION AND RESULTS

3.1 OPERATIONAL DATA AND CASE DESCRIPTION

To validate the simulation developed, real case study data from the SNS CMS system were procured from a test performed from 05/29/2021 to 05/30/2021, an approximate 24-hour operating window. The test window contains several beam power ramp-up transients and multiple beam trips, some planned and some incidental. The data were extracted as a comma-separated value (.csv) file using SNS's custom CS-Studio Data Browser. The historical data are recorded in even increments 9 times per minute. Key signals are selected as shown in Table 18 for this comparative study.

Table 18. Column data labels for SNS CMS system case record

Parameter	Unit	Description
Time	MM/DD/YYYY H:M	Date and time
RTBT_Diag:BCM25I:Power1 Value	W	Beam power
TGT_H2:IOC1:ZI_6101 Value	%	Accumulator LVDT range
TGT_H2:IOC1:PI_6102 Value	psia	H2 circulator outlet pressure
TGT_He:IOC1:TI_6522 Value	K	HX helium inlet temperature
TGT_He:IOC1:PI_6516 Value	psia	HX helium inlet pressure
TGT_He:IOC1:FI_6501 Value	g/sec	HX helium mass flowrate
TGT_He:IOC1:PI_6510 Value	psia	HX helium outlet pressure
TGT_He:IOC1:TI_6525 Value	K	HX helium outlet temperature
TGT_H2:IOC1:PI_6101 Value	psia	HX H2 outlet pressure
TGT_He:IOC1:TI_6103 Value	K	HX H2 outlet temperature
TGT_H2:IOC1:FI_6101 Value	g/sec	H2 mass flowrate
TGT_H2:IOC1:TI_6102 Value	K	HX H2 inlet temperature
TGT_H2:IOC1:TI_6101 Value	K	H2 circulator inlet temperature
TGT_H2:IOC1:PI_6109 Value	psia	Accumulator helium pressure

Data from the file can be used to gather descriptive statistics and to provide graphical analysis. Maximum beam power reaches approximately 1.4k W during full power operations. Approximately 10% of this power becomes heat energy in the moderator. The transient power profile of the test data is shown in Figure 17. It can be seen that there are several large transient events and beam trips. A detail of one of the power ramps with a beam trip can be seen in Figure 18.

3.2 SIMULATION RESULTS

The model was simulated for the full time of the collected dataset as a transient. This allows for the overall performance of the model to be evaluated and also allows for key areas to be selected for closer investigation. The parameter of greatest interest for comparison is the outlet temperature of the hydrogen coming from the target itself. The model has a total of just over 10,000 equations and unknowns to solve. The full simulation required about 3 hours of runtime on a desktop PC, so it has the potential for better–than–real-time performance.

A few plots are created to show the performance of the simulation model compared to the real data. Figure 19 shows a comparison of the hydrogen outlet temperature from the simulation and the real data. It can be seen that all of the major trends are captured very well, and the magnitude is slightly offset from the real

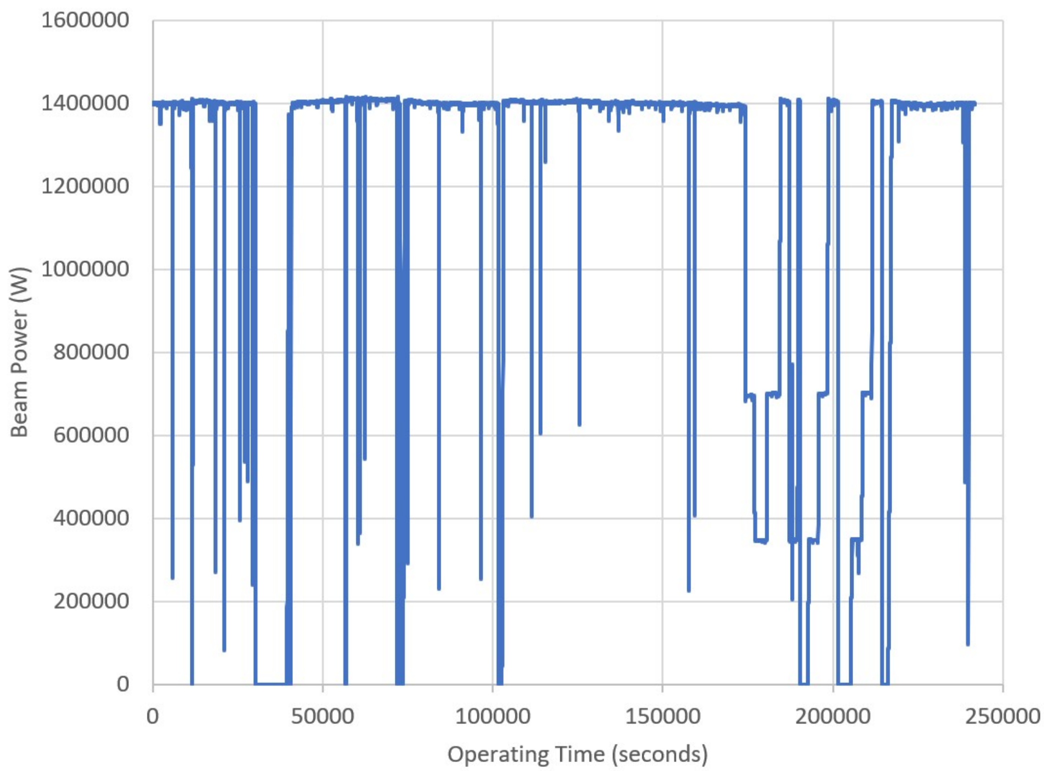

Figure 17. Beam power as a function of time from test data.

data, but it is generally within acceptable tolerance for error. It is an interestingly positive outcome, because there was minimal "tuning" of the model beyond simply entering the geometry and operating parameters of the loop without detailed geometry in the moderator vessel or in the heat exchanger.

Detail plots show how the simulation responds to power trips and power ramps in Figures 20 and 21. It can be seen that the simulation results match well with the real data. However it appears that some minor higher frequency responses are not captured in the simulation. This is likely a result of the simulation's simple nature, and it does not capture details of potential 3D effects of geometry and physics.

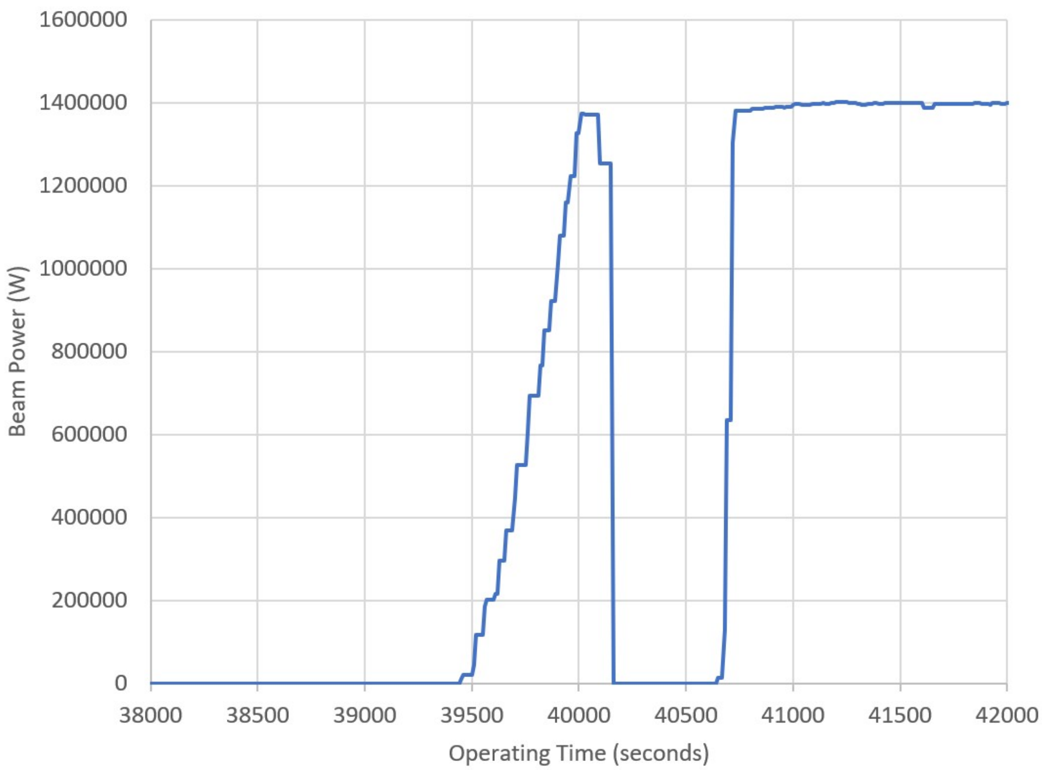

Figure 18. Detail of beam power showing ramp and trip as a function of time from test data.

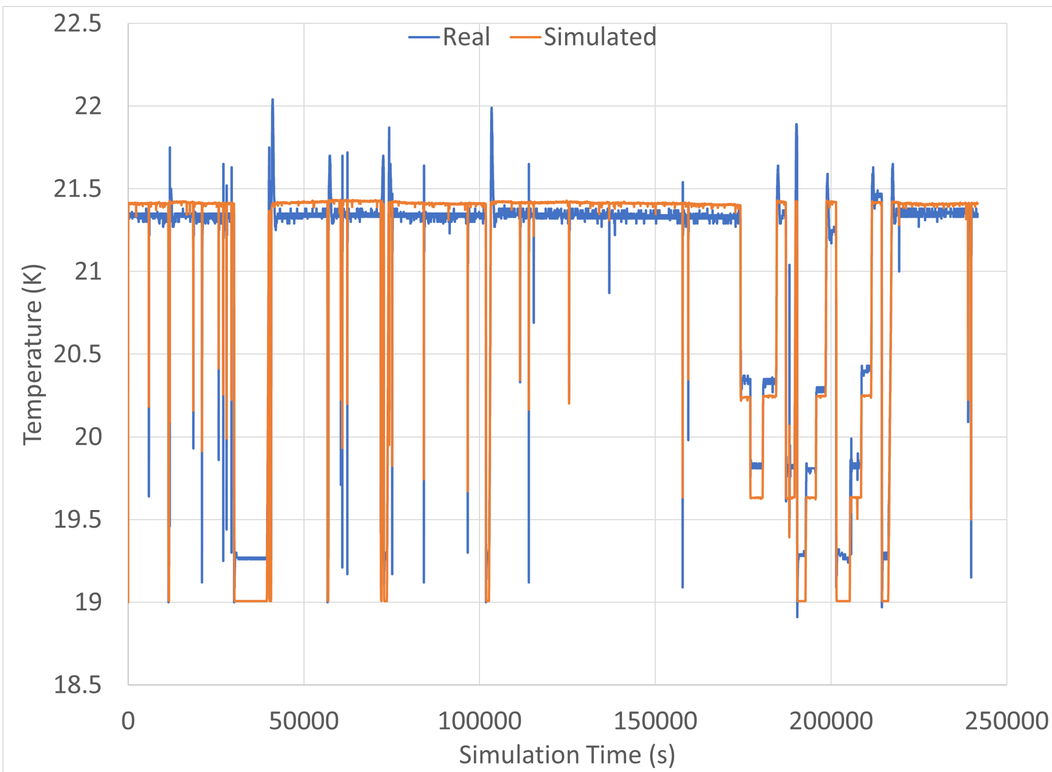

Figure 19. Simulation results for hydrogen temperature exiting the moderator vessel compared to real data.

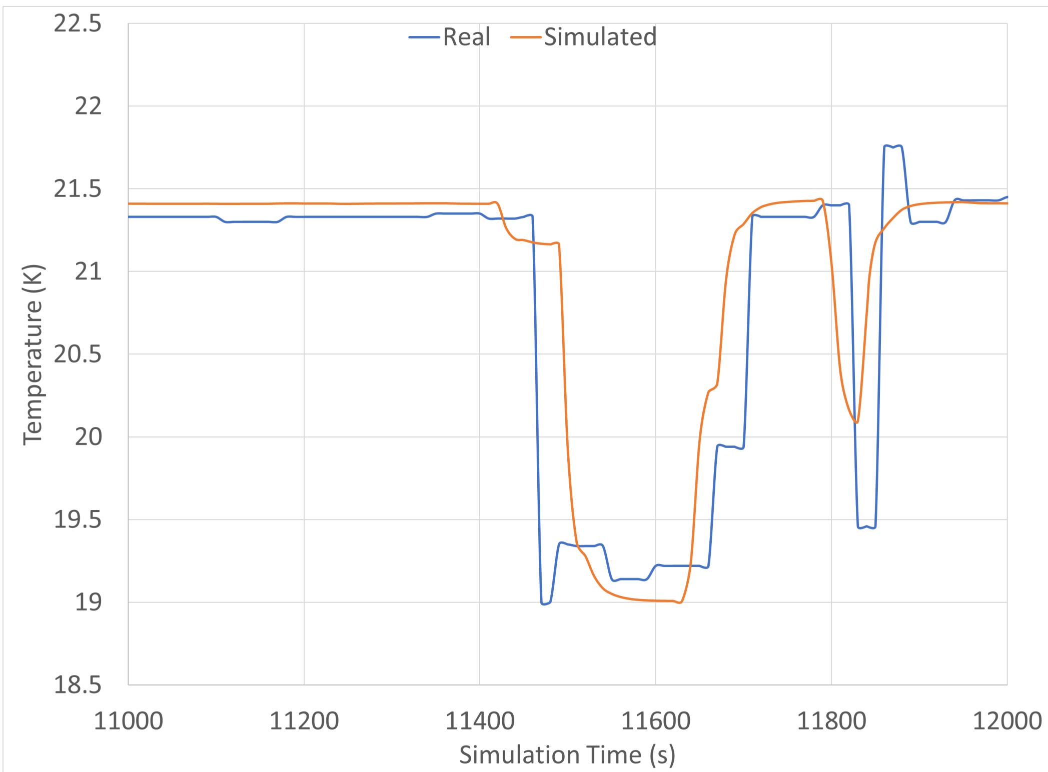

Figure 20. Simulation results for hydrogen temperature exiting the moderator vessel compared to real data detail of trip.

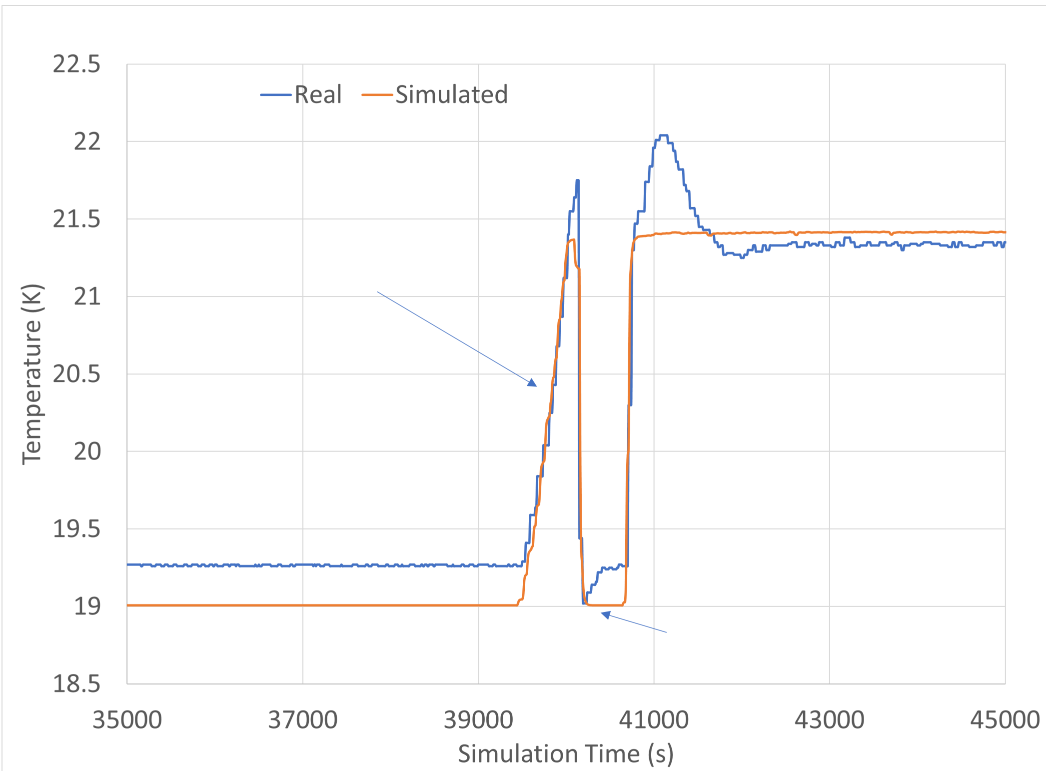

Figure 21. Simulation results for hydrogen temperature exiting the moderator vessel compared to real data detail of power ramp and trip.

4. CONCLUSIONS AND FUTURE WORK

4.1 CONCLUSIONS

This work showed the ability of building a functional dynamic model of the SNS CMS system in Dymola/TRANSFORM. The model benefited from the existing component libraries in TRANSFORM which allowed for simple, quick modeling without the need for extensive customization. A quick performance investigation showed the ability to closely model the real data collected from the CMS system for various complex transient events. This opens the door for more complex models of the CMS systems and allows for the ability to combine them with real-time data for increased understanding of operational performance.

