DATE: 6/30/94

GT-MHR PROGRAM
IRRADIATION DATA FOR REACTOR VESSEL MATERIALS
(Modified 9Cr-1Mo, SA-387 Grade 91, Class 2 Plate and SA-336 Grade F91 Forging)
DDN C.12.01.01

PLANT: GT-MHR/System 12

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The data base for determining the neutron-induced property changes for Modified 9Cr-1Mo reactor vessel materials (SA-387 Grade 91, Class 2 plate and SA-336 Grade F91 forging), weldments, and heat-affected zones is based mainly on a test reactor operating with a fast neutron energy spectrum, and very little data from LWR irradiation environments. The database for fracture toughness, tensile, and creep properties must be expanded to cover GT-MHR conditions.

1.1 Summary of Function and Assumptions

"Maintain Material Strength," Assumptions: The fast neutron spectrum data base for Modified 9Cr-1Mo provides a very conservative estimate of the changes in mechanical properties: tensile and creep strengths, and fracture toughness, as well as effects on microstructures and swelling. Use of Reg. Guide 1.99, Rev. 2 along with recommended correction factors for the GT-MHR environment does not adequately predict the fracture properties.

1.2 Current Data Base Summary

Studies of the effects of radiation on Modified 9Cr-1Mo steel were conducted under the LMR Fuels and Materials and the Fusion Energy (FE) First Wall and Blanket Materials Programs. Emphasis of the LMR program was on the effects of elevated temperature (400-600°C/750-1100°F) irradiations on the swelling, microstructural, tensile, and fracture toughness at high displacements per atom (dpa). Emphasis of the FE program was on the effects of neutronically produced helium combined with high dpa on swelling, microstructure, tensile properties, and nil-ductility transition temperature (NDTT). Tests were conducted in EBR-II, FFTF, and HFIR (Ref. 1).

Irradiations in EBR-II were conducted to characterize the fracture toughness properties of T-91 for fluences in the range 3.8-4.7 x 10^{22} n/cm^2 (E>0.1 MeV)/20-25 dpa and temperatures in the range 384-425°C (723-797°F). The NDTT shift was approximately 80°C (144°F), and the upper shelf energy reduced about 15%. Additional tests were conducted at 390°C (734°F) and 13 dpa, and at temperatures 450°C (842°F), 500°C (932°F), and 550°C (1022°F). Little, if any, shift in NDTT and reduction in upper shelf energy resulted at the higher temperature.

Elastic-plastic fracture toughness (J-R curves) data were obtained from EBR-II after irradiation to 30 dpa at 410°C (770°F). J_{IC} and tearing modulus data at 25°C (77°F), 232°C (450°F), and 427°C (800°F) are available.

Irradiation in the mixed spectrum HFIR resulted in larger reductions in tensile ductility and fracture toughness properties than in fast reactors such as EBR-II. Helium produced by thermal and epithermal neutron reactions with nickel in alloys degrades mechanical properties more rapidly and severely than displacement damage areas. J_{IC} and tearing modulus over a temperature range 93-450°C (200-843°F) are available. The irradiations in HFIR, however, were at 50°C (122°F), so no thermally induced recovery of irradiation-induced defect structure occurs as would occur in the EBR-II irradiations at 390-550°C (734-1022°F).

1.3 Data Needed

Data are needed to characterize the neutron-induced changes in fracture toughness, tensile, and creep properties for the reactor vessel plate and forging materials, weldments, and heat-affected zone at irradiation temperatures (427° to 491°C/800-915°F) and neutron flux, fluence, and spectrum levels expected for the GT-MHR. Key materials variables include chemical composition (e.g., Cu, Ni, S, P, V, N), product form and size, and heat treatment. The data are required to develop and validate a correlative procedure of properties vs exposure in order to predict fracture toughness properties over the life of the GT-MHR reactor vessel materials. Mechanical property and creep data are required in order to establish whether irradiation has a significant impact on time dependent properties. Materials properties must also be baselined: initial RT_{NDT} and upper shelf energy, linear elastic fracture toughness curves, elastic-plastic fracture toughness, fatigue crack growth curves, and flaw evaluation criteria and properties. The locations of concern, for which data are needed, include the reactor vessel beltline, main flange, and closure head. The data should be sufficient to meet a 95% confidence that the toughness properties meet or exceed ASME code requirements. Quality Assurance must be in accordance with requirements for experimental data or validation testing which is safety related.

1.4 Data Parameters and Service Conditions

The results of this program are expected to provide the designer a means of conservatively estimating the fracture toughness behavior and changes due to irradiation.

[DDN C.12.01.01]

The specified service conditions for the reactor vessel are as follows:

a. Normal Operation

RV Beltline (shell)

- Metal Temperature
  - inner surface 482-491°C (900-915°F)
  - outer surface 427-435°C (800-815°F)

- 1025 psia (7.07 MPa)

- 305,000 h (40 years at 87% availability).
  457,000 h (60 years at 87% availability).

- Fluence at inner surface (n/cm^2)*

	40 yrs	60 yrs
E > 0.9 MeV	6.6×10^{17}	9.9×10^{17}
0.1 MeV < E < 0.9 MeV	2.9×10^{18}	4.3×10^{18}
3.05 eV < E < 0.1 MeV	6.6×10^{18}	9.9×10^{18}
E < 3.05 eV	2.2×10^{18}	3.3×10^{18}
Total	1.23×10^{19}	1.84×10^{19}

RV Closure Head (shell)

- Metal Temperature TBD

- 1025 psia (7.07 MPA)

- 305,000 h (40 years at 87% availability)
  457,000 h (60 years at 87% availability)

- Fluence at inner surface (n/cm^2) TBD

RV Closure Head (forging)

- Metal Temperature TBD

- 1025 psia (7.07 MPA)

*Nominally calculated values. The uncertainty factor on the fluence could be as high as 7 at the RV beltline and 10 elsewhere.

- 305,000 h (40 years at 87% availability)
  457,000 h (60 years at 87% availability)

- Fluence at inner surface (n/cm^2) TBD

2. DESIGNER'S ALTERNATIVES

A data base sufficient to satisfy 10CFR50 Appendix A, General Design Criteria 31, "Fracture Prevention of Reactor Coolant Pressure Boundary" is required. In absence of a general data base, an accelerated surveillance program could be designed to provide specific vessel materials data on a timely basis. The surveillance samples would have to be positioned within the reactor vessel to obtain neutron exposures sufficiently in advance to allow retrieval, testing, analysis, and use of the results in operating procedures. This would require a very conservatively designed vessel based on the available data. It would also require regulatory concurrence.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The proposed approach is to obtain a sufficiently large data base for the expected GT-MHR operating temperature range and bounding fluence. The resulting data will provide a correlation with operating conditions, and flaw evaluation criteria and properties to judge acceptability. This will provide the designer with an acceptably conservative procedure to estimate vessel irradiation damage.

4. SCHEDULE REQUIREMENTS

Interim results on all data are needed as soon as they become available. Final results on all data are needed by the completion of the preliminary design phase.

5. PRIORITY

Urgency: 1
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

A thicker reactor vessel could be sized to keep the operating stresses sufficiently low so that a best-judged, conservative margin to brittle failure based on existing data is maintained. The effect of these measures would be increased capital costs, and require large operating margins during the plant starting up and shutting down phases. Continued operation would be contingent on timely retrieval and use of data from a surveillance program.

[DDN C.12.01.01]

7. REFERENCES

1. ORNL-6303, October 1986.

Chris Hoffman 6-30-94
Originator Date

J. de Lauro 6-30-94
Task Manager Date

Program Manager Date

[DDN C.12.01.02]

DATE: 6/30/94

GT-MHR PROGRAM
PROPERTIES OF HEAVY SECTION VESSEL MATERIALS
SA-387 GRADE 91, CLASS 2 PLATE AND SA-336 GRADE F91
FORGING AND THEIR WELDEMENTS AT ELEVATED TEMPERATURES
DDN C.12.01.02

PLANT: GT-MHR/System 12

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

An insufficient property data base exists for the design of the reactor vessel fabricated from Modified 9Cr-1Mo, SA-387 Grade 91, Class 2 plate and SA-336 Grade F91 forging materials and associated weldments.

1.1 Summary of Function and Assumptions

"Maintain Primary Coolant Boundary Integrity," Assumptions: The current data base and its extrapolation to [60] year component life is adequate to confirm that the vessel system components can sustain the lifetime duty cycle.

1.2 Current Data Base Summary

Modified 9Cr-1Mo is already approved and in use for elevated-temperature service up to 1200°F under ASME Boiler and Pressure Vessel Code Section I (Power Boilers) and Section VIII (unfired pressure vessels). The material is also approved for nuclear vessel applications up to 700°F under Section III, Code Case N-466-1.

Since circa 1985 the ASME Code Committee has been examining this material for nuclear components at elevated-temperature (>700°F) service. The essential data on material properties to support component design up to 280,000 hours service life already exist: including creep-rupture, isochronous stress-strain curves, creep-fatigue interactions, aging factors and weld strength reduction factors. Allowable stress intensities, time-dependent and time-independent values, have been derived. Data and associated analysis have been submitted for most Code Case N-47 properties.

1.3 Data Needed

The existing database for Modified 9Cr-1Mo must be evaluated against all anticipated conditions encountered in the GT-MHR application. The data and analysis basis for Modified 9Cr-1Mo must be compiled and reviewed to confirm completeness. The database must be assembled and analyzed to establish allowable stress intensities and other required properties for submittal to the ASME code committees and task groups along with a draft of the proposed revision to Code Case N-47. In addition, the available long-term data must be examined in order to support an extension of the database for a 460,000 hour service life. This must also be included in the submittal to the ASME code committees.

The interaction with the ASME code committee will further define required data analyses and/or additional required data. This data should be sufficient to meet a 95% confidence that the properties meet or exceed ASME code requirements. Quality Assurance must be in accordance with requirements for experimental data or validation testing which is safety related.

1.4 Data Parameters and Service Conditions

The specified service conditions for the reactor vessel are as follows:

a. Normal Operation

- Metal temperature $\leq$491°C (915°F).
- 460,000 hours (60 yr at 87% availability).
- Service environment:

  Helium on the internal surface.

O_2	Nil
H_2O	[0.01-0.1] ppmv
CO	[0.02-0.8] ppmv
CO_2	[0.03-0.2] ppmv
H_2	[0.5-1.5] ppmv
CH_4	[0.05-0.2] ppmv
N_2	[0.15-1.0] ppmv

  Air in reactor building on the external surface.

b. Off-Normal Operation

- Service Levels C and D (Ref. 1)
  Pressurized conduction cooldown event
  - RV beltline (shell, midwall)
    Maximum metal temperature 482°C (900°F)

Depressurized conduction cooldown event

- RV beltline (shell, midwall)
  Maximum metal temperature 512°C (954°F)

2. DESIGNER'S ALTERNATIVES

The alternatives are as follows:

2.1 Use the standard light-water reactor technology materials (SA-533 Grade B, Class 1 plate and SA-508 Class 3 forging).

2.2 Code Case N-47 approved material could be selected for the Vessel System. The current choices are 2-1/4 Cr - 1 Mo, 304SS, 316SS, and Alloy 800H.

2.3 High temperature ASME Section VIII materials (e.g., 2¼Cr-1Mo-¼V, 3Cr-1Mo-¼V) could be selected for the Vessel System. These would require an extensive extension of the data base to qualify as Code Case N-47 materials, and an irradiation data base would also be required.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected design approach is to design and fabricate the reactor vessel from a high-temperature ferritic steel, 9Cr-1Mo-V. This approach meets the design requirements in a most cost effective manner.

Design Alternative 2.1 uses materials which must be kept under 371°C (700°F) during normal operation and most transients. This could be accomplished with by-passing a small fraction of the cold helium flow from the compressor outlet and circulating it to the annular space adjacent to the reactor vessel wall. A dedicated vessel wall cooling system could be used.

Design Alternative 2.2 would lead to the selection of a material that has lower allowable stress intensities than Modified 9Cr-1Mo, resulting in thicker walls, and heavier and more costly Vessel System components.

Design Alternative 2.3 would result in a selection of a material which would require developing an extensive data base to qualify it under ASME Section III Code Case N-47. In addition, an associated irradiation data base relating to material toughness would have to be developed.

4. SCHEDULE REQUIREMENTS

Interim results on all data are needed as soon as they become available. Final results on all data are needed by the completion of the preliminary design phase.

5. PRIORITY

Urgency: 1
Cost Benefits: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is to use a Code Case N-47 approved material.

7. REFERENCES

1. GA/ABB-CE-005-94, May 19, 1994.

Chris Hoffman 6-30-94
Originator Date

J. di Lauro 6-30-94
Task Manager Date

Program Manager Date

[DDN C.12.01.03]

DATE: 6/30/94

GT-MHR PROGRAM
REACTOR VESSEL EMISSIVITY
(Modified 9Cr-1Mo, SA-387 Grade 91, Class 2 Plate and
SA-336 Grade F91 Forging)
DDN C.12.01.03

PLANT: GT-MHR/System 12

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Reactor vessel emissivity is an important parameter in the removal of residual and decay heat during core conduction cooldown events. In order to satisfy radiological release criteria and their associated fuel temperature limit, a minimum emissivity of 0.8 is required of the reactor vessel materials throughout its operating life.

1.1 Summary of Function and Assumptions

"Maintain Primary Coolant Boundary Integrity," Assumption: Vessel plate material (SA-387 Grade 91, Class 2) and forging material (SA-336 Grade F91, Class 2) can be processed during fabrication to provide surfaces with lifetime emissivities of at least 0.8.

1.2 Current Data Base Summary

Initial library research investigations on thermal emissivity have not uncovered specific data for the selected reactor vessel materials (SA-387 Grade 91, Class 2 plate and SA-336 Grade F91 forgings). A general investigation of steel emissivities indicates the importance of surface oxide layer and roughness on the emissivity values. For steel surfaces with a very thin oxide layer, emissivity values in the range of 0.20-0.35 appear appropriate for the temperatures expected for the reactor vessel. For more heavily oxidized surfaces, values in the range 0.80-0.97 appear appropriate, depending on oxide layer thickness, surface roughness, and temperature.

1.3 Data Needed

Data are needed to demonstrate that the thermal emissivity of the reactor vessel materials is at least 0.8 for the temperatures that occur during conduction cooldown events (370°C to 512°C/698°F to 954°F) over the entire life of the vessel. In addition, the emissivities for normal operation and upset conditions are needed in order to characterize the vessel temperatures and heat loss. The materials should be characteristic of reactor vessel product forms including heat to heat variations. If the emissivities do not satisfy the design requirement, methods of surface treatments such as surface roughening and oxidizing shall be investigated. Surface treatments, however, must be compatible with ultrasonic testing used in ISI of welds. The data need to be sufficient to meet a 95% confidence that this property meets or exceeds the design value. Quality Assurance must be in accordance with the requirement for experimental data or validation testing which is safety related.

1.4 Data Parameters and Service Condition

Data are needed for the total hemispherical emissivity of SA-387 Grade 91, Class 2 and SA-336 Grade F91 for temperatures from 121°C (250°F) to 538°C (1000°F).

The specified service conditions for the reactor vessel are as follows:

a. Normal Operation

- Metal Temperatures 427°C to 491°C (800°F to 915°F)
- 460,000 hours (60 yr at 87% availability)
- Service Environment
  Helium on the internal surface

O_2	Nil
H_2O	[0.01-0.1] ppmv
CO	[0.02-0.8] ppmv
CO_2	[0.03-0.2] ppmv
H_2	[0.5-1.5] ppmv
CH_4	[0.05-0.2] ppmv
N_2	[0.15-1.0] ppmv

Air in the Reactor Building with [TBD environmental conditions] on the external surface of the vessel.

b. Off-Normal Operation

- Pressurized Conduction Cooldown Events (Ref. 1)
  Maximum Calculated Midwall Metal Temperature: 482°C (900°F)
- Depressurized Conduction Cooldown Events
  Maximum Calculated Midwall Metal Temperature: 512°C (954°F)

2. DESIGNER'S ALTERNATIVES

The only alternative is to select a material with a well characterized thermal emissivity that satisfies the design requirement and is already qualified under ASME Section III to withstand the duty cycle. In addition, the material must be well characterized under the neutron irradiation environment.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The proposed approach is to obtain the thermal emissivity of the reactor vessel material which demonstrates that the product forms of the material satisfy the design requirements. Additionally, product processing or surface coating may need to be developed in order to meet the design requirement.

4. SCHEDULE REQUIREMENTS

Results are needed by the completion of the preliminary design phase.

5. PRIORITY

Urgency: 2
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCE OF NONEXECUTION

The fallback position is to assume a more conservative value for emissivity in the calculation of the conduction cooldown events. Resultant fuel and vessel temperatures may be unacceptable, thereby not meeting top-level regulatory requirements. To avoid this, additional, active systems could be used to ensure acceptable fuel and metal temperatures during all events, or the reactor module power rating could be reduced to achieve acceptable temperatures during all events.

7. REFERENCES

1. GA/ABB-CE-005-94, May 19, 1994.

[signature] 6-30-94
Originator Date

[signature] 6-30-94
Task Manager Date

Program Manager Date

DATE: 6/30/94

GT-MHR PROGRAM
HELIUM SEAL DATA FOR BOLTED CLOSURES
DDN C.12.01.04

PLANT: GT-MHR/System 12

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Seal design for containing high pressure helium is always a concern. A requirement to limit helium loss, coupled with the high vessel operating temperatures that occur in the GT-MHR concepts, and the numerous bolted closures incorporated in these designs, amplify the importance of a good seal design. Development work is needed to refine and confirm the seal techniques currently available in the industry, and to quantify helium leak rates at the operating conditions for the GT-MHR.

1.1 Summary of Functions and Assumptions

"Maintain Primary Coolant Boundary Integrity," Assumption: Satisfactory helium leakage rates must be maintained at all vessel system bolted closures in order to minimize the loss of primary coolant. The Vessel System bolted closures include the following: (1) RV Main Closure Flange, (2) SCHE Housing Flange, (3) PCV Main Closure Flange, (4) Generator Housing Upper Dome Flange, and (5) Generator Housing Spool Piece Flange.

1.2 Current Data Base Summary

The current data base on sealing methods for high-pressure, high-temperature helium was developed for the NP-MHTGR design (Ref. 1). This data base considers nine types of seals including non-metallic gaskets, solid metal O-rings, hollow metal O-rings, machined metal seals, solid metal seals, conflat seals, welded seals, Helicoflex seals, and machined seals with a seal weld. This data base does not include specific data on helium leakage rates for the design configuration and design conditions of the GT-MHR vessels.

1.3 Data Needed

Data are needed to demonstrate that the helium leakage requirement (TBD) for the Vessel System can be achieved for normal operating temperatures and pressures. The data must be determined for the specific design configuration used in the GT-MHR Vessel System. The current design uses for flanged joints with sealing provided by two Helicoflex O-rings located in grooves in the bottom flange face. The data needs to be sufficient to meet a 95% confidence that the leakage satisfies the Vessel System requirement. Quality Assurance must be in accordance with the requirements for experimental data or validation testing for safety-related components.

1.4 Data Parameters and Service Conditions

Data are needed for the helium leakage rate through a typical flanged joint using two Helicoflex O-ring seals located in grooves in the lower flange face. The flange material is 9Cr-1Mo-V (SA-182 F91). The stud and nut material is Alloy-718 (SB-637). The flange geometry has not been selected as yet, but will be typical of the Vessel System bolted connections. The Vessel System total allowable helium leakage is [TBD]. Based on past experience with vessels for steam cycle MHR's, a typical leakage rate is 0.75 ft^3 per year per linear inch of seal.

