The High Flux Isotope Reactor (HFIR) Cold Source Project at ORNL

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ABSTRACT: Following the decision to cancel the Advanced Neutron Source (ANS) Project at Oak Ridge National Laboratory (ORNL), it was determined that a hydrogen cold source should be retrofitted into an existing beam tube of the High Flux Isotope Reactor (HFIR) at ORNL. The preliminary design of this system has been completed and an "approval in principle" of the design has been obtained from the internal ORNL safety review committees and the U.S. Department of Energy (DOE) safety review committee. The cold source concept is basically a closed loop forced flow supercritical hydrogen system. The supercritical approach was chosen because of its enhanced stability in the proposed high heat flux regions. Neutron and gamma physics of the moderator have been analyzed using the 3D Monte Carlo code MCNP[1]. A 3D structural analysis model of the moderator vessel, vacuum tube, and beam tube was completed to evaluate stress loadings and to examine the impact of hydrogen detonations in the beam tube. A detailed ATHENA[2] system model of the hydrogen system has been developed to simulate loop performance under normal and off-normal transient conditions. Semi-prototypic hydrogen loop tests of the system have been performed at the Arnold Engineering Design Center (AEDC) located in Tullahoma, Tennessee to verify the design and benchmark the analytical system model. A 3.5 kW refrigerator system has been ordered and is expected to be delivered to ORNL by the end of this calender year. Our present schedule shows the assembling of the cold source loop on site during the fall of 1999 for final testing before insertion of the moderator plug assembly into the reactor beam tube during the end of the year 2000.

Introduction: In February 1995, Oak Ridge National Laboratory's deputy director formed a group to examine the need for upgrades to the HFIR system in light of the cancellation of the ANS Project. One of the major findings of this study was that there was an immediate need for the installation of a cold neutron source facility in the HFIR complex. In May 1995, a team was formed to examine the feasibility of retrofitting a liquid hydrogen (LH$_2$) cold source facility into an existing HFIR beam tube. The results of this feasibility study indicated that the most practical location for such a cold source was the HB-4 beam tube. It was determined that at the 100 MW reactor power level, the cold neutron beam produced by the proposed cold moderator would be comparable, in cold neutron brightness, to the best facilities in the world. As a result, a decision was made to proceed with the design, safety evaluation, and procurement necessary to install a working LH$_2$ cold source in the HFIR HB-4 beam tube. During the development of the reference design the liquid hydrogen concept was changed to a supercritical hydrogen system for a number of reasons, but primarily because of the enhanced stability of the supercritical system over the liquid system in the proposed high heat flux location in the reactor reflector region.

Reference Design: The reference design (as illustrated in Fig. 1) uses hydrogen gas at a supercritical pressure of 14 to 15 bar (1.4 to 1.5 MPa) that enters the cold source moderator vessel at 18 K and leaves at approximately 21 K. A volumetric flow rate of 1 L/s is maintained by a mechanical circulator that is backed up by an installed standby circulator that can be brought on-line remotely from the control center. The major advantage of supercritical hydrogen is freedom from problems associated with two-phase fluid during cool-down, warm-up, transitioning to a standby state or possible off-normal transients. It also eliminates any possibility of local boiling in the moderator vessel and permits more flexibility in its operating temperature. This more than

compensates for the increased pressure and the resulting increased heat load from thicker structure walls.

The total heat load that must be removed from the cryogenic system has been calculated to be slightly more than 2 kW, of which about 1.3 kW represents heat generated in the aluminum moderator vessel walls, with the majority of the remaining heat load being generated in the hydrogen itself. A contingency of 200 W is allowed for intrinsic heat loads and nuclear heating of the feed and return lines close to the core. A 15% uncertainty factor for the heat load along with a 40% margin factor were applied to the anticipated 2.2 kW load to size the refrigerator at 3.5 kW. The fluid volumetric flow rate of 1 L/s was chosen in order to generate velocities within the moderator vessel that provide adequate heat transfer between the fluid and the vessel walls. The circulator speed is adjustable by about ±20%, allowing the system to be finally trimmed as necessary.