One key finding during this process is the art behind a dynamic system modeling effort. The objective is to capture maximum detail without excessive modeling. This requires an integrated vision of the end usage of the model. A "perfect" model would capture any and all performance of the system being modeled as a true digital twin. The reality is that compromises must be made to capture the essential behaviors without losing the needed fidelity. The model does not remove human judgement from the understanding, it only helps shed light on some of the key pieces that require judgement to have an adequate understanding of the dynamic system behavior.

An important component of this effort is the acquisition of as-built geometric parameters of the system. Many details are not recorded and are not accessible. An example would be the He-H2 heat exchanger geometry. There is no detailed information about the actual internal geometry of the heat exchanger. Without this geometry, the best that can be done is to "tune" the Nusselt parameter in the model to best match the heat exchanger performance. There are other examples with regards to the geometry of the moderator vessel and the actual internal heat generation—a problem that would depend on detailed modeling of coupled neutronics and thermal hydraulics. This kind of 3D modeling is not possible in TRANSFORM and would require other methods. However, it does open many doors for continuing work.

4.2 FUTURE WORK

This project approaches dynamic system modeling with the goal of preparing sufficiently detailed simulations that can become future real-time assets or digital twins of the engineered system under investigation. The limitations of this technique are displayed in the unknowable unknowns of geometry and physics, which require both expert judgement and potentially more advanced methods to resolve. Future work can focus on two fronts: theoretical/simulation and data-driven simulation. For the realization of digital twins, the models must be on a spectrum between purely theoretical and purely data driven. The former provides assurance in the "realness" of the simulation, and the latter provides an exactness of the model that theory cannot fully capture.

4.2.1 Advanced Simulation Techniques

Advanced simulation techniques would use coupled TRANSFORM models with CFD and other finite element or reactor physics codes to get a more detailed modeling of components with heavy 3D or more complex physics effects than are possible to be captured by the TRANSFORM models alone. Direct coupling for dynamic transient simulations would likely be very computationally intensive and would not be capable of real-time performance. However, reduced order models (ROMs) could be used in which the high-fidelity simulations are replaced with surrogates generated by performance in a restricted operating space and fitted with either machine learning or traditional curve-fitting methods. The reduction of fidelity can be captured in uncertainties, and the limits can be known so as to maintain the simulations within the known limits. Surrogate modeling will play an important role in the realization of digital twins.

4.2.2 Data-Driven Methods

Another approach to increasing the accuracy and speed of dynamic system modeling is to model the major physics with TRANSFORM and then to allow knowledge-informed machine learning to bridge the gaps of unknown unknowns in the physics and geometries. In systems like the SNS CMS, there are plenty of operational data that can be used to train the machine learning models. These models can identify underlying physics and model it more efficiently, thus reducing the burden of exact traditional modeling of the system. Machine learning methods are being identified as essential components of digital twin missions, especially in real operating systems where components can age, degrade, or be impacted by exogenous parameters that are not actively being measured by the data acquisition system. However, the essential physics can be captured by the dynamic system model and thus can help inform the data-driven approach, minimizing the uncertainties and providing more assurance in the data-driven model.

4.2.3 Expanding the Model of the CMS

This current simulation does not capture the actual dynamics of the entire system because the helium cooling loop is not modeled directly. To make this project more modular, the CMS hydrogen system will be refined and simplified into either a ROM or an FMU to be used in a more detailed model of the helium cooling system. The interesting control problems in the helium system can be investigated with the validated hydrogen loop FMU. Once the helium model is completed, it can also be refined and simplified into a ROM or FMU that can go back into the hydrogen loop model. This modular process will allow for the ability to capture important secondary dynamics in a system without losing focus on the desired detailed system.

4.2.4 Modeling in Modelon Impact

At the beginning of FY22, a license of Modelon Impact was purchased to try and create a better, more accessible dynamic system model than that provided by Dymola. Modelon Impact has many components similar to TRANSFORM, and where it does not, TRANSFORM libraries can be imported. The additional benefit of batch running Modelica models and FMUs from Python/Jupiter Notebooks will allow for additional flexibility to generate surrogate models and FMUs. This new software can open many pathways for future digital twins of the SNS CMS system and other SNS and ORNL systems.

5. REFERENCES

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M. S. Greenwood. TRANSFORM - TRANsient Simulation Framework of Reconfigurable Models, 2017. URL https://github.com/ORNL-Modelica/TRANSFORM-Library.

J. W. Leachman, R. T Jacobsen, S. G. Penoncello, and E. W. Lemmon. Fundamental Equations of State for Parahydrogen, Normal Hydrogen, and Orthohydrogen. *Journal of Physical and Chemical Reference Data*, 38(3):721–748, 2009. doi: 10.1063/1.3160306. URL https://aip.scitation.org/doi/abs/10.1063/1.3160306.

APPENDIX A. ATHENA/RELAP INPUT DECK FOR CMS MODEL

APPENDIX A. ATHENA/RELAP INPUT DECK FOR CMS MODEL

```
=SNS Cold Source - TU Hydrogen Circuit
* recommended options for Mod 3.2.2-gamma plus:
* option 10 for timestep control based on pressure changes
* option 41 for energy dissipation
* option 45 for new condensing interphase heat transfer model
*crd.no
0000001  10 15 41 45 53 54 55 56 57 58 60 61
*crd.no  prob.type  prob.option
0000100  newath     transnt
*crd.no  check.option
0000101  run
*crd.no  unit.in  unit.out
0000102  si       si
*crd.no  rstplt.opt
0000104  ncmpress
*crd.no  cpu.lim1  cpu.lim2  cpu.end
0000105  10.       20.       999999.
*crd.no  time.end  dt.min  dt.max    ssdtt  min.frq  maj.frq  rst.frq
*                                           1.0      25.0     5000.0
0000201  1000.     1.e-10  0.1       00007  10       250      50000
***** control system constants ***************************
**********************************************************
***** system hydrogen mass (kg) **************************
*crd.no   name      type      value
20511000  mh2sys    constant  2.41870
***** accumulator helium mass (kg) ***********************
*crd.no   name      type      value
20512200  mheaccum  constant  1.41383
*
***********************************************
* variable-speed circulator maximum power     *
***********************************************
* vsc-1                                       *
20545000   pow_set1   constant   810.   * watts*
***********************************************
*
***********************************************
* variable-speed circulator dp set points     *
***********************************************
* vsc-1                                       *
20544700 spd_set1 constant 18000.*emergency speed*
20545100 dp_set1 constant 0.99636  * dp, bar    *
*20545100 dp_set1 constant 1.000    * flow, L/s  *
***********************************************
```

```
*
***** variable trips ************************************
*******************************************************
*
********************************
* variable-speed circulator trips *
********************************
451 time 0 lt null 0 0.0 l -1.0   *
********************************
*
********************************
* all-power lost (AC, UPS, diesel)*
* variable-speed circulator trips *
********************************
454 time 0 lt null 0 0.0 l -1.0   *
********************************
*
****************************************
* speed below 15000 rpm (1570.80 rad/sec)  *
* variable-speed circulator trips          *
****************************************
457 pmpvel 040 lt null 0 1570.80 n -1.0    *
****************************************
*
*******************************************
* override circulator control on low pressure *
* set to fixed low speed p <= p_crit          *
*******************************************
460 p  030010000 le null  0  1283800.  n -1.0 *
*******************************************
*
***** logical trips *************************************
*******************************************************
*
*****************************
* trip vsc AND lose all power *
* to vsc motor and controls   *
*****************************
637  451 and 454 n -1.0       *
*****************************
*
*crd.no   expanded plot var
20800001  systms 1
20800002  sysmer 1
20800003  systms 2
```

```
20800004  sysmer 2
***** hydrodynamic components *****************************
***********************************************************
***** volume 030 ******************************************
***** circulator inlet ************************************
*crd.no  name      type
0300000  circ-in   snglvol
*crd.no  area.v    len      vol  h.ang  v.ang  del.z
0300101  4.1592e-4  1.00000  0.0  0.0    0.0    0.0
*crd.no  rough     h.dia    tlpvbfe
0300102  2.0e-6    0.02301  0000000
*crd.no  ebt  press    temp
0300200  303  14.91e5  17.00
***** pump 040 *******************************************
***** variable speed circulator ***************************
*crd.no  name      type
0400000  vsc       pump
*crd.no  area.v    len      vol  h.ang  v.ang  del.z  tlpvbfe
0400101  4.1592e-4  0.91371  0.0  0.0    0.0    0.0    0000000
*crd.no  from.vol   area.j    f.los  r.los  efvcahs
0400108  030010000  0.0       6.5    6.5    0001000
*crd.no  to.vol     area.j    f.los  r.los  efvcahs
0400109  050000000  0.0       6.5    6.5    0001000
*crd.no  h.dia    beta  icept  slope
0400110  0.02301  0.0   1.0    1.0
0400111  0.02301  0.0   1.0    1.0
*crd.no  ebt  press    temp
0400200  303  14.91e5  17.00
*crd.no  ctrl  mdot.f   mdot.g   vel.int
0400201  1     0.07500  0.07500  0.0
0400202  1     0.07500  0.07500  0.0
*crd.no  1-p tabl  2-p tabl  2-p diff  torque  tim dep  trip  reverse
0400301  0         0         -2        -1      -1       0     1
* 1527.86 = 14590*2pi/60 = rated velocity (rad/s)
* 0.82248 = 12000/14590 = initial velocity ratio
* 0.001   = 1.0/1000 = rated flow (m3/s) coverted from L/s
* 134.85  = 1.0*10^5/75.62/9.80665 = rated head (m)
*           where hydrogen density = 75.62 kg/m3 at 15 bar, 17 K
* 0.12959 = 198/1527.86 = rated torque (N*m)
*         = heat addition (W) / rated speed (rad/s)
*crd.no  rate.vel  init.vel  rate.flow  rate.head  rate.torq
0400302  1527.86   0.82248   0.001      134.85     0.12959
* From Bill Batton of Barber-Nichols, 8/24/00 via e-mail:
* mass of shaft = 8.31 lbm
* I_xx = I_yy = 89.4 lbm*in2 = 0.026162 kg*m2
```

```
*          I_zz = 3.66 lbm*in2 = 0.001071 kg*m2
*          (shaft + impeller + tube)
* 75.62 = rated hydrogen density (kg/m3) at 15 bar, 17 K
*crd.no   mom.inert    rate.den     motor.torq   tf2   tf0   tf1   tf3
0400303   0.001071     75.62        0.0          0.0   0.0   0.0   0.0
*crd.no   var.shaft
0400309   499
*
* homologous curves
*
*            head          regime
0401100          1               1
*          v/a=Q/Q_r    h/a^2=H/H_r, for Q <= Q_r
0401101      0.0           0.8634
0401102      0.1382        0.9135
0401103      0.2764        0.9536
0401104      0.4147        0.9834
0401105      0.5529        1.0032
0401106      0.6911        1.0130
0401107      0.8293        1.0124
0401108      0.9675        1.0019
0401109      1.0000        0.9980
* torque is for fluid at rho-rated
* internal code multiplier of rho/rho-rated is used to determine
* b=tau/tau_r=(b/a^2)*a^2*(rho/rho-rated)
*        torque    regime
0401200        2          1
*           v/a        b/a^2=tau/tau_r, for Q <= Q_r
0401201      0.0         0.0
0401202      1.0         1.0
*          head    regime
0401300        1          2
*           a/v        h/v^2, for Q >= Q_r
0401301     0.3689      0.0
0401302     0.3808      0.01246
0401303     0.4019      0.03521
0401304     0.4256      0.06152
0401305     0.4522      0.09230
0401306     0.4823      0.1287
0401307     0.5168      0.1721
0401308     0.5565      0.2249
0401309     0.6029      0.2898
0401310     0.6577      0.3714
0401311     0.7235      0.4761
0401312     0.8039      0.6142
```

```
0401313    0.9043     0.8025
0401314    0.9998     0.9976
0401315    1.0        0.9980
* torque is for fluid at rho-rated
* internal code multiplier of rho/rho-rated is used to determine
* b=tau/tau_r=(b/v^2)*v^2*(rho/rho-rated)
*       torque    regime
0401400       2         2
*          a/v       b/v^2, for Q >= Q_r
0401401    0.3689     0.1361
0401402    0.3808     0.1450
0401403    0.4019     0.1615
0401404    0.4256     0.1811
0401405    0.4522     0.2045
0401406    0.4823     0.2326
0401407    0.5168     0.2671
0401408    0.5565     0.3097
0401409    0.6029     0.3635
0401410    0.6577     0.4326
0401411    0.7235     0.5234
0401412    0.8039     0.6462
0401413    0.9043     0.8178
0401414    0.9998     0.9996
0401415    1.0        1.0
*         head    regime
0401500       1         3
*          v/a     h/a^2 (assume same as zero-flow for neg flows)
0401501    -1.0    0.8634
0401502     0.0    0.8634
*       torque    regime
0401600       2         3
*          v/a       tau/tau_r (assume same as zero-flow for neg flows)
0401601    -1.0       0.0
0401602     0.0       0.0
*         head     regime
0401700       1          4
*          a/v      h/v^2
0401701    -1.0          0.8634
0401702     0.0          0.0
*       torque     regime
0401800       2          4
*          a/v      b/v^2
0401801    -1.0          0.0
0401802     0.0          0.0
* borrow some 2-phase multiplier tables from another source
```

```
* and assume they are correct
0403000      0
*            void       head multiplier
0403001      0.0        0.0
0403002      0.100      0.0
0403003      0.150      0.050
0403004      0.240      0.800
0403005      0.300      0.960
0403006      0.400      0.980
0403007      0.600      0.970
0403008      0.800      0.900
0403009      0.900      0.800
0403010      0.960      0.500
0403011      1.000      0.0
*
0403100      0
*            void      torque multiplier
0403101      0.0        0.0
0403102      0.100      0.0
0403103      0.150      0.050
0403104      0.240      0.800
0403105      0.300      0.960
0403106      0.400      0.980
0403107      0.600      0.970
0403108      0.800      0.900
0403109      0.900      0.800
0403110      0.960      0.500
0403111      1.000      0.0
***** volume 050 ****************************************
***** circulator outlet **********************************
*crd.no   name       type
0500000   circ-out   pipe
*crd.no   no.vol
0500001   2
*crd.no   area.v        vol
0500101   4.1592e-4     2
*crd.no   area.j        jun
0500201   0.0           1
*crd.no   len           vol
0500301   1.00000       2
*crd.no   vol           vol
0500401   0.0           2
*crd.no   v.ang         vol
0500601   0.0           2
*crd.no   del.z         vol
```

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0500701   0.0            2
*crd.no   rough          h.dia        vol
0500801   2.0e-6         0.02301      2
*crd.no   f.los          r.los        jun
0500901   6.5            6.5          1
*crd.no   tlpvbfe        vol
0501001   0000000        2
*crd.no   efvcahs        jun
0501101   0001000        1
*crd.no   ebt   press     temp    w4    w5    w6    vol
0501201   303   14.91e5   17.00   0.0   0.0   0.0   2
*crd.no   ctrl
0501300   1
*crd.no   mdot.f    mdot.g    vel.int   jun
0501301   0.07500   0.07500   0.0       1
*crd.no   h.dia     beta   icept   slope   jun
0501401   0.02301   0.0    1.0     1.0     1
***** junction 065 ****************************************
***** heat exchanger hydrogen inlet ***********************
*crd.no   name       type
0650000   jun065     sngljun
*crd.no   from.vol   to.vol      area.j     f.los   r.los   efvcahs
0650101   050010000  070000000   0.0        6.5     6.5     0001100
*crd.no   h.dia      beta   icept   slope
0650110   0.00400    0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
0650201   1      0.07500   0.07500   0.0
***** volume 070 ******************************************
***** heat exchanger - hydrogen side **********************
*crd.no   name       type
0700000   hx-h2      pipe
*crd.no   no.vol
0700001   6
*crd.no   area.v         vol
0700101   22.000e-4      6
*crd.no   area.j         jun
0700201   0.0            5
*crd.no   len            vol
0700301   0.14854        6
*crd.no   vol            vol
0700401   0.0            6
*crd.no   v.ang          vol
0700601   0.0            6
*crd.no   del.z          vol
0700701   0.0            6
```