The specified service conditions for the Vessel System are:

Reactor Vessel	
Helium Design Pressure	7.89 MPa (1145 psi)
Helium Design Temperature	496°C (925°F)
Power Conversion Vessel	
Helium Design Pressure	5.72 MPa (830 psi)
Helium Design Temperature	218°C (425°F)

2. DESIGNER'S ALTERNATIVES

The only alternative is to use a welded omega seal at each bolted connection. Such seals are difficult to design, difficult to install, complicate the removal and re-installation of the joint, and are susceptible to fatigue cracking. Several sealing methods were studied in Ref. 1 including the Helicoflex O-rings and omega seals. None of the other methods were judged acceptable.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The proposed approach is to obtain the helium leakage rate for a typical GT-MHR Vessel System bolted connection using Helicoflex O-rings and demonstrate that this leakage rate meets the design requirement.

4. SCHEDULE REQUIREMENTS

Results are needed by the completion of the preliminary design phase.

5. PRIORITY

Urgency: 2
Cost Benefit: H
Uncertainty of Existing Data: M
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is to use both the two Helicoflex O-rings and the welded omega seal at each Vessel System bolted joint. This will increase the Vessel System initial cost, the cost of in-service repairs involving removal and re-installation of the bolted connections, and the cost of in-service inspection (to check for fatigue cracks in the omega seals).

7. REFERENCES

1. Helium Seals Design Configuration Assessment Study for HTGR-NPR Reactor Vessel, DSG-91-099, May 1991.

James Hillichey 6/30/94
Originator Date

M. Basol 6/30/94
Task Manager Date

Program Manager Date

DATE: 6/30/94

GT-MHR PROGRAM
SCS CIRCULATOR MAGNETIC AND CATCHER BEARINGS
DESIGN VERIFICATION
DDN C.14.01.01

PLANT: GT-MHR/System 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The SCS circulator magnetic bearings comprise variable strength magnetic fields that suspend the high speed/large mass rotor in position. The rotor and support housing shall have no resonant frequencies throughout the full speed range. In the event of a failure in the magnetic suspension system, catcher bearings are used to support the rotor and are required to withstand at least [20] drops without the need for replacement.

1.1 Summary of Function and Assumptions

"Support Shaft," Assumption: Magnetic bearing (including catcher) dynamic properties will be verified.

"Protect the Capability to Support Shaft," Assumption: Reliability of catcher bearings will be verified.

1.2 Current Data Base Summary

Magnetic bearings have been built and operated successfully for a wide range of equipment similar in nature to the GT-MHR SCS circulator but for horizontal shaft applications. There are, nevertheless, no rotor dynamic issues which would prevent a successful design being built for the GT-MHR vertical shaft circulator. The "built-in" components are expected to operate essentially without maintenance. A non-redundant (standard) control system would be expected to be out of service for maintenance for an hour or two per year, based on current technology, and for lesser periods in the future as more experience is required. Magnetic Bearing, Inc. (MBI's) goal is 40,000 mean-time-between-failure which appears possible but has not been demonstrated yet as the early turbomachinery applications are just reaching this number of running hours.

The "catcher" bearings, both journal and thrust, are the most significant technical issue with respect to the use of magnetic bearings. On failure of the magnetic bearings, gravity will force the shaft weight down onto the thrust catcher bearing after a 10 mil drop. As the shaft is vertical the lower end will be free to precess within the annular gap of the lower journal catcher bearing. At this stage the shaft could be still rotating at up to 5,000 rpm generating potentially high contact loads.

The tests performed by James Howden to develop and qualify a thrust catcher bearing were performed for the following conditions:

Maximum Steady State Thrust	7,470 lb
Maximum Dynamic Thrust for a Drop of 0.5 mm	22,400 lb
Operating Speed at Time of Drop	6000 rpm
Design Number of Drops	20 (27 achieved without failure)

The design developed consisted of an angular contact ball bearing supporting a thrust ring onto which a thrust collar on the circulator shaft could be dropped. The tests were carried out in a dry helium environment representative of the reactor environment.

The design evolved by this test program for the thrust catcher bearing should be adequate as a basis for detail design and final testing and qualification in the prototype circulator.

When the magnetic bearings fail, the circulator shaft drops onto the thrust catcher bearing that allows the lower end of the shaft to swing freely within the constraints of the journal catcher bearing.

A design for the journal catcher bearing needs to be developed. This design should be able to withstand the impact from the shaft swings during its coastdown on the thrust catcher bearing. The performance of this design then needs to be evaluated in a test.

1.3 Data Needed

There are four categories of data required to provide an adequate basis for final design and performance of the GT-MHR SCS circulator with magnetic bearings.

First, data need to be acquired from ongoing observations of magnetic bearing applications to obtain up-to-date estimate of the expected reliability of the current generation of magnetic bearing control systems. A number of problems have been seen caused by poor QC specifications for wiring, terminations, etc. This data needs to be available prior to procurement of the magnetic bearing system.

Second, there is a mandatory confirmatory, bearing electric insulation qualification test, needed prior to committing to bearing manufacture.

Thirdly, the journal catcher bearing design must be qualified for [20] drops.

Finally, there is a need for confirmation of the pressure vessel electric penetrations design, and the development of in-service inspection methods for monitoring the catcher bearing condition, the power and instrument cables and the controls.

Quality assurance must satisfy non safety-related requirements.

1.4 Data Parameters and Service Conditions

Data are required to validate the adequacy of the active magnetic and catcher bearings design for the following main circulator service conditions:

Fluid	Helium: [0.5] ppmv H_2O; [3.0] ppmv $CO + CO_2$; [3.0] ppmv H_2; [0.1] ppmv CH_4; [2.0] ppmv N_2
Temperature	100°F - 300°F
Speed Range	0 to [6820] rpm (constant and transient speed conditions)
Load Range	Axial: [2000] lb downward at nominal [6200] rpm speed to [6500] lb at 0 rpm Radial: [200] in.-oz unbalance
No. of Drops on Catcher Bearing	[20] minimum

2. DESIGNER'S ALTERNATIVES

The following alternatives are available:

2.1 Obtain FRG proprietary data assuming their availability in a timely manner and establish applicability to GA design.

2.2 Perform scale model tests and extrapolate results.

2.3 Use 350 MW(t) NP-MHTGR grease bearing SCS circulator design.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to continue to develop a database of the actual experience of users for the bearings control systems supplied by vendors who are qualified to bid on the GT-MHR circulator procurement. The bearings wiring and insulation, the bearing power leads, and the instrumentation and control wiring needs to be qualified in an environment representative of the GT-MHR normal and off-normal operations.

The design of the thrust catcher bearing evolved from the test program performed by J. Howden and should be adequate as a basis for final testing and qualification.

[DDN C.14.01.01]

For the backup journal catcher bearings, the needed design approach is to:

- upgrade the code developed by Howden to include the close conformity rolling resistance model as recommended,
- correlate the code using the ¼ scale model already constructed, data from Novacorp or Mafi Trench if available,
- continue this code and model development until confidence is sufficient to perform a detail design of the journal bearing for the GT-MHR, and
- perform a design verification test similar to that performed by J. Howden for the thrust catcher bearing (see Section 1.2), to scale if considered possible, and in the representative dry helium environment, and in a water vapor environment representative of off-normal helium chemistry encountered, for example, after refueling.

The design evolved by the above test program will form a basis for final design of the journal catcher bearings. This design will go through its final testing and qualification during the circulator prototype test. In particular, the following will be verified.

- qualification of journal thrust and radial catcher bearing to survive [20] drops in a helium environment as described above,
- development of a monitoring system for the thrust and radial catcher bearings which can be used without entry to the primary coolant circuit,
- satisfactory operation of the penetration seals for control and instrumentation wiring, and
- satisfactory operation of the magnetic bearing close to the drive motor.

4. SCHEDULE REQUIREMENTS

Completion of validation test required at begining of final design.

5. PRIORITY

Urgency: 2
Cost benefit: H
Uncertainty in existing data: H
Importance of new data: H

[DDN C.14.01.01]

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

If magnetic and catcher bearings tests are not performed prior to prototype circulator manufacture and testing, then any major design changes required after prototype tests would cause cost and schedule impact. The fallback position is to use the 350 MW(t) NP-MHTGR SCS circulator type grease lubricated bearing system.

R.C. Potter 7/27/94

7-27-94

Originator Date

7/28/94

Task Manager Date

Program Manager Date

[DDN C.14.01.02]

DATE: 6/30/94

GT-MHR PROJECT
SCS CIRCULATOR PROTOTYPE
IMPELLER AERODYNAMIC AND ACOUSTIC TEST DATA
DDN C.14.01.02

PLANT: GT-MHR/System 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The aerodynamic performance of the shutdown circulator must be verified to assure adequate primary coolant circulation for various plant operating conditions.

1.1 Summary of Function and Assumptions

"Provide circulation of the helium around the reactor during shutdown." Assumption: The selected aerodynamic design must be capable of achieving and reliably maintaining the rate of circulation required by the reactor thermodynamics.

1.2 Current Data Base Summary

The conceptual design is based on a centrifugal impeller which has been in operation in AGRs in the UK for about 20 years. Inevitably, however, each project has its own aerodynamic duty and gas flow arrangements local to the circulator and, particularly where high efficiency is required, the performance can only be ensured by testing.

The nonstandard features which justify the testing in this case are:

- Impeller and diffuser combination deviates from proven, standard design.
- Influence of the Shutdown Loop Shutoff Valve (SLSV).
- Bypasses through seals at fixed/removable junctures in ducts and casings.

1.3 Data Needed

Aerodynamic performance data for the circulator, in air, is needed to allow optimization of aerodynamic design details and to give assurance that the design, when manufactured to contract specifications and running in helium will achieve the duty specified (see Section 1.4).

Measurement of the axial thrust generated by the impeller is also required.

Testing will be generally in accordance with BS 848, Parts 1 and 2. Quality assurance must be in accordance with the requirements for experimental data or validation testing per non safety-related components.

[DDN C.14.01.02]

1.4 Data Parameters and Service Conditions

Service conditions of interest are given below:

Atmosphere	Helium
Pressure	14.7 - 1040 psia
Temperature	Up to 915°F
RPM	Variable, up to [5000] rpm

2. DESIGNER'S ALTERNATIVES

Redesign existing test rigs to permit means of accurate flow measurement.

3. SELECTED DESIGN APPROACH AND EXPLANATION

A full scale test rig, but using models of simple construction will be used to obtain early performance data. This facility will allow certain settings to be optimized and also modifications to flow passages, diffuser vane angle etc., to be investigated and finalized prior to manufacture of contract components.

4. SCHEDULE REQUIREMENTS

Essential testing should be completed by the end of preliminary design.

5. PRIORITY

Urgency: 2
Benefit/cost: H
Uncertainty in existing data: M
Importance of New Data: M

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is Alternative 2. This alternative could cause schedule delays and cost increases. If Alternative 2 is impractical, margins must be added to the circulator design since its aerodynamic performance will not be known with any accuracy when the circulator is installed in the reactor and would not have been optimized.

R. C. Potter 7/27/94
7-27-94

Originator Date

7/28/94

Task Manager Date

Program Manager Date

[DDN C.14.01.03]

DATE: 6/30/94

GT-MHR PROGRAM
SCS CIRCULATOR PROTOTYPE TEST IN HIGH PRESSURE TEST FACILITY (HPTF)
DDN C.14.01.03

PLANT: GT-MHR/System 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The SCS circulator must meet its performance and reliability targets in order that the reactor module can meet its power generation goals.

1.1 Summary of Function and Assumptions

"Circulate the primary coolant through the SCS heat exchanger," Assumption: The machine will operate with a high availability and reliability with minimum maintenance.

1.2 Current Data Base Summary

The conceptual design is based on existing circulators presently operating in AGR type reactors. The main differences are:

- Helium rather than carbon dioxide
- Variable speed
- Higher head of fluid
- Different bearing system
- High pressure

Years of experience of operating reactors have demonstrated the exceptionally good reliability of this type of machine. In every case the HPTF exposed the requirement for minor modifications to achieve this reliability.

1.3 Data Needed

The testing in the HPTF is the first time the motor is fully loaded and the bearings and impeller see the conditions that they have to operate in, and the interaction of all the components on each other. Data is needed to verify the design and performance of the shutdown circulator, including the magnetic bearings and their control, the variable speed induction motor, the motor cooling system, the circulator impeller and diffuser, and the shutdown loop shutoff valve. In particular data is needed for the temperatures of windings (efficiency of cooling system), acoustic response of structural components, bearing performance and wear or fretting damage. Quality Assurance must be in accordance with the requirements for experimental data or validation testing per nonsafety-related components.

1.4 Data Parameters and Service Conditions

Service conditions of interest are given below:

Atmosphere	Helium
Pressure range* (nominal operation)	12 to 1025 psia
Temperature range* at circulator inlet (nominal operation)	77 to 915°F
Speed range	0% to 100%
Voltage range	[TBD]
Cooling water inlet temperature range	60 to 122°F

2. DESIGNER'S ALTERNATIVES

The following alternative has been considered:

2.1 Test the equipment in low pressure (approximately 105 psi) nitrogen (to give equivalent density).

3. SELECTED DESIGN APPROACH AND EXPLANATION

The full scale test rig is selected because it simulates the actual operating conditions as closely as possible. This gives all the data required to assure a rapid commissioning. The HPTF, after the prototype machine, is used to routinely test all subsequent machines, i.e., production test facility.

Alternative 2.1 cannot test rapid depressurization, low density helium (poor dielectric strength) and due to nitrogen's poorer heat transfer capability, cold cooling water must be used producing the thermal gradients.

4. SCHEDULE REQUIREMENTS

Testing to be completed 6 months prior to delivery.

5. PRIORITY

Urgency: 2
Benefit/cost: M
Uncertainty in existing data: H
Importance of New Data: M

*For pressurized and depressurized decay heat removal.

[DDN C.14.01.03]

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is option 2.1. The major concerns about not adopting the preferred approach would be insufficient structural and performance response data which will require additional design margins with a potential impact on schedule and cost.

R.C. Potter 7/27/94

[signature] 7-27-94

Originator Date

[signature] 7/28/94

Task Manager Date

Program Manager Date

DATE: 6/30/94

GT-MHR PROGRAM
SHUTDOWN CIRCULATOR LOOP SHUT-OFF VALVE (SLSV)
AERODYNAMIC AND LIFE CYCLE TEST DATA
DDN C.14.01.04

PLANT: GT-MHR/System 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The SLSV must open and close under the aerodynamic, pressure and gravity forces which are dependent on whether the Power Conversion System (PCS) or shutdown cooling system (SCS), are operating. The SLSV must open fully under SCS operations and must cause minimal disruption to the gas flow entering the SCS circulator impeller to enable the impeller to function within its design limits. The SLSV must close fully under all operating conditions. The SLSV must be highly reliable in order to open and close when required.

1.1 Summary of Function and Assumption

"SLSV Life and Operation," Assumption: The SLSV opens fully under all of the SCS operating conditions. The SLSV closes under its own action when the SCS circulator is stopped and permits a minimum defined leakage to bypass the valve under operation of the PCS. The SLSV performance is highly reliable over its design life.

1.2 Current Data Base Summary

The SLSV conceptual design is based on the shutoff valve used in Fort St. Vrain (FSV). The SLSV differs from the FSV assembly as follows:

- Actuator assist is provided for closure of the valve, which is additional to the FSV system.
- Each of the two valve plates are fixed to individual shafts mounted in bushings rather than a single fixed shaft with the plates mounted on bushings.
- The leading edge of the SLSV assembly is blunt.

Years of experience with the FSV SLSV have demonstrated reliable features of the design, some of which have been improved or supplemented. The differences listed here are proposed as improvements but must be tested to verify that they are as good or better than the FSV SLSV.

[DDN C.14.01.04]

1.3 Data Needed

Data are needed to verify that the SLSV design has a reliable performance within the leakage (when closed) and pressure drop (when open) specified limits under the service condition in Section 1.4. Data are also needed to verify the SLSV mechanical integrity under the maximum ΔP and under the number of cycles expected during its life. Quality assurance must be in accordance with the requirements for experimental data or validation testing per non safety-related components.

1.4 Data Parameters and Service Conditions

Service conditions of interest which cover SCS and PCS operations are given below:

Internal atmosphere	Helium	
Pressure*	12 to 1025 psia	
Helium inlet gas temperature*	77° to 915°F	
Gas flow (valve open)	20% to 100% steady state Minimum transient 8% (100% is [57] lb/s nominal)	
Helium chemistry (nominal)	H_2O	0.5 ppmv
	$CO + CO_2$	3.0 ppmv
	H_2	3.0 ppmv
	CH_4	0.1 ppmv
	N_2	2.0 ppmv

2. DESIGNER'S ALTERNATIVES

The following alternatives have been considered:

2.1 Test the equipment in the High Pressure Test Facility (HPTF).

2.2 Test the equipment during system preoperational tests.

3. SELECTED DESIGN APPROACH AND EXPLANATION

A full-scale test rig and test valve assembly will be used to obtain early operability data for the machine and its subcomponents. This will provide an opportunity to correct deficiencies so that the assembly will function satisfactorily in all operating modes during the system qualification test. Alternatives 2.1 and 2.2 carry substantial risk of schedule delay because of the discovery of problems later in the schedule. The selected approach reduces the potential for schedule delay because the problems are identified earlier and, therefore, can be fixed earlier.

*For pressurized and depressurized decay heat removal.

[DDN C.14.01.04]

The full-scale test will include the valve response (opening and closing) under various air density and flow conditions, the gas leakage through the closed valve, and the verification of the valve mechanical integrity under the cycle loading to be expected during the life of the valve and under the maximum ΔP conditions to be encountered during a small primary coolant leak (up to 1 in.^{2}) at the worst location for the valve.

4. SCHEDULE REQUIREMENTS

Testing to be completed by month [TBD].

5. PRIORITY

Urgency: 2
Benefit/cost: L
Uncertainty in existing data: L
Importance of new data: L

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is Alternative 2.2. Alternative 2.1 does not provide suitable inlet flow profiles. Nonexecution of the preferred approach would lead to total dependence on Alternative 2.2, which could only provide very limited data, and failure at that time would most certainly lead to schedule delays while the problems were investigated and corrected. Failure of the valve to close in situ under some upset conditions could result in limitations of the life of the shutdown cooling heat exchanger.

R. C. Potter 7/27/94
7-27-94

Originator Date

7/28/94

Task Manager Date

Program Manager Date

DATE: 7/22/94

GT-MHR PROGRAM
SCHE INSULATION VERIFICATION TESTS

DDN.C.14.04.01

PLANT: GT-MHR/System 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Thermal and mechanical performance of the insulation located in the active flow region (i.e., upper helium inlet plenum from bottom of reactor of the shutdown cooling heat exchanger) needs to be verified. The concerns are the possibility of insulation becoming loose during operation and blocking helium flow areas and the difficulty with accessibility for maintenance or alteration once the shutdown cooling heat exchanger is installed.

1.1 Summary of Functions/Assumptions

"Flow Primary Coolant Through Heat Exchanger," Assumption: Thermal and mechanical performance of the insulation(s) is (are) adequate.

"Channel Primary Coolant Through Heat Exchanger," Assumption: Thermal and mechanical performance of the insulation(s) is (are) adequate.

"Discharge Primary Coolant," Assumption: Thermal and mechanical performance of the insulation(s) is (are) adequate.

1.2 Current Data Base Summary

A considerable amount of literature is available relative to high temperature insulation physical and thermophysical properties. A variety of insulations are available in special forms to meet specific service requirements.

1.3 Data Needed

Physical and operational characteristics of insulation are required. Specific data needed would be relative to thermal cycling of fibrous insulation, effects of mechanical and acoustic vibrations, and effects of flow and thermal gradients. These tests will produce temperature data for certain critical components of the shutdown cooling heat exchanger and verify the proposed thermal barrier for the life of the plant. Additional test data relative to any destructive impact on insulation due to vibrations and sliding contacting surfaces, as needed, would be obtained.

Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

Sufficient test data is required to demonstrate the adequacy of the installed insulation under simulated critical environmental conditions. The insulation materials will be subjected to flow velocities, thermal cycling, mechanical and acoustic vibrations, and sliding loads depending on the critical locations of interest. The test data will be used to confirm the thermal and mechanical viability of the chosen insulation materials and the methods of installation.

2. DESIGNER'S ALTERNATIVES

2.1 Rely on manufacturer insulation specification for mechanical and thermal performance.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to perform testing of different critical regions under simulated environment conditions. Thermal performance of the insulation can be obtained by analysis; however, analysis alone is not sufficient to assure the mechanical performance of the insulation.

Performing the described tests is the only way of checking the mechanical performance of the insulation.

4. SCHEDULE REQUIREMENTS

Data is needed one year into the final design phase.

5. PRIORITY

Urgency: 3
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONACCOMPLISHMENT

The fallback positions would be to rely on Alternate 2.1. The insulation system will have to be consecutively designed to endure areas of high vibration and acoustic loads. The consequences of this on the program would be the possibility of failure of the insulation resulting in possible damage to components of the shutdown cooling heat exchanger and other components of the shutdown cooling system.

[DDN.C.14.04.01]

A. W. Lubkowitz 7/22/94
Originator Date

M. Basol 7/26/94
Engineering Manager Date

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Project Manager Date

DATE: 7/22/94

GT-MHR PROGRAM
SCHE VIBRATIONAL FRETTING WEAR AND SLIDING WEAR OF TRDs FOR BARE TUBES

DDN.C.14.04.02

PLANT: GT-MHR/System 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The wear protection method for the bare tubes, which are in direct contact with the drilled support plates or other support structures, is of concern in the present design of the shutdown cooling heat exchanger.

In the present design it is proposed that a tube retention and wear protection device (TRD) be mechanically attached to the tube at each location where a tube passes through a support. In order to alleviate thermal interaction stresses, the tubes are loosely held in the supports by providing a small clearance between the TRD and the supports. This may result in impact and fretting wear of the TRD due to the flow-induced vibration. Vortex shedding and/or turbulence are the major flow mechanisms which can contribute to the fretting wear of the TRD.

1.1 Summary of Functions/Assumptions

"Protect the Capability to Support Heat Transfer Surfaces". Assumption: Vibrational wear and sliding wear protection methods will be verified.

1.2 Current Data Base Summary

In December 1989 a review of the fretting and wear technology was performed under Subtask 6 of WBS 1713.2 Steam Generator Design Support. The review encompassed the majority of the experimental and analytical work performed at General Atomics and some of the important work done by Sulzer Bros., Central Electricity Research Laboratories (England), and Atomic Energy of Canada.

Based on the review it appears that the necessary fretting and impact wear rate data exists. Also, many analytical models which use the wear rate data to predict the long-term wear also are available. However, the fretting wear prediction analysis is not an exact science and the difference between predicted and actual wear may be significant. The analytical models are typically used to qualitatively examine the relative influence of the various parameters expressed in the equations such as frequency, clearance, impact forces, sliding distance, wear rate, vibration amplitude, and coefficient of friction.

1.3 Data Needed

A significant amount of fretting and impact wear rate data exists and different wear prediction models are available. However, the applicability of the usable data and verified, workable models to analyze the TRD for the shutdown cooling heat exchanger for wear are marginal.

A testing program is needed to validate the use of existing wear rate data and wear prediction models for the TRD design. The purpose of the proposed test program is not to generate additional wear rate data, but to demonstrate that the existing TRD design is conservative and that it will protect the tube for the design life of the plant.

Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The following presents the applicable range of parameters and service conditions which influence the predicted wear of the TRD.

Temperature: 21°C to 850°C ± [TBD] Hot Streaks
(70°F to 1562°F ± [TBD] Hot Streaks)

Material Substrate: 2¼ Cr - 1 Mo

Coating: Nitriding

Clearance between tube O.D. and support I.D.: 0.508 mm (0.02 in.) max.

Environment: Helium with impurities - [TBD]

Helium Gap Velocity: Up to 61 m/sec (200 ft/sec)

Natural Frequency of Tube: 24 Hz - 300 Hz

Vibration Amplitude: 0.127 mm - 0.254 mm (0.005 in. - 0.010 in.)

Coefficient of Friction: 0.4 to 0.6 (will be measured experimentally)

Wear Coefficient: [TBD]

Normal Impact Force: 1.4 kg - 3.6 kg (3 lb - 8 lb)

Damping Characteristic of Tube: 1% to 5% (will be measured experimentally)

Material Characteristics: Density and Modulus of Elasticity - 2¼ Cr - 1 Mo

Tube Geometry: O.D. and I.D., Bare Tube

2. DESIGNER'S ALTERNATIVES

2.1 Utilize the existing vibrational fretting wear and sliding wear data.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to conduct accelerated impact/fretting wear testing under prototypical geometrical and environmental conditions using prototypical tube dynamics.

Prior to initiating testing, a simple but conservative mechanistic model for tube fretting and wear prediction will be developed. This model will be validated by comparing the analytical results with the test results. The development of a complex model which simulates the time dependent motion of the helical tube and accounts for all nonlinearities (such as friction, impact forces, uneven clearances and sliding distance) would not be within the scope of this DDN.

Alternative 2.1 data were not generated using prototypical TRD geometry or tube dynamics (frequency, clearance, vibration amplitude, and normal impact force) and it is therefore difficult to assess the degree of conservatism or nonconservatism in the design of the TRD.

4. SCHEDULE REQUIREMENTS

The results to be available prior to the completion of preliminary design.

5. PRIORITY

Urgency: 2
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is to use the existing fretting and wear data.

The consequences of nonexecution of this test program could potentially result in an overly conservative design of the TRD which may significantly increase the cost of the shutdown cooling heat exchanger. Should a nonconservative design emerge, it has the potential consequence of affecting the shutdown cooling heat exchanger performance and possibly life.

[DDN.C.14.04.02]

A. W. Lubkowitz 7/22/94
Originator Date

M. Basol 7/26/94
Engineering Manager Date

Allen W. ... for SAL 7/28/94
Project Manager Date

DATE: 7/22/94

GT-MHR PROGRAM
SCHE INSTRUMENTATION ATTACHMENT TESTS

DDN.C.14.04.03

PLANT: GT-MHR/System 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The lessons learned from earlier gas cooled reactors indicate that temperature measurements will be required at various locations within the tube bundles of heat exchangers. The Instrumentation Requirements Study performed for the NP-MHTGR steam generator, for example, has recommended that measurements be made for gas temperature, steam/tube temperature, and structural considerations of stress, strain, and acceleration for first-of-a-kind (FOAK) instrumentation. Instrumentation will be required to obtain input for the Reactor Protection System, Investment Protection System, and Plant Control, Data, and Instrumentation System.

A testing program is needed to obtain data to be used in designing and installing the necessary instrumentation for operation of the GT-MHR shutdown cooling heat exchanger. This includes heat exchanger performance instrumentation and those required by the control system, both of which are required for the lifetime of the unit. It also includes FOAK instrumentation which need only last for the early stages of the heat exchanger lifetime. Mockups are needed to confirm both the design and installation techniques for critical instrumentation as well as to confirm the ability for removal and replacement for lifetime instrumentation.

1.1 Summary of Functions/Assumptions

"Transfer Heat from Primary Coolant to Heat Exchanger (Performance Evaluation Methodology will be Verified)". Assumption: Instrumentation, particularly for the FOAK unit, is needed to confirm heat exchanger performance predictions implicit in the evaluation models. Instrumentation can be installed in critical locations within the heat exchanger and such instrumentation will be reliable with long-term integrity. Some instrumentation must be removable in order to be replaced in the event that it is rendered inoperable.

1.2 Current Data Base Summary

Prior HTGR steam generators have required instrumentation (ABB Report DPS-91-269, "Instrumentation Requirements Study for NP-MHTGR Steam Generator," September, 1991).

AGR - One of four steam generators in the first reactor at each site was extensively instrumented for measurements of vibrations and strains. Thermocouples were installed in all steam generators.

THTR - The internal instrumentation consisted of 71 thermocouples; 21 were for gas temperatures around the tubes and 50 were for steam/water temperatures inside the tubes. Accelerometers and strain gages were considered not to be reliable enough and they were not included.

FSV - The instrumentation was extensive and is difficult to summarize. There were 13 units (steam generators) built, one of which was fully instrumented with 116 thermocouples while the standard units had 24 thermocouples. One unit had 70 strain gages for vibration data. Five units had additional thermocouples to provide gas temperatures and superheater temperature distribution.

1.3 Data Needed

Test data are needed for use in designing and installing into the shutdown cooling heat exchanger, the appropriate instrumentation for reliable operation of the units. Mockups will confirm the designs and assembly techniques for critical instrumentation. The ease of removal and replacement can be demonstrated to a degree. Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The data are required at the following service conditions:

Coolant	-	Helium on the shell side and water on the tube side
Operating Conditions	-	Standby, pressurized and depressurized cooldown, hot restart after conduction cooldown, and refueling
Helium inlet temp.	-	Up to maximum temperature during hot restart after conduction cooldown [TBD]
Helium outlet temp.	-	Up to maximum temperature during hot restart after conduction cooldown [TBD]
Helium pressure	-	Up to 7.6 MPa (1100 psia) at SCHE top inlet
Helium flow	-	[TBD] by Shutdown Cooling Circulator (SCC)
Water inlet temp.	-	[TBD] by Shutdown Cooling Water System (SCWS) and Shutdown Cooling Heat Exchanger (SCHE)
Water pressure	-	Up to [TBD] to guarantee 39°C (70°F) subcooled water during all transients
Water flow	-	Maximum water flow rate [TBD] during hot restart after conduction cooldown. Minimum flow rate [TBD] for standby.
Water outlet temp.	-	[TBD] by Shutdown Cooling Heat Exchanger (SCHE)

2. DESIGNER'S ALTERNATIVE

2.1 Utilize previous designs which may not be suitable for the GT-MHR shutdown cooling heat exchanger design.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to use mockups to replicate the internal surfaces where instrumentation will be required. The design and assembly techniques will be used on representative surfaces.

4. SCHEDULE REQUIREMENTS

Test results are needed early in final design in order to finalize the shutdown cooling heat exchanger designs and to be used in interfaces with Instrumentation organizations. The expected designs for instrumentation are expected to be incorporated into component test plans to determine their effects on gas flow distribution where critical.

5. PRIORITY

Urgency: 2
Cost Benefit: M
Uncertainty in Existing Data: M
Importance of New Data: M

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is to use data from earlier designs which are not the same as the GT-MHR shutdown cooling heat exchanger.

The consequences of nonexecution of this program would place at risk the ability to provide adequate instrumentation for the heat exchangers for either the FOAK or NOAK units. Performance of the units would have to be evaluated on the basis of the resulting instrumentation.

A. W. Lubkowitz 7/22/94
Originator Date

M. Basol 7/26/94
Engineering Manager Date

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Project Manager Date

DATE: 7/22/94

GT-MHR PROGRAM
SCHE BARE TUBES INSPECTION METHODS AND EQUIPMENT

DDN.C.14.04.04

PLANT: GT-MHR/System 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The tubing and welds in the shutdown cooling heat exchanger bare tube circuits must be capable of being inspected to provide safe and reliable operation of the units with high availability. The helical tubes are different from existing PWR steam generator tubes in three major areas:

a. The helical tubes are much longer, with more bends than the PWR U-tubes. There are longer, more torturous lengths of tubes to be inspected.

b. The tube materials are different from PWR SG tube materials. There are also several similar metal butt welds in each tube circuit.

c. The shutdown cooling heat exchanger tubing is about 2 times thicker than PWR SG tubing.

The effort of this DDN will provide data on the ability to deliver and recover an NDE probe the full length of the shutdown cooling heat exchanger tubes and the sensitivity of that equipment to detect tubing flaws. In addition, the choice of either eddy current (ECT) or ultrasonic inspection (UT) will be made.

1.1 Summary of Functions/Assumptions

"Protect the Capability to Channel Secondary Coolant Through the Heat Exchanger", Assumption: Inspection of the shutdown cooling heat exchanger tubing is possible. Adequate radius of the necessary tube bends will allow passage of an inspection probe. In addition the ID of the tube will be large enough to allow suitable probe passage and the wall thickness will not preclude acceptable sensitivity of the testing equipment.

1.2 Current Data Base Summary

Previous testing experience by Babcock & Wilcox (Karl C. Henderson, et al, "A Single Pass Volumetric Ultrasonic Inspection System for Helical Coil Steam Generators," JPGC, 1984) and Southwest Research Institute (SWRI Project No. 17-5077, "Phase I Final Report-Examination System for Helical Steam Generator Tubes," May, 1978) and the recent engineering development program performed by ABB Combustion Engineering (ABB Report TR-ESE-990, "Status Report for the Engineering Development of the NP-MHTGR Steam Generator Tube ISI Probe and Delivery System," May, 1993 and ABB Report DPS-93-003, "Assessment of the Impact of NP-MHTGR SG Test Programs on the SCHE

Design", February 1993) indicates that it is possible to deliver an inspection probe from the boreside of the helical tubing.

1.3 Data Needed

Test data are needed first to guarantee the capability, and secondly, inspection sensitivity for the specific geometry of the shutdown cooling heat exchanger tube circuits. From this a testing program can be developed which will be compatible with outage times and the necessary NDE requirements.

Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The probe delivery and inspection development tests shall be performed in an air atmosphere at ambient temperature with additional tests at as high a temperature as can be tolerated by the NDE probe without affecting the data obtained.

For the probe delivery system the data parameters of interest include the loads necessary to push and pull the probe with its carrier, and the times necessary to deliver the probe, to inspect the tube areas, and to retract the probe.

The NDE data shall be obtained and recorded in accordance with the approved procedures.

2. DESIGNER'S ALTERNATIVE

2.1 Utilize data from previous tests and developmental programs. Design the heat exchanger tubing bends to that criteria. Defer testing until baseline testing is to be done at the site.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to test with representative probes and NDE equipment of representative tubing coils and lead-in and lead-out tubing. The test program will confirm the ability to conduct tubing NDE.

NDE is required, and is critical to the operation of the precooler and intercooler. Detection of degradation will allow the operator to assess certain operating practices, and possibly preclude moisture ingress due to tube failures.

4. SCHEDULE REQUIREMENTS

Initial test results are needed before the end of preliminary design in order to firm up the shutdown cooling heat exchanger design.

5. PRIORITY

Urgency: 2
Cost Benefit: H
Uncertainty in Existing Data: M
Importance of New Data: M

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is to use data from previous testing which may not be the same as for the GT-MHR design. Conservative estimates would have to be made for NDE sensitivity and tube inspection times.

The consequences of nonexecution of the test program would place at risk the ability to provide adequate NDE capability for the shutdown cooling heat exchanger tubing.

A. W. Lubkowitz 7/22/94
Originator Date

M. Basol 7/26/94
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DATE: 7/22/94

GT-MHR PROGRAM
SCHE SHROUD SEAL TEST

DDN.C.14.04.05

PLANT: GT-MHR SYSTEM 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The reference GT-MHR shutdown cooling heat exchanger design requires the capability of removal and replacement. To satisfy this requirement a seal design between the SCHE shroud and the Metallic Core Support Structure (MCSS) was developed. The location of the seal and its potential configuration was agreed upon among SCHE and the MCSS designers. The design data is needed to verify the preliminary seal design and to obtain a reasonable estimate of leakage for the SCHE performance analysis.

1.1 Summary of Functions/Assumptions

"Flow Primary Coolant Through Heat Exchanger," Assumption:

Mechanical and thermal performance of the seal is adequate.

1.2 Current Data Base Summary

The type of seal chosen for the present design consists of a double seal whose type is given below.

a. Seals which allow low stress axial thermal growth:
   - Expansion joint (metal bellows).

b. Circumferential or annular seals which allow considerable radial mismatch of mating components.
   - Custom fabricated packing from ceramic or graphite braided rope, or hybrid ceramic/Inconel, graphite/Inconel braided rope.

The above two types of seals are industry standard designs for static seals. However, most of these standard designs are for high pressure, low temperature and small diameter applications.

Adopting any standard seal design for the shutdown cooling heat exchanger applications such as larger diameter [(1905mm - 2159mm), (75 in - 85 in)], higher temperatures [(490°C - 1093°C), (915°F - 2000°F)] and small differential pressures [(<68.9 KPa), (< 10 psi)] will require additional consideration.

Based on the vendor's responses, type a and b seal designs will require developmental testing to confirm the design feasibility. These two types are located on the outer shroud of the SCHE to control bypass helium flow.

1.3 Data Needed

The designs of the fabricated packing and metal bellows seal will require testing which will:

a. Confirm the design feasibility prior to completion of preliminary design.
b. Measure leakage rates under prototypical operating conditions.
c. Provide information on the effects of the following factors on the seal performance:
   - Surface finish of the mating components.
   - Flatness of the mating surfaces.
   - Differential pressure across seals.
   - Seating load, which will be applied by the metal bellows.
   - Size, and rating of the compression bellows.

The results of the testing will be used to refine the seal design and the test data (leakage rate) will be used in the performance analysis of the SCHE.

Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The critical test parameters will be the geometric similitudes of the mating surfaces, helium temperature and the differential pressure across the seal.

2. DESIGNER'S ALTERNATIVES

The purpose of the SCHE-MCSS seal interface is to facilitate the installation, removability and replaceability of the SCHE, maintaining, at the same time, the leakage rate at the seals below predetermined values during operating conditions.

2.1 If the above seal configuration is used without confirmatory development testing, extra conservative assumptions will have to be made in order to calculate a leakage rate using existing analytical methods which have been incorporated in computer programs of the vendors. These leakage rates will increase the helium flow requirement through the SCHE during pressurized shutdown and depressurized shutdown conditions.

3.0 SELECTED DESIGN APPROACH AND EXPLANATION

The selected design approach is to incorporate the bellows and fabrication experience in a scale model of prototypical geometry and operating conditions, except helium velocity, in a small test chamber. The test data will be collected to measure the influence of the critical design details and to finalize the seal designs. The test results will also be used in the SCHE performance analysis.

[DDN.C.14.04.05]

4.0 SCHEDULE REQUIREMENTS

Since the SCHE does not require procurement of long lead materials, test results are required by [TBD].

5.0 PRIORITY

Urgency: 3
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONACCOMPLISHMENT

The fallback position is design alternative 2.1. The consequences of this fallback position could result in an increase in helium flow requirement through the SCHE, which would decrease efficiency during normal operations.

A. W. Lubhoritz 7/22/94
Originator Date

M. Basol 7/26/94
Engineering Manager Date

Alan M for SAC 7/28/94
Project Manager Date

DATE: 7/22/94

GT-MHR PROGRAM
ACOUSTICAL RESPONSE OF THE SCHE HELICAL BARE TUBE BUNDLE

DDN.C.14.04.06

PLANT: GT-MHR/System 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Acoustic vibrations generated by vortex shedding and flow separation from multiple tubes can be amplified by tuned resonant chambers. While the problem may manifest itself in the form of excessive noise levels, it may also lead to substantial structural damage to tubes, shrouds or thermal barrier surfaces of the heat exchanger and the primary coolant loop.

1.1 Summary of Functions/Assumptions

"Flow Primary Coolant Through Heat Exchanger", Assumption: Methods will be developed for the timely prediction of acoustic loads within the primary coolant loop.

"Receive Primary Coolant", Assumption: Shutdown cooling heat exchanger helical tube bundle/cavity will not generate excessive acoustic loads on the shrouds and thermal barrier surfaces.

"Channel Primary Coolant Through Heat Exchanger", Assumption: Shutdown cooling heat exchanger helical tube bundle/cavity will not generate excessive acoustic loads on the shrouds and thermal barrier surfaces.