A vacuum envelope that is split into three sections insulates all cold components of the loop. One section is dedicated to the moderator plug assembly, the second section is dedicated to the hydrogen lines inside the reactor building and the third section is dedicated to the hydrogen lines and equipment outside of the reactor building. The entire hydrogen system, including the vacuum chambers and their pumping systems, is further enclosed by a continuous inert blanket that is segmented at different areas of the system.

If a problem necessitates shutting down the cold source, it can be put into a standby mode that controls the moderator vessel temperature at an acceptable level, even with the reactor at full power. The standby state is achieved by circulating hydrogen gas at 2.25 L/s and 85 K with a low density circulator. At this temperature, the hydrogen gas density is only about 20% of that at 20 K. Cooling of the hydrogen to 85 K is effected using the passive liquid nitrogen precooling stage of the refrigerator. With the active section of the refrigerator bypassed, it can be shut down and serviced, leaving the system operating in standby. The standby state allows the reactor to continue in full power operation in the event of the more common cold source failure modes, such as refrigerator or circulator problems, though other applicable failure modes might be identified when the system becomes operational. This reduces the impact of cold source failure on other user activities at the HFIR.

Early in the project a decision was made to locate the major mechanical equipment of the hydrogen loop (e.g. the circulators and heat exchanger) outside of the reactor building. This decision was made for two reasons: 1) there was essentially no space in the immediate vicinity of the reactor for locating the equipment, and 2) it was perceived that the potential impact on reactor safety would be reduced, if the primary sources for hydrogen leaks were moved outside of the reactor building even though the increased transfer line length greatly increased the total hydrogen inventory. The proposed equipment layout is illustrated in Fig. 2.

Physics Analysis: Physics analyses have been performed to characterize the cold source performance. Because of the inherent 3-D nature of the HFIR core, the various experimental and user facilities in the reflector, and the location of the proposed cold source in the HB-4 beam tube, the 3-D MCNP Monte Carlo code (version 4a) was used in virtually all of the analyses performed to date. Acceptable statistical uncertainties (less than 2–3%) at the various point detectors of interest generally required 288 batches of 10,000 source neutrons, for a total of 2,880,000 histories. Final reference design analysis was performed with 1224 batches of 10,000 source neutrons, for a total of 12,240,000 histories.

The cold neutron beam magnitude is typically expressed in terms of its "brightness," which is defined as the "number of neutrons per second, per square centimeter, per angstrom, per steradian" at a point detector 477 cm from the center of the former HB-1/HB-4 throughtube, or

466 cm from the cold source capsule. Table 1 indicates the calculated gain factors for the proposed hydrogen cold source at the HFIR.

Table 1 - Gain factors as calculated for the proposed HFIR liquid hydrogen cold source

Wavelength (Å)	Neutron energy range (meV)	HFIR brightness with LH_2 cold source $(s^{-1} \cdot cm^{-2} \cdot Å^{-1} \cdot steradian^{-1})$	HFIR brightness without LH_2 cold source $(s^{-1} \cdot cm^{-2} \cdot Å^{-1} \cdot steradian^{-1})$	Gain ratio
0.887–2.86	10.0–104.0	1.09×10^{13}	3.79×10^{13}	0.29
2.86–5.02	3.25–10.0	7.54×10^{12}	1.61×10^{12}	4.68
5.02–7.51	1.45–3.25	1.55×10^{12}	1.16×10^{11}	13.36
7.51–9.81	0.85–1.45	3.99×10^{11}	1.95×10^{10}	20.46
9.81–11.93	0.58–0.85	1.56×10^{11}	Not available	–
11.98–15.86	0.33–0.85	5.44×10^{10}	Not available	–