```
*crd.no   rough        h.dia       vol
0700801   2.0e-6       0.00400     6
*crd.no   f.los        r.los       jun
0700901   6.5          6.5         5
*crd.no   tlpvbfe      vol
0701001   0000000      6
*crd.no   efvcahs      jun
0701101   0001000      5
*crd.no   ebt   press     temp    w4    w5    w6    vol
0701201   303   14.91e5   17.00   0.0   0.0   0.0   6
*crd.no   ctrl
0701300   1
*crd.no   mdot.f    mdot.g    vel.int   jun
0701301   0.07500   0.07500   0.0       5
*crd.no   h.dia     beta   icept   slope   jun
0701401   0.00400   0.0    1.0     1.0     5
***** junction 075 ***************************************
***** heat exchanger hydrogen outlet *********************
*crd.no   name       type
0750000   jun075     sngljun
*crd.no   from.vol   to.vol      area.j      f.los   r.los   efvcahs
0750101   070010000  080000000   0.0         6.5     6.5     0001100
*crd.no   h.dia      beta   icept   slope
0750110   0.00400    0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
0750201   1      0.07500   0.07500   0.0
***** volume 080 *****************************************
***** hydrogen supply - pump module **********************
*crd.no   name       type
0800000   rigid080   pipe
*crd.no   no.vol
0800001   4
*crd.no   area.v       vol
0800101   4.1592e-4    4
*crd.no   area.j       jun
0800201   0.0          3
*crd.no   len          vol
0800301   1.00000      2
0800302   0.91371      3
0800303   0.97000      4
*crd.no   vol          vol
0800401   0.0          4
*crd.no   v.ang        vol
0800601   0.0          4
*crd.no   del.z        vol
```

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0800701   0.0            4
*crd.no   rough          h.dia        vol
0800801   2.0e-6         0.02301      4
*crd.no   f.los          r.los        jun
0800901   6.5            6.5          3
*crd.no   tlpvbfe        vol
0801001   0000000        4
*crd.no   efvcahs        jun
0801101   0001000        3
*crd.no   ebt   press     temp    w4    w5    w6    vol
0801201   303   14.91e5   17.00   0.0   0.0   0.0   4
*crd.no   ctrl
0801300   1
*crd.no   mdot.f    mdot.g    vel.int   jun
0801301   0.07500   0.07500   0.0       3
*crd.no   h.dia     beta   icept   slope   jun
0801401   0.02301   0.0    1.0     1.0     3
***** junction 115 ****************************************
***** hydrogen supply - separate to concentric lines *******
*crd.no   name       type
1150000   jun115     sngljun
*crd.no   from.vol   to.vol      area.j      f.los   r.los   efvcahs
1150101   080010000  120000000   0.0         6.5     6.5     0001000
*crd.no   h.dia      beta   icept   slope
1150110   0.02301    0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
1150201   1      0.07500   0.07500   0.0
***** volume 120 ******************************************
***** hydrogen supply - rigid tubing *********************
*crd.no   name       type
1200000   rigid120   pipe
*crd.no   no.vol
1200001   11
*crd.no   area.v         vol
1200101   4.1592e-4      11
*crd.no   area.j         jun
1200201   0.0            10
*crd.no   len            vol
1200301   0.84500        11
*crd.no   vol            vol
1200401   0.0            11
*crd.no   v.ang          vol
1200601   0.0            1
1200602   -90.0          10
1200603   0.0            11
```

```
*crd.no   del.z          vol
1200701   0.0            1
1200702   -0.46450       2
1200703   -0.84500       9
1200704   -0.65640       10
1200705   0.0            11
*crd.no   rough          h.dia         vol
1200801   2.0e-6         0.02301       11
*crd.no   f.los          r.los         jun
1200901   6.5            6.5           10
*crd.no   tlpvbfe        vol
1201001   0000000        11
*crd.no   efvcahs        jun
1201101   0001000        10
*crd.no   ebt   press     temp    w4    w5    w6    vol
1201201   303   14.91e5   17.00   0.0   0.0   0.0   11
*crd.no   ctrl
1201300   1
*crd.no   mdot.f    mdot.g    vel.int   jun
1201301   0.07500   0.07500   0.0       10
*crd.no   h.dia     beta   icept   slope   jun
1201401   0.02301   0.0    1.0     1.0     10
***** junction 125 ****************************************
***** hydrogen supply - rigid to flexible line *************
*crd.no   name        type
1250000   jun125      sngljun
*crd.no   from.vol    to.vol       area.j       f.los   r.los   efvcahs
1250101   120010000   130000000    0.0          6.5     6.5     0001100
*crd.no   h.dia       beta   icept   slope
1250110   0.01566     0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
1250201   1      0.07500   0.07500   0.0
***** volume 130 ******************************************
***** hydrogen supply - flexible line *********************
*crd.no   name        type
1300000   flex130     pipe
*crd.no   no.vol
1300001   4
*crd.no   area.v         vol
1300101   4.0471e-4      4
*crd.no   area.j         jun
1300201   0.0            3
*crd.no   len            vol
1300301   0.92805        4
*crd.no   vol            vol
```

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1300401   0.0          4
*crd.no   v.ang        vol
1300601   0.0          4
*crd.no   del.z        vol
1300701   0.0          4
*crd.no   rough        h.dia       vol
1300801   2.0e-4       0.01566     4
*crd.no   f.los        r.los       jun
1300901   6.5          6.5         3
*crd.no   tlpvbfe      vol
1301001   0000000      4
*crd.no   efvcahs      jun
1301101   0001000      3
*crd.no   ebt  press     temp   w4   w5   w6   vol
1301201   303  14.91e5   17.00  0.0  0.0  0.0  4
*crd.no   ctrl
1301300   1
*crd.no   mdot.f    mdot.g    vel.int   jun
1301301   0.07500   0.07500   0.0       3
*crd.no   h.dia     beta   icept   slope   jun
1301401   0.01566   0.0    1.0     1.0     3
***** junction 135 *****************************************
***** hydrogen supply - flexible to rigid line *************
*crd.no   name       type
1350000   jun135     sngljun
*crd.no   from.vol   to.vol      area.j    f.los   r.los   efvcahs
1350101   130010000  140000000   0.0       6.5     6.5     0001100
*crd.no   h.dia      beta   icept   slope
1350110   0.01566    0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
1350201   1      0.07500   0.07500   0.0
***** volume 140 *******************************************
***** hydrogen supply - rigid tubing **********************
*crd.no   name       type
1400000   rigid140   pipe
*crd.no   no.vol
1400001   8
*crd.no   area.v       vol
1400101   4.1592e-4    8
*crd.no   area.j       jun
1400201   0.0          7
*crd.no   len          vol
1400301   0.81242      8
*crd.no   vol          vol
1400401   0.0          8
```

```
*crd.no   v.ang         vol
1400601   0.0           8
*crd.no   del.z         vol
1400701   0.0           8
*crd.no   rough         h.dia        vol
1400801   2.0e-6        0.02301      8
*crd.no   f.los         r.los        jun
1400901   6.5           6.5          7
*crd.no   tlpvbfe       vol
1401001   0000000       8
*crd.no   efvcahs       jun
1401101   0001000       7
*crd.no   ebt   press     temp    w4    w5    w6    vol
1401201   303   14.91e5   17.00   0.0   0.0   0.0   8
*crd.no   ctrl
1401300   1
*crd.no   mdot.f    mdot.g    vel.int   jun
1401301   0.07500   0.07500   0.0       7
*crd.no   h.dia     beta   icept   slope   jun
1401401   0.02301   0.0    1.0     1.0     7
***** junction 145 ****************************************
***** hydrogen supply - rigid to flexible line *************
*crd.no   name       type
1450000   jun145     sngljun
*crd.no   from.vol   to.vol      area.j      f.los   r.los   efvcahs
1450101   140010000  150000000   0.0         6.5     6.5     0001100
*crd.no   h.dia      beta   icept   slope
1450110   0.01566    0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
1450201   1      0.07500   0.07500   0.0
***** volume 150 ******************************************
***** hydrogen supply - flexible line *********************
*crd.no   name        type
1500000   flex150     snglvol
*crd.no   area.v      len       vol   h.ang   v.ang   del.z
1500101   4.0471e-4   0.83820   0.0   0.0     -90.0   -0.55880
*crd.no   rough       h.dia     tlpvbfe
1500102   2.0e-4      0.01566   0000000
*crd.no   ebt   press     temp
1500200   303   14.91e5   17.00
***** junction 155 ****************************************
***** hydrogen supply - flexible to rigid line *************
*crd.no   name       type
1550000   jun155     sngljun
*crd.no   from.vol   to.vol      area.j      f.los   r.los   efvcahs
```