"Discharge Primary Coolant", Assumption: Shutdown cooling heat exchanger helical tube bundle/cavity will not generate excessive acoustic loads on the shrouds and thermal barrier surfaces.

1.2 Current Data Base Summary

Acoustic resonance in heat exchangers is a common cause of excessive noise and failure in tube and shell heat exchangers with gas on the shell side. Acoustic resonance has occurred in chemical process heat exchangers, in heat recovery boilers, in power plants, with finned tubes, with plain tubes, in spiral tube heat exchangers, and with both inline and staggered tube arrangements. A reliable and accurate method of predicting the magnitude of the acoustic resonance is not available at this time.

In order to design against acoustic resonance, it is necessary to predict the excitation frequency for a given tube array and ensure that it does not coincide with the acoustic natural frequency of the tube shell. However, there is considerable controversy on the type of excitation mechanism against which this comparison should be made.

The only acoustic vibration test results available for a tube bundle geometry similar to the current design configuration were generated by Sulzer Brothers for FSV steam generators. The conclusions of this testing were that the various acoustic vibrations occurred at or near the frequencies calculated, and that no distinct resonances with the vortex shedding frequencies were found, this being a major advantage of helical bundles over straight tube bundles.

1.3 Data Needed

The noise source level is characterized by a spectrum of acoustical power distributed over a frequency range. A major source of noise in the GT-MHR is the turbine. Data are needed to investigate the effects of this noise on the large surface area structures of the heat exchangers, such as the flow shrouds, baffles, and thermal barriers, as a function of varying frequencies.

It is also necessary to measure the acoustical response of the heat exchanger tube bundle and cavity during simulated primary flow. Data are needed that will produce representative frequency spectra and sound pressure levels generated by the helical tube bundle as a function of flow velocities and geometry variations.

Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The critical test parameters are geometric similitude, Reynolds number and speed of sound.

The helium gas flow conditions that should be simulated are as follows:

- Temperatures from 490°C (915°F) to 1093°C (2000°F)
- Pressure range from 0.08MPa to 7.6MPa (11 to 1100 psia)
- Gap velocities up to 61 m/sec (200 ft/sec) at the entrance to the bundles.
- Reynolds Numbers up to 9000 based on bare tube hydraulic diameter.
- Speed of sound of 1396 m/sec (4580 ft/sec) to 2179 m/sec (7150ft/sec)
- Sound pressure levels up to 160 dB.

2. DESIGNER'S ALTERNATIVES

The alternatives are as follows:

2.1 Rely on analysis and avoid large resonant plates or other acoustic sensitive surfaces in the design.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach involves experimentally evaluating the geometry, flow conditions and sound levels in the helical tube bundle that could result in acoustic resonance. A model test is proposed for this purpose. The model will be designed so that the bundle geometry can be varied. The sound produced by flow through the test model as a function of bundle geometry and flow velocity will be measured. Also measured will be the response of the bundle and the cavity to the sound pressure levels generated by the turbine.

The shutdown cooling heat exchanger designs incorporate shrouds, flow baffles and/or shields which may be acoustically sensitive. Theoretical analysis by itself is not considered adequate for a complex geometry such as the helical tube bundle (Alternative 2.1) and experiments are therefore necessary to confirm the acceptability of the design.

4. SCHEDULE REQUIREMENTS

Data are needed by start of final design.

5. PRIORITY

Urgency: 2
Cost Benefit: M
Uncertainty of Existing Data: M
Importance of New Data: M

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is Alternative 2.1. The consequences of nonexecution to the program could involve design modifications after the initial startup testing of the plant. This could prove to be quite costly.

A. W. Lubkowitz 7/22/94
Originator Date

M. Basol 7/26/94
Engineering Manager Date

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Project Manager Date

DATE: 7/22/94

GT-MHR PROGRAM
SCHE INLET FLOW AND
TEMPERATURE DISTRIBUTION TEST

DDN.C.14.04.07

PLANT: GT-MHR/System 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Knowledge of the magnitude and location of hot/cold streaks and velocity distribution of the primary coolant flow entering the shutdown cooling heat exchanger tube bundle is needed. The presence of hot/cold streaks and flow maldistribution could impact the performance and structural constraints of these heat exchangers. It may be necessary to include mixing devices and/or flow distribution devices at the inlet to these heat exchanger tube bundles.

1.1 Summary of Functions/Assumptions

"Channel Primary Coolant Through Heat Exchanger," Assumptions:

Acceptable flow and temperature distribution at the entrance to the shutdown cooling heat exchanger tube bundles can be achieved.

Test data will be available for the timely prediction of flow distribution at the entrance to the shutdown cooling heat exchanger tube bundle.

"Transfer Decay Heat from Primary Coolant to Heat Exchanger," Assumptions:

The primary coolant is uniformly distributed around the cooling tubes.

The local stresses and temperatures resulting from the inlet flow and temperature distributions are acceptable.

"Transfer Decay Heat from Heat Exchanger to Secondary Coolant," Assumptions:

There is no boiling inside the tubes during steady state and transient conditions.

The local stresses and temperatures resulting from the inlet flow and temperature distributions are acceptable.

1.2 Current Data Base Summary

Analytical methods, such as flow distribution codes, and Computational Fluid Dynamics (CFD) codes are available for predicting the flow field that can be realized for a given geometric configuration and inlet conditions. Experimental data exists on the hydraulic resistance of screens and baffles. Significant flow distribution and hot streak tests along with CFD analysis has been performed by ABB Combustion Engineering on a full scale helical steam generator model (see CEGA-002840, Rev. N/C, Test Evaluation Report for Final Flow Distribution Test for NP-MHTGR Steam Generator Final Test Model, dated September, 1993, and CEGA-002710, Rev. N/C, Test Evaluation Report for Hot Streak Test for NP-MHTGR Steam Generator, dated September, 1993). Some difficulties were encountered with all CFD codes in matching the results of the tests to the code outputs. It was concluded that CFD codes alone cannot accurately predict flow and temperature distribution in such complicated geometries. Some amount of experimental work duplicating the inlet geometry is necessary.

1.3 Data Needed

The data needed to determine the flow distribution and the magnitude of hot/cold streaks are the velocity, temperature and static pressure profiles measured circumferentially and radially at various cross sections along the primary coolant flow path, including:

- The inlet to the tube bundles.
- At a cross section in the tube bundle or equivalent resistance.

In addition, the corresponding overall flow rate and ambient pressure and temperature will be needed.

Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The service conditions of interest range from Pressurized and Depressurized Cooldowns, to Hot Restart after a Conduction Cooldown.

The Hot Restart after a Conduction Cooldown service condition of interest at the tube bundle inlet is summarized below:

Environment	Helium
Temperature	1093°C (2000°F)
Pressure	7.6 MPa (1100 psia)
Reynolds Number	[TBD] (based on tube hydraulic diameter)
Mach Number	[TBD]

2. DESIGNER'S ALTERNATIVES

The alternatives are as follows:

2.1 Rely solely on analytical methods (flow distribution or CFD codes) and utilize the available experimental data on the hydraulic resistance of screens and baffles.

2.2 Utilize one or two perforated plates with a very high resistance just upstream of the tube bundles to assure that the velocity maldistribution is corrected.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected design approach is to perform the inlet flow distribution and temperature tests to determine the primary coolant velocity, temperature and static pressure profiles and the location of flow distribution devices which will yield the required radial and circumferential velocity and temperature profiles at the shutdown cooling heat exchanger tube bundle inlets.

Alternative 2.1 involves uncertainty in meeting the performance requirements and structural constraints of these heat exchangers.

Alternative 2.2 may result in unnecessarily high shellside pressure loss which in turn affects the shutdown circulator size.

It is judged that performing the tests is technically prudent to support the plant design.

4. SCHEDULE REQUIREMENTS

Final test data are needed before the start of the final design phase to remove uncertainties in the designs.

5. PRIORITY

Urgency: 1
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is Alternative 2.1; this is, rely solely on analytical methods (flow and temperature distribution codes) and utilize the available experimental data on the hydraulic resistance of helical tube bundles, and entrance and exit loss coefficients.

The consequences to the program of non-execution may involve plant design modifications and risk of customer and licensing nonacceptance. Plant operation and life could be greatly limited.

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Originator Date

M. Basol 7/26/94
Engineering Manager Date

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DATE: 7/22/94

GT-MHR PROGRAM
SCHE TUBE BUNDLE
LOCAL HEAT TRANSFER AND FLOW RESISTANCE CHARACTERISTICS

DDN.C.14.04.08

PLANT: GT-MHR/System 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Data are needed to confirm the shell- and tube-side heat transfer characteristics and shell-side flow resistance of the helical tube bundle. Shell side helium heat transfer coefficients are needed for the first few tube rows of the tube bundle and within the tube bundle. Both the average coefficient and the distribution as a function of the circumferential angle around the tube are needed. In addition, the effective flow resistance of the bare tube bundle which accounts for the variation from a square pitch to a staggered pitch is needed.

The shutdown cooling heat exchanger tube bundle sizes are sensitive to the shellside heat transfer coefficients used for bare tubes. The heat transfer coefficient and pressure drop parameters that are currently being used in the analysis of bare tube heat exchangers are based on old and outdated data, and show a large scatter. Also, the tube temperatures are sensitive to local heat transfer coefficients. Shell heat transfer coefficients can be sensitive to local variations in flow geometry and flow resistance. These individual heat transfer coefficients, or "hot spot factors" must be known in order to adequately identify the tube temperatures in the tube bundle. Adequately identifying the tube bundle flow resistances is also required to determine the tube bundle pressure drops.

1.1 Summary of Functions/Assumptions

"Transfer decay heat from primary coolant to heat exchanger." Assumptions:

A hot spot (maximum to average) factor of 1.35 is used at the entrance to the tube bundles for the helium heat transfer coefficient. This value is based on test data which was obtained for the Fort St. Vrain steam generator. Data reported in the literature indicates cases where this factor was higher.

The helium heat transfer coefficient which has been used for the tube bundle entrance regions is the average bundle helium heat transfer coefficient. The helium heat transfer coefficient at the entrance to the tube bundles can be as low as 64% of the average bundle helium heat transfer coefficient.

The shellside heat transfer and pressure drop for the bare tube helical bundles are based on the Grimison Study for combined staggered and inline tube bundles.

1.2 Current Data Base Summary

Analysis in the open literature and limited test data, e.g., Fort St. Vrain (Efferding, L.E, et al," PSC Steam Generator Sizing and Performance", GADR-110, July, 1971), and Grimison Study ("Correlation and Utilization of New Data on Flow Resistance and Heat Transfer for Cross Flow and Gases Over Tube Banks", E. D.Grimison, ASME Transaction, Proceeding 59-8, 1937).

1.3 Data Needed

1.3.1 Heat transfer coefficient circumferential variation around the outside of a bare tube at the entrance region of a helical tube bundle.

1.3.2 Average heat transfer coefficients on the outside of the bare tubes for the entrance region of a helical tube bundle.

1.3.3 Tube bundle friction factors for bare tube bundles with a variation from a square pitch to a staggered pitch.

Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The service conditions of interest are:

Fluid	Helium
Pressure	0.08 to 7.6 MPa (11-1100 psia)
Temperature	490 to 850°C (915-1562°F)
Reynolds Number	Up to 9,000 (Based on tube hydraulic diameter)
Tube OD (at the base of fins)	22.2 mm (0.875 inch)
Transverse Tube Pitch	38.1 mm (1.5 inch)
Longitudinal Tube Pitch	36.4 mm (1.434 inch nominal)

2. DESIGNER'S ALTERNATIVES

The alternative is to rely solely on analytical methods utilizing the available experimental data.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected design approach is to perform the heat transfer and flow resistance test utilizing full-scale and sector models to yield the required data.

It is judged that performing the test will minimize conservatism to support the plant design.

4. SCHEDULE REQUIREMENTS

Test results are needed by the end of preliminary design.

5. PRIORITY

Urgency: 1
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

Excessive margin may be required in order to meet performance requirements.

A. W. Lubkowitz 7/22/94
Originator Date

M. Basol 7/26/94
Engineering Manager Date

for SAC 7/28/94
Project Manager Date

DATE: 7/22/94

GT-MHR PROGRAM
SCHE TUBE HELICAL COIL PROGRAM

DDN.C.14.04.09

PLANT: GT-MHR/System 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Determine the feasibility of coiling and threading multiple bare tubes in concentric coils through holes in full and partial support plates (drilled or scalloped). Concerns are: ease of coiling and threading, clearances between tube and plate; wear protection device installation; tolerances; and fabrication time.

1.1 Summary of Functions/Assumptions

"Support Heat Transfer Surfaces", Assumption: The method of manufacturing of a helical coil tube bundle with drilled radial tube support plates will be verified. Alternatively, manufacturing with scalloped bar support concept will be verified.

1.2 Current Data Base Summary

Several full-scale fabrication tests and production bundles have demonstrated the coiling and threading of bare tubes through similar support structures. However, the assembly has been demonstrated on bare tube bundles of smaller diameters, with fewer number of coils, shorter tube lengths, and fewer number of tubes than for the shutdown cooling heat exchanger. The differences in these parameters, in addition to the differences in the details of the support structure and the shroud structure, create a concern over the applicability of the current data base to the shutdown cooling heat exchanger design. Aside from the differences, the data base will provide useful information in defining a test program.

1.3 Data Needed

The data needed from the performance of this test are to demonstrate the fabrication of a large bare tube helical bundle, and to provide input for fabrication procedures and sequence.

Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

Data parameters needed from the test shall include:

1.4.1 Detailed fabrication procedures for handling, coiling, and threading tubes (i.e., quantity and placement of support points, bending rate, thread-in forces, etc.).

1.4.2 Types and designs of tooling required for performing operations (i.e., tube support tools, tube wear protection device upsetting tool, thread-in tools, etc.).

1.4.3 Tolerances (tube forming, support plate holes, etc.).

1.4.4 Fabrication time (broken down for each operation).

2. DESIGNER'S ALTERNATIVES

The alternatives are as follows:

2.1 Extrapolate data base parameters and information to current design.

2.2 Arbitrarily increase fabrication time to allow for unknowns and potential problem areas.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach involves coiling and threading a number of selected bare tubes into a full-scale, drilled plate support structure. Tubes will be selected to fully represent the spectrum of coiling and threading possibilities.

This selection is based upon utilization of the helical bundle supported by solid, drilled plates. The helical bundle is the most compact heat exchanger design for this application and the solid, drilled plate support system appears to best satisfy the requirements of thermal expansion and seismic load paths. Adaptation of the data base poses questions of applicability because of the many differences in bundle parameters. Arbitrarily increasing the fabrication schedule to allow for unknowns and learning would directly and adversely affect the cost as well as the "real" schedule.

4. SCHEDULE REQUIREMENTS

Data are needed prior to the start of the shutdown cooling heat exchanger fabrication.

5. PRIORITY

Urgency: 2
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position should only consider an extrapolation and adaptation of the current data base or arbitrarily increasing the fabrication span.

[DDN.C.14.04.09]

The consequences of nonexecution of this test will leave a concern of the fabrication procedures for a large helical tube coil bundle. Proceeding with the current design but without fabrication testing would likely result in increased costs and increased fabrication schedule.

A. W. Lubkowitz 7/22/94
Originator Date

M. Bowal 7/26/94
Engineering Manager Date

for SAC 7/25/94
Project Manager Date

DATE: 7/22/94

GT-MHR PROGRAM
SCHE LEAD-IN/LEAD-OUT/EXPANSION LOOP TUBE DESIGN AND FABRICATION

DDN.C.14.04.10

PLANT: GT-MHR/System 14

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

For those portions of each tube circuit not included in the helical bundle, data are needed to develop: spatial envelope; support configurations; thermal movement characteristics including as-installed and operating clearances; and assembly sequence.

1.1 Summary of Functions/Assumptions

"Channel Secondary Coolant Through Heat Exchanger", Assumptions:
Space allocated for the lead-in, lead-out and expansion tubes is sufficient.

Methods will be available to accurately predict support locations in the expansion loop in order to provide adequate thermal expansion accommodation.

Methods will be available to adequately predict the support locations in the lead-out tubes and corresponding conduits, and expansion loop so that adequate tube-to-tube clearances could be provided, and multiple tube interaction and wear could be avoided.

Methods will be available to accurately predict support locations in the lead-out tubes inside corresponding conduits, and expansion loop in order to prevent tube binding.

1.2 Current Data Base Summary

Previous experience with similar designs (FSV, THTR) gives some information on spatial requirements for assembly, welding, means of support and wear protection. The information is very configuration dependent and generally not generic.

1.3 Data Needed

For the specific configuration of the GT-MHR shutdown cooling heat exchanger, development of specific routing and support configurations is needed to confirm the adequacy of the spatial envelope and structural design. Testing via a mock-up of the non-helical portions of the tube bundle is needed to determine: Spatial envelope, characteristic thermal movements and interactions of tubes and supports, and the adequacy of clearances to avoid multiple tube interactions.

Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

Test data required are:

- Overall spatial requirements for assembly.
- Tube-to-tube dimensional relationship when subjected to deflections representative of thermal movements.
- Photographic documentation of assembly sequence(s) for the non-helical tubes.

2. DESIGNER'S ALTERNATIVES

The alternatives are as follows:

2.1 Do not perform mock-up test. Rely on design layout work and analysis including CAD and ANSYS (finite element) modeling as well as available FSV, THTR background.

2.2 Use less than prototypical (e.g., small scale plastic models) to partially satisfy data needs, i.e., spatial envelope and assembly sequence.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to perform a near full scale metallic mock-up of the non-helical portions of the tube bundles based on design layouts and analysis to be performed in preliminary design. Test results will be an integral part of the completion of preliminary design and will confirm adequacy of spatial envelope and structural design as inputs to PSSAR.

Alternative 2.1 represents risk of later changes to spatial envelope and consequent impacts on overall Nuclear Island design. The design configuration differs significantly enough in layout and size (number of tubes, tube size, finned tubes) from FSV and THTR that direct application of experience is questionable.

Alternative 2.2 will partially address the uncertainties of spatial envelope and assembly sequence, but will have limited value for determining structural adequacy.

4. SCHEDULE REQUIREMENTS

The results are needed prior to the fabrication of the shutdown cooling heat exchanger.

5. PRIORITY

Urgency: 2
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback positions are Alternatives 2.1 and 2.2. Either alternative may lead to design schedule delays and design changes, and higher cost design/analysis iterations to arrive at a defensible final design.

A. W. Lubkowitz 7/22/94
Originator Date

M. Basol 7/26/94
Engineering Manager Date

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Project Manager Date

[DDN C.16.00.01]

DATE: 6/30/94

GT-MHR PROGRAM
EMISSIVITY OF RCCS PANEL SURFACES
DDN C.16.00.01

PLANT: GT-MHR/System 16

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The cooling panel emissivity is a key parameter with respect to RCCS decay heat removal. A predictable and reasonably uniform emissivity is necessary to support the safety analysis.

1.1 Summary of Function and Assumptions

"Absorb Radiant Heat from Vessel Wall," "Transfer Heat to Coolant," Assumption: RCCS panel surface emissivity equal to 0.8.

1.2 Current Data Base Summary

Cooling panel emissivity is a key parameter with respect to decay heat removal. Adequate emissivity data is not available for candidate panel materials for the service conditions identified.

1.3 Data Needed

The following data are needed to validate the applicability of the existing analytical models:

a. The mean and variation of emissivity from one piece to the next.

b. Variation of emissivity over a large surface.

c. Sensitivity of emissivity to various factors including manufacturing processes, operating service conditions, and aging.

Quality Assurance must be in accordance with requirements for experimental data or validation testing which is safety related.