A parametric study was performed to determine the sensitivity of the cold source performance to the ortho-H/para-H ratio. Previous analyses had indicated that this ratio had little impact on the optimal hydrogen thickness for the proposed geometric shape of the HFIR cold source. This was found to be inconsistent with evaluations performed at the National Institute of Standards and Technology (NIST), and, therefore, a decision was made to model the NIST cold source geometry and examine the spectrum changes when the ortho/para ratio was significantly changed. The results of this study implied that the geometry of the system dictated the impact of the ortho/para ratio. For the NIST geometry we obtained the significant sensitivity in performance to this ratio that NIST had reported. However, for the HFIR cold source geometry the same analysis approach indicated a relative insensitivity to this ratio with only a 1-2% change in going from 0% ortho-H to 50% ortho-H.

Structural Analysis: The HFIR cold source moderator vessel, vacuum tube, and beam tube are being designed to the guidance of the ASME Boiler and Pressure Vessel Code Section III, Division I, Class I, Code Case N-519 for aluminum 6061-T6. This code case is reported to be good down to a temperature of about 4 K. A 3D finite element stress analysis has been performed using the ABAQUS[3] code to evaluate stresses in these three components. The moderator vessel model has a total of 10,984 elements. The stress load is obtained for three points of each element: the outer shell surface, the middle shell surface and the inner shell surface. The stress load distribution for the middle shell surface is shown in Fig. 3. As shown in this figure the maximum stress load is found in the corner areas of the region where the vessel transitions from the hydrogen flow pipes to the moderator chamber. It has been determined that more curvature can be added to round the corners found in the conceptual design and these peak loadings are expected to be greatly reduced. All stress loadings are expected to be below the N-519 code case allowable stress loading of 13.5 ksi at the peak system design pressure (rupture disk set-point) of 19 bar (1.9 MPa).

In addition to the deterministic structural analysis performed for the moderator vessel, a fracture probabilistic analysis has also been performed. The fracture mechanics calculations are made in order to evaluate the safety of the moderator vessel with respect to catastrophic fracture failure. This analysis consisted of probabilistic fracture analysis at the high stress points of the vessel, a leak before break analysis, and a crack penetration analysis as a function of radiation embrittlement. The analysis provides a quantitative estimate on how the capsule is structurally

weakened as a result of the embrittlement of the material after an extended period of irradiation. Also, an estimate of the equilibrium crack length is made in order to determine the leak-before-break condition.

The probability of fracture is obtained as a measure of the embrittlement condition for the moderator capsule. The method used for this analysis is a standard approach for the nuclear industry. The results indicate that although the probability of failure increases several orders of magnitude over the planned irradiation period, the estimated probability of failure is acceptable at the design end of life of the vessel. The path-to-failure calculation also indicates that, after a period of irradiation, the failure mode of the moderator capsule wall will change from rupture to brittle fracture. The present result is only a preliminary estimate and further evaluations will be performed.

Hydrogen System Transient Analysis: A preliminary systems transient analysis capability has been developed to support the safety analysis of the HFIR cold source. The analysis capability is based on the Advanced Thermal Hydraulic Energy Network Analyzer (ATHENA) code. ATHENA is a computer program for simulating thermal-hydraulic systems. ATHENA is essentially the same code as the Reactor Linearized Analysis Program 5 (RELAP5),[4] developed by the Idaho National Engineering and Environmental Laboratory for detailed thermal-hydraulic safety analysis in the nuclear industry. ATHENA essentially provides a one-dimensional (1-D), time-dependent solution to the coupled nonequilibrium thermodynamic two-fluid (phase) conservation law equation system of fluid mass, momentum, and energy, coupled with the energy equation applied to a 1-D volume of metal. Some multidimensional extensions are available where a single dimensional representation is not adequate. For example, a "reflood" option is available for the heat structures that allows for some two-dimensional (2-D) simulation capability. The present HFIR cold source ATHENA model utilizes the reflood option within a portion of the model to simulate a required 2-D heat transfer component. As a thermal-hydraulic systems simulator, including control system integration, ATHENA is very good and is considered the best available.