```
1550101   150010000  160000000   0.0          6.5      6.5      0001100
*crd.no   h.dia       beta   icept   slope
1550110   0.01566     0.0     1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
1550201   1       0.07500   0.07500   0.0
***** volume 160 ****************************************
***** hydrogen supply - rigid tubing *********************
***** volumes 160-2 thru 160-5 are water cooled ***********
*crd.no   name       type
1600000   rigid160   pipe
*crd.no   no.vol
1600001   5
*crd.no   area.v        vol
1600101   4.1592e-4     5
*crd.no   area.j        jun
1600201   0.0           4
*crd.no   len           vol
1600301   1.20714       1
1600302   0.92774       2
1600303   0.96203       4
1600304   1.17502       5
*crd.no   vol           vol
1600401   0.0           5
*crd.no   v.ang         vol
1600601   -90.0         5
*crd.no   del.z         vol
1600701   -1.12014      1
1600702   -0.15240      2
1600703   -0.96203      4
1600704   -0.76023      5
*crd.no   rough         h.dia        vol
1600801   2.0e-6        0.02301      5
*crd.no   f.los         r.los        jun
1600901   6.5           6.5          4
*crd.no   tlpvbfe       vol
1601001   0000000       5
*crd.no   efvcahs       jun
1601101   0001000       4
*crd.no   ebt   press     temp    w4    w5    w6    vol
1601201   303   14.91e5   17.00   0.0   0.0   0.0   5
*crd.no   ctrl
1601300   1
*crd.no   mdot.f    mdot.g    vel.int   jun
1601301   0.07500   0.07500   0.0       4
*crd.no   h.dia     beta   icept   slope   jun
```

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1601401   0.02301   0.0    1.0     1.0     4
***** junction 195 ***************************************
***** hydrogen supply to moderator vessel *****************
*crd.no   name       type
1950000   jun195     sngljun
*crd.no   from.vol   to.vol      area.j      f.los   r.los   efvcahs
1950101   160010000  200000000   0.0         6.5     6.5     0001100
*crd.no   h.dia      beta   icept   slope
1950110   0.02301    0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
1950201   1      0.07500   0.07500   0.0
***** volume 200 *****************************************
***** moderator vessel ***********************************
*crd.no   name       type
2000000   mod-vesl   pipe
*crd.no   no.vol
2000001   2
*crd.no   area.v        vol
2000101   53.288e-4     2
*crd.no   area.j        jun
2000201   0.0           1
*crd.no   len           vol
2000301   0.08128       2
*crd.no   vol           vol
2000401   0.0           2
*crd.no   v.ang         vol
2000601   90.0          2
*crd.no   del.z         vol
2000701   0.08128       2
*crd.no   rough         h.dia        vol
2000801   2.0e-6        0.03004      2
*crd.no   f.los         r.los        jun
2000901   6.5           6.5          1
*crd.no   tlpvbfe       vol
2001001   0000000       2
*crd.no   efvcahs       jun
2001101   0001000       1
*crd.no   ebt   press     temp    w4    w5    w6    vol
2001201   303   14.91e5   17.00   0.0   0.0   0.0   2
*crd.no   ctrl
2001300   1
*crd.no   mdot.f    mdot.g    vel.int   jun
2001301   0.07500   0.07500   0.0       1
*crd.no   h.dia     beta   icept   slope   jun
2001401   0.03004   0.0    1.0     1.0     1
```

```
***** junction 205 *****************************************
***** moderator vessel to hydrogen return *****************
*crd.no   name       type
2050000   jun205     sngljun
*crd.no   from.vol   to.vol      area.j      f.los   r.los   efvcahs
2050101   200010000  240000000   0.0         6.5     6.5     0001100
*crd.no   h.dia      beta   icept   slope
2050110   0.00993    0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
2050201   1      0.07500   0.07500   0.0
***** volume 240 *******************************************
***** hydrogen return - rigid tubing **********************
***** volumes 240-1 thru 240-4 are water cooled ************
*crd.no   name       type
2400000   rigid240   pipe
*crd.no   no.vol
2400001   5
*crd.no   area.v        vol
2400101   5.4821e-4     5
*crd.no   area.j        jun
2400201   0.0           4
*crd.no   len           vol
2400301   1.01246       1
2400302   0.96203       3
2400303   0.92774       4
2400304   1.20714       5
*crd.no   vol           vol
2400401   0.0           5
*crd.no   v.ang         vol
2400601   90.0          5
*crd.no   del.z         vol
2400701   0.59767       1
2400702   0.96203       3
2400703   0.15240       4
2400704   1.12014       5
*crd.no   rough         h.dia        vol
2400801   2.0e-6        0.00993      5
*crd.no   f.los         r.los        jun
2400901   6.5           6.5          4
*crd.no   tlpvbfe       vol
2401001   0000000       5
*crd.no   efvcahs       jun
2401101   0001000       4
*crd.no   ebt   press     temp    w4    w5    w6    vol
2401201   303   14.91e5   17.00   0.0   0.0   0.0   5
```

```
*crd.no   ctrl
2401300   1
*crd.no   mdot.f    mdot.g    vel.int   jun
2401301   0.07500   0.07500   0.0       4
*crd.no   h.dia     beta   icept   slope   jun
2401401   0.00993   0.0    1.0     1.0     4
***** junction 245 ****************************************
***** hydrogen return - rigid to flexible line *************
*crd.no   name        type
2450000   jun245      sngljun
*crd.no   from.vol    to.vol      area.j      f.los   r.los   efvcahs
2450101   240010000  250000000   0.0         6.5     6.5     0001100
*crd.no   h.dia       beta   icept   slope
2450110   0.00600     0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
2450201   1      0.07500   0.07500   0.0
***** volume 250 ******************************************
***** hydrogen return - flexible line *********************
*crd.no   name        type
2500000   flex250     snglvol
*crd.no   area.v      len        vol   h.ang   v.ang   del.z
2500101   5.0222e-4   0.83820   0.0   0.0     90.0    0.55880
*crd.no   rough       h.dia      tlpvbfe
2500102   2.0e-4      0.00600   0000000
*crd.no   ebt   press     temp
2500200   303   14.91e5   17.00
***** junction 255 ****************************************
***** hydrogen return - flexible to rigid line *************
*crd.no   name        type
2550000   jun255      sngljun
*crd.no   from.vol    to.vol      area.j      f.los   r.los   efvcahs
2550101   250010000  260000000   0.0         6.5     6.5     0001100
*crd.no   h.dia       beta   icept   slope
2550110   0.00600     0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
2550201   1      0.07500   0.07500   0.0
***** volume 260 ******************************************
***** hydrogen return - rigid tubing **********************
*crd.no   name        type
2600000   rigid260    pipe
*crd.no   no.vol
2600001   8
*crd.no   area.v        vol
2600101   5.4821e-4     8
*crd.no   area.j        jun
```

```
2600201   0.0             7
*crd.no   len             vol
2600301   0.81242         8
*crd.no   vol             vol
2600401   0.0             8
*crd.no   v.ang           vol
2600601   0.0             8
*crd.no   del.z           vol
2600701   0.0             8
*crd.no   rough           h.dia         vol
2600801   2.0e-6          0.00993       8
*crd.no   f.los           r.los         jun
2600901   6.5             6.5           7
*crd.no   tlpvbfe         vol
2601001   0000000         8
*crd.no   efvcahs         jun
2601101   0001000         7
*crd.no   ebt   press     temp    w4    w5    w6    vol
2601201   303   14.91e5   17.00   0.0   0.0   0.0   8
*crd.no   ctrl
2601300   1
*crd.no   mdot.f    mdot.g    vel.int   jun
2601301   0.07500   0.07500   0.0         7
*crd.no   h.dia     beta   icept   slope   jun
2601401   0.00993   0.0    1.0     1.0     7
***** junction 265 ****************************************
***** hydrogen return - rigid to flexible line *************
*crd.no   name        type
2650000   jun265      sngljun
*crd.no   from.vol    to.vol       area.j       f.los   r.los   efvcahs
2650101   260010000   270000000    0.0          6.5     6.5     0001100
*crd.no   h.dia       beta   icept   slope
2650110   0.00600     0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
2650201   1      0.07500   0.07500   0.0
***** volume 270 ******************************************
***** hydrogen return - flexible line *********************
*crd.no   name        type
2700000   flex270     pipe
*crd.no   no.vol
2700001   4
*crd.no   area.v          vol
2700101   5.0222e-4       4
*crd.no   area.j          jun
2700201   0.0             3
```

```
*crd.no   len          vol
2700301   0.92805      4
*crd.no   vol          vol
2700401   0.0          4
*crd.no   v.ang        vol
2700601   0.0          4
*crd.no   del.z        vol
2700701   0.0          4
*crd.no   rough        h.dia       vol
2700801   2.0e-4       0.00600     4
*crd.no   f.los        r.los       jun
2700901   6.5          6.5         3
*crd.no   tlpvbfe      vol
2701001   0000000      4
*crd.no   efvcahs      jun
2701101   0001000      3
*crd.no   ebt  press     temp   w4   w5   w6   vol
2701201   303  14.91e5   17.00  0.0  0.0  0.0  4
*crd.no   ctrl
2701300   1
*crd.no   mdot.f   mdot.g   vel.int  jun
2701301   0.07500  0.07500  0.0      3
*crd.no   h.dia    beta  icept  slope  jun
2701401   0.00600  0.0   1.0    1.0    3
***** junction 275 ****************************************
***** hydrogen return - flexible to rigid line *************
*crd.no   name      type
2750000   jun275    sngljun
*crd.no   from.vol  to.vol     area.j     f.los  r.los  efvcahs
2750101   270010000 280000000  0.0        6.5    6.5    0001100
*crd.no   h.dia     beta  icept  slope
2750110   0.00600   0.0   1.0    1.0
*crd.no   ctrl  mdot.f   mdot.g   vel.int
2750201   1     0.07500  0.07500  0.0
***** volume 280 ******************************************
***** hydrogen return - rigid tubing **********************
*crd.no   name      type
2800000   rigid280  pipe
*crd.no   no.vol
2800001   11
*crd.no   area.v       vol
2800101   5.4821e-4    11
*crd.no   area.j       jun
2800201   0.0          10
*crd.no   len          vol
```

```
2800301   0.84500        11
*crd.no   vol            vol
2800401   0.0            11
*crd.no   v.ang          vol
2800601   0.0            1
2800602   90.0           10
2800603   0.0            11
*crd.no   del.z          vol
2800701   0.0            1
2800702   0.65640        2
2800703   0.84500        9
2800704   0.46450        10
2800705   0.0            11
*crd.no   rough          h.dia        vol
2800801   2.0e-6         0.00993      11
*crd.no   f.los          r.los        jun
2800901   6.5            6.5          10
*crd.no   tlpvbfe        vol
2801001   0000000        11
*crd.no   efvcahs        jun
2801101   0001000        10
*crd.no   ebt   press     temp    w4    w5    w6    vol
2801201   303   14.91e5   17.00   0.0   0.0   0.0   11
*crd.no   ctrl
2801300   1
*crd.no   mdot.f    mdot.g    vel.int   jun
2801301   0.07500   0.07500   0.0       10
*crd.no   h.dia     beta   icept   slope   jun
2801401   0.00993   0.0    1.0     1.0     10
***** junction 285 ****************************************
***** hydrogen return - concentric to separate lines *******
*crd.no   name        type
2850000   jun285      sngljun
*crd.no   from.vol    to.vol      area.j      f.los   r.los   efvcahs
2850101   280010000  030000000   0.0         6.5     6.5     0001100
*crd.no   h.dia       beta   icept   slope
2850110   0.00993     0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
2850201   1      0.07500   0.07500   0.0
***** junction 315 ****************************************
***** accumulator hydrogen ********************************
*crd.no   name        type
3150000   jun315      sngljun
*crd.no   from.vol    to.vol      area.j      f.los   r.los   efvcahs
3150101   080030004  320000000   4.1592e-4   0.0     0.0     0001100
```

```
*crd.no   h.dia      beta   icept   slope
3150110   0.02301    0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
3150201   1      0.0       0.0       0.0
***** volume 320 *****************************************
***** accumulator hydrogen ********************************
*crd.no   name       type
3200000   acumh2     snglvol
*crd.no   area.v     len        vol   h.ang   v.ang   del.z
3200101   55.843e-4  0.17761    0.0   0.0     90.0    0.17761
*crd.no   rough      h.dia      tlpvbfe
3200102   2.0e-4     0.05232    0000000
*crd.no   ebt   press     temp
3200200   303   14.91e5   17.06
***** junction 325 ***************************************
***** accumulator hydrogen dummy hx ***********************
*crd.no   name       type
3250000   jun325     sngljun
*crd.no   from.vol   to.vol      area.j      f.los   r.los   efvcahs
3250101   320010000  330000000   0.0         0.0     0.0     0001000
*crd.no   h.dia      beta   icept   slope
3250110   0.0        0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
3250201   1      0.0       0.0       0.0
***** volume 330 *****************************************
***** accumulator hydrogen dummy hx ***********************
*crd.no   name       type
3300000   acumh2-x   snglvol
*crd.no   area.v     len        vol   h.ang   v.ang   del.z
3300101   55.843e-4  0.09620    0.0   0.0     0.0     0.0
*crd.no   rough      h.dia      tlpvbfe
3300102   0.0        0.0        0000010
*crd.no   ebt   press     temp
3300200   303   14.91e5   17.06
***** junction 335 ***************************************
***** accumulator hydrogen pressure bc ********************
*crd.no   name       type
3350000   jun335     sngljun
*crd.no   from.vol   to.vol      area.j      f.los   r.los   efvcahs
3350101   330010000  340000000   0.0         0.0     0.0     0001000
*crd.no   h.dia      beta   icept   slope
3350110   0.0        0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
3350201   1      0.0       0.0       0.0
***** volume 340 *****************************************
```

```
***** accumulator hydrogen pressure bc *******************
*crd.no   name       type
3400000   acumh2-p   tmdpvol
*crd.no   area.v     len       vol   h.ang   v.ang   del.z
3400101   55.843e-4  0.09620   0.0   0.0     0.0     0.0
*crd.no   rough      h.dia     tlpvbfe
3400102   0.0        0.0       0000000
*crd.no   ebt   trip   v.name    v.code
3400200   303   0      cntrlvar  126
*crd.no   search   press    temp
3400201   1.0e3    1.0e3    17.50
3400202   1.0e7    1.0e7    17.50
***** junction 345 ****************************************
***** accumulator hydrogen temperature bc ****************
*crd.no   name      type
3450000   jun345    tmdpjun
*crd.no   from.vol   to.vol     area.j
3450101   330010000 350000000   0.0
*crd.no   ctrl   trip   v.name    v.code
3450200   0      0      velgj     325000000
*crd.no   search   vel.f    vel.g    vel.int
3450201   -100.0   -101.0   -101.0   0.0
3450202      0.0   -0.001   -0.001   0.0
3450203    100.0   -0.001   -0.001   0.0
***** volume 350 ******************************************
***** accumulator hydrogen temperature bc ****************
*crd.no   name       type
3500000   acumh2-t   tmdpvol
*crd.no   area.v     len       vol   h.ang   v.ang   del.z
3500101   55.843e-4  0.09620   0.0   0.0     0.0     0.0
*crd.no   rough      h.dia     tlpvbfe
3500102   0.0        0.0       0000000
*crd.no   ebt   trip   v.name    v.code
3500200   303   0      tempg     320010000
*crd.no   search   press       temp
3500201     14.0   15.00e5     14.00
3500202   1000.0   15.00e5   1000.00
***** volume 420 ******************************************
***** accumulator helium **********************************
*crd.no   name       type
4200000   acumhe     snglvol
*crd.no   area.v     len       vol   h.ang   v.ang   del.z
4200101   378.35e-4  0.87425   0.0   0.0     90.0    0.34341
*crd.no   rough      h.dia     tlpvbfe
4200102   2.0e-4     0.12616   0000000
```

```
*crd.no   ebt   press     temp
4200200   603   14.91e5   17.06
***** junction 425 ****************************************
***** accumulator helium dummy hx *************************
*crd.no   name        type
4250000   jun425      sngljun
*crd.no   from.vol    to.vol      area.j      f.los   r.los   efvcahs
4250101   420010000  430000000   0.0         0.0     0.0     0001000
*crd.no   h.dia       beta   icept   slope
4250110   0.0         0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
4250201   1      0.0       0.0       0.0
***** volume 430 ******************************************
***** accumulator helium dummy hx *************************
*crd.no   name        type
4300000   acumhe-x    snglvol
*crd.no   area.v      len        vol   h.ang   v.ang   del.z
4300101   378.35e-4   0.09620    0.0   0.0     0.0     0.0
*crd.no   rough       h.dia      tlpvbfe
4300102   0.0         0.0        0000010
*crd.no   ebt   press     temp
4300200   603   14.91e5   17.06
***** junction 435 ****************************************
***** accumulator helium pressure bc **********************
*crd.no   name        type
4350000   jun435      sngljun
*crd.no   from.vol    to.vol      area.j      f.los   r.los   efvcahs
4350101   430010000  440000000   0.0         0.0     0.0     0001000
*crd.no   h.dia       beta   icept   slope
4350110   0.0         0.0    1.0     1.0
*crd.no   ctrl   mdot.f    mdot.g    vel.int
4350201   1      0.0       0.0       0.0
***** volume 440 ******************************************
***** accumulator helium pressure bc **********************
*crd.no   name        type
4400000   acumhe-p    tmdpvol
*crd.no   area.v      len        vol   h.ang   v.ang   del.z
4400101   378.35e-4   0.09620    0.0   0.0     0.0     0.0
*crd.no   rough       h.dia      tlpvbfe
4400102   0.0         0.0        0000000
*crd.no   ebt   trip   v.name     v.code
4400200   603   0      cntrlvar   126
*crd.no   search   press     temp
4400201   1.0e3    1.0e3     17.50
4400202   1.0e7    1.0e7     17.50
```

```
***** junction 445 ******************************************
***** accumulator helium temperature bc *******************
*crd.no   name       type
4450000   jun445     tmdpjun
*crd.no   from.vol   to.vol      area.j
4450101   430010000  450000000   0.0
*crd.no   ctrl   trip   v.name     v.code
4450200   0      0      velgj      425000000
*crd.no   search   vel.f     vel.g     vel.int
4450201   -100.0   -101.0    -101.0    0.0
4450202      0.0   -0.001    -0.001    0.0
4450203    100.0   -0.001    -0.001    0.0
***** volume 450 *******************************************
***** accumulator helium temperature bc *******************
*crd.no   name        type
4500000   acumhe-t    tmdpvol
*crd.no   area.v      len        vol   h.ang   v.ang   del.z
4500101   378.35e-4   0.09620    0.0   0.0     0.0     0.0
*crd.no   rough       h.dia      tlpvbfe
4500102   0.0         0.0        0000000
*crd.no   ebt   trip   v.name     v.code
4500200   603   0      tempg      420010000
*crd.no   search   press       temp
4500201     10.0   15.00e5     10.00
4500202   1000.0   15.00e5   1000.00
***** heat structures **************************************
************************************************************
***** heat structure 0401 **********************************
***** hydrogen return - circulator tubing *****************
*crd.no    no.ax.hs   no.mp     geom.typ   ss.flag   left.coord
10401000   4          4         2          0         0.01151
*crd.no    mesh.loc   mesh.fmt
10401100   0          1
*crd.no    no.int     rt.coord