1.4 Data Parameters and Service Conditions

The above data must be valid for the following service conditions:

Service Life	40 years
Service Temperatures:	
Shutdown	-45 to 110°F
Maximum accident	Approx. 430°F
Nominal operation	220°F maximum
(70°F ambient air)	180°F average
Relative humidity	0 to 100%

2. DESIGNER'S ALTERNATIVES

The following alternatives were considered:

2.1 Use conservative values (based on available data) for safety analysis.

2.2 Perform the proposed tests (selected).

3. SELECTED DESIGN APPROACH AND EXPLANATION

Testing for emissivity is necessary to validate the values used in the thermal analysis models. An improved understanding of actors affecting emissivity will allow further optimization with respect to emissivity. Optimization of emissivity is desirable because the effectiveness of decay heat removal to the RCCS influences the core power rating and/or vessel and internals performance requirements.

4. SCHEDULE REQUIREMENTS

The data is required by month [TBD] one year prior to final design.

5. PRIORITY

Urgency: 2
Benefit/cost: H
Uncertainty in existing data: M
Importance of New Data: M

[DDN C.16.00.01]

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

Use conservative emissivity values for safety analyses. This would result in conservative limits on core power or vessel and internals design temperatures.

[signature] 7/21/94

Originator Date

[signature] 7/21/94

Task Manager Date

Program Manager Date

DATE: 6/30/94

GT-MHR PROGRAM
WIND TUNNEL TEST OF SCALE MODEL RCCS I/O STRUCTURE
DDN C.16.00.02

PLANT: GT-MHR/System 16

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

1.1 Summary of Function and Assumptions

"Transport Heat to Ultimate Heat Sink," "Maintain Flow Path," Circulate Coolant,"
Assumption: Coolant flow path to be designed for natural circulation.

1.2 Current Data Base Summary

The design of the RCCS inlet/outlet structure is unique to the GT-MHR. No experimental data on wind effects exists for this configuration.

1.3 Data Needed

The following data are needed to validate the applicability of the existing analytical models:

Pressure profiles inside and in the vicinity of the inlet/outlet structures for:

a. Various locations of the I/O structure along the length of the nuclear island.

b. Various wind directions and velocities.

Quality Assurance must be in accordance with requirements for experimental data or validation testing which is safety related.

1.4 Data Parameters and Service Conditions

The above data must be valid for the following service conditions:

Maximum wind speed	110 mph at a height of 33 ft above grade	
Elevation	Sea level to 6000 ft	
Air temperature	110°F to -45°F	Dry bulb
	82°F (max.)	Wet bulb

[DDN C.16.00.02]

2. DESIGNER'S ALTERNATIVES

The following alternatives were considered:

2.1 Full scale testing on the first plant.

2.2 Scale model testing in the wind tunnel (selected).

3. SELECTED DESIGN APPROACH AND EXPLANATION

Task would involve scale model wind tunnel testing of the inlet/outlet structure.

Design optimization using scale model will be less costly. Scale model testing will allow earlier design verification and as a result will aid the licensing process.

4. SCHEDULE REQUIREMENTS

The data is required by month [TBD] one year prior to final design.

5. PRIORITY

Urgency: 2
Benefit/cost: H
Uncertainty in existing data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

Full-scale testing of as-built structure using available wind conditions. Potential delays in licensing and startup due to testing, wind conditions, and/or design modifications (if needed).

[signature] 7/21/94
Originator Date

[signature] 7/21/94
Task Manager Date

Program Manager Date

DATE: 6/30/94

GT-MHR PROGRAM
INTEGRATED RCCS PERFORMANCE
DDN C.16.00.03

PLANT: GT-MHR/System 16

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Pressurized and depressurized conduction cooldown of the reactor core provides a passive method for removing decay heat if both the main loop and shutdown cooling system fail. The GT-MHR's low core power density coupled with the thermodynamic properties of an annular graphite core provides a passive means for heat removal. Decay heat is removed by conduction from the fuel rods to the graphite blocks and then by natural convection, conduction, and radiative heat transfer to the graphite reflectors. heat transfer from the reflectors through the core barrel and reactor vessel ultimately transfers heat through the uninsulated vessel to the reactor silo and the RCCS panels. Unless effective heat transfer and heat removal takes place, allowable reactor core, reactor internal component, and reactor vessel temperatures cannot be assured.

1.1 Summary of Function and Assumptions

"Maintain Plant Protection," Assumption: Data are available to adequately assess forced outages and investment risk.

"Protect the Capability to Maintain Energy Transfer," Assumption: Methods will be available for the timely prediction of NSSS component behavior during loss of main and shutdown cooling loops.

"Maintain Alternate Cooling," Assumption: Validated methods and data are available for the prediction of fuel, core reactor internals, and reactor vessel temperatures.

1.2 Current Data Base Summary

The heat transport from the core to the vessel and finally to the RCCS for pressurized and depressurized conduction cooldown is calculated with the SINDA computer code. SINDA is used extensively in the aerospace industry and has been tested against a series of benchmark problems as well as numerical solutions published in the literature. Validation of heat transport modeling and calculations of component temperatures have not been performed for the regimes of interest in conduction cooldowns. No experimental data on the heat transport process from the annular core to the vessel and then to the RCCS exists.

[DDN.C.16.00.03]

1.3 Data Needed

Data are needed to validate the prediction of plant response during conduction cooldown events. Key parameters which must be calculated by conduction cooldown methods are primary coolant pressure and fuel, upper plenum shroud, control rods, core barrel, reactor vessel temperatures. The conduction cooldown methods will model the thermal-hydraulic phenomena necessary to predict the key parameters listed above. The data required will specifically support the validation of these phenomena in the methods. Data must be experimentally obtained where adequate data do not currently exist in the literature.

The phenomena of interest include:

- Combined radiation and conduction within the graphite core,
- Natural convection and circulation within the primary coolant loop,
- Combined convection and radiation between the core and reactor vessel.
- Combined radiation and natural convection in the reactor cavity between the reactor vessel.

Quality assurance must be in accordance with the requirements for experimental data or validation testing for safety related components.

1.4 Data Parameters and Service Conditions

The data are required to validate the conduction cooldown methods under the following service conditions:

Reactor configuration	Annular reactor core with prismatic graphite fuel blocks and reflector blocks, control rods, core barrel, core support plate, reactor vessel and cross duct, cooling system primary loop components.
Reactor coolant	Helium
Reactor conditions	a. Conduction cooldown; Pressurized: 7.07 MPa (1025 psig); Depressurized: near atmospheric b. Time dependent decay heat power levels
Fuel temperature	1600°C (2912°F) maximum 1093°C (2000°F) average
Fuel block irradiation	Up to 4.5 x 10^{25} n/m^2 exposure (E > 29 fJ)
Irradiation temperature	Up to 1205°C (2200°F)
Conduction cooldown	Up to ~500 h time period

2. DESIGNER'S ALTERNATIVES

The following alternative may be considered in lieu of the selected approach in Section 3:

2.1 Predict the thermal data with present methods derived from fundamental materials properties and accept the uncertainties in the predictions. Compare analytical results with other independent analytical methods.Design affected components conservatively as needed by selecting more temperature resistant materials and/or reduce the module power output, thereby reducing the probability of component damage.

3. SELECTED DESIGN APPROACH AND EXPLANATION

Carry out tests necessary to reduce uncertainties and eliminate unnecessary design conservatism. Data may be obtained at required service conditions from either (1) an integrated test on a simulated nonnuclear scale model (scale = TBD) of the GT-MHR reactor, or (2) separate tests on component/phenomena models. Either approach can provide realistic heat transfer parameters associated with the conduction cooldown event. The separate effects test approach complimented by comprehensive startup testing, however, may prove to be more conducive to resolving specific phenomenological uncertainties required for code validation. Compared to the alternative design approach in Section 2.1, code validation with test data can remove excess conservatism in the design since the uncertainties in the analysis are reduced.

Scale of model(s) and total projected test program costs established following preparation of test specifications.

4. SCHEDULE REQUIREMENTS

These data are required before the end of the first year of Final Design in order to permit the validation of methods to be used for completion of Final Design.

5. PRIORITY

Urgency: 1
Cost benefit: H
Uncertainty in existing data: M
Importance of new data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

If the selected task is not performed, the fallback position is alternative 2.1 which relies on existing analytical models and conservative design measures to assure adequate design margins. This could require more temperature resistant materials for the reactor vessel, control rods, and reactor internal components or result in a reduced core output. Consequently, plant costs could increase and schedule delays could occur due to material development needs.

7/27/94

Originator Date

7/25/94

Task Manager Date

Program Manager Date

DATE: 6/30/94

GT-MHR PROGRAM
RCCS COOLING PANEL HEAT TRANSFER COEFFICIENT AND FRICTION FACTOR
DDN C.16.00.04

PLANT: GT-MHR/System 16

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The cooling panel heat transfer coefficient and friction factor are important parameters with respect to RCCS heat removal. Predictable data over the expected range of operating conditions is necessary to support the safety analysis.

1.1 Summary of Function and Assumptions

"Transfer Heat to Coolant," "Transport Heat to Ultimate Heat Sink," Assumption: Heat transfer from panel to air assumed to be mixed convection.

1.2 Current Data Base Summary

Heat transfer coefficient and friction factor of the RCCS cooling panel hot risers are important parameters for heat removal from the reactor cavity. Adequate and reliable heat transfer and friction factor data for the specific hot riser geometry and service condition is not available.

1.3 Data Needed

The heat transfer and friction factor data is needed (for geometrically similar riser tubes) over the following conditions to validate the analytical models:

a. Effect of heated tube at different temperatures and heat fluxes.

b. Effect of Reynolds number.

c. Effect of riser internal surface conditions.

d. Effect of entry region condition.

1.4 Data Parameters and Service Conditions

The above data must be valid for the following service conditions:

Riser surface temperature	150 to 450°F
Riser surface heat flux:	
Maximum accident	10 kW/ft^2
100% power operation	3 kW/ft^2
Low power operation	0.5 kW/ft^2
Reynolds number:	
Maximum accident	$\sim 10^5$
100% power operation	10^4 to 10^5
Low power operation	10^3 to 10^4

2. DESIGNER'S ALTERNATIVES

The following alternatives were considered:

2.1 Use conservative values (based on available data) for safety analysis.

2.2 Perform the proposed tests (selected).

3. SELECTED DESIGN APPROACH AND EXPLANATION

Testing is necessary to validate the values used in the thermal analysis models. An improved understanding of factors affecting heat transfer coefficient and friction factor will allow further optimization with respect to these parameters. Optimization is desirable because the effectiveness of decay heat removal to the RCCS influences the core power rating and/or vessel and internals performance requirements.

4. SCHEDULE REQUIREMENTS

This data is required by month [TBD] one year prior to final design.

5. PRIORITY

Urgency: 2
Cost benefit: M
Uncertainty in existing data: M
Importance of new data: M

[DDN.C.16.00.04]

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

Use conservative heat transfer coefficient and friction factor values for safety analyses. This would result in conservative limits on core power or vessel and internals design temperatures.

[signature]	7/21/94
Originator	Date
[signature]	7/21/94
Task Manager	Date
Program Manager	Date

[DDN C.16.00.05]

DATE: 6/30/94

GT-MHR PROGRAM
EFFECTIVE CONDUCTIVITY OF CORE BLOCKS
DDN C.16.00.05

PLANT: GT-MHR/SYSTEM 16

[LATER]

[DDN C.16.00.06]

DATE: 6/30/94

GT-MHR PROGRAM
BUOYANCY INDUCED FLUID MIXING IN A HIGH ASPECT RATIO CAVITY
DDN C.16.00.06

PLANT: GT-MHR/SYSTEM 16

[LATER]

[DDN C.21.01.01]

DATE: 6/30/94

GT-MHR PROGRAM
FUEL HANDLING MACHINE (FHM)/HANDLING MECHANISM DESIGN VERIFICATION
DDN C.21.01.01

PLANT: GT-MHR/System 21

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The fuel handling machine (and its components) must be highly reliable in order to perform the fuel handling sequences in the scheduled time. Related DDN C.21.01.05.

1.1 Summary of Function and Assumptions

"Fuel Handling," Assumption: Operability and reliability of the fuel handling mechanisms are sufficient to meet availability requirements for the plant. Individual mechanisms must meet individual reliability goals, and overall system must meet its reliability goal.

1.2 Current Data Base Summary

The FHM conceptual design is based on the refueling equipment at Fort St. Vrain and the various large HTGR designs developed over the past 20 years. The FHM mechanisms differ from the Fort St. Vrain assembly as follows:

- Shorter grapple probe.
- Electrically controlled grapple mechanisms rather than pneumatic.
- Electrically controlled grapple head rotation mechanism rather than pneumatic.
- Handling mechanism linkage radial displacement increased.
- Viewing system and electronic control system revised to incorporate current technology.
- Telescoping tube guide sleeve is transported and inserted by the FHM rather than the Auxiliary Service Cask (ASC).
- Vertical travel requirement is greater in order to operate in a deeper core.

Years of experience with the FSV FHM have demonstrated reliable features of the design and some which could be improved. The differences listed here are proposed as improvements, but must be tested to verify that they are as good as or better than the FSV FHM.

1.3 Data Needed

Data are needed for the FHM on functional and performance limits in anticipated operating modes in order to establish the operability and reliability of components under expected environmental conditions (see Section 1.4). Quality assurance must be in accordance with the requirements for experimental data or validation testing per nonsafety-related components.

1.4 Data Parameters and Service Conditions

Service conditions of interest are given below:

Internal atmosphere	Helium
Pressure	14.7 psia
Helium inlet gas temperature	250°F (shutdown)
Hoist speed range	2 to 24 in./s

2. DESIGNER'S ALTERNATIVES

The following alternatives have been considered:

2.1 Test the equipment at the site during preoperational checkout.

2.2 Test the equipment during system integration test.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The test will be done in 3 phases. Phase 1 will be an automated checkout of the grapple head. Phase 2 will be an automated checkout of all element transfer mechanisms operating over a full core sector. Phase 3 will be an automated cycle test in 250°F helium with element transfer cycles equivalent to 25 refuelling outages.

A full scale test rig and test article will be used to obtain early reliability (life) data for the machine and its subcomponents. This will provide an opportunity to correct deficiencies so that the assembly will function satisfactorily in all operating modes during the system qualification test. Alternatives 2.1 and 2.2 carry substantial risk of schedule delay because of the discovery of problems late in the schedule. The selected approach reduces the potential for schedule delay because the problems are identified earlier and, therefore, can be fixed earlier.

[DDN C.21.01.01]

4. SCHEDULE REQUIREMENTS

Phase 1, month [TBD] after start of final design through [TBD].
Phase 2, month [TBD] after start of final design through [TBD].
Phase 3, month [TBD] after start of final design through [TBD].

5. PRIORITY

Urgency: 2
Cost benefit: H
Uncertainty in existing data: M
Importance of new data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is Alternative 2.2. Nonexecution of the preferred approach would lead to total dependence on Alternative 2.2, and failure at that time would most certainly lead to schedule delays while the problems were investigated and corrected.

[signature] 7-27-94
Originator Date

[signature] 7/28/94
Task Manager Date

Program Manager Date

DATE: 6/30/94

GT-MHR PROGRAM
FUEL TRANSFER CASK COMPONENT DESIGN VERIFICATION
DDN C.21.01.02

PLANT: GT-MHR/System 21

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The fuel transfer cask (and its components) must be highly reliable in order to perform the fuel handling sequences in the scheduled time. Related DDN C.21.01.05.

1.1 Summary of Function and Assumptions

"Fuel Handling," Assumption: Operability and reliability of the fuel handling mechanisms are sufficient to meet availability requirements for the plant. Individual mechanisms must meet individual reliability goals, and overall system must meet its reliability goal.

1.2 Current Data Base Summary

The fuel transfer cask is an entirely new machine for which there are no data even though the design is similar to the cask design developed for earlier HTGRs.

1.3 Data Needed

There are several mechanisms within the fuel transfer cask which must be evaluated under the conditions of Section 1.4. These include the vertical drive system for the hoist grapple, horizontal transfer table drive, and the complete grapple system which operate in a helium environment. The automated hold-down system and remote services connections also require evaluation.

Data are needed on functional and performance limits in anticipated operating modes in order to establish the operability and reliability of components under expected environmental conditions.

Quality assurance must be in accordance with the requirements for experimental data on validation testing per non safety-related components.

1.4 Data Parameters and Service Conditions

Service conditions of interest are given below:

Internal atmosphere	Helium
Pressure	14.7 psia
Helium inlet gas temperature	250°F (shutdown)
Hoist speed range	2 to 24 in./s

2. DESIGNER'S ALTERNATIVES

The following alternatives have been considered:

2.1 Test the equipment at the site during preoperational checkout.

2.2 Test the equipment during system integration test.

3. SELECTED DESIGN APPROACH AND EXPLANATION

A full-scale test rig and test article will be used to obtain early reliability (life) data for the machine and its subcomponents and will be tested in air (Test Phase 1) and helium (Test Phase 2). Helium testing will include the handling cycle equivalent of 25 refuelling outages. This will provide an opportunity to correct deficiencies so that the assembly will function satisfactorily in all operating modes during the system qualification test. Alternatives 2.1 and 2.2 carry substantial risk of schedule delay because of the discovery of problems late in the schedule. The selected approach reduces the potential for schedule delay because the problems are identified earlier and, therefore, can be fixed earlier.

Test Phase 3 is a separate cyclic test of the automated hold-downs and remote connections.

4. SCHEDULE REQUIREMENTS

Testing to be completed by month [TBD], six months prior to the start of the integrated system test DDN C.21.01.05.

5. PRIORITY

Urgency: 2
Cost benefit: H
Uncertainty in existing data: M
Importance of new data: H

[DDN C.21.01.02]

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The preferred fallback position is Alternative 2.2. Nonexecution of the preferred approach would lead to total dependence on Alternative 2.2 and failure at that time would most certainly lead to schedule delays while the problems were investigated and corrected.

Originator 7-27-94 Date

Task Manager 7/28/94 Date

Program Manager Date

DATE: 6/30/94

GT-MHR PROGRAM
ELEMENT HOIST AND GRAPPLE ASSEMBLY ROBOT DESIGN VERIFICATION
DDN C.21.01.03

PLANT: GT-MHR/System 21

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The element hoist and grapple assembly (EHGA) and its components must be highly reliable in order to perform the refueling sequences in the scheduled time. Related DDN C.21.01.05.

1.1 Summary of Function and Assumptions

"Fuel Handling," Assumption: Operability and reliability of the fuel handling mechanisms are sufficient to meet availability requirements for the plant. Individual mechanisms must meet individual reliability goals, and overall system must meet its reliability goal.

1.2 Current Data Base Summary

The EHGA is an entirely new machine for which there are no data even though some components are similar to the mechanisms developed for earlier HTGRs.

1.3 Data Needed

Data are needed to verify the EHGA design under the conditions in Section 1.4.

There are several mechanisms which must be evaluated including the vertical drive system for the grapples, two independent grapple systems, and the positioning capability of the overhead crane.

Data are needed on functional and performance limits in anticipated operating modes in order to establish the operability and reliability of components under expected environmental conditions.

Quality assurance must be in accordance with the requirements for experimental data or validation testing per non safety-related components.

1.4 Data Parameters and Service Conditions

Service conditions of interest are given below:

Internal atmosphere	Helium/air
Pressure	14.7 psia
Temperature	Ambient

2. DESIGNER'S ALTERNATIVES

The following alternatives have been considered:

2.1 Test the equipment at the site during preoperational checkout.

2.2 Test the equipment during system integration test.

3. SELECTED DESIGN APPROACH AND EXPLANATION

A full-scale test rig and test article will be used to obtain early reliability (life) data for the machine and its subcomponents. This will provide an opportunity to correct deficiencies so that the assembly will function satisfactorily in all operating modes during the system qualification test. Alternatives 2.1 and 2.2 carry substantial risk of schedule delay because of the discovery of problems late in the schedule. The selected approach reduces the potential for schedule delay because the problems are identified earlier and, therefore, can be fixed earlier.