The hydrogen system including the circulators, heat exchanger, moderator vessel, transfer lines, valves, and control system is simulated by an ATHENA model composed of approximately 275 volume nodes. Transients ranging from normal startup and shutdown to large hydrogen line breaks have been simulated and require 10^7 or more time steps per simulation. The results of this analysis will be used to define the interfaces between the cold source operation and the reactor operation.

Although the validation database for the light water companion code RELAP5 is extensive, the validation data for the extension ATHENA-fluids is essentially nil. Therefore, as part of our cold source testing activities, as described below, data will be obtained on hydrogen loop performance under transient conditions to benchmark the ATHENA model.

Cold Source Testing: In addition to a number of individual component tests, a decision was made early in the project to build a representative hydrogen loop for integrated system testing. The AEDC was selected as the site for these tests because 1) they had a large vacuum chamber (42 ft in diameter and 82 ft high designed for satellite testing) available which was capable of housing a simple but full-scale test loop made up of realistic size and length pipework, and active components identical to (or representative of) those to be used in the final system; 2) they already had a refrigerator system, similar to that ordered for the HFIR cold source, piped into the chamber; and 3) the chamber was previously approved for the use of hydrogen; thus, operating procedures and safety requirements were already in place. The major objectives of this test were

to validate expected operation of the system design and demonstrate its stability under all normal circumstances and anticipated faulted situations that could be practically replicated; to provide benchmarking data for computer models that would be used to evaluate accident scenarios that are impractical to reproduce in real tests; and to evaluate the conceptual control and instrumentation system and provide feedback on the philosophy of operational interlocks and safety shutdown systems.

The loop was designed by ORNL and built by AEDC staff. Some compromises had to be accepted, and the main heat exchanger between the refrigerator and the hydrogen loop was physically larger and heavier than the heat exchanger planned for the HFIR cold source system. Valves and circulators had to be modified to operate entirely within a vacuum, which added more complexity to the test program. A photograph of the cold source test layout inside the AEDC vacuum chamber is provided in Fig. 4. Assembly and testing of the loop was performed over a six month period.

Each test series performed provided new information and insights into the operation of the hydrogen loop. Although there were some disappointments in not fulfilling all the goals of the test plan, the major objectives of the test program were accomplished. The viability of the system was clearly demonstrated; a substantial data base for validation of the analytical models was obtained; and a good evaluation of the control system was performed. It is believed that unless the model evaluations of the tests uncover unexpected results, the usefulness of this test loop is now exhausted, and the next full loop tests will be conducted at the HFIR site using the final system before its installation into the reactor.