10401101   3          0.01207    * ss
*crd.no    comp       int.no
10401201   010        3          * ss
*crd.no    source     int.no
10401301   1.0        3          * ss
*crd.no    temp.flg
10401400   0
*crd.no    temp       mp.no
10401401     17.00    4
*crd.no    left.vol   incr    bc.typ   sa.cod   sa.fac    hs.no
10401501   030010000  10000   1        1        1.00000   1
```

```
10401502  040010000  10000   1        1        0.91371   2
10401503  050010000  10000   1        1        1.00000   4
*crd.no   rt.vol     incr    bc.typ   sa.cod   sa.fac    hs.no
10401601  -010       0       3011     1        1.00000   1
10401602  -010       0       3011     1        0.91371   2
10401603  -010       0       3011     1        1.00000   4
*crd.no   s.typ      s.mult     dir.left   dir.rt    hs.no
10401701  0          0.0        0.0        0.0       4
*crd.no   ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
10401801  0.       100.   100.   0.   0.   0.   0.   1.0   4
***** heat structure 0701 *********************************
***** heat exchanger - hydrogen/helium boundary ************
*crd.no   no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
10701000  6          4          1          0         0.0
*crd.no   mesh.loc   mesh.fmt
10701100  0          1
*crd.no   no.int     rt.coord
10701101  3          0.00100    * al
*crd.no   comp       int.no
10701201  020        3          * al
*crd.no   source     int.no
10701301  1.0        3          * al
*crd.no   temp.flg
10701400  0
*crd.no   temp       mp.no
10701401   17.00     4
*crd.no   left.vol   incr    bc.typ   sa.cod   sa.fac    hs.no
10701501  070010000  10000   1        1        0.27600   6
*crd.no   rt.vol     incr    bc.typ   sa.cod   sa.fac    hs.no
10701601  0          0       1030     1        0.27600   6
*crd.no   s.typ      s.mult     dir.left   dir.rt    hs.no
10701701  0          0.0        0.0        0.0       6
*crd.no   ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
10701801  0.       100.   100.   0.   0.   0.   0.   1.0   6
***** heat structure 0801 *********************************
***** hydrogen supply - pump module ***********************
*crd.no   no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
10801000  2          4          2          0         0.01151
*crd.no   mesh.loc   mesh.fmt
10801100  0          1
*crd.no   no.int     rt.coord
10801101  3          0.01207    * ss
*crd.no   comp       int.no
10801201  010        3          * ss
*crd.no   source     int.no
```

```
10801301   1.0        3          * ss
*crd.no    temp.flg
10801400   0
*crd.no    temp       mp.no
10801401    17.00     4
*crd.no    left.vol   incr     bc.typ   sa.cod   sa.fac     hs.no
10801501   080010000  10000    1        1        1.00000    2
*crd.no    rt.vol     incr     bc.typ   sa.cod   sa.fac     hs.no
10801601   -010       0        3011     1        1.00000    2
*crd.no    s.typ      s.mult     dir.left   dir.rt     hs.no
10801701   0          0.0        0.0        0.0        2
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
10801801   0.       100.   100.   0.   0.   0.   0.   1.0   2
***** heat structure 0802 ********************************
***** accumulator vessel wall ****************************
*crd.no    no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
10802000   1          6          1          0         0.0
*crd.no    mesh.loc   mesh.fmt
10802100   0          1
*crd.no    no.int     rt.coord
10802101   5          0.00996    * ss
*crd.no    comp       int.no
10802201   010        5          * ss
*crd.no    source     int.no
10802301   1.0        5          * ss
*crd.no    temp.flg
10802400   0
*crd.no    temp       mp.no
10802401    17.00     6
*crd.no    left.vol   incr     bc.typ   sa.cod   sa.fac     hs.no
10802501   080030000  10000    1        1        0.51887    1
*crd.no    rt.vol     incr     bc.typ   sa.cod   sa.fac     hs.no
10802601   420010000  10000    1        1        0.51887    1
*crd.no    s.typ      s.mult     dir.left   dir.rt     hs.no
10802701   0          0.0        0.0        0.0        1
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
10802801   0.       100.   100.   0.   0.   0.   0.   1.0   1
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
10802901   0.       100.   100.   0.   0.   0.   0.   1.0   1
***** heat structure 0803 ********************************
***** accumulator inlet pipe *****************************
*crd.no    no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
10803000   1          6          1          0         0.0
*crd.no    mesh.loc   mesh.fmt
10803100   0          1
```

```
*crd.no    no.int     rt.coord
10803101   5          0.01234    * ss
*crd.no    comp       int.no
10803201   010        5          * ss
*crd.no    source     int.no
10803301   1.0        5          * ss
*crd.no    temp.flg
10803400   0
*crd.no    temp       mp.no
10803401    17.00     6
*crd.no    left.vol   incr     bc.typ   sa.cod   sa.fac     hs.no
10803501   080030000  10000    1        1        0.00360    1
*crd.no    rt.vol     incr     bc.typ   sa.cod   sa.fac     hs.no
10803601   320010000  10000    1        1        0.00360    1
*crd.no    s.typ      s.mult     dir.left   dir.rt     hs.no
10803701   0          0.0        0.0        0.0        1
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
10803801   0.       100.   100.   0.   0.   0.   0.   1.0   1
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
10803901   0.       100.   100.   0.   0.   0.   0.   1.0   1
***** heat structure 0804 *********************************
***** hydrogen supply - pump module ***********************
*crd.no    no.ax.hs   no.mp     geom.typ   ss.flag   left.coord
10804000   1          4         2          0         0.01151
*crd.no    mesh.loc   mesh.fmt
10804100   0          1
*crd.no    no.int     rt.coord
10804101   3          0.01207    * ss
*crd.no    comp       int.no
10804201   010        3          * ss
*crd.no    source     int.no
10804301   1.0        3          * ss
*crd.no    temp.flg
10804400   0
*crd.no    temp       mp.no
10804401    17.00     4
*crd.no    left.vol   incr     bc.typ   sa.cod   sa.fac     hs.no
10804501   080040000  10000    1        1        0.97000    1
*crd.no    rt.vol     incr     bc.typ   sa.cod   sa.fac     hs.no
10804601   -010       0        3011     1        0.97000    1
*crd.no    s.typ      s.mult     dir.left   dir.rt     hs.no
10804701   0          0.0        0.0        0.0        1
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
10804801   0.       100.   100.   0.   0.   0.   0.   1.0   1
***** heat structure 1201 *********************************
```

```
***** hydrogen supply - rigid tubing **********************
*crd.no   no.ax.hs  no.mp    geom.typ  ss.flag  left.coord
11201000  11        4        2         0        0.01151
*crd.no   mesh.loc  mesh.fmt
11201100  0         1
*crd.no   no.int    rt.coord
11201101  3         0.01207  * ss
*crd.no   comp      int.no
11201201  010       3        * ss
*crd.no   source    int.no
11201301  1.0       3        * ss
*crd.no   temp.flg
11201400  0
*crd.no   temp      mp.no
11201401   17.00    4
*crd.no   left.vol  incr     bc.typ  sa.cod  sa.fac   hs.no
11201501  120010000 10000    1       1       0.84500  11
*crd.no   rt.vol    incr     bc.typ  sa.cod  sa.fac   hs.no
11201601  0         0        0       1       0.84500  11
*crd.no   s.typ     s.mult   dir.left  dir.rt   hs.no
11201701  0         0.0      0.0       0.0      11
*crd.no   ht.dia   hl.f  hl.r  w4  w5  w6  w7  lbf  hs.no
11201801  0.       100.  100.  0.  0.  0.  0.  1.0  11
***** heat structure 1301 *********************************
***** hydrogen supply - flexible line *********************
*crd.no   no.ax.hs  no.mp    geom.typ  ss.flag  left.coord
11301000  4         4        2         0        0.01135
*crd.no   mesh.loc  mesh.fmt
11301100  0         1
*crd.no   no.int    rt.coord
11301101  3         0.01179  * ss, eqiv. thick = 1.45 * 0.3 mm
*crd.no   comp      int.no
11301201  010       3        * ss
*crd.no   source    int.no
11301301  1.0       3        * ss
*crd.no   temp.flg
11301400  0
*crd.no   temp      mp.no
11301401   17.00    4
*crd.no   left.vol  incr     bc.typ  sa.cod  sa.fac   hs.no
11301501  130010000 10000    1       1       0.92805  4
*crd.no   rt.vol    incr     bc.typ  sa.cod  sa.fac   hs.no
11301601  0         0        0       1       0.92805  4
*crd.no   s.typ     s.mult   dir.left  dir.rt   hs.no
11301701  0         0.0      0.0       0.0      4
```

```
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
11301801   0.       100.   100.   0.   0.   0.   0.   1.0   4
***** heat structure 1401 **********************************
***** hydrogen supply - rigid tubing ***********************
*crd.no    no.ax.hs   no.mp     geom.typ   ss.flag   left.coord
11401000   8          4         2          0         0.01151
*crd.no    mesh.loc   mesh.fmt
11401100   0          1
*crd.no    no.int     rt.coord
11401101   3          0.01207   * ss
*crd.no    comp       int.no
11401201   010        3         * ss
*crd.no    source     int.no
11401301   1.0        3         * ss
*crd.no    temp.flg
11401400   0
*crd.no    temp       mp.no
11401401    17.00     4
*crd.no    left.vol   incr    bc.typ   sa.cod   sa.fac    hs.no
11401501   140010000  10000   1        1        0.81242   8
*crd.no    rt.vol     incr    bc.typ   sa.cod   sa.fac    hs.no
11401601   0          0       0        1        0.81242   8
*crd.no    s.typ      s.mult    dir.left   dir.rt    hs.no
11401701   0          0.0       0.0        0.0       8
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
11401801   0.       100.   100.   0.   0.   0.   0.   1.0   8
***** heat structure 1501 **********************************
***** hydrogen supply - flexible line **********************
*crd.no    no.ax.hs   no.mp     geom.typ   ss.flag   left.coord
11501000   1          4         2          0         0.01135
*crd.no    mesh.loc   mesh.fmt
11501100   0          1
*crd.no    no.int     rt.coord
11501101   3          0.01179   * ss, eqiv. thick = 1.45 * 0.3 mm
*crd.no    comp       int.no
11501201   010        3         * ss
*crd.no    source     int.no
11501301   1.0        3         * ss
*crd.no    temp.flg
11501400   0
*crd.no    temp       mp.no
11501401    17.00     4
*crd.no    left.vol   incr    bc.typ   sa.cod   sa.fac    hs.no
11501501   150010000  10000   1        1        0.83820   1
*crd.no    rt.vol     incr    bc.typ   sa.cod   sa.fac    hs.no
```

```
11501601   0           0         0         1         0.83820    1
*crd.no    s.typ       s.mult     dir.left   dir.rt     hs.no
11501701   0           0.0        0.0        0.0        1
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
11501801   0.       100.   100.   0.   0.   0.   0.   1.0   1
***** heat structure 1601 ********************************
***** hydrogen supply - rigid tubing *********************
*crd.no    no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
11601000   5          4          2          0         0.01151
*crd.no    mesh.loc   mesh.fmt
11601100   0          1
*crd.no    no.int     rt.coord
11601101   3          0.01207    * ss
*crd.no    comp       int.no
11601201   010        3          * ss
*crd.no    source     int.no
11601301   1.0        3          * ss
*crd.no    temp.flg
11601400   0
*crd.no    temp       mp.no
11601401    17.00     4
*crd.no    left.vol   incr    bc.typ   sa.cod   sa.fac    hs.no
11601501   160010000  10000   1        1        1.20714   1
11601502   160020000  10000   1        1        0.92774   2
11601503   160030000  10000   1        1        0.96203   4
11601504   160050000  10000   1        1        1.17502   5
*crd.no    rt.vol     incr    bc.typ   sa.cod   sa.fac    hs.no
11601601   0          0       0        1        1.20714   1
11601602   0          0       0        1        0.92774   2
11601603   0          0       0        1        0.96203   4
11601604   0          0       0        1        1.17502   5
*crd.no    s.typ       s.mult     dir.left   dir.rt     hs.no
11601701   0           0.0        0.0        0.0        5
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
11601801   0.       100.   100.   0.   0.   0.   0.   1.0   5
***** heat structure 2001 ********************************
***** moderator vessel - aluminum wall *******************
*crd.no    no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
12001000   2          6          1          0         0.0
*crd.no    mesh.loc   mesh.fmt
12001100   0          1
*crd.no    no.int     rt.coord
12001101   5          0.00508    * al
*crd.no    comp       int.no
12001201   020        5          * al
```

```
*crd.no    source     int.no
12001301   1.0        5          * al
*crd.no    temp.flg
12001400   0
*crd.no    temp       mp.no
12001401    17.00     6
*crd.no    left.vol   incr      bc.typ   sa.cod   sa.fac     hs.no
12001501   200010000  10000     1        1        0.03619    2
*crd.no    rt.vol     incr      bc.typ   sa.cod   sa.fac     hs.no
12001601   0          0         0        1        0.03619    2
*crd.no    s.typ      s.mult     dir.left   dir.rt     hs.no
12001701   020        0.23       0.1863     0.0        2
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
12001801   0.       100.   100.   0.   0.   0.   0.   1.0   2
***** heat structure 2002 *********************************
***** moderator vessel - poison plate *********************
*crd.no    no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
12002000   2          6          1          0         0.0
*crd.no    mesh.loc   mesh.fmt
12002100   0          1
*crd.no    no.int     rt.coord
12002101   5          0.00203    * al
*crd.no    comp       int.no
12002201   020        5          * al
*crd.no    source     int.no
12002301   1.0        5          * al
*crd.no    temp.flg
12002400   0
*crd.no    temp       mp.no
12002401    17.00     6
*crd.no    left.vol   incr      bc.typ   sa.cod   sa.fac     hs.no
12002501   200010000  10000     1        1        0.00934    2
*crd.no    rt.vol     incr      bc.typ   sa.cod   sa.fac     hs.no
12002601   200010000  10000     1        1        0.00934    2
*crd.no    s.typ      s.mult     dir.left   dir.rt     hs.no
12002701   020        0.09       0.0        0.0        2
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
12002801   0.       100.   100.   0.   0.   0.   0.   1.0   2
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
12002901   0.       100.   100.   0.   0.   0.   0.   1.0   2
***** heat structure 2401 *********************************
***** intermediate vacuum - rigid tubing ******************
*crd.no    no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
12401000   5          4          2          0         0.01420
*crd.no    mesh.loc   mesh.fmt
```

```
12401100   0          1
*crd.no    no.int     rt.coord
12401101   3          0.01509    * ss
*crd.no    comp       int.no
12401201   010        3          * ss
*crd.no    source     int.no
12401301   1.0        3          * ss
*crd.no    temp.flg
12401400   0
*crd.no    temp       mp.no
12401401    17.00     4
*crd.no    left.vol   incr     bc.typ   sa.cod   sa.fac     hs.no
12401501   0          0        0        1        1.01246    1
12401502   0          0        0        1        0.96203    3
12401503   0          0        0        1        0.92774    4
12401504   0          0        0        1        1.20714    5
*crd.no    rt.vol     incr     bc.typ   sa.cod   sa.fac     hs.no
12401601   240010000  10000    1        1        1.01246    1
12401602   240020000  10000    1        1        0.96203    3
12401603   240040000  10000    1        1        0.92774    4
12401604   240050000  10000    1        1        1.20714    5
*crd.no    s.typ      s.mult     dir.left   dir.rt     hs.no
12401701   0          0.0        0.0        0.0        5
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
12401901   0.       100.   100.   0.   0.   0.   0.   1.0   5
***** heat structure 2501 *********************************
***** intermediate vacuum - flexible line *****************
*crd.no    no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
12501000   1          4          2          0         0.01562
*                               note: eqiv. thick = 1.45 * 0.4 mm
*crd.no    mesh.loc   mesh.fmt
12501100   0          1
*crd.no    no.int     rt.coord
12501101   3          0.01620    * ss
*crd.no    comp       int.no
12501201   010        3          * ss
*crd.no    source     int.no
12501301   1.0        3          * ss
*crd.no    temp.flg
12501400   0
*crd.no    temp       mp.no
12501401    17.00     4
*crd.no    left.vol   incr     bc.typ   sa.cod   sa.fac     hs.no
12501501   0          0        0        1        0.83820    1
*crd.no    rt.vol     incr     bc.typ   sa.cod   sa.fac     hs.no
```

```
12501601  250010000  10000    1        1        0.83820    1
*crd.no   s.typ      s.mult     dir.left   dir.rt     hs.no
12501701  0          0.0        0.0        0.0        1
*crd.no   ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
12501901  0.       100.   100.   0.   0.   0.   0.   1.0   1
***** heat structure 2601 *********************************
***** intermediate vacuum - rigid tubing *****************
*crd.no   no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
12601000  8          4          2          0         0.01420
*crd.no   mesh.loc   mesh.fmt
12601100  0          1
*crd.no   no.int     rt.coord
12601101  3          0.01509    * ss
*crd.no   comp       int.no
12601201  010        3          * ss
*crd.no   source     int.no
12601301  1.0        3          * ss
*crd.no   temp.flg
12601400  0
*crd.no   temp       mp.no
12601401   17.00     4
*crd.no   left.vol   incr     bc.typ   sa.cod   sa.fac     hs.no
12601501  0          0        0        1        0.81242    8
*crd.no   rt.vol     incr     bc.typ   sa.cod   sa.fac     hs.no
12601601  260010000  10000    1        1        0.81242    8
*crd.no   s.typ      s.mult     dir.left   dir.rt     hs.no
12601701  0          0.0        0.0        0.0        8
*crd.no   ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
12601901  0.       100.   100.   0.   0.   0.   0.   1.0   8
***** heat structure 2701 *********************************
***** intermediate vacuum - flexible line *****************
*crd.no   no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
12701000  4          4          2          0         0.01562
*                               note: eqiv. thick = 1.45 * 0.4 mm
*crd.no   mesh.loc   mesh.fmt
12701100  0          1
*crd.no   no.int     rt.coord
12701101  3          0.01620    * ss
*crd.no   comp       int.no
12701201  010        3          * ss
*crd.no   source     int.no
12701301  1.0        3          * ss
*crd.no   temp.flg
12701400  0
*crd.no   temp       mp.no
```

```
12701401    17.00      4
*crd.no     left.vol   incr     bc.typ   sa.cod   sa.fac     hs.no
12701501   0           0        0        1        0.92805    4
*crd.no     rt.vol     incr     bc.typ   sa.cod   sa.fac     hs.no
12701601   270010000  10000    1        1        0.92805    4
*crd.no     s.typ      s.mult     dir.left   dir.rt     hs.no
12701701   0           0.0        0.0        0.0        4