Testing will be ambient air and simulate cyclic operation equivalent to 25 refuelling outages.

4. SCHEDULE REQUIREMENTS

Testing to start by month [TBD] after start of final design and complete by month [TBD].

5. PRIORITY

Urgency: 1
Cost benefit: H
Uncertainty in existing data: M
Importance of new data: H

[DDN C.21.01.03]

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The preferred fallback position is Alternative 2.2. Nonexecution of the preferred approach would lead to total dependence on Alternative 2.2 and failure at that time would most certainly lead to schedule delays while the problems were investigated and corrected.

7-27-94

Originator Date

7/28/94

Task Manager Date

Program Manager Date

[DDN C.21.01.04]

DATE: 6/30/94

GT-MHR PROGRAM
VERIFY FUEL HANDLING SYSTEM INSTRUMENTATION AND CONTROLS
DDN C.21.01.04

PLANT: GT-MHR/System 21

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The Fuel Handling Control System requires rapid and positive identification and manipulation of elements during remote fuel handling. The purpose of this DDN is to determine performance characteristics of the control system components and ensure control system compatibility with the fuel handling mechanisms. Related DDN C.21.01.05.

1.1 Summary of Function and Assumptions

"Fuel Handling," Assumption: Operability and reliability of fuel handling mechanisms are sufficient to meet the availability requirement for the plant. Individual mechanisms meet individual reliability goals, and overall system meets its reliability goal.

1.2 Current Data Base Summary

The current data base is Fort St. Vrain experience, large HTGR designs and industrial applications for computer controlled equipment. Recent experience includes a major up grade of the FSV fuel handling control system. Warm helium environment imposes special requirements on lubricants, electrical insulation, seals and TV systems.

1.3 Data Needed

The data needed for the Fuel Handling Control System is the following:

a. Performance of instrumentation and control components including limiting values for factors (element motion, direction, velocity, size of identification marking, temperature) which cause failures in serial number identification under conditions of Section 1.4.

b. Demonstration that the Fuel Handling Control System, including software, meets its design requirements and is compatible with the fuel handling mechanism.

Quality Assurance must be in accordance with experimental data or validation testing per non safety-related components.

1.4 Data Parameters and Service Conditions

Service conditions of interest are given below:

Console and Electronics Cabinets

Atmosphere	Air
Temperature	Room temperature air
Pressure	Atmospheric
Relative humidity	10-90% for air

In-Reactor Components

Atmosphere	Helium
Temperature	[250°F]
Pressure	Atmosphere

2. DESIGNER'S ALTERNATIVE

2.1 Verify performance of computer control software and instruments only during assembly/checkout of Fuel Handling Control Station.

2.2 Verify performance of the Fuel Handling Control Station only during development and systems integration tests (DDNs C.21.01.01 through C.21.01.03).

3. SELECTED DESIGN APPROACH AND EXPLANATION

Phase 1 testing will qualify element identification components in air. Phase 2 testing will qualify electronic instrumentation, viewing systems, etc. for operation in helium.

It is recommended that the performance and environmental compatibility of control components and control systems be verified to firm up design prior to the overall system development and verification. Early confirmation of performance and compatibility of control software and instruments is needed to support the design of machines and of the control system to reduce potential delays in performing the mechanical equipment development and system integration tests (2.2) (DDNs C.21.01.01, C.21.01.02, C.21.01.05, and C.21.01.03).

4. SCHEDULE REQUIREMENTS

Phase 1 will start month [TBD] after start of final design and complete by month [TBD].

Phase 2 will start month [TBD] after start of final design and complete by month [TBD].

[DDN C.21.01.04]

5. PRIORITY

Urgency: 2
Cost benefit: H
Uncertainty in existing data: H
Importance of new data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is to verify performance of the instrumentation components subsystems of computer control and instruments during the development and system integration tests. If prior verification is not performed, some schedule delay and probable control system redesign during performance and integrated system tests may be experienced (DDNs C.21.01.01 through C.21.01.03).

7-27-94

Originator Date

7/28/94

Task Manager Date

Program Manager Date

[DDN C.21.01.05]

DATE: 6/30/94

GT-MHR PROGRAM
INTEGRATED FUEL HANDLING SYSTEM TEST DATA
DDN C.21.01.05

PLANT: GT-MHR/System 21

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The fuel handling system must be highly reliable in order to perform the operational sequences in the scheduled time.

1.1 Summary of Function and Assumptions

"Fuel Handling," Assumption: Operability and reliability of the fuel handling mechanisms are sufficient to meet availability requirements for the plant. Individual mechanisms must meet individual reliability goals, and overall system meets its reliability goal.

1.2 Current Data Base Summary

The conceptual design of the fuel handling equipment is based upon the fuel handling equipment at Fort St. Vrain and the designs of various large HTGR plants over the past 20 years. However, because of increased automation and larger number of machines involved, there are no data to confirm the adequacy of the control system in integrating the combined operations of the individual machines.

1.3 Data Needed

Operability and reliability data for the components of the fuel handling system when they are operating together are needed under the conditions of Section 1.4. This includes verification of physical compatibility, alignment requirements, tolerances, and coordination by the control system. Human factors data on the control station are also needed.

Quality assurance must be in accordance with the requirements for experimental data or validation testing per non safety-related components for the integral fuel handling mechanism testing.

1.4 Data Parameters and Service Conditions

Service conditions of interest are given below:

Internal atmosphere	Helium
Pressure	14.7 psia
Helium inlet gas temperature	250°F (shutdown)

2. DESIGNER'S ALTERNATIVES

The following alternatives have been considered:

2.1 Test fuel handling equipment and control station at the site during preoperational checkout.

2.2 Rely on analysis to determine time and motion required for refueling outages.

3. SELECTED DESIGN APPROACH AND EXPLANATION

Full-scale fuel handling and control equipment will be tested with simulated fuel elements. The fuel handling machine and fuel transfer cask will be mounted on a full-scale equipment support structure and the upper plenum and the first two layers of the core will be simulated using the control system automation. Full-scale equipment positioner, casks, and floor valves will be utilized to test the integrated system. Two full refueling sequences should be simulated to assure the dependability and reliability of the system.

The complexity of the components and system operation/control require that problems be identified sufficiently early in the schedule to allow time for correction. Alternative 2.1 and 2.2 does not leave adequate time for the solution of problems which may arise without significant schedule impact.

4. SCHEDULE REQUIREMENTS

Completion of integrated system testing is required by month [TBD], to support site assembly, checkout, and preoperational testing prior to loading fuel into reactor module 1. The testing is planned to start month [TBD] after start of final design. Transfer of the defueling operational data from Fort St. Vrain is required by month [TBD] prior to final design.

5. PRIORITY

Urgency: 1
Cost benefit: H
Uncertainty in existing data: M
Importance of new data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is Alternative 2.1 for the system equipment testing. Nonexecution of the preferred approach would increase the risk of a delay in demonstrating acceptability of the fuel handling system and consequential delay in operation of the plant.

Alternative 2.2 relies on analysis only, without backup data.

7-27-94

Originator Date

7/28/94

Task Manager Date

Program Manager Date

[DDN C.21.01.06]

DATE: 6/30/94

GT-MHR PROGRAM
FUEL HANDLING EQUIPMENT POSITIONER DESIGN VERIFICATION
DDN C.21.01.06

PLANT: GT-MHR/SYSTEM 21

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The Fuel Handling Equipment Positioner Machine (FHEP) must accurately retrieve, transport and place large, heavy machines and structures. The reliability and positioning accuracy of the machine must be proven, under expected load conditions, prior to use in integrated operations.

1.1 Summary of Function and Assumptions

"Fuel Handling," Assumption: The reliability of the motion control system and the effect of machine deflections under load and no-load conditions are adequate to manipulate and position the Fuel Handling Equipment (i.e. FHM, FTC, FTCA, RIV, FHESS, ASC) at the required speed and accuracy.

1.2 Current Data Base Summary

This is a first of a kind machine in size and function. No performance data for the required design exists. However, bridge robots and cranes, drives and controls of similar scale and capacity have, separately, been designed and built.

1.3 Data Needed

The data needed on the FHEP are position certainty of the control axes under expected static and dynamic load conditions (see Section 1.4). The design of interfaces between the FHESS and the Reactor, the FHESS and the FHM, FTC, ASC, FTCA, RIV, and handling equipment to the equipment positioner will determine the degree of precision that the four positioning axes of the positioner must produce.

The four axis acceleration and velocity capabilities under load conditions is to be measured. The point to point positioning time for each axis and load condition is to be measured. This data is to be compared to the system simulation model to validate process speed/performance predictions.

Quality assurance must be in accordance with the requirements for experimental data or validation testing per non safety-related components.

1.4 Data Parameters and Service Conditions

Service conditions of interest are given below:

Transport Payload	100 Tons	
Travel distances:		
X axis	100 ft (minimum test condition)	
Y axis	70 ft	
Z axis	6 ft	
Rotation	350 degrees	
Velocities:		
Trolley, bridge	Slow	50 ft/min
	Medium	100 ft/min
Hoisting	Slow	4 ft/min
	Medium	7 ft/min
Environment	Room temperature	
Desired Accuracy	±0.25 in. (x, y, or z direction)	
	±0.25 degrees (rotational)	

2. DESIGNER'S ALTERNATIVES

The following alternatives have been considered:

2.1 Test the equipment at the installation site during plant checkouts.

2.2 Test the equipment at the integrated test facility.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to conduct the design verification tests at the vendor plant. The primary purpose of the FHEP design verification testing is to verify the integration of controls, axes position repeatability and the structural integrity in an environment and at a time when alterations, if necessary, are practical. The fabrication vendor will support speed, accuracy, extended cyclic endurance and structural testing. The cyclic testing will be equivalent to at least 10 refueling outages. The alterations that may occur will be identified earlier for implementation on the second machine.

The alternatives considered are not selected because testing would be delayed possibly risking plant availability. If alterations are necessary the implementation cost on both machines would increase.

4. SCHEDULE REQUIREMENTS

Testing is to start upon completion of assembly which is planned for month [TBD] after start of final design and completion of testing to be month [TBD].

[DDN C.21.01.06]

5. PRIORITY

Urgency: 3
Cost benefit: M
Uncertainty in existing data: M
Importance of new data: M

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback for testing this machine would be alternate 2.2. This alternative would be technically acceptable, in that acceptable quality performance would be achieved, but could involve excess cost and schedule delays. The potential cost and schedule problems rejects these alternatives.

7-27-94
Originator Date

7/28/94
Task Manager Date

Program Manager Date

DATE: 6/30/94

GT-MHR PROGRAM
FUEL HANDLING EQUIPMENT SUPPORT STRUCTURE DESIGN VERIFICATION
DDN C.21.01.07

PLANT: GT-MHR/SYSTEM 21

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The Fuel Handling Equipment Support Structure (FHESS) provides the structural interface for the Auxiliary Service Cask and the Fuel Handling Machine. The active components of the Support Structure are the reactor isolation valves and the NCA housing seals. Validation testing of the valve and seal leakage with and without the load of the supported equipment, with misalignment of the NCA housings is required.

A set of guide pins are provided to align the Support Structure to the structural support. The dimensional misalignment limits between the support guide pins, the FHESS structure, the NCA housings and the positioning uncertainty of the fuel handling equipment positioner (FHEP) relative to valve seal performance are to be determined.

1.1 Summary of Function and Assumptions

"Fuel Handling," Assumption: The valves and seals will isolate the internal reactor environment from the service area for all conditions of applied load and interface misalignment.

1.2 Current Data Base Summary

The support structure and its multiple interfaces is a first of a kind unit. The inflatable seals and valve operating drive components have vendor documentation. However, design validation data is required to prove the assembled units' ability to align to the reactor skirt and to align, anchor and seal to NCA housings, ASC, and fuel handling equipment.

1.3 Data Needed

Determine the FHESS mispositioning limits relative to each of the interfaces which permit the valves, seals, and mechanical interfaces to perform to design specification under the conditions in Section 1.4. Reliability and maintenance data for valve actuators, seal quality (leakage), and anchoring mechanisms is needed.

Quality assurance must be in accordance with the requirements for experimental data or validation testing per non safety-related components.

1.4 Data Parameters and Service Conditions

Service conditions of interest are given below:

Structure load:

FHM	75 Tons
FTC	60 Tons
ASC	100 Tons

Internal environment:

Atmosphere	Helium
Temperature	250°F (shutdown)
Pressure	< 1 atmosphere

2. DESIGNER'S ALTERNATIVES

The following alternatives have been considered:

2.1 Determine alignment/sealing limits at the plant site during precommissioning check-out.

2.2 Validate the design with the deliverable full scale support structure with simulated interfaces, loads, positioning, and internal reactor environment.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to conduct material qualification, functional and endurance testing with prototypic test articles and simulated interfaces. These tests can be conducted relatively (versus other alternatives) early in the development program, will provide a practical site for an extended 2000 cycle endurance test and will yield design and performance data for the remaining floor and machine isolation valves. This method of test would exclude the effects, if any, of applied loads and possible deflections imposed by the fuel handling equipment. Structural deflections are considered to be a low design risk which can be reasonably calculated and validated during integrated testing, ref DDN B.21.01.04. The possible effects of the heated helium on the seal material can be tested separately if the seal material selection is in doubt.

Alternate 2.1 would occur too late in the project to economically benefit the floor and machine isolation valve design and/or production.

Alternate 2.2 utilizes the actual manufactured design in simulated service conditions and to this extent is a more thorough design validation. This test would be costly for the load and helium environment that would be gained relative to the selected approach. This approach would occur too late to economically benefit the production of the remaining floor and machine isolation valves.

4. SCHEDULE REQUIREMENTS

The selected testing is to start by month [TBD] before completion of final design and complete by month [TBD].

5. PRIORITY

Urgency: 3
Cost benefit: M
Uncertainty in existing data: M
Importance of new data: M

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

If the seal/valve integrity is not adequate the reactor will ingest humid air which would subsequently be removed by the helium purification system. The consequence then is the lost time to remove the ingested air and the effects on the fuel elements.

7-27-94
Originator Date

7/28/94
Task Manager Date

Program Manager Date

[DDN C.21.01.08]

DATE: 6/30/94

GT-MHR PROGRAM
FUEL SEALING AND INSPECTION EQUIPMENT DESIGN VERIFICATION
DDN C.21.01.08

PLANT: GT-MHR/SYSTEM 21

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The Fuel Sealing and Inspection Equipment is utilized in an automated process which receives spent core elements from the spent fuel cooling pools and inspects and packages them into sealed canisters for shipment or storage. Design verification testing is required prior to shipment and installation in the plant.

1.1 Summary of Function and Assumptions

"Fuel Handling," Assumption: The equipment will reliably receive, process, inspect and deliver core elements, sealed in shipping containers, by remote automatic control.

1.2 Current Data Base Summary

This equipment will be a first of a kind design which has no performance history.

1.3 Data Needed

Data on verification of the automated packaging, sealing and inspection process including extended cycle endurance tests is needed under the conditions in Section 1.4.

Quality assurance must be in accordance with the requirements for experimental data or validation testing per nonsafety-related components.

1.4 Data Parameters and Service Conditions

Service conditions are temperature Helium at a pressure at [0.2] psia lower than neighboring air atmosphere. The core elements will be radioactive with decay heat.

2. DESIGNER'S ALTERNATIVES

The following alternatives have been considered:

2.1 Test the equipment at the plant construction site during post installation checkouts.

2.2 Functional and extended cycle tests of the equipment prior to shipment.

[DDN C.21.01.08]

3. SELECTED DESIGN APPROACH AND EXPLANATION

Alternate 2.2 is selected because it provides the earliest opportunity to perform the tests with the necessary facilities and equipment available. Alternate 2.1 is not recommended because it would occur too late in the project to make corrections.

4. SCHEDULE REQUIREMENTS

Successful testing to be complete and ready for shipment by month [TBD] after start of final design.

5. PRIORITY

Urgency: 3
Cost benefit: H
Uncertainty in existing data: M
Importance of new data: M

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

If the tests cannot be accomplished prior to shipment the plant start-up will be vulnerable to first trial failures, their remedies and related schedule impact.

7-27-94
Originator Date

7/28/94
Task Manager Date

Program Manager Date

DATE: 6/30/94

GT-MHR PROGRAM
INFLATABLE SEAL AND S/N IDENTIFICATION TESTS DESIGN VERIFICATION
DDN C.21.01.09

PLANT: GT-MHR/SYSTEM 21

[LATER]

DATE: 6/30/94

GT-MHR PROGRAM
VERIFY HELIUM MASS FLOW MEASUREMENT INSTRUMENTATION
DDN C.31.01.01

PLANT: GT-MHR/System 31

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The Reactor Protection System initiates a reactor trip to prevent fuel damage when a reactor power/primary coolant flow mismatch occurs. The Plant Control, Data and Instrumentation System (PCDIS) uses the helium mass flow in the primary coolant energy balance to compute reactor power. The purpose of this DDN is to verify the design and performance of the helium mass flow measurement primary element and instrumentation.

1.1 Summary of Function and Assumptions

Assumption: Primary coolant helium mass flow instruments of sufficient accuracy and sensitivity are available for application in a high temperature helium environment.

1.2 Current Data Base Summary

The current data base for the helium mass flow measurement in the GT-MHR is derived from the Fort St. Vrain steam cycle experience where the mass flow measurement is calculated by using the differential static pressure generated in the helium circulator inlet diffuser. This calculated mass flow was used at Fort St. Vrain only for monitoring but not for control.

The German THTR uses the same mass flow measurement principle as Fort St. Vrain, except the differential static pressure is generated in the circulator outlet venturi.

1.3 Data Needed

In the GT-MHR, turbine flow is equal to the total core flow if there is no seal leakage. Turbine exit is tentatively selected as the most feasible location for the instrumentation considering accessibility. Therefore, verification of a new design for helium mass flow measurement at the turbine exit is needed for measurement of core flow. The expected static and dynamic performance of the flow instrumentation at GT-MHR plant service conditions (see Section 1.4) are needed. These include accuracy, repeatability, linearity, response time, drift and signal-to-noise ratio. Verification of calibration and sensor replaceability is also needed.

Quality Assurance must be in accordance with the requirements for experimental data or validation testing for safety-related components.

1.4 Data Parameters and Service Conditions

Service conditions at the turbine exit are given below:

Atmosphere	Helium
Pressure range	[1 atm] to [1016] psia
Temperature range	[TBD] to 1562°F
Mass flow rate range	[35] to [700] lbm/sec

2. DESIGNER'S ALTERNATIVES

2.1 Instrument only compressor to obtain inlet temperature and pressure for both compressors. Use inlet conditions and speed to obtain the compressor performance maps. Instrument bypass flow and subtract from compressor helium mass flow to obtain inferred flow for the core. Method is likely to be inaccurate due to leakage in circuit.

2.2 Use other locations in the power conversion system to install core flow measurement devices. Instrumentation is likely to be less accessible.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The recommended approach consists of performing instrumentation development/design verification testing in a full-scale turbomachine power conversion loop to develop, optimize, and prove the design. The testing will determine the effect of the following influence parameters on the helium mass flow measurement at the turbine exit:

1. Power Conversion System geometry (including different static pressure taps locations).

2. Undetected significant bias errors (such as seals leaks).

3. Large differences in flow between design level flow and decay heat removal level flow.

4. Velocity profile distortion across the turbine exit.

5. Unsteady or pulsating flow (including acoustic effects).

The tests will also calibrate the GT-MHR full-scale turbomachine power conversion loop mass flow using an accurate flow standard.