Schedule: The HFIR cold source project is presently in the detailed design phase. Some equipment items have already been procured as part of the AEDC test program. A 3.5 kW refrigerator was ordered approximately 15 months ago and is expected to be delivered to ORNL during the fall of this year. Procurement specifications for other long lead procurement items are expected to be completed later this summer. The system is scheduled to be assembled outside of the reactor building during the fall of 1999. The moderator plug and new beam tube assembly is scheduled to be installed into the reactor during a 6 month scheduled shutdown of the reactor during the summer of 2000 to replace the reactor beryllium reflector.
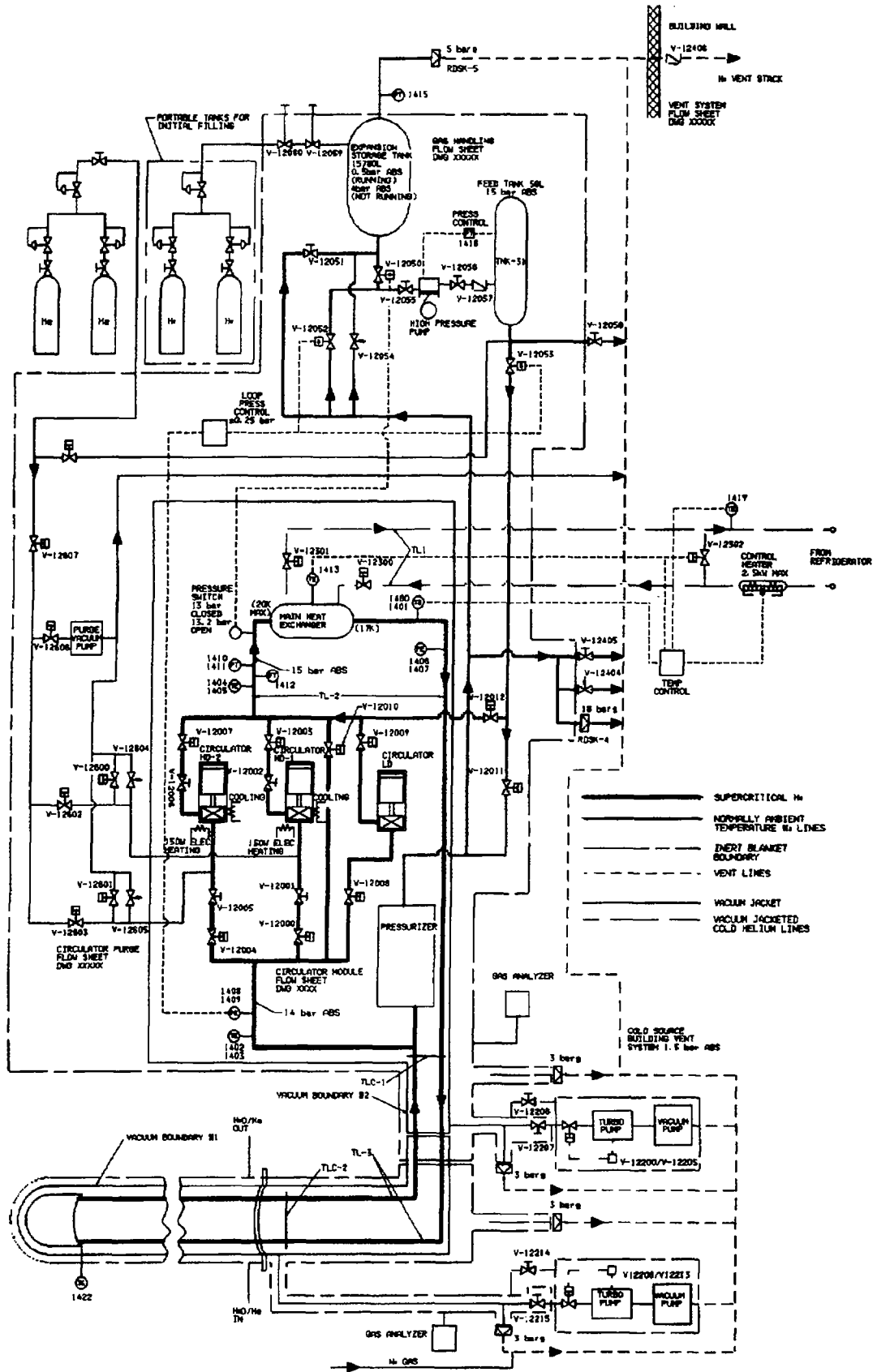
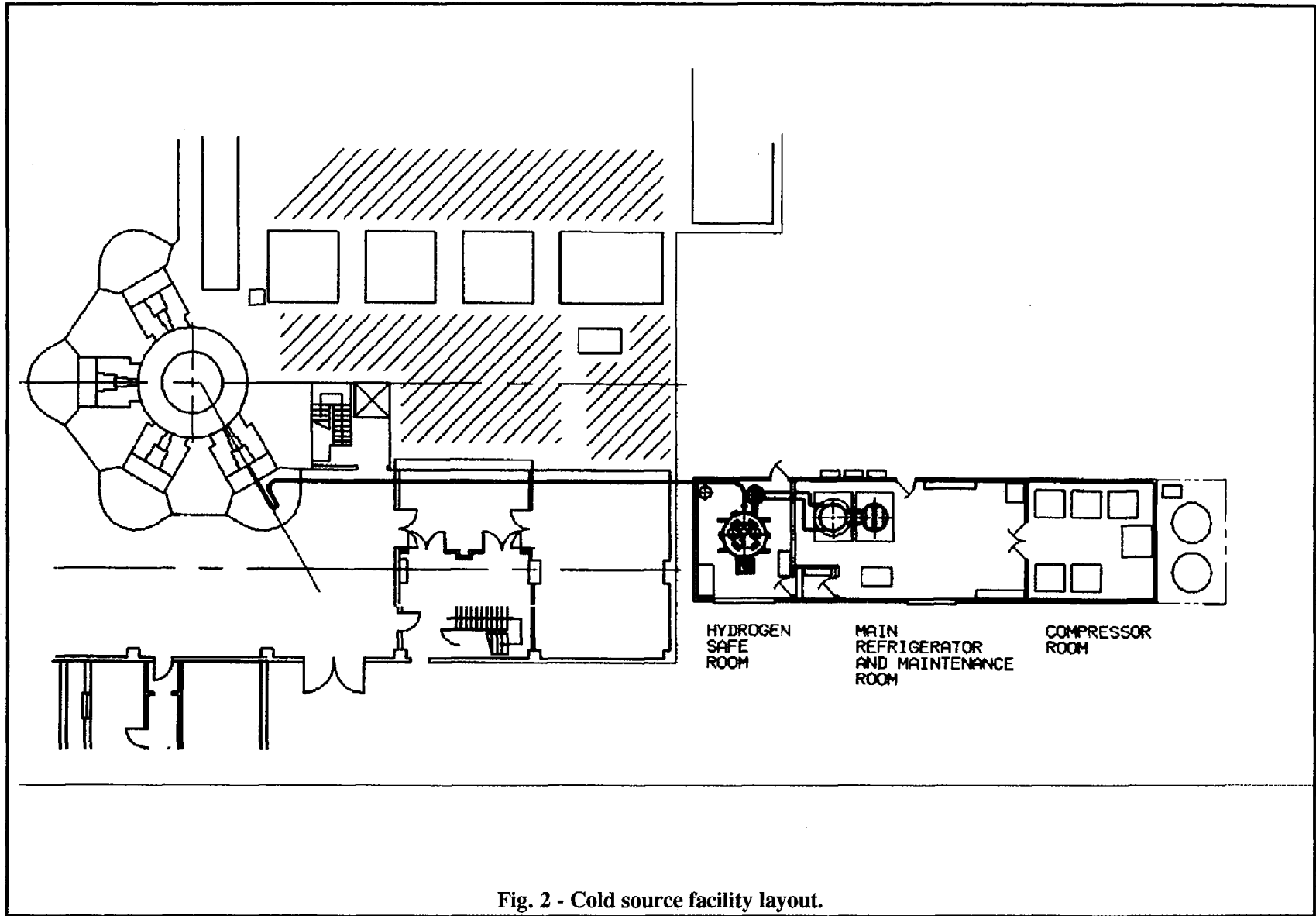Fig. 1 - HFIR cold source system flow diagram.