*crd.no     ht.dia    hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
12701901   0.        100.   100.   0.   0.   0.   0.   1.0   4
***** heat structure 2801 **********************************
***** intermediate vacuum - rigid tubing ******************
*crd.no     no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
12801000   11          4          2          0         0.01420
*crd.no     mesh.loc   mesh.fmt
12801100   0           1
*crd.no     no.int     rt.coord
12801101   3           0.01509    * ss
*crd.no     comp       int.no
12801201   010         3          * ss
*crd.no     source     int.no
12801301   1.0         3          * ss
*crd.no     temp.flg
12801400   0
*crd.no     temp       mp.no
12801401    17.00      4
*crd.no     left.vol   incr     bc.typ   sa.cod   sa.fac     hs.no
12801501   0           0        0        1        0.84500    11
*crd.no     rt.vol     incr     bc.typ   sa.cod   sa.fac     hs.no
12801601   280010000  10000    1        1        0.84500    11
*crd.no     s.typ      s.mult     dir.left   dir.rt     hs.no
12801701   0           0.0        0.0        0.0        11
*crd.no     ht.dia    hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
12801901   0.        100.   100.   0.   0.   0.   0.   1.0   11
***** heat structure 2402 **********************************
***** hydrogen return - rigid tubing **********************
*crd.no     no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
12402000   5           4          2          0         0.02005
*crd.no     mesh.loc   mesh.fmt
12402100   0           1
*crd.no     no.int     rt.coord
12402101   3           0.02064    * ss
*crd.no     comp       int.no
12402201   010         3          * ss
*crd.no     source     int.no
12402301   1.0         3          * ss
```

```
*crd.no    temp.flg
12402400   0
*crd.no    temp       mp.no
12402401    17.00     4
*crd.no    left.vol   incr     bc.typ   sa.cod   sa.fac     hs.no
12402501   240010000  10000    1        1        1.01246    1
12402502   240020000  10000    1        1        0.96203    3
12402503   240040000  10000    1        1        0.92774    4
12402504   240050000  10000    1        1        1.20714    5
*crd.no    rt.tbl     incr     bc.typ   sa.cod   sa.fac     hs.no
12402601   -010       0        3011     1        1.01246    1
12402602   -010       0        3011     1        0.96203    3
12402603   -010       0        3011     1        0.92774    4
12402604   -010       0        3011     1        1.20714    5
*crd.no    s.typ      s.mult     dir.left   dir.rt     hs.no
12402701   0          0.0        0.0        0.0        5
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
12402801   0.       100.   100.   0.   0.   0.   0.   1.0   5
***** heat structure 2502 **********************************
***** hydrogen return - flexible line *********************
*crd.no    no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
12502000   1          4          2          0         0.02055
*crd.no    mesh.loc   mesh.fmt
12502100   0          1
*crd.no    no.int     rt.coord
12502101   3          0.02113    * ss, eqiv. thick = 1.45 * 0.4 mm
*crd.no    comp       int.no
12502201   010        3          * ss
*crd.no    source     int.no
12502301   1.0        3          * ss
*crd.no    temp.flg
12502400   0
*crd.no    temp       mp.no
12502401    17.00     4
*crd.no    left.vol   incr     bc.typ   sa.cod   sa.fac     hs.no
12502501   250010000  10000    1        1        0.83820    1
*crd.no    rt.tbl     incr     bc.typ   sa.cod   sa.fac     hs.no
12502601   -010       0        3012     1        0.83820    1
*crd.no    s.typ      s.mult     dir.left   dir.rt     hs.no
12502701   0          0.0        0.0        0.0        1
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
12502801   0.       100.   100.   0.   0.   0.   0.   1.0   1
***** heat structure 2602 **********************************
***** hydrogen return - rigid tubing **********************
*crd.no    no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
```

```
12602000   8           4          2          0          0.02005
*crd.no    mesh.loc    mesh.fmt
12602100   0           1
*crd.no    no.int      rt.coord
12602101   3           0.02064    * ss
*crd.no    comp        int.no
12602201   010         3          * ss
*crd.no    source      int.no
12602301   1.0         3          * ss
*crd.no    temp.flg
12602400   0
*crd.no    temp        mp.no
12602401    17.00      4
*crd.no    left.vol    incr     bc.typ   sa.cod   sa.fac    hs.no
12602501   260010000   10000    1        1        0.81242   8
*crd.no    rt.tbl      incr     bc.typ   sa.cod   sa.fac    hs.no
12602601   -010        0        3011     1        0.81242   8
*crd.no    s.typ       s.mult     dir.left   dir.rt    hs.no
12602701   0           0.0        0.0        0.0       8
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
12602801   0.       100.   100.   0.   0.   0.   0.   1.0   8
***** heat structure 2702 ***********************************
***** hydrogen return - flexible line ***********************
*crd.no    no.ax.hs    no.mp      geom.typ   ss.flag   left.coord
12702000   4           4          2          0         0.02055
*crd.no    mesh.loc    mesh.fmt
12702100   0           1
*crd.no    no.int      rt.coord
12702101   3           0.02113    * ss, eqiv. thick = 1.45 * 0.4 mm
*crd.no    comp        int.no
12702201   010         3          * ss
*crd.no    source      int.no
12702301   1.0         3          * ss
*crd.no    temp.flg
12702400   0
*crd.no    temp        mp.no
12702401    17.00      4
*crd.no    left.vol    incr     bc.typ   sa.cod   sa.fac    hs.no
12702501   270010000   10000    1        1        0.92805   4
*crd.no    rt.tbl      incr     bc.typ   sa.cod   sa.fac    hs.no
12702601   -010        0        3012     1        0.92805   4
*crd.no    s.typ       s.mult     dir.left   dir.rt    hs.no
12702701   0           0.0        0.0        0.0       4
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
12702801   0.       100.   100.   0.   0.   0.   0.   1.0   4
```

```
***** heat structure 2802 *********************************
***** hydrogen return - rigid tubing *********************
*crd.no    no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
12802000   11         4          2          0         0.02005
*crd.no    mesh.loc   mesh.fmt
12802100   0          1
*crd.no    no.int     rt.coord
12802101   3          0.02064    * ss
*crd.no    comp       int.no
12802201   010        3          * ss
*crd.no    source     int.no
12802301   1.0        3          * ss
*crd.no    temp.flg
12802400   0
*crd.no    temp       mp.no
12802401    17.00     4
*crd.no    left.vol   incr     bc.typ   sa.cod   sa.fac     hs.no
12802501   280010000  10000    1        1        0.84500    11
*crd.no    rt.tbl     incr     bc.typ   sa.cod   sa.fac     hs.no
12802601   -010       0        3011     1        0.84500    11
*crd.no    s.typ      s.mult     dir.left   dir.rt     hs.no
12802701   0          0.0        0.0        0.0        11
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
12802801   0.       100.   100.   0.   0.   0.   0.   1.0   11
***** heat structure 3201 *********************************
***** accumulator bellows wall ***************************
*crd.no    no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
13201000   1          4          1          0         0.0
*crd.no    mesh.loc   mesh.fmt
13201100   0          1
*crd.no    no.int     rt.coord
13201101   3          0.00203    * ss
*crd.no    comp       int.no
13201201   010        3          * ss
*crd.no    source     int.no
13201301   1.0        3          * ss
*crd.no    temp.flg
13201400   0
*crd.no    temp       mp.no
13201401    17.00     4
*crd.no    left.vol   incr     bc.typ   sa.cod   sa.fac     hs.no
13201501   320010000  10000    1        1        0.63134    1
*crd.no    rt.vol     incr     bc.typ   sa.cod   sa.fac     hs.no
13201601   420010000  10000    1        1        0.63134    1
*crd.no    s.typ      s.mult     dir.left   dir.rt     hs.no
```

```
13201701   0          0.0        0.0        0.0        1
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
13201801   0.       100.   100.   0.   0.   0.   0.   1.0   1
*crd.no    ht.dia   hl.f   hl.r   w4   w5   w6   w7   lbf   hs.no
13201901   0.       100.   100.   0.   0.   0.   0.   1.0   1
***** heat structure 3301 ********************************
***** accumulator hydrogen dummy hx **********************
*crd.no    no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
13301000   1          2          2          0         0.04216
*crd.no    mesh.loc   mesh.fmt
13301100   0          1
*crd.no    no.int     rt.coord
13301101   1          0.04236    * al
*crd.no    comp       int.no
13301201   020        1          * al
*crd.no    source     int.no
13301301   1.0        1          * al
*crd.no    temp.flg
13301400   0
*crd.no    temp       mp.no
13301401    17.00     2
*crd.no    left.vol   incr     bc.typ   sa.cod   sa.fac    hs.no
13301501   330010000 0         1000     1        0.09620   1
*crd.no    rt.vol     incr     bc.typ   sa.cod   sa.fac    hs.no
13301601   350010000 0         1000     1        0.09620   1
*crd.no    s.typ      s.mult     dir.left   dir.rt    hs.no
13301701   0          0.0        0.0        0.0       1
***** heat structure 4301 ********************************
***** accumulator helium dummy hx ************************
*crd.no    no.ax.hs   no.mp      geom.typ   ss.flag   left.coord
14301000   1          2          2          0         0.10974
*crd.no    mesh.loc   mesh.fmt
14301100   0          1
*crd.no    no.int     rt.coord
14301101   1          0.11024    * al
*crd.no    comp       int.no
14301201   020        1          * al
*crd.no    source     int.no
14301301   1.0        1          * al
*crd.no    temp.flg
14301400   0
*crd.no    temp       mp.no
14301401    17.00     2
*crd.no    left.vol   incr     bc.typ   sa.cod   sa.fac    hs.no
14301501   430010000 0         1000     1        0.09620   1
```

```
*crd.no    rt.vol     incr     bc.typ   sa.cod   sa.fac     hs.no
14301601   450010000  0        1000     1        0.09620    1
*crd.no    s.typ      s.mult     dir.left   dir.rt     hs.no
14301701   0          0.0        0.0        0.0        1
***** heat structure thermal properties *******************
***********************************************************
***** composition 010 **************************************
***** stainless steel 304 **********************************
***** k from "Cryogenic Systems", 2nd edition, *************
***** Randall F. Barron, 1985, p 21 ***********************
*crd.no    mat.typ    k.flg   cp.flg
20101000   tbl/fctn   1       1
*            temp        k
*crd.no       K       W/(m*K)
20101001      0.          0.
20101002      2.          1.
20101003      4.          3.
20101004      6.          4.2
20101005      8.          6.
20101006     10.          8.
20101007     20.         15.
20101008     40.         30.
20101009     60.         38.
20101010     80.         45.
20101011    100.         50.
20101012    200.         70.
20101013    400.         95.
20101014    1.+6        100.    *assumed
***** rho = 7.817 g/cm3 from Holman, "Heat Transfer", ******
***** 4th edition, p 497 **********************************
***** Cp from "Cryogenic Systems", 2nd edition, ************
***** Randall F. Barron, 1985, pp 24-29 *******************
*              temp        rho*Cp
*crd.no         K          J/(m3*K)
20101051    0.0          0.0
20101052    1.00000      3.421921
20101053    10.9750      4523.594
20101054    20.9500      31464.60
20101055    30.9250      101204.4
20101056    40.9000      231054.8
20101057    50.8750      420131.9
20101058    60.8500      652333.6
20101059    70.8250      905411.4
20101060    80.8000      1158173.
20101061    90.7750      1391255.
```

```
20101062    100.750     1609011.
20101063    110.725     1811161.
20101064    120.700     1980647.
20101065    130.675     2143125.
20101066    140.650     2270874.
20101067    150.625     2398225.
20101068    160.600     2494280.
20101069    170.575     2590335.
20101070    180.550     2666489.
20101071    190.525     2739327.
20101072    200.500     2800342.
20101073    210.475     2856334.
20101074    220.450     2903151.
20101075    230.425     2942350.
20101076    240.400     2981549.
20101077    250.375     3020749.
20101078    260.350     3056660.
20101079    270.325     3081902.
20101080    280.300     3107144.
20101081    290.275     3132386.
20101082    300.250     3157628.
20101083    310.225     3175305.
20101084    320.200     3192367.
20101085    330.175     3209429.
20101086    340.150     3226491.
20101087    350.125     3240470.
20101088    360.100     3252510.
20101089    370.075     3264551.
20101090    380.050     3276591.
20101091    390.025     3287641.
20101092    1.+6        3287641.
***** composition 020 ************************************
***** aluminum 6061-T6 ***********************************
***** k for 10.8-921.9 K from DOD, Metallic Materials ******
***** and Elements for Aerospace Vehicle Structures, *******
***** MIL-HDBK-5E, 6/1/87 *********************************
***** code will automatically die if temp. < 10.8 K ********
*crd.no    mat.typ    k.flg   cp.flg
20102000   tbl/fctn   1       1
*            temp        k
*crd.no       K        W/(m*K)
20102001    10.8        17.305
20102002    21.9        29.419
20102003    33.0        39.802
20102004    55.2        65.759
```

```
20102005     77.4        83.064
20102006     99.7        98.639
20102007    121.9       107.291
20102008    144.1       117.674
20102009    166.3       124.596
20102010    188.6       131.518
20102011    210.8       136.710
20102012    233.0       141.901
20102013    255.2       145.362
20102014    277.4       148.823
20102015    299.7       152.284
20102016    321.9       155.745
20102017    344.1       159.206
20102018    366.3       160.937
20102019    388.6       162.667
20102020    410.8       166.128
20102021    433.0       169.589
20102022    455.2       171.320
20102023    477.4       173.050
20102024    499.7       174.781
20102025    521.9       176.511
20102026    544.1       177.030
20102027    566.3       178.242
20102028    588.6       179.972
20102029    677.4       179.972
20102030    699.7       178.242
20102031    733.0       176.511
20102032    766.3       173.050
20102033    788.6       171.320
20102034    810.8       169.589
20102035    921.9       160.937
20102036    1.0+6       160.937
***** rho = 2.7 g/cm3 from SRL, Aluminum Alloy Property ****
***** Data Book, M. F. Marchbanks, 5/88 *******************
***** Cp for 10.8-921.9 K from DOD, Metallic Materials *****
***** and Elements for Aerospace Vehicle Structures, *******
***** MIL-HDBK-5E, 6/1/87 **********************************
*               temp         rho*Cp
*crd.no          K          J/(m3*K)
20102051        10.8         56.7e3
20102052        21.9         78.3e3
20102053        33.0        172.8e3
20102054        55.2        340.2e3
20102055        77.4        791.1e3
20102056        99.7       1131.3e3
```

```
20102057        121.        1412.1e3
20102058        144.        1582.2e3
20102059        166.        1752.3e3
20102060        188.        1922.4e3
20102061        210.        2033.1e3
20102062        233.        2146.5e3
20102063        255.        2214.0e3
20102064        277.        2316.6e3
20102065        299.        2373.3e3
20102066        321.        2430.0e3
20102067        344.        2486.7e3
20102068        366.        2519.1e3
20102069        388.        2543.3e3
20102070        410.        2600.1e3
20102071        433.        2632.5e3
20102072        455.        2656.8e3
20102073        477.        2678.4e3
20102074        499.        2713.5e3
20102075        521.        2724.3e3
20102076        544.        2756.7e3
20102077        566.        2770.2e3
20102078        588.        2791.8e3
20102079        610.        2826.9e3
20102080        655.        2859.3e3
20102081        677.        2880.9e3
20102082        721.        2937.6e3
20102083        744.        2951.1e3
20102084        766.        2983.5e3
20102085        788.        3005.1e3
20102086        810.        3051.0e3
20102087        921.        3277.8e3
20102088        1.+6        3277.8e3
***** general tables ************************************
********************************************************
***** table 010 *****************************************
***** ambient temperature for heat inleakage **************
*crd.no    type
20201000   temp
*crd.no    time     temp
20201001     -1.0   300.0
20201002   9000.0   300.0
***** table 011 *****************************************
***** ht coefficient for rigid tubing heat inleakage   *****
***** htc below yields inleakage of 1 W/m of tubing    *****
***** assuming 300 K ambient and 23 K tube wall,       *****
```

```
***** use htc.mult to specify other inleakage rates     *****
*crd.no    type     trip   time.mult   htc.mult
20201100   htc-t    0      1.0         2.8
*crd.no    time     htc [W/(m2*K)]
20201101     -1.0   0.02784
20201102   9000.0   0.02784
***** table 012 ******************************************
***** ht coefficient for flexible line heat inleakage  *****
***** htc below yields inleakage of 1 W/m of tubing    *****
***** assuming 300 K ambient and 23 K tube wall,       *****
***** use htc.mult to specify other inleakage rates     *****
*crd.no    type     trip   time.mult   htc.mult
20201200   htc-t    0      1.0         3.2
*crd.no    time     htc [W/(m2*K)]
20201201     -1.0   0.02719
20201202   9000.0   0.02719
***** table 020 ******************************************
***** moderator vessel heat generation *******************
*crd.no    type
20202000   power
*crd.no    time     power
20202001     -1.0      0.0
20202002    201.0      0.0
20202003    202.0   3120.0
20202004   9000.0   3120.0
***** table 030 ******************************************
***** heat exchanger wall temperature ********************
*crd.no    type
20203000   temp
*crd.no    time     temp
20203001     -1.0   17.00
20203002   9000.0   17.00
***** table 458 ******************************************
***** vsc windage torque (see speed controller section) ****
*
***** control variables **********************************
**********************************************************
***** flow loop pressure drop (bar) **********************
*crd.no    name       type       s.fact      init.val   init.flg
20500200   dp-loop    sum        1.0e-5      0.0        1
*crd.no    ao    a1    v.name  v.code
20500201   0.0   1.0   p 050010000   -1.0 p 030010000
***** circulator speed (rpm) *****************************
*crd.no    name       type       s.fact      init.val   init.flg
20500400   circ-rpm   sum        1.0         0.0        1
```

```
*crd.no    ao    a1    v.name   v.code
20500401   0.0   9.549297   pmpvel 040
***** circulator power (W) *********************************
*crd.no    name       type       s.fact       init.val   init.flg
20500600   circ-pow   mult       -1.0         0.0        1
*crd.no    v.name   v.code
20500601   pmptrq 040   pmpvel 040
***** moderator vessel hydrogen average temperature (K) ****
*crd.no    name       type       s.fact       init.val   init.flg