This testing will result in a high degree of confidence in the accuracy of the helium mass flow measurement. Accuracy includes precision (sensitivity, resolution, and repeatability) and bias or systematic error. The test data will be used by the designers to provide instrument specifications for determination of helium mass flow rate. Additionally, the data will provide confirmation of the direct flow measurement design under varying primary coolant pressure conditions. The designers will use the data to verify primary element and secondary device (temperature sensors and static pressure transducers) accuracies for use in the Reactor Protection System design and for use in establishing the requirements for flow calibration in the Qualification and Production Acceptance testing.

The use of a helium mass flow measurement system without testing would require overly conservative setpoints in the Reactor Protection System because a helium mass flow calculated indirectly from compressor and bypass flow data is believed to be less accurate. This could adversely affect plant availability by causing spurious trips during transients. The PCDIS heat balances would also be less accurate.

4. SCHEDULE REQUIREMENTS

Design verification must be completed by the end of [TBD] with final calibration data due [TBD] before start of final design.

5. PRIORITY

Urgency: 2
Benefit/cost: M
Uncertainty in existing data: M
Importance of New Data: M

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback positions are to use indirect calculations of flow that would be based on other measurements and would not include design verification.

The consequences are that more conservative assumptions must be utilized in performing plant dynamic analysis, establishing trip setpoints and calculating heat balances. This has a detrimental effect on overall plant performance and performance verification.

R. D. Jfrommer 7/28/94
Originator Date

[signature] 7/28/94
Task Manager Date

Program Manager Date

[DDN C.31.01.02]

DATE: 6/30/94

GT-MHR PROGRAM
VERIFY CONDUCTION COOLDOWN TEMPERATURE MONITORING INSTRUMENTATION
DDN C.31.01.02

PLANT: GT-MHR/System 31

[LATER]

DATE: 6/30/94

GT-MHR PROGRAM
VERIFY CORE INLET AND OUTLET HELIUM TEMPERATURE MEASUREMENT INSTRUMENTATION
DDN C.34.01.01

PLANT: GT-MHR/SYSTEM 34

[LATER]

DATE: 6/30/94

GT-MHR PROGRAM
VERIFY PLATEOUT PROBE OPERATION
DDN C.34.01.02

PLANT: GT-MHR/SYSTEM 34

[LATER]

DATE: 6/30/64

GT-MHR PROGRAM
PCS/SCS TEMPERATURE MIXING AND VELOCITY DISTRIBUTIONS
DDN C.41.00.01

PLANT: GT-MHR/System 41

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The velocity and temperature distributions downstream of the reactor core during Power Conversion System (PCS) and shutdown cooling system (SCS) operation is important in establishing component performance, e.g., core support structure, hot duct, PCS component, and shutdown heat exchanger (SHE) performance. The main concern is hot/cold streaks and coolant velocity maldistribution during steady-state operations.

1.1 Summary of Function and Assumptions

"Transport Energy in Primary Coolant"

Assumption 1: A method is available for the prediction of hot/cold streaks attenuation from the core exit to the turbine inlet.

Assumption 2: A method is available for the prediction of local primary coolant velocity maldistributions.

Assumption 3: Test data will be available for the timely prediction of hot streak mixing, hot helium flow maldistribution in the core lower plenum, duct, and plenum inlet to the turbine.

"Remove Decay Heat," Assumption 1: Test data will be available for the timely prediction of hot streak mixing, hot helium flow maldistribution in the core lower plenum, and plenum leading to the SHE bundle.

1.2 Current Data Base Summary

The current understanding of flow behavior and hot/cold streaks in a core outlet plenum has been obtained from air flow tests carried out on a 1/6-scale model of the 2240 MW(t) HTGR-SC/C lower plenum and hot duct configurations (HTGR-85-108). These data are considered largely specific to the 2240 MW(t).

In 1991-1992, Combustion Engineering/Chattanooga performed a series of flow and pressure distribution tests with a full scale model of the hot duct and the steam generator bundle inlet diffuser. Data from these tests are directly applicable to the 450 MW(t) MHTGR design and they will be used to specify the scope of the data needed described in Section 1.3.

Analytical methods, like the turbulent fluid codes FIDAP or FLUENT, are available which can provide velocity, pressure, and temperature profiles downstream of the core in three dimensions. Because of the complexity of the flow field downstream of the core, some of the turbulent diffusivity models used by these codes have to be validated through tests specific to a given design. Some of the 2240 MW(t) model test data can be used to validate turbulent fluid codes like FIDAP or FLUINT, but specific data are required.

1.3 Data Needed

Data on the velocity, temperature, pressure, and flow distributions for the primary coolant are needed for the main loop operations shown in Section 1.4 at the hot duct inlet, hot duct outlet, and turbine inlet. The velocity, temperature, pressure, and flow distributions for the primary coolant are also needed for the shutdown cooling system (SCS) operations shown in Section 1.4 at the outlet of the core support ducts and at the shutdown heat exchanger bundle inlet.

Temperature measurements should be obtained in such a way as to characterize primary coolant mixing from the core outlets to the hot duct, the turbine, and SHE bundle.

Quality assurance must be in accordance with the requirements for experimental data or validation testing per non safety-related components.

1.4 Data Parameters and Service Conditions

The data are required at the following service conditions:

Configuration	Core support element blocks, core lower plenum, hot duct, and steam generator and SCHE inlet plenums up to the bundles.
Operating conditions	15% to 100% power main loop operation. SCS pressurized and depressurized operation.
Coolant	Helium.
Nominal pressure range (100%-25%)	1025 to 934 psia (turbine inlet) main loop operation. 1040 psia to atmospheric pressure SCS operation.
Nominal bulk temperature range (100%-25%)	1300 to 1105°F average core outlet temperature main loop operation. 1685 to 153°F average core outlet temperature SCS operation.

Nominal mass flow rate range (100%-25%)	467 to 151 lb/s at the turbine outlet. 33 to 4 lb/s at the shutdown circulator outlet.
Helium flow	$<1.68 \times 10^6$ lb/h main loop operation. $<126{,}000$ lb/h SCS operation.

2. DESIGNER'S ALTERNATIVES

The following alternative is considered:

2.1 Predict the flow field with present methods incorporating results from previous model tests on other reactor configurations. Design affected components conservatively to increase the margins to plant performance requirements, e.g., use of high temperature materials.

3. SELECTED DESIGN APPROACH AND EXPLANATION

Obtain the data needs from air flow distribution tests on a one-half or full scale model of the GT-MHR core exit plenum, hot duct and inlet configurations for turbine and SHE. The core, turbine and SHE will be modeled by appropriate flow resistances. The selected approach provides realistic flow parameters compared to the alternate approach and has a potential to remove excessive conservatism in the design by reducing uncertainties in the analysis. The test rig will be used also to determine the location of flow distribution devices and their performance (e.g., improving helium mixing and velocity distributions).

4. SCHEDULE REQUIREMENTS

These data are required during the first two years of preliminary design phase to remove uncertainties in the design.

5. Priority

Urgency: 1
Cost benefit: M
Uncertainty in existing data: H
Importance of new data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

If the selected task is not performed, the fallback position is Alternative 2.1, which relies on analysis based on available data from model tests on other reactor configurations and conservative design measures to assure adequate design margins. The consequences are potential for increased cost of hot duct, PCS and SHE components, and/or reduced plant performance.

R.C. Potter 7/27/94
Originator Date

7/25/94
Task Manager Date

Program Manager Date

[DDN C.41.00.02]

DATE: 6/30/64

GT-MHR PROGRAM
POWER CONVERSION SYSTEM INTEGRATED PERFORMANCE
DDN C.41.00.02

PLANT: GT-MHR/System 41

[LATER]

[DDN C.41.01.01]

DATE: 6/30/94

GT-MHR PROGRAM
TURBOCOMPRESSOR MATERIALS DATA
DDN C.41.01.01

PLANT: GT-MHR/SYSTEM 41

[LATER]

[DDN C.41.01.02]

DATE: 6/30/94

GT-MHR PROGRAM
TURBOMACHINE BEARING SYSTEM DESIGN VERIFICATION
DDN C.41.01.02

PLANT: GT-MHR/SYSTEM 41

[LATER]

DATE: 6/30/94

GT-MHR PROGRAM
TURBOCOMPRESSOR SEAL SYSTEM VERIFICATION
DDN C.41.01.03

PLANT: GT-MHR/SYSTEM 41

[LATER]

[DDN C.41.01.04]

DATE: 6/30/94

GT-MHR PROGRAM
TURBOCOMPRESSOR FLOW DISTRIBUTION TESTS
DDN C.41.01.04

PLANT: GT-MHR/SYSTEM 41

[LATER]

DATE: 6/30/94

GT-MHR PROGRAM
GENERATOR ELECTRICAL INSULATION DATA
DDN C.41.01.05

PLANT: GT-MHR/SYSTEM 41

[LATER]

[DDN C.41.01.06]

DATE: 6/30/94

GT-MHR PROGRAM
GENERATOR BRUSHLESS EXCITER PERFORMANCE
DDN C.41.01.06

PLANT: GT-MHR/SYSTEM 41

[LATER]

DATE: 6/30/94

GT-MHR PROGRAM
INSTRUMENTATION AND ELECTRICAL PENETRATION PERFORMANCE
DDN C.41.01.07

PLANT: GT-MHR/SYSTEM 41

[LATER]

DATE: 6/30/94

GT-MHR PROGRAM
RECUPERATOR STRUCTURAL DESIGN VERIFICATION
DDN C.41.02.01

PLANT: GT-MHR/SYSTEM 41

[LATER]

[DDN C.41.02.02]

DATE: 6/30/94

GT-MHR PROGRAM
RECUPERATOR LOW AND HIGH PRESSURE INLETS FLOW DISTRIBUTION
DDN C.41.02.02

PLANT: GT-MHR/SYSTEM 41

[LATER]

[DDN C.41.02.03]

DATE: 6/30/94

GT-MHR PROGRAM
RECUPERATOR FLOW INDUCED VIBRATION CHARACTERISTICS
DDN C.41.02.03

PLANT: GT-MHR/SYSTEM 41

[LATER]

DATE: 6/30/94

GT-MHR PROGRAM
RECUPERATOR LEAD DETECTION METHODS AND EQUIPMENT
DDN C.41.02.04

PLANT: GT-MHR/SYSTEM 41

[LATER]

[DDN C.41.02.05]

DATE: 6/30/94

GT-MHR PROGRAM
RECUPERATOR SEALS TESTS
DDN C.41.02.05

PLANT: GT-MHR/SYSTEM 41

[LATER]

[DDN C.41.02.06]

DATE: 6/30/94

GT-MHR PROGRAM
RECUPERATOR HEAT TRANSFER AND PRESSURE DROP PERFORMANCE VERIFICATION
DDN C.41.02.06

PLANT: GT-MHR/SYSTEM 41

[LATER]

[DDN C.41.02.11]

DATE: 6/30/94

GT-MHR PROGRAM
ENVIRONMENTAL EFFECTS ON 316L STAINLESS STEEL
DDN C.41.02.11

PLANT: GT-MHR/SYSTEM 41

[LATER]

[DDN.C.41.03.01]

DATE: 7/25/94

GT-MHR PROGRAM
ACOUSTICAL RESPONSE OF THE HELICAL FINNED TUBE BUNDLE

DDN.C.41.03.01

PLANT: GT-MHR/System 41

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Acoustic vibrations generated by vortex shedding and flow separation from multiple tubes can be amplified by tuned resonant chambers. While the problem may manifest itself in the form of excessive noise levels, it may also lead to substantial structural damage to tubes, shrouds or thermal barrier surfaces of the heat exchanger and the primary coolant loop.

1.1 Summary of Functions/Assumptions

"Flow Primary Coolant Through Heat Exchanger", Assumption: Methods will be developed for the timely prediction of acoustic loads within the primary coolant loop.

"Receive Primary Coolant", Assumption: Precooler and intercooler helical finned tube bundle/cavity will not generate excessive acoustic loads on the shrouds and thermal barrier surfaces.

"Channel Primary Coolant Through Heat Exchanger", Assumption: Precooler and intercooler helical finned tube bundle/cavity will not generate excessive acoustic loads on the shrouds and thermal barrier surfaces.

"Discharge Primary Coolant", Assumption: Precooler and intercooler helical finned tube bundle/cavity will not generate excessive acoustic loads on the shrouds and thermal barrier surfaces.

1.2 Current Data Base Summary

Acoustic resonance in heat exchangers is a common cause of excessive noise and failure in tube and shell heat exchangers with gas on the shell side. Acoustic resonance has occurred in chemical process heat exchangers, in heat recovery boilers, in power plants, with finned tubes, with plain tubes, in spiral tube heat exchangers, and with both inline and staggered tube arrangements. A reliable and accurate method of predicting the magnitude of the acoustic resonance is not available at this time.

In order to design against acoustic resonance, it is necessary to predict the excitation frequency for a given tube array and ensure that it does not coincide with the acoustic natural frequency of the tube shell. However, there is considerable controversy on the type of excitation mechanism against which this comparison should be made.

The only acoustic vibration test results available for a tube bundle geometry similar to the current design configuration, but with bare tubes, were generated by Sulzer Brothers for FSV steam generators. The conclusions of this testing were that the various acoustic vibrations occurred at or near the frequencies calculated, and that no distinct resonances with the vortex shedding frequencies were found, this being a major advantage of helical bundles over straight tube bundles.

1.3 Data Needed

The noise source level is characterized by a spectrum of acoustical power distributed over a frequency range. A major source of noise in the GT-MHR is the turbine. Data are needed to investigate the effects of this noise on the large surface area structures of the heat exchangers, such as the flow shrouds, baffles, and thermal barriers, as a function of varying frequencies.

It is also necessary to measure the acoustical response of the heat exchanger finned tube bundles and cavity during simulated primary flow. Data are needed that will produce representative frequency spectra and sound pressure levels generated by the helical finned tube bundle as a function of flow velocities and geometry variations. Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The critical test parameters are geometric similitude, Reynolds number and speed of sound.

The helium gas flow conditions that should be simulated are as follows:

- Temperatures from 21°C (70°F) to 177°C (350°F)
- Pressure range from 2.4MPa to 4.8MPa (350 to 700 psia)
- Gap velocities up to 18 m/sec (60 ft/sec) at the entrance to the bundles.
- Reynolds Numbers up to 8000 based on finned tube hydraulic diameter.
- Speed of sound of 990 m/sec (3300 ft/sec) to 1230 m/sec (4100ft/sec)
- Sound pressure levels up to 160 dB.

2. DESIGNER'S ALTERNATIVES

The alternatives are as follows:

2.1 Rely on analysis and avoid large resonant plates or other acoustic sensitive surfaces in the design.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach involves experimentally evaluating the geometry, flow conditions and sound levels in the helical finned tube bundle that could result in acoustic resonance. A model test is proposed for this purpose. The model will be designed so that the bundle geometry can be varied. The sound produced by flow through the test model as a function of bundle geometry and flow velocity will be measured. Also measured will be the response of the bundle and the cavity to the sound pressure levels generated by the turbine.

The precooler and intercooler designs incorporate shrouds, flow baffles and/or shields which may be acoustically sensitive. Theoretical analysis by itself is not considered adequate for a complex geometry such as the helical finned tube bundle (Alternative 2.1) and experiments are therefore necessary to confirm the acceptability of the design.

4. SCHEDULE REQUIREMENTS

Data are needed by start of final design.

5. PRIORITY

Urgency: 2
Cost Benefit: M
Uncertainty of Existing Data: M
Importance of New Data: M

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is Alternative 2.1. The consequences of nonexecution to the program could involve design modifications after the initial startup testing of the plant. This could prove to be quite costly.

M. Basel — 7-25-94
Originator — Date

[signature] — 7-26-94
Engineering Manager — Date

[signature] for SAC — 7-26-94
Project Manager — Date

DATE: 7/25/94

GT-MHR PROGRAM
FINNED TUBE HELICAL COIL PROGRAM

DDN.C.41.03.02

PLANT: GT-MHR/System 41

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Determine the feasibility of coiling and threading multiple externally finned tubes in concentric coils through holes in full and partial support plates (drilled or scalloped). Concerns are: ease of coiling and threading, clearances between tube and plate; wear protection device installation; tolerances; and fabrication time.

1.1 Summary of Functions/Assumptions

"Support Heat Transfer Surfaces", Assumption: The method of manufacturing of a helical coil bundle with externally finned tubes and drilled radial tube support plates will be verified. Alternatively, manufacturing with scalloped bar support concept will be verified.

1.2 Current Data Base Summary

Several full-scale fabrication tests and production bundles have demonstrated the coiling and threading of bare tubes through similar support structures. However, the assembly has been demonstrated on bare tube bundles of smaller diameters, with fewer number of coils, shorter tube lengths, and fewer number of tubes than for the precooler and the intercooler. The differences in these parameters, the use of finned tubes, in addition to the differences in the details of the support structure and the shroud structure, create a concern over the applicability of the current data base to the precooler and intercooler designs. Aside from the differences, the data base will provide useful information in defining a test program.

1.3 Data Needed

The data needed from the performance of this test are to demonstrate the fabrication of a large finned tube helical bundle and to provide input for fabrication procedures and sequence. Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

Data parameters needed from the test shall include:

1.4.1 Detailed fabrication procedures for handling, coiling, and threading tubes (i.e., quantity and placement of support points, bending rate, thread-in forces, etc.).

1.4.2 Types and designs of tooling required for performing operations (i.e., tube support tools, tube wear protection device upsetting tool, thread-in tools, etc.).

1.4.3 Tolerances (tube forming, support plate holes, etc.).

1.4.4 Fabrication time (broken down for each operation).

2. DESIGNER'S ALTERNATIVES

The alternatives are as follows:

2.1 Extrapolate data base parameters and information to current design.

2.2 Arbitrarily increase fabrication time to allow for unknowns and potential problem areas.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach involves coiling and threading a number of selected externally finned tubes into a full-scale, drilled plate support structure. Tubes will be selected to fully represent the spectrum of coiling and threading possibilities.

This selection is based upon utilization of the helical bundle supported by solid, drilled plates. The helical bundle is the most compact heat exchanger design for this application and the solid, drilled plate support system appears to best satisfy the requirements of thermal expansion and seismic load paths. Adaptation of the data base poses questions of applicability because of the many differences in bundle parameters. Arbitrarily increasing the fabrication schedule to allow for unknowns and learning would directly and adversely affect the cost as well as the "real" schedule.

4. SCHEDULE REQUIREMENTS

Data are needed prior to the start of precooler and intercooler fabrication.

5. PRIORITY

Urgency: 2
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position should only consider an extrapolation and adaptation of the current data base or arbitrarily increasing the fabrication span.

The consequences of nonexecution of this test will leave a concern of the fabrication procedures for a large finned tube helical coil bundle. Proceeding with the current design but without fabrication testing would likely result in increased costs and increased fabrication schedule.

M. Basol 7-25-94
Originator Date

[signature] 7-26-94
Engineering Manager Date

[signature] for SAC 7-26-94
Project Manager Date

DATE: 7/25/94

GT-MHR PROGRAM
PRECOOLER/INTERCOOLER INLET FLOW AND TEMPERATURE DISTRIBUTION TEST

DDN.C.41.03.03

PLANT: GT-MHR/System 41

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Knowledge of the magnitude and location of hot/cold streaks and velocity distribution of the primary coolant flow entering the precooler and intercooler tube bundles is needed. The presence of hot/cold streaks and flow maldistribution could impact the performance and structural constraints of these heat exchangers. It may be necessary to include mixing devices and/or flow distribution devices at the inlet to these heat exchanger tube bundles.

1.1 Summary of Functions/Assumptions

"Channel Primary Coolant Through Heat Exchanger," Assumptions:

Acceptable flow and temperature distribution at the entrance to the precooler and intercooler tube bundles can be achieved.

Test data will be available for the timely prediction of flow distribution at the entrance to the precooler and intercooler tube bundles.