HYDROGEN
SAFE
ROOM

MAIN
REFRIGERATOR
AND MAINTENANCE
ROOM

COMPRESSOR
ROOM

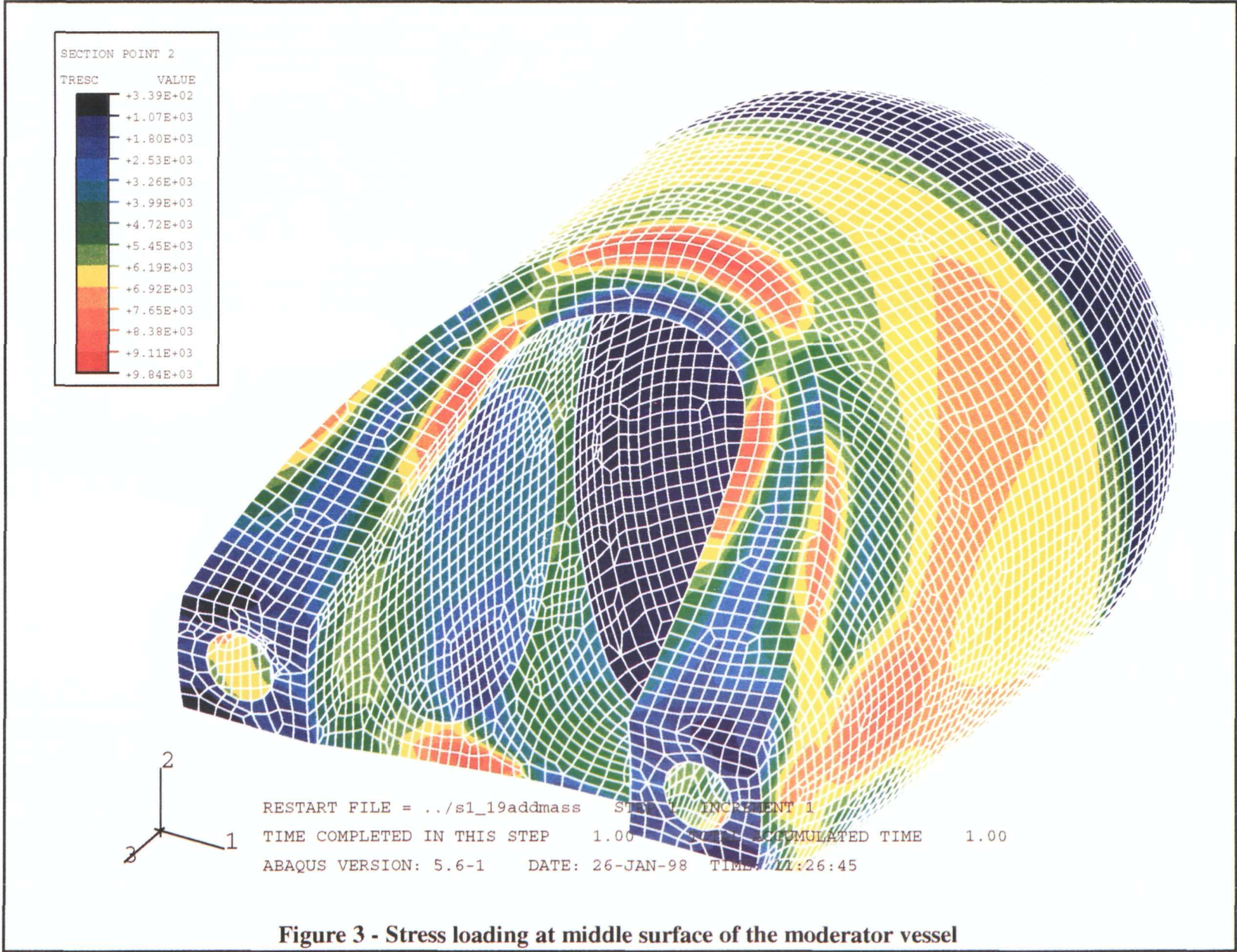Fig. 2 - Cold source facility layout.