20500800   tav-mvh2   sum        0.5          0.0        1
*crd.no    ao    a1    v.name   v.code
20500801   0.0   0.5   tempg 160050000   1.0   tempg 200010000
20500802         0.5   tempg 200020000
***** hx heat removal (W) from hydrogen *******************
*crd.no    name       type       s.fact       init.val   init.flg
20501000   hx-heat    sum        1.0          0.0        1
*crd.no    ao    a1    v.name   v.code
20501001   0.0   0.27600   htrnr 070100101   0.27600   htrnr 070100201
20501002         0.27600   htrnr 070100301   0.27600   htrnr 070100401
20501003         0.27600   htrnr 070100501   0.27600   htrnr 070100601
***** flow loop hydrogen mass formulation #1 (kg) **********
* *crd.no    name       type       s.fact       init.val   init.flg
* 20510100   mh2lop1    sum        1.0          0.0        1
* *crd.no    ao    a1    v.name   v.code
* 20510101   0.0   1.0   tmassv 030010000
* 20510102         1.0   tmassv 040010000
* 20510103         1.0   tmassv 050010000   1.0   tmassv 050020000
* 20510104         1.0   tmassv 070010000   1.0   tmassv 070020000
* 20510105         1.0   tmassv 070030000   1.0   tmassv 070040000
* 20510106         1.0   tmassv 070050000   1.0   tmassv 070060000
* 20510107         1.0   tmassv 080010000   1.0   tmassv 080020000
* 20510108         1.0   tmassv 080030000   1.0   tmassv 080040000
* *crd.no    name       type       s.fact       init.val   init.flg
* 20510200   mh2lop2    sum        1.0          0.0        1
* *crd.no    ao    a1    v.name   v.code
* 20510201   0.0   1.0   tmassv 120010000   1.0   tmassv 120020000
* 20510202         1.0   tmassv 120030000   1.0   tmassv 120040000
* 20510203         1.0   tmassv 120050000   1.0   tmassv 120060000
* 20510204         1.0   tmassv 120070000   1.0   tmassv 120080000
* 20510205         1.0   tmassv 120090000   1.0   tmassv 120100000
* 20510206         1.0   tmassv 120110000
* 20510207         1.0   tmassv 130010000   1.0   tmassv 130020000
* 20510208         1.0   tmassv 130030000   1.0   tmassv 130040000
* *crd.no    name       type       s.fact       init.val   init.flg
* 20510300   mh2lop3    sum        1.0          0.0        1
```

```
* *crd.no    ao    a1    v.name   v.code
* 20510301   0.0   1.0   tmassv  140010000   1.0   tmassv  140020000
* 20510302         1.0   tmassv  140030000   1.0   tmassv  140040000
* 20510303         1.0   tmassv  140050000   1.0   tmassv  140060000
* 20510304         1.0   tmassv  140070000   1.0   tmassv  140080000
* 20510305         1.0   tmassv  150010000
* 20510306         1.0   tmassv  160010000   1.0   tmassv  160020000
* 20510307         1.0   tmassv  160030000   1.0   tmassv  160040000
* 20510308         1.0   tmassv  160050000
* 20510309         1.0   tmassv  200010000   1.0   tmassv  200020000
* *crd.no    name       type       s.fact       init.val   init.flg
* 20510400   mh2lop4    sum        1.0          0.0        1
* *crd.no    ao    a1    v.name   v.code
* 20510401   0.0   1.0   tmassv  240010000   1.0   tmassv  240020000
* 20510402         1.0   tmassv  240030000   1.0   tmassv  240040000
* 20510403         1.0   tmassv  240050000
* 20510404         1.0   tmassv  250010000
* 20510405         1.0   tmassv  260010000   1.0   tmassv  260020000
* 20510406         1.0   tmassv  260030000   1.0   tmassv  260040000
* 20510407         1.0   tmassv  260050000   1.0   tmassv  260060000
* 20510408         1.0   tmassv  260070000   1.0   tmassv  260080000
* *crd.no    name       type       s.fact       init.val   init.flg
* 20510500   mh2lop5    sum        1.0          0.0        1
* *crd.no    ao    a1    v.name   v.code
* 20510501   0.0   1.0   tmassv  270010000   1.0   tmassv  270020000
* 20510502         1.0   tmassv  270030000   1.0   tmassv  270040000
* 20510503         1.0   tmassv  280010000   1.0   tmassv  280020000
* 20510504         1.0   tmassv  280030000   1.0   tmassv  280040000
* 20510505         1.0   tmassv  280050000   1.0   tmassv  280060000
* 20510506         1.0   tmassv  280070000   1.0   tmassv  280080000
* 20510507         1.0   tmassv  280090000   1.0   tmassv  280100000
* 20510508         1.0   tmassv  280110000
* *crd.no    name       type       s.fact       init.val   init.flg
* 20510800   mh2lopt1   sum        1.0          0.0        1
* *crd.no    ao    a1    v.name   v.code
* 20510801   0.0   1.0   cntrlvar 101   1.0   cntrlvar 102
* 20510802         1.0   cntrlvar 103   1.0   cntrlvar 104
* 20510803         1.0   cntrlvar 105
***** flow loop hydrogen mass formulation #2 (kg) **********
*crd.no    name       type       s.fact       init.val   init.flg
20510900   mh2lopt2   sum        1.0          0.0        1
*crd.no    ao    a1    v.name   v.code
20510901   0.0   1.0   systms 1          -1.0   tmassv 320010000
20510902        -1.0   tmassv 330010000
***** accumulator hydrogen mass (kg) *********************
```

```
*crd.no    name       type       s.fact       init.val   init.flg
20511200  mh2accum   sum        1.0          0.0        1
*crd.no   ao   a1   v.name  v.code
20511201  0.0  1.0  cntrlvar 110  -1.0  cntrlvar 109
***** accumulator hydrogen volume (m3) *******************
*crd.no    name       type       s.fact       init.val   init.flg
20511400  vh2accum   div        1.0          0.0        1
*crd.no   v1.name  v1.code    v2.name  v2.code
20511401  rho      320010000  cntrlvar 112
***** bellows expansion volume (m3) **********************
***** 0.0012782 m3 = accum. hydrogen minimum volume ********
*crd.no    name       type       s.fact       init.val   init.flg
20511600  vbellow    sum        1.0          0.0        1
*crd.no   ao   a1   v.name  v.code
20511601  -0.0012782  1.0  cntrlvar 114
***** bellows expansion volume fraction ******************
***** 154.490 = 1/(0.0064729 m3) ************************
*crd.no    name       type       s.fact       init.val   init.flg
20511800  fbellow    sum        1.0          0.0        1
*crd.no   ao   a1   v.name  v.code
20511801  0.0  154.490  cntrlvar 116
***** accumulator helium volume (m3) *********************
***** 0.0340032 m3 = accum. helium maximum volume *********
*crd.no    name       type       s.fact       init.val   init.flg
20512000  vheaccum   sum        1.0          0.0        1
*crd.no   ao   a1   v.name  v.code
20512001  0.0340032  -1.0  cntrlvar 116
***** accumulator pressure numerator *********************
***** 2077 J/(kg*K) = helium gas constant ****************
*crd.no    name       type       s.fact       init.val   init.flg
20512400  paccum-n   mult       2077.0       0.0        1
*crd.no   v.name  v.code
20512401  cntrlvar 122  tempg 420010000
***** accumulator pressure (Pa) **************************
*crd.no    name       type       s.fact       init.val   init.flg
20512600  paccum     div        1.0          14.91e5    0
*crd.no   v1.name  v1.code    v2.name  v2.code
20512601  cntrlvar 120        cntrlvar 124
***** constant accumulator pressure (Pa) *****************
*crd.no    name       type       value
*20512600  paccum     constant  14.91e5
*
****************************************
* volumetric flow into transfer line    *
********************************************
```

```
20500100 vol_flow  sum  1.0 0.0     1         *
*    0.41592 = 4.1592e-4 m^2 * 10^3 (L/m^3)    *
20500101  0.0  0.41592  velgj  080030000      *
***********************************************
*
*******************************************************************
* establish emergency speed control when pressure is out of control*
*******************************************************************
*
*******************************************************************
* if p <= p_crit is true, cv_408 = 1.0                            *
* if p >  p_crit it true, cv_408 = 0.0                            *
*******************************************************************
20540800  tripped2  tripunit  1.0   0.0  1                        *
20540801   460                                                    *
*******************************************************************
* if p <= p_crit is true, cv_409 = 0.0                            *
* if p >  p_crit it true, cv_409 = 1.0                            *
*******************************************************************
20540900  tripped3  tripunit  1.0   0.0  1                        *
20540901  -460                                                    *
*******************************************************************
*
****************************************************************
* compute the differential speed rad/s/10^3 for all circulators *
* note: 1.047198e-4 = 2pi/60/1000 (rpm to (rad/s)/10^3)        *
****************************************************************
20541000  d_spd_1   sum    1.0   0.0  1                         *
20541001  0.0  1.047198e-4 cntrlvar 447  -1.0e-3  cntrlvar 499  *
****************************************************************
*
***********************************************************
* compute the differential pressure across all circulators *
***********************************************************
20541300 dp_act1  sum  1.0e-5  0.0  1                     *
20541301 0.0 1.0 p 050010000 -1.0 p 030010000             *
*20541301 0.0 1.0+5 cntrlvar 001                           *
***********************************************************
*
********************************
* assign the setpoint based on *
* emergency or not-emergency   *
*************************************
* vsc #1/3                          *
20541700 dp_sp1   mult  1.0  0.0  1 *
```

```
20541701 cntrlvar 451  cntrlvar 409  *
************************************
*
*********************************
* assign the sensed data based on *
* emergency or not-emergency      *
************************************
* vsc #1/3                         *
20542200 spdctrl1  mult -1.0  0.0  1 *
20542201 cntrlvar 410  cntrlvar 408  *
20542300 dpctrl1   mult  1.0  0.0  1 *
20542301 cntrlvar 413  cntrlvar 409  *
************************************
*
*******************************************************
* variable speed circulator (vsc) #1 of 3 speed control *
******************************************************************
20544900   senspt1   sum   1.0   0.0 1                            *
20544901 0.0 1.0 cntrlvar 422 1.0 cntrlvar 423                    *
* delayed set point change due to signal processing               *
*20545200   ss_del1  delay 1.0   0.0 1                             *
*20545201   cntrlvar 449  -0.1    1                                *
******************************************************************
*                                                                 *
* if pump trip is true, pump is tripped off, tripunit -451 = 0.0  *
* if pump trip is false, pump is tripped on, tripunit -451 = 1.0  *
*                                                                 *
20545300  tripped1   tripunit   1.0   0.0   1                     *
20545301  -451                                                    *
*                                                                 *
* vsc-1 torque                                                    *
* the minimum torque is assumed to be zero N*m                    *
* set the initial torque to the max torque = 0.131 N*m (B Batton  *
* 21-sept-01) or zero if the circulator is initially stationary   *
20545400  vscl_tr1    pumpctl  1.0   0.088     0  3  0.0  0.150   *
*          set-point      sensed          S      T_i    T_p       *
20545401   cntrlvar  417  cntrlvar  449   1.0   1.5    0.15       *
*                                                                 *
20545500  max_trq1   div      1.0     0.0   1  1  0.0             *
20545501  pmpvel    040   cntrlvar  450                           *
*                                                                 *
* limit the delivered torque to that corresponding to 810 watts   *
* drawn from motor(independent of torque limit of controller)     *
*                                                                 *
20545600  lim_trq1   stdfnctn   1.0   0.0  1                      *
```

```
20545601  min  cntrlvar  454   cntrlvar   455                                  *
*                                                                              *
* set delivered shaft torque to zero if pump is tripped                        *
*                                                                              *
20545700  vscl_ne1   mult    1.0    0.0   1                                    *
20545701  cntrlvar   453     cntrlvar   456                                    *
*                                                                              *
* define the windage loss for this circulator                                  *
*                                                                              *
20545800  wind1   function   1.0   0.0   1                                     *
20545801  pmpvel   040     458                                                 *
*                   0.1047198=(2*pi)/60.0                                      *
20245800  reac-t 0   0.1047198   1.0                                           *
*                  speed        windage torque   windage power                 *
*                  (rpm)           (N*m)           (watts)                     *
20245801              0.        0.0           *    0.                          *
20245802           2791.        0.00342146    *    1.                          *
20245803           4727.        0.00404032    *    2.                          *
20245804          10000.        0.00420169    *    4.4                         *
20245805          15000.        0.00636620    *   10.                          *
20245806          20000.        0.00859436    *   18.                          *
20245807          21163.        0.00902452    *   20.                          *
20245808          25349.        0.0113014     *   30.                          *
20245809          28372.        0.0134630     *   40.                          *
20245810          31395.        0.0152083     *   50.                          *
20245811          33256.        0.0172287     *   60.                          *
20245812          35581.        0.0187867     *   70.                          *
20245813          37442.        0.0204034     *   80.                          *
20245814          38837.        0.0221293     *   90.                          *
20245815          40698.        0.0234638     *  100.                          *
20245816          50000.        0.0343775     *  180.                          *
20245817          52791.        0.0361777     *  200.                          *
20245818          60000.        0.0461549     *  290.                          *
*                                                                              *
* all electric power lost to vsc (grid, UPS, diesel)                           *
*                                                                              *
20546600 nopwr1  tripunit  1.0  0.0  1                                         *
20546601  637                                                                  *
*                                                                              *
* speed of vsc less than threshold of 15 krpm                                  *
*                                                                              *
20546700 lospd1a tripunit  1.0  0.0  1                                         *
20546701  457                                                                  *
*                                                                              *
* compute touch-down bearings (TDB) power loss                                 *
```

```
* now set as constant torque = 500/15000*60/2 pi=0.31831 N*m          *
*fix 20546800 tautdb1  div  500.0  0.0  1                              *
*fix 20546801 pmpvel 040                                               *
20546800 tautdb1 constant 0.31831                                      *
*                                                                      *
* zero tdb losses if speed is sufficiently high                        *
*                                                                      *
20546900 lospd1b mult  1.0    0.0  1                                   *
20546901 cntrlvar  467  cntrlvar  468                                  *
*                                                                      *
* compute regenerative (RG) power loss  term 1/2                       *
*                                                                      *
20547000 taurg11  div  150.0  0.0  1                                   *
20547001 pmpvel 040                                                    *
*                                                                      *
* compute regenerative (RG) power loss  term 2/2                       *
*                                                                      *
20547100 taurg12  sum  1.0    0.0  1                                   *
*        9.549297e-3=60.0/speed_max                                    *
20547101 9.549297e-3  1.0  cntrlvar 470                                *
*                                                                      *
* sum all no-power losses                                              *
*                                                                      *
20547200 taunp1   sum  1.0    0.0  1                                   *
20547201 0.0  1.0  cntrlvar  469  1.0  cntrlvar  471                   *
*                                                                      *
* zero torque losses if power is available                             *
*                                                                      *
20547300 tnpon1  mult  1.0    0.0  1                                   *
20547301 cntrlvar  466  cntrlvar  472                                  *
*                                                                      *
* create overall torque preserving sign                                *
*                                                                      *
20547400 alltau1  sum  1.0    0.0  1                                   *
20547401 0.0  1.0  cntrlvar  457   * torque delivered by motor         *
20547402     -1.0  cntrlvar  458   * windage loss                      *
20547403     -1.0  cntrlvar  473   * TDB + regeneration losses         *
************************************************************************
* shaft speed is limited to 60 krpm, i.e.,                             *
* 6283.185 = 60,000 * 2 * pi / 60                                      *
* unused torque may result if max speed is reached                     *
************************************************************************
20549900  vsc1_sft   shaft   1.0  1256.64  0  3  1.0e-6  6283.185      *
* assume all the moment of inertia is accounted for in the pump        *
* component and set the shaft moment of inertia to zero                *
```

```
20549901    474     0.0          0.0     pump   040                        *
*******************************************************************
*
. end of input cards
```