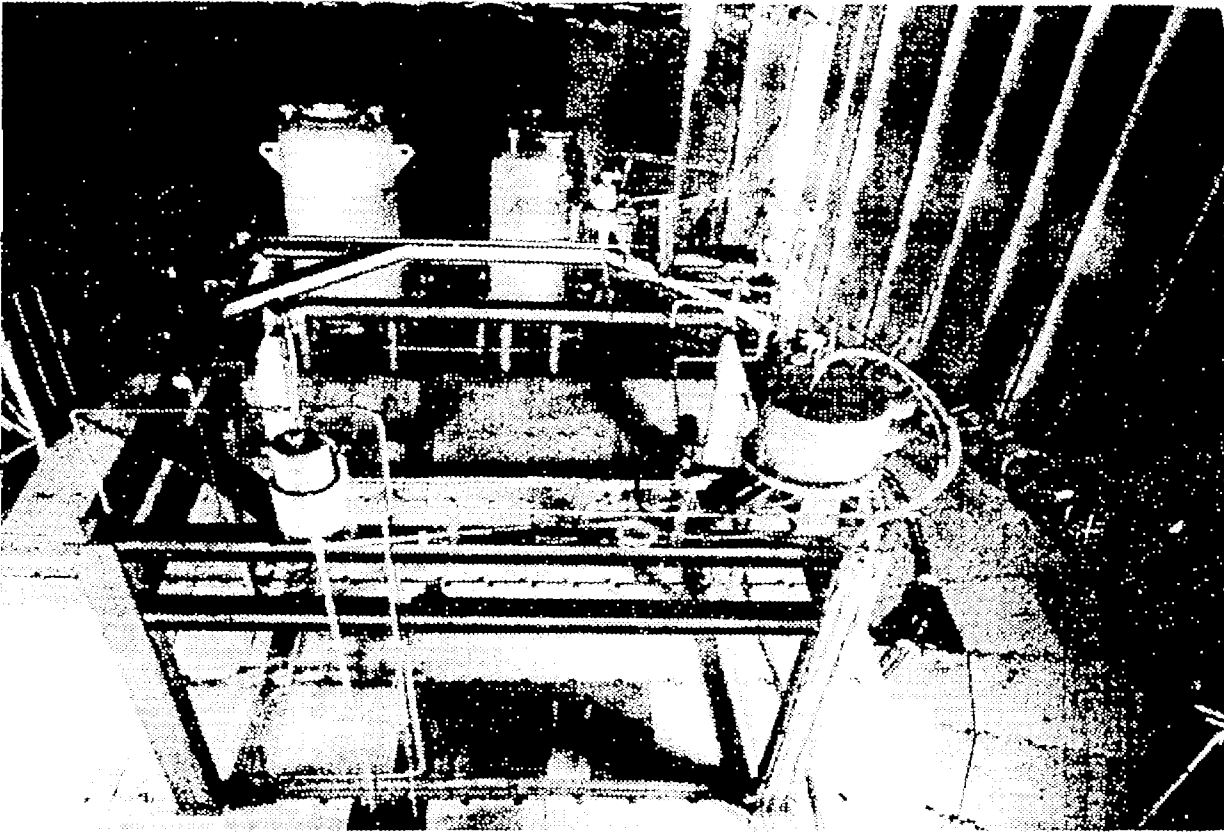**Figure 3 - Stress loading at middle surface of the moderator vessel**

Fig. 4 - Top view of hydrogen test loop inside the AEDC (42' diam) Mark-I vacuum chamber.

REFERENCES

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2.   ATHENA [see RELAP5/Mod3 Code Manual, Volumes 1-7 Inclusive, The RELAP5 Code Development Team, NUREG/CR-5535, INEL-95/0174 (formerly EGG-2596), June 1995.]

3.   ABAQUS 5.6, Hibbit, Karlsson, and Sorensen, Inc., Pawtucket, Rhode Isand, 1997.

4.   RELAP5/Mod3 Code Manual, Volumes 1-7 Inclusive, The RELAP5 Code Development Team, NUREG/CR-5535, INEL-95/0174 (formerly EGG-2596), June 1995.