APPENDIX B. MODELICA INPUT DECK FOR CMS MODEL

APPENDIX B. MODELICA INPUT DECK FOR CMS MODEL

```
model CMS_H2_RealGeoV1NoHxTempRamp
  Real V(start = 10);
  package Medium =
      TRANSFORM.Media.ExternalMedia.CoolProp.Hydrogen;

  TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
    CircOutlet_50(
    redeclare package Medium = Medium,
    Ts_start(displayUnit="K"),
    p_a_start=99999.99999999999*(0.0689476*187),
    p_b_start=99999.99999999999*(0.0689476*187),
    T_a_start(displayUnit="K") = 19,
    T_b_start(displayUnit="K") = 19,
    m_flow_a_start=0.075,
    redeclare model Geometry =
        TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
        StraightPipe(
        dimension(displayUnit="m") = 0.02301,
        length(displayUnit="m") = 2,
        roughness(displayUnit="m") = 2e-6))
    annotation (Placement(transformation(extent={{-60,30},
          {-40,50}})));

  TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
    H2Supply_80_1(
    redeclare package Medium = Medium,
    Ts_start(displayUnit="K"),
    p_a_start=99999.99999999999*(0.0689476*187),
    p_b_start=99999.99999999999*(0.0689476*187),
    T_a_start(displayUnit="K") = 19,
    T_b_start(displayUnit="K") = 19,
    m_flow_a_start=0.075,
    redeclare model Geometry =
        TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
        StraightPipe(
        dimension(displayUnit="m") = 0.02301,
        length(displayUnit="m") = 2,
        roughness(displayUnit="m") = 2e-6,
        nV=2),
    exposeState_b=true)
              annotation (Placement(
        transformation(extent={{8,30},{28,50}})));

  TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
```

```
  Moderator_200(
  nParallel=8,
  redeclare package Medium = Medium,
  Ts_start(displayUnit="K"),
  p_a_start=99999.99999999999*(0.0689476*187),
  p_b_start=99999.99999999999*(0.0689476*187),
  T_a_start(displayUnit="K") = 19,
  T_b_start(displayUnit="K") = 19,
  m_flow_a_start=0.075,
  redeclare model Geometry =
      TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
      StraightPipe(
      dimension(displayUnit="m") = 0.03004,
      length(displayUnit="m") = 0.16256,
      roughness(displayUnit="m") = 2e-6,
      dheight=0.00016256,
      nV=4),
  use_HeatTransfer=false,
  redeclare model InternalHeatGen =
      TRANSFORM.Fluid.ClosureRelations.InternalVolumeHeatGeneration.Models.
      DistributedVolume_1D.GenericHeatGeneration
      (Q_gen=fixedDelay.y/Moderator_200.nV),
  exposeState_a=true,
  exposeState_b=false) annotation (Placement(
      transformation(
      extent={{10,-10},{-10,10}},
      rotation=0,
      origin={118,-84})));

TRANSFORM.Fluid.Machines.Pump_SimpleMassFlow Circulator_40(
    redeclare package Medium = Medium,
    m_flow_nominal=0.075)          annotation (
    Placement(transformation(extent={{-90,32},{-70,
         52}})));

TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
  HX_70(
  nParallel=175,
  redeclare package Medium = Medium,
  Ts_start(displayUnit="K"),
  p_a_start=99999.99999999999*(0.0689476*187),
  p_b_start=99999.99999999999*(0.0689476*187),
  T_a_start(displayUnit="K") = 19,
  T_b_start(displayUnit="K") = 19,
  m_flow_a_start=0.075,
```

```
  redeclare model Geometry =
      TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
       StraightPipe(
       dimension(displayUnit="m") = 0.004,
       length(displayUnit="m") = 0.89124,
       roughness(displayUnit="m") = 2e-6,
      nV=4),
  use_HeatTransfer=true,
  redeclare model HeatTransfer =
      TRANSFORM.Fluid.ClosureRelations.HeatTransfer.Models.
       DistributedPipe_1D_MultiTransferSurface.Nus
       (Nu0=275))
  annotation (Placement(transformation(extent={{-28,30},
          {-8,50}})));
parameter Modelica.Blocks.Interfaces.RealOutput
  y=-1 "Value of Real output";

TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
  CircInlet_30(
  redeclare package Medium = Medium,
  Ts_start(displayUnit="K"),
  p_a_start=99999.99999999999*(0.0689476*187),
  p_b_start=99999.99999999999*(0.0689476*187),
  T_a_start(displayUnit="K") = 19,
  T_b_start(displayUnit="K") = 19,
  m_flow_a_start=0.075,
  redeclare model Geometry =
      TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
       StraightPipe(
       dimension(displayUnit="m") = 0.02301,
       length(displayUnit="m") = 1,
       roughness(displayUnit="m") = 2e-6,
      nV=2),
  exposeState_b=true)
  annotation (Placement(transformation(extent={{-118,30},
          {-98,50}})));
TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
  H2Supply_80_2(
  redeclare package Medium = Medium,
  Ts_start(displayUnit="K"),
  p_a_start=99999.99999999999*(0.0689476*187),
  p_b_start=99999.99999999999*(0.0689476*187),
  T_a_start(displayUnit="K") = 19,
  T_b_start(displayUnit="K") = 19,
  m_flow_a_start=0.075,
```

```
  redeclare model Geometry =
      TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
      StraightPipe(
      dimension(displayUnit="m") = 0.02301,
      length(displayUnit="m") = 1.88371,
      roughness(displayUnit="m") = 2e-6,
      nV=1)) annotation (Placement(
      transformation(extent={{60,30},{80,50}})));
TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
  H2Supply_120(
  redeclare package Medium = Medium,
  Ts_start(displayUnit="K"),
  p_a_start=99999.99999999999*(0.0689476*187),
  p_b_start=99999.99999999999*(0.0689476*187),
  T_a_start(displayUnit="K") = 19,
  T_b_start(displayUnit="K") = 19,
  m_flow_a_start=0.075,
  redeclare model Geometry =
      TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
      StraightPipe(
      dimension(displayUnit="m") = 0.02301,
      length(displayUnit="m") = 9.295,
      roughness(displayUnit="m") = 2e-6,
      dheight(displayUnit="m") = -7.0359,
      nV=1)) annotation (Placement(
      transformation(
      extent={{-10,-10},{10,10}},
      rotation=-90,
      origin={82,16})));
TRANSFORM.Fluid.FittingsAndResistances.SpecifiedResistance
  resistance(redeclare package Medium = Medium, R=
      0.0001)
          annotation (Placement(transformation(
        extent={{-10,-10},{10,10}},
      rotation=-90,
      origin={36,56})));
TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
  H2Supply_130(
  nParallel=2,
  redeclare package Medium = Medium,
  Ts_start(displayUnit="K"),
  p_a_start=99999.99999999999*(0.0689476*187),
  p_b_start=99999.99999999999*(0.0689476*187),
  T_a_start(displayUnit="K") = 19,
  T_b_start(displayUnit="K") = 19,
```

```
    m_flow_a_start=0.075,
    redeclare model Geometry =
        TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
        StraightPipe(
        dimension(displayUnit="m") = 0.01566,
        length(displayUnit="m") = 3.7122,
        roughness(displayUnit="m") = 2e-4,
        dheight(displayUnit="m"),
        nV=1)) annotation (Placement(
        transformation(extent={{90,-12},{110,8}})));
  TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
    H2Supply_140(
    redeclare package Medium = Medium,
    Ts_start(displayUnit="K"),
    p_a_start=99999.99999999999*(0.0689476*187),
    p_b_start=99999.99999999999*(0.0689476*187),
    T_a_start(displayUnit="K") = 19,
    T_b_start(displayUnit="K") = 19,
    m_flow_a_start=0.075,
    redeclare model Geometry =
        TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
        StraightPipe(
        dimension(displayUnit="m") = 0.02301,
        length(displayUnit="m") = 6.49936,
        roughness(displayUnit="m") = 2e-6,
        dheight(displayUnit="m"),
        nV=1)) annotation (Placement(
        transformation(extent={{118,-12},{138,8}})));
  TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
    H2Supply_150(
    nParallel=2,
    redeclare package Medium = Medium,
    Ts_start(displayUnit="K"),
    p_a_start=99999.99999999999*(0.0689476*187),
    p_b_start=99999.99999999999*(0.0689476*187),
    T_a_start(displayUnit="K") = 19,
    T_b_start(displayUnit="K") = 19,
    m_flow_a_start=0.075,
    redeclare model Geometry =
        TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
        StraightPipe(
        dimension(displayUnit="m") = 0.01566,
        length(displayUnit="m") = 0.8382,
        roughness(displayUnit="m") = 2e-4,
        dheight(displayUnit="m") = -0.5588,
```

```
      nV=1)) annotation (Placement(
      transformation(
      extent={{-10,-10},{10,10}},
      rotation=-90,
      origin={140,-28})));
TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
  H2Supply_160(
  redeclare package Medium = Medium,
  Ts_start(displayUnit="K"),
  p_a_start=99999.99999999999*(0.0689476*187),
  p_b_start=99999.99999999999*(0.0689476*187),
  T_a_start(displayUnit="K") = 19,
  T_b_start(displayUnit="K") = 19,
  m_flow_a_start=0.075,
  redeclare model Geometry =
      TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
      StraightPipe(
      dimension(displayUnit="m") = 0.02301,
      length(displayUnit="m") = 5.23396,
      roughness(displayUnit="m") = 2e-6,
      dheight(displayUnit="m") = -3.95683,
      nV=1)) annotation (Placement(
      transformation(
      extent={{-10,-10},{10,10}},
      rotation=-90,
      origin={140,-56})));
TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
  H2Supply_240(
  nParallel=7,
  redeclare package Medium = Medium,
  Ts_start(displayUnit="K"),
  p_a_start=99999.99999999999*(0.0689476*187),
  p_b_start=99999.99999999999*(0.0689476*187),
  T_a_start(displayUnit="K") = 19,
  T_b_start(displayUnit="K") = 19,
  m_flow_a_start=0.075,
  redeclare model Geometry =
      TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
      StraightPipe(
      dimension(displayUnit="m") = 0.009933,
      length(displayUnit="m") = 5.0714,
      roughness(displayUnit="m") = 2e-6,
      dheight(displayUnit="m") = 3.79427,
      nV=1)) annotation (Placement(
      transformation(
```

```
      extent={{10,-10},{-10,10}},
      rotation=-90,
      origin={90,-72})));
TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
  H2Supply_250(
  nParallel=18,
  redeclare package Medium = Medium,
  Ts_start(displayUnit="K"),
  p_a_start=99999.99999999999*(0.0689476*187),
  p_b_start=99999.99999999999*(0.0689476*187),
  T_a_start(displayUnit="K") = 19,
  T_b_start(displayUnit="K") = 19,
  m_flow_a_start=0.075,
  redeclare model Geometry =
      TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
      StraightPipe(
      dimension(displayUnit="m") = 0.006,
      length(displayUnit="m") = 0.8382,
      roughness(displayUnit="m") = 2e-4,
      dheight(displayUnit="m") = 0.5588,
      nV=1)) annotation (Placement(
      transformation(
      extent={{10,-10},{-10,10}},
      rotation=-90,
      origin={90,-42})));
TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
  H2Supply_260(
  nParallel=7,
  redeclare package Medium = Medium,
  Ts_start(displayUnit="K"),
  p_a_start=99999.99999999999*(0.0689476*187),
  p_b_start=99999.99999999999*(0.0689476*187),
  T_a_start(displayUnit="K") = 19,
  T_b_start(displayUnit="K") = 19,
  m_flow_a_start=0.075,
  redeclare model Geometry =
      TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
      StraightPipe(
      dimension(displayUnit="m") = 0.009933,
      length(displayUnit="m") = 6.49936,
      roughness(displayUnit="m") = 2e-6,
      dheight(displayUnit="m"),
      nV=1)) annotation (Placement(
      transformation(
      extent={{10,-10},{-10,10}},
```

```
        rotation=0,
        origin={64,-24})));
TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
    H2Supply_270(
    nParallel=18,
    redeclare package Medium = Medium,
    Ts_start(displayUnit="K"),
    p_a_start=99999.99999999999*(0.0689476*187),
    p_b_start=99999.99999999999*(0.0689476*187),
    T_a_start(displayUnit="K") = 19,
    T_b_start(displayUnit="K") = 19,
    m_flow_a_start=0.075,
    redeclare model Geometry =
        TRANSFORM.Fluid.ClosureRelations.Geometry.Models.DistributedVolume_1D.
        StraightPipe(
        dimension(displayUnit="m") = 0.006,
        length(displayUnit="m") = 3.7122,
        roughness(displayUnit="m") = 2e-4,
        dheight(displayUnit="m"),
        nV=1)) annotation (Placement(
        transformation(
        extent={{-10,10},{10,-10}},
        rotation=180,
        origin={34,-24})));
TRANSFORM.Fluid.Pipes.GenericPipe_MultiTransferSurface
    H2Supply_280(
    nParallel=7,
    redeclare package Medium = Medium,
    Ts_start(displayUnit="K"),
    p_a_start=99999.99999999999*(0.0689476*187),
    p_b_start=99999.99999999999*(0.0689476*187),
    T_a_start(displayUnit="K") = 19,
    T_b_start(displayUnit="K") = 19,
    m_flow_a_start=0.075,
    redeclare model Geometry =
        TRANSFORM.Fluid.ClosureRelations.Geometry.Models.
        DistributedVolume_1D.StraightPipe(
        dimension(displayUnit="m") = 0.009933,
        length(displayUnit="m") = 9.295,
        roughness(displayUnit="m") = 2e-6,
        dheight(displayUnit="m") = 7.0359,
        nV=1)) annotation (Placement(
        transformation(
        extent={{10,-10},{-10,10}},
        rotation=-90,
```

```
        origin={-124,-8})));
  TRANSFORM.Fluid.FittingsAndResistances.SpecifiedResistance
    resistance1(redeclare package Medium = Medium,
      R=0.0001)
            annotation (Placement(transformation(
          extent={{-10,-10},{10,10}},
        rotation=0,
        origin={48,42})));
  TRANSFORM.Fluid.BoundaryConditions.Boundary_pT
    boundary(
    redeclare package Medium = Medium,
    p=99999.99999999999*(0.0689476*187),
    T(displayUnit="K") = 19,
    nPorts=1) annotation (Placement(
        transformation(
        extent={{-10,-10},{10,10}},
        rotation=-90,
        origin={36,128})));
  TRANSFORM.Fluid.Sensors.MassFlowRate
    sensor_m_flow(redeclare package Medium =
        Medium) annotation (Placement(
        transformation(
        extent={{-10,-10},{10,10}},
        rotation=-90,
        origin={36,104})));
  Modelica.Blocks.Nonlinear.FixedDelay fixedDelay(
      delayTime=0.001) annotation (Placement(
        transformation(extent={{-24,-78},{-4,-58}})));
  Modelica.Blocks.Math.Add add annotation (
      Placement(transformation(extent={{-68,-78},{
            -48,-58}})));
  Modelica.Blocks.Sources.Sine sine(amplitude=0.001,
      f=100) annotation (Placement(transformation(
          extent={{-112,-92},{-92,-72}})));
  Modelica.Blocks.Continuous.Integrator
    integrator annotation (Placement(
        transformation(extent={{80,106},{100,126}})));
  Modelica.Blocks.Math.Product product1
    annotation (Placement(transformation(extent={{120,100},
            {140,120}})));
  Modelica.Blocks.Sources.RealExpression
    realExpression(y=-1/(accum_area*boundary.medium.d)
        /0.0508)
    annotation (Placement(transformation(extent={{84,74},
            {104,94}})));
```

```
Real accum_area(unit="m2") = 2*3.14159*(4.0*0.0254)
                                                    ^2 "Area of Accumulator";

TRANSFORM.HeatAndMassTransfer.Resistances.Heat.Specified_Resistance
  generic(R_val=0.000001)
                        annotation (Placement(
       transformation(
       extent={{-10,-10},{10,10}},
       rotation=90,
       origin={-18,62})));

TRANSFORM.HeatAndMassTransfer.BoundaryConditions.Heat.Temperature
  boundary1(T(displayUnit="K") = 19)
  annotation (Placement(transformation(extent={{
          -54,72},{-34,92}})));
TRANSFORM.Fluid.Volumes.SimpleVolume volume(
  redeclare package Medium = Medium,
  p_start=99999.99999999999*(0.0689476*187),
  T_start(displayUnit="K") = 19,
  redeclare model Geometry =
       TRANSFORM.Fluid.ClosureRelations.Geometry.Models.LumpedVolume.
       GenericVolume(V=0.00015)) annotation (Placement(
       transformation(
       extent={{-10,-10},{10,10}},
       rotation=-90,
       origin={36,78})));
Modelica.Blocks.Sources.TimeTable timeTable(
     table=[0,0; 10,13.067; 20,13.067; 30,13.067;
       40,24.789; 50,82.139; 60,82.139; 70,
       82.139; 80,160.873; 90,207.368; 100,
       207.368; 110,207.368; 120,209.002; 130,
       209.002; 140,209.002; 150,262.873; 160,
       334.806; 170,334.806; 180,334.806; 190,
       334.806; 200,423.682; 210,503.065; 220,
       503.065; 230,503.065; 240,503.065; 250,
       585.478; 260,585.478; 270,668.368; 280,
       668.368; 290,668.368; 300,741.691; 310,
       741.691; 320,741.691; 330,741.691; 340,
       741.691; 350,829.837; 360,914.6; 370,
       914.6; 380,914.6; 390,914.6; 400,993.717;
       410,1074.649; 420,1074.649; 430,1074.649;
       440,1074.649; 450,1155.154; 460,1239.678;
       470,1239.678; 480,1239.678; 490,1318.757;
       500,1318.757; 510,1318.757; 520,1318.757;
       530,1393.28; 540,1407.264; 550,1407.264;
```

```
        560,1407.264; 570,1407.264; 580,1405.373;
        590,1402.946; 600,1402.946; 610,1402.946;
        620,1402.946; 630,1400.209; 640,1400.209;
        650,1400.209; 660,1400.209; 670,1401.952;
        680,1401.952; 690,369.828; 700,369.828;
        710,799.132; 720,799.132; 730,1369.31;
        740,1369.31; 750,1369.31; 760,1400.506;
        770,1400.506; 780,1398.824; 790,1398.824;
        800,1402.715; 810,1402.715; 820,1402.715;
        830,1404.536; 840,1404.016; 850,1404.016;
        860,1404.016; 870,1404.016; 880,1404.016;
        890,1404.495; 900,1405.254; 910,1405.254;
        920,1405.254; 930,1405.254; 940,1405.464;
        950,1403.923; 960,1403.923; 970,1403.923;
        980,1403.923; 990,1405.204; 1000,1405.204;
        1010,1405.204; 1020,1405.204; 1030,
        1405.204; 1040,1404.916; 1050,1406.674;
        1060,1406.674; 1070,1406.674; 1080,
        1402.483; 1090,1401.603; 1100,1401.603;
        1110,1401.603; 1120,1401.603; 1130,
        1402.241; 1140,1402.246; 1150,1402.246;
        1160,1402.246; 1170,1401.707; 1180,
        1401.707; 1190,1401.707; 1200,1403.916;
        1210,1403.916; 1220,1406.252; 1230,
        1406.252; 1240,1406.252; 1250,1404.561;
        1260,1403.326; 1270,1403.326; 1280,
        1403.326; 1290,1403.326; 1300,1403.308;
        1310,1403.308; 1320,1404.948; 1330,
        1404.948; 1340,1404.948; 1350,1403.62;
        1360,1403.62; 1370,1403.62; 1380,1403.62;
        1390,1405.095; 1400,1404.802; 1410,
        1404.802; 1420,1404.802], timeScale=1)
    annotation (Placement(transformation(extent={
          {-124,-58},{-104,-38}})));
equation
  V = 10-sensor_m_flow.port_a.m_flow;

  connect(CircOutlet_50.port_a, Circulator_40.port_b)
    annotation (Line(points={{-60,40},{-66,40},{-66,
        42},{-70,42}},
        color={0,127,255}));
  connect(CircOutlet_50.port_b, HX_70.port_a)
    annotation (Line(points={{-40,40},{-38,40},{-38,
        38},{-34,38},{-34,40},{-28,40}},
        color={0,127,255}));
```

```
connect(H2Supply_80_1.port_a, HX_70.port_b)
  annotation (Line(points={{8,40},{4,40},{4,38},
        {0,38},{0,40},{-8,40}},
      color={0,127,255}));
connect(H2Supply_80_2.port_b, H2Supply_120.port_a)
  annotation (Line(points={{80,40},{82,40},{82,26}},
      color={0,127,255}));
connect(H2Supply_120.port_b, H2Supply_130.port_a)
  annotation (Line(points={{82,6},{82,-2},{90,-2}},
      color={0,127,255}));
connect(H2Supply_130.port_b, H2Supply_140.port_a)
  annotation (Line(points={{110,-2},{112,-2},{112,
        -4},{114,-4},{114,-2},{118,-2}},
      color={0,127,255}));
connect(H2Supply_140.port_b, H2Supply_150.port_a)
  annotation (Line(points={{138,-2},{140,-2},{140,
        -18}},color={0,127,255}));
connect(H2Supply_150.port_b, H2Supply_160.port_a)
  annotation (Line(points={{140,-38},{140,-46}},
      color={0,127,255}));
connect(H2Supply_160.port_b, Moderator_200.port_a)
  annotation (Line(points={{140,-66},{140,-84},{
        128,-84}}, color={0,127,255}));
connect(Moderator_200.port_b, H2Supply_240.port_a)
  annotation (Line(points={{108,-84},{100,-84},{
        100,-82},{90,-82}},
      color={0,127,255}));
connect(H2Supply_240.port_b, H2Supply_250.port_a)
  annotation (Line(points={{90,-62},{90,-52}},
      color={0,127,255}));
connect(H2Supply_250.port_b, H2Supply_260.port_a)
  annotation (Line(points={{90,-32},{90,-24},{74,
        -24}}, color={0,127,255}));
connect(H2Supply_260.port_b, H2Supply_270.port_a)
  annotation (Line(points={{54,-24},{44,-24}},
      color={0,127,255}));
connect(CircInlet_30.port_a, H2Supply_280.port_b)
  annotation (Line(points={{-118,40},{-124,40},{
        -124,2}},   color={0,127,255}));
connect(H2Supply_280.port_a, H2Supply_270.port_b)
  annotation (Line(points={{-124,-18},{-124,-24},
        {24,-24}}, color={0,127,255}));
connect(CircInlet_30.port_b, Circulator_40.port_a)
  annotation (Line(points={{-98,40},{-94,40},{-94,
        42},{-90,42}},
```

```
      color={0,127,255}));
  connect(H2Supply_80_2.port_a, resistance1.port_b)
    annotation (Line(points={{60,40},{58,40},{58,42},
          {55,42}},
      color={0,127,255}));
  connect(H2Supply_80_1.port_b, resistance.port_b)
    annotation (Line(points={{28,40},{36,40},{36,49}},
                  color={0,127,255}));
  connect(resistance1.port_a, resistance.port_b)
    annotation (Line(points={{41,42},{36,42},{36,49}},
                  color={0,127,255}));
  connect(boundary.ports[1], sensor_m_flow.port_a)
    annotation (Line(points={{36,118},{36,114}},
      color={0,127,255}));
  connect(add.u2, sine.y) annotation (Line(points=
         {{-70,-74},{-80,-74},{-80,-82},{-91,-82}},
      color={0,0,127}));
  connect(fixedDelay.u, add.y) annotation (Line(
      points={{-26,-68},{-47,-68}}, color={0,0,127}));
  connect(sensor_m_flow.m_flow, integrator.u)
    annotation (Line(points={{39.6,104},{70,104},{
          70,116},{78,116}},
      color={0,0,127}));
  connect(integrator.y, product1.u1) annotation (
     Line(points={{101,116},{118,116}},
                  color={0,0,127}));
  connect(product1.u2, realExpression.y)
    annotation (Line(points={{118,104},{110,104},{
          110,84},{105,84}},
                  color={0,0,127}));
  connect(HX_70.heatPorts[1, 1], generic.port_a)
    annotation (Line(points={{-18,45},{-18,55}},
      color={191,0,0}));
  connect(generic.port_b, boundary1.port)
    annotation (Line(points={{-18,69},{-18,82},{-34,
          82}}, color={191,0,0}));
  connect(volume.port_b, resistance.port_a)
    annotation (Line(points={{36,72},{36,63}},
      color={0,127,255}));
  connect(volume.port_a, sensor_m_flow.port_b)
    annotation (Line(points={{36,84},{36,94}},
      color={0,127,255}));
  connect(add.u1, timeTable.y) annotation (Line(
      points={{-70,-62},{-98,-62},{-98,-48},{
          -103,-48}}, color={0,0,127}));
```

```
  annotation (
    Icon(coordinateSystem(preserveAspectRatio=false, extent={{-140,
            -100},{160,140}})),
    Diagram(coordinateSystem(preserveAspectRatio=false, extent={{-140,
            -100},{160,140}})),
    uses(TRANSFORM(version="0.5"), Modelica(
          version="4.0.0")),
    experiment(
      StopTime=2000,
      __Dymola_NumberOfIntervals=2000,
      Tolerance=1e-05,
      __Dymola_Algorithm="Sdirk34hw"));
end CMS_H2_RealGeoV1NoHxTempRamp;
```