"Transfer Heat from Primary Coolant to Heat Exchanger," Assumptions:

The primary coolant is uniformly distributed around the cooling tubes.

The local stresses and temperatures resulting from the inlet flow and temperature distributions are acceptable.

"Transfer Heat from Heat Exchanger to Secondary Coolant," Assumptions:

There is no boiling inside the tubes during steady state conditions.

The local stresses and temperatures resulting from the inlet flow and temperature distributions are acceptable.

1.2 Current Data Base Summary

Analytical methods, such as flow distribution codes, and Computational Fluid Dynamics (CFD) codes are available for predicting the flow field that can be realized for a given geometric configuration and inlet conditions. Experimental data exists on the hydraulic resistance of screens and baffles. Significant flow distribution and hot streak tests along with CFD analysis has been performed by ABB Combustion Engineering on a full scale helical steam generator model (see CEGA-002840, Rev. N/C, Test Evaluation Report for Final Flow Distribution Test for NP-MHTGR Steam Generator Final Test Model, dated September, 1993, and CEGA-002710, Rev. N/C, Test Evaluation Report for Hot Streak Test for NP-MHTGR Steam Generator, dated September, 1993). Some difficulties were encountered with all CFD codes in matching the results of the tests to the code outputs. It was concluded that CFD codes alone cannot accurately predict flow and temperature distribution in such complicated geometries. Some amount of experimental work duplicating the inlet geometry is necessary.

1.3 Data Needed

The data needed to determine the flow distribution and the magnitude of hot/cold streaks are the velocity, temperature and static pressure profiles measured circumferentially and radially at various cross sections along the primary coolant flow path, including:

- The inlet to the tube bundles.
- At a cross section in the tube bundle or equivalent resistance.

In addition, the corresponding overall flow rate and ambient pressure and temperature will be needed. The above data could be generated in conjunction with DDN.C.41.03.05. Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The service conditions of interest range from [15%] power to 100% power.

The 100% power service conditions of interest at the precooler and intercooler tube bundle inlets are summarized below:

	Precooler	Intercooler
Environment	Helium	Helium
Temperature	177°C (350°F)	149°C (300°F)
Pressure	2.8 MPa (400 psia)	4.8 MPa (700 psia)
Reynolds Number	8,000 (based on tube hydraulic diameter)	8,000 (based on tube hydraulic diameter)
Mach Number	[TBD]	[TBD]

2. DESIGNER'S ALTERNATIVES

The alternatives are as follows:

2.1 Rely solely on analytical methods (flow distribution or CFD codes) and utilize the available experimental data on the hydraulic resistance of screens and baffles.

2.2 Utilize one or two perforated plates with a very high resistance just upstream of the tube bundles to assure that the velocity maldistribution is corrected.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected design approach is to perform the inlet flow distribution and temperature tests to determine the primary coolant velocity, temperature and static pressure profiles and the location of flow distribution devices which will yield the required radial and circumferential velocity and temperature profiles at the precooler and intercooler tube bundle inlets.

Alternative 2.1 involves uncertainty in meeting the performance requirements and structural constraints of these heat exchangers.

Alternative 2.2 may result in unnecessarily high shellside pressure loss which in turn affects the plant efficiency.

It is judged that performing the tests is technically prudent to support the plant design.

4. SCHEDULE REQUIREMENTS

Final test data are needed before the end of the preliminary design phase to remove uncertainties in the designs.

5. PRIORITY

Urgency: 1
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is Alternative 2.1. The consequences of non-execution would involve possible modifications to plant operation to maintain current limits on operating conditions or reduced plant efficiency.

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Originator Date

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GT-MHR PROGRAM
PC/IC SHROUD SEAL TESTS

DDN.C.41.03.04

PLANT: GT-MHR/System 41

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The current concept of the precooler and intercooler arrangement incorporates seals at two different interfaces to prevent high pressure helium leakage. One interface is at the low pressure compressor inlet interface. The piston seals at this location prevent high pressure/high temperature helium from bypassing the intercooler. A second set of piston seals are located at the intercooler outlet/high pressure compressor inlet shroud interface where leakage would bypass the high pressure compressor. As the precooler and intercooler designs evolve, it is anticipated that other types of seals (i.e., bellows, omega seals) will be introduced to the design.

1.1 Summary of Functions/Assumptions

"Channel Primary Coolant Through Heat Exchanger", Assumption: Thermal and mechanical performance of the seals are adequate.

1.2 Current Data Base Summary

Listed below are the types of seal designs considered for different seal locations:

I. Piston rings, which allow axial sliding of mating components

II. Metal bellows, which allow stress free axial thermal growth

III. Metal omega seals which allow radial mismatch in displacement of mating components

The above first two types of seals are industry standard designs for static seals (no rotating components). However, most of these standard designs are for high pressure, low temperature and small diameter applications in air environment. Adopting any standard seal design for GT-MHR applications for high differential pressure (250 to 300 psi) in helium environment will require careful considerations.

1.3 Data Needed

The seals designs will require confirmatory testing which will:

a. Confirm the design feasibility prior to completion of preliminary design.

b. Measure performance, mainly leak rates, under prototypical operating conditions.

c. Measure the influence of the following factors on the seal performance.

- Surface finish of the mating components
- Flatness of the mating surfaces
- Differential pressure across seals
- Seating load

The results of the testing will be used to enhance the conceptual designs and the test data (leakage rate and bypass flow) will be used in the performance analysis of the components. Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The critical test parameters will be the geometric similitudes of the mating surfaces, helium temperature and the differential pressure across the seal.

2. DESIGNER'S ALTERNATIVES

The need for the proposed testing arises primarily to accommodate differential thermal movements between interfacing components and to accommodate installation and removal of the Power Conversion System (PCS) components. The alternative is to develop an alternative arrangement of the PCS components and associated ducting and shrouds to minimize the need for or the number of the seals within the system.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to incorporate piston seals in the design and to perform tests using small sections of seals of prototypical geometry and subject them to prototypical operating conditions, except the helium velocity, in a small test chamber. The performance test data will be collected to measure the influence of the items described in Section 1.3 and to finalize the seal designs. The test results will also be used in the component and system performance analysis.

4. SCHEDULE REQUIREMENTS

The test data are needed by the end of the preliminary design.

5. PRIORITY

Urgency: 2
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

Confirmatory testing of the seals should be performed prior to incorporating these seals into the final design. The basic fallback position is to select a design which eliminates the need for seals. This may not be possible due to numerous components operating under different conditions within a common vessel. The consequence of nonexecution is possible penalty in the plant economics.

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GT-MHR PROGRAM
FLOW INDUCED VIBRATION CHARACTERISTICS OF THE FINNED TUBE HELICAL BUNDLE

DDN.C.41.03.05

PLANT: GT-MHR/System 41

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Flow-induced vibrations are widely recognized as potentially major concerns in the design of modern tube-and-shell type heat exchangers. Fluid flowing across a tube array can cause dynamic instability. Should large-amplitude oscillations occur, severe damage to the tubes may result in a short time. Therefore, flow-induced vibration characteristics of the precooler and intercooler finned helical tube bundle, the lead-out tubes, and the lead-in tubes should be determined by test to verify the design and confirm the absence of such problems in service.

1.1 Summary of Functions/Assumptions

"Support Heat Transfer Surfaces", Assumptions: Methods will be developed and/or specific geometry dependent empirical constants will be determined in order to accurately predict helium flow-induced vibration mechanisms within the tube bundle and to avoid excessive tube vibrations. The semi- empirical models currently available to predict the onset of fluid-elastic instability are applicable to the finned helical tube bundle geometry.

1.2 Current Data Base Summary

Helical tube bundles differ in their geometry from tube bundles employing straight tubes. The main differences are the irregular and changing local tube array, caused by variations in the number of tubes and in the longitudinal pitch from one tube cylinder to another, the effect of the curvature and the slope of the tubes, variations in the natural frequencies of adjacent tubes, and the cylindrical shape of the casing. Flow-induced vibrational analysis of helical bundles has typically been based on parameters obtained in tests with straight-tube bundles. Until recently, the GAVEL Experiment performed by Sulzer in the late 1960's, formed the only test that involved tests of a full-size bare tube helical tube bundle, which represented a section of the FSV steam generator (GAVEL EXPERIMENT-Final Report on Vibration and Flow Tests, July, 1969).

The recent experimental work on bare tube helical tube bundles was performed by ABB Combustion Engineering, as part of the steam generator development program for NP-MHTGR project (CEGA-002915, Rev. N/C, Test Evaluation Report for Flow-Induced Vibration Test for NP-MHTGR Steam Generator Final Test Model, November 1993). The approach was to utilize full scale testing of the helical tube bundle with its lead-outs and transition tubes in the Air Flow Test

Facility. The specific goal of the testing was to identify the flow-induced vibration phenomena of significance and to quantify the tube vibrations. This test program was successfully completed, providing much needed tube damping parameters, vibration amplitudes and empirical constants for bare tube helical bundles with its lead-outs and transition tubes.

Earlier, as part of its PWR steam generator development program, ABB Combustion Engineering performed flow-induced vibration tests in water with both bare tube and knurled (roughened) straight tube bundles simulating externally finned tubes. The limited test results indicated that the vortex shedding phenomena is less of a concern with knurled tube bundles, whereas, fluid-elastic instability is achieved sooner, as compared to the bare tube bundles.

Flow induced excitation mechanisms can be broadly classified as: (a) turbulent buffeting, (b) vortex shedding, (c) fluid-elastic instability and (d) acoustic resonance. Among these mechanisms, fluid-elastic instability is the excitation mechanism with the greatest potential for short term damage to heat exchangers, including those with helical tube bundles. In the current precooler and intercooler designs, this mechanism controls the maximum allowable unsupported tube spans within the bundle. The models currently available to predict the onset of fluid-elastic instability are all semi-empirical, and based on bare (or smooth) tubes. The original stability criterion was developed by Connors using the following relationship for the threshold velocity U_c beyond which fluid-elastic instability occurs:

$$U_c/f_n D = K\ (m\delta/\rho D^2)^{1/2}$$

where K is the fluid-elastic instability coefficient and δ is the logarithmic decrement associated with tube damping. However, the coefficient K varies with specific array characteristics, fluid flow conditions, surface roughness, and all other parameters that can affect the instability. There is a significant scatter in the experimental data obtained by different investigators using straight tube models with bare tubes and values of coefficient K have been reported from 2.0 to 9.9. At the time the GAVEL Experiment was performed, fluid-elastic instability was not considered to be important, and tests concentrated on the vortex shedding phenomena. Later experimental data generated by Blevins, in which he varied the spacings between tubes and inclined alternate tube columns to simulate a counterwound helical bundle, found the fluid-elastic instability to be an important consideration in these bundles and that the coefficient K could be as low as 1.7. The flow-induced vibration tests performed by ABB Combustion Engineering indicated a K of 6.44 for the helical bundle based on the 75 percent quartile value obtained from these tests.

1.3 Data Needed

Data is needed in order to accurately determine the flow-induced vibration characteristics of the precooler and intercooler specific finned tube helical bundle, the lead-out tubes, and the lead-in tubes. The flow-induced excitation mechanisms of concern are turbulent buffeting, vortex shedding and fluid-elastic instability, with the latter considered the most important. The data generated should provide the essential information to the designer in order to accurately verify the response of the structure to the shellside fluid flow conditions, especially the prediction of the threshold for fluid elastic instability. The model used in the tests should be able to accurately simulate the specific array characteristics, geometry and the shellside fluid flow conditions of these tube bundles. Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The critical test parameters are geometric similitude representing the top (hot end) of the finned tube helical bundles, and lead-out tubes, and the lead-in tube array characteristics and support conditions, as well as the shellside fluid flow conditions including the flow velocities, densities and the Reynolds numbers.

The shellside helium gas flow conditions that should be simulated are as follows:

- Temperatures from 93°C (200°F) to 177°C (350°F)
- Pressure range from 2.1 MPa to 4.8 MPa (300 to 700 psia)
- Gap velocities up to 18 m/sec (60 ft/sec)
- Reynolds Numbers up to 8000 (based on tube hydraulic diameter)

The tubeside conditions at the hot end of the tube bundles can be satisfied by using water inside the tubes.

The tests, as a minimum, should give the following results:

a. Instability coefficients (K) for the finned tube helical bundle, the lead-out tubes, and the lead-in tubes.

b. Damping characteristics for the tubes.

c. Strouhal numbers (S).

d. Tube displacements and the amplification factors.

e. Lift (C_L) and Drag (C_D) coefficients.

f. Pressure Spectra (Pi) and the Lift Force (F_L).

2. DESIGNER'S ALTERNATIVES

The alternative is as follows:

2.1 Rely on the existing information and data developed by various investigators based on the parameters obtained in tests with bare tube straight-tube bundles and, though limited, data on helical and/or simulated helical bundles, for analysis of the precooler and intercooler tube bundle geometries.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach involves flow-induced vibration testing of a representative model (or models) that simulates the specific array characteristics, geometry and the shell-side fluid flow conditions of the precooler and intercooler tube bundles. This model (or models) need only simulate the conditions at the hot end of the helical tube bundle, at the lead-out tubes and the lead-in tubes, which are considered to be most susceptible to the flow-induced vibration mechanisms of concern.

Alternative 2.1 would involve uncertainties in the design. The approach would of necessity be conservative due to the scatter in the parameters from existing test results.

4. SCHEDULE REQUIREMENTS

Interim results are needed before the end of preliminary design phase.

5. PRIORITY

Urgency: 1
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is Alternative 2.1. Nonexecution may lead the designer to choose what he thinks is the most appropriately conservative correlation in the analyses, resulting in an over-conservative design. This could affect the overall envelope of the tube bundles.

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GT-MHR PROGRAM
FINNED TUBES INSPECTION METHODS AND EQUIPMENT

DDN.C.41.03.06

PLANT: GT-MHR/System 41

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The tubing and welds in the precooler and intercooler finned tube circuits must be capable of being inspected to provide safe and reliable operation of the units with high availability. The helical tubes are different from existing PWR steam generator tubes in three major areas:

a. The helical tubes are much longer, with more bends than the PWR U-tubes. There are longer, more torturous lengths of tubes to be inspected.

b. The tube materials are different from PWR SG tube materials. There are also several similar metal butt welds in each tube circuit.

c. The precooler and intercooler tubing is about 2 times thicker than PWR SG tubing, and is externally finned.

The effort of this DDN will provide data on the ability to deliver and recover an NDE probe the full length of the precooler and intercooler tubes and the sensitivity of that equipment to detect tubing flaws. In addition, the choice of either eddy current (ECT) or ultrasonic inspection (UT) will be made.

1.1 Summary of Functions/Assumptions

"Protect the Capability to Channel Secondary Coolant Through the Heat Exchanger", Assumption: Inspection of the precooler and intercooler tubing is possible. Adequate radius of the necessary tube bends will allow passage of an inspection probe. In addition the ID of the tube will be large enough to allow suitable probe passage and the wall thickness will not preclude acceptable sensitivity of the testing equipment.

1.2 Current Data Base Summary

Previous testing experience by Babcock & Wilcox (Karl C. Henderson, et al, "A Single Pass Volumetric Ultrasonic Inspection System for Helical Coil Steam Generators," JPGC, 1984) and Southwest Research Institute (SWRI Project No. 17-5077, "Phase I Final Report-Examination System for Helical Steam Generator Tubes," May, 1978) and the recent engineering development program performed by ABB Combustion Engineering (ABB Report TR-ESE-990, "Status Report for the Engineering Development of the NP-MHTGR Steam Generator Tube ISI Probe and Delivery System," May, 1993) indicates that it is possible to deliver an inspection probe from the boreside of the helical tubing. No data is available relative to the inspection sensitivity of the finned tubes.

1.3 Data Needed

Test data are needed first to guarantee the capability, and secondly, inspection sensitivity for the specific geometry of the precooler and intercooler tube circuits. From this a testing program can be developed which will be compatible with outage times and the necessary NDE requirements.

Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The probe delivery and inspection development tests shall be performed in an air atmosphere at ambient temperature with additional tests at as high a temperature as can be tolerated by the NDE probe without affecting the data obtained.

For the probe delivery system the data parameters of interest include the loads necessary to push and pull the probe with its carrier, and the times necessary to deliver the probe, to inspect the tube areas, and to retract the probe.

The NDE data shall be obtained and recorded in accordance with the approved procedures.

2. DESIGNER'S ALTERNATIVE

2.1 Utilize data from previous tests and developmental programs. Design the heat exchanger tubing bends to that criteria. Defer testing until baseline testing is to be done at the site.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to test with representative probes and NDE equipment of representative tubing coils and lead-in and lead-out tubing. The test program will confirm the ability to conduct tubing NDE.

NDE is required, and is critical to the operation of the precooler and intercooler. Detection of degradation will allow the operator to assess certain operating practices, and possibly preclude moisture ingress due to tube failures.

4. SCHEDULE REQUIREMENTS

Initial test results are needed before the end of preliminary design in order to firm up the precooler and intercooler designs.

5. PRIORITY

Urgency: 2
Cost Benefit: H
Uncertainty in Existing Data: M
Importance of New Data: M

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is to use data from previous testing which may not be the same as for the GT-MHR design. Conservative estimates would have to be made for NDE sensitivity and tube inspection times.

The consequences of nonexecution of the test program would place at risk the ability to provide adequate NDE capability for the precooler and intercooler tubing.

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GT-MHR PROGRAM
FINNED TUBE HELICAL BUNDLE
LOCAL HEAT TRANSFER AND FLOW RESISTANCE CHARACTERISTICS

DDN.C.41.03.07

PLANT: GT-MHR/System 41

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Data are needed to confirm the shell- and tube-side heat transfer characteristics and shell-side flow resistance of the finned tube helical bundle. Shell side helium heat transfer coefficients are needed for the first few tube rows of the tube bundles and within the tube bundles. Both the average coefficient and the distribution as a function of the circumferential angle around the tube are needed. In addition, the effective flow resistance of the finned tube bundle which accounts for the variation from a square pitch to a staggered pitch is needed.

The precooler and intercooler tube bundle sizes are sensitive to the shellside heat transfer coefficients used for finned tubes. The heat transfer coefficient and pressure drop parameters that are currently being used in the analysis of finned tube heat exchangers are based on old and outdated data, and show a large scatter. Also, the tube temperatures are sensitive to local heat transfer coefficients. Shell heat transfer coefficients can be sensitive to local variations in flow geometry and flow resistance. These individual heat transfer coefficients, or "hot spot factors" must be known in order to adequately identify the tube temperatures in the tube bundle. Adequately identifying the tube bundle flow resistances is also required to determine the tube bundle pressure drops.

1.1 Summary of Functions/Assumptions

"Transfer heat from primary coolant to heat exchanger." Assumptions:

A hot spot (maximum to average) factor of 1.35 is used at the entrance to the tube bundles for the helium heat transfer coefficient. This value is based on test data which was obtained for the Fort St. Vrain steam generator. Data reported in the literature indicates cases where this factor was higher.

The helium heat transfer coefficient which has been used for the tube bundle entrance regions is the average bundle helium heat transfer coefficient. The helium heat transfer coefficient at the entrance to the tube bundles can be as low as 64% of the average bundle helium heat transfer coefficient.

The shellside heat transfer and pressure drop for the finned tube helical bundles are based on the 1976 Battelle Study for extended surfaces for purely staggered tube bundles.

1.2 Current Data Base Summary

Analysis in the open literature and limited test data, e.g., Fort St. Vrain (Efferding, L.E, et al," PSC Steam Generator Sizing and Performance, GADR-110, July, 1971), and Battelle Study ("Heat Transfer and Pressure Drop Characteristics of Dry Power Extended Surface, Part II: Data Analysis and Correlation," Battelle Memorial Institute, PFR 7-102, June, 1976).

1.3 Data Needed

1.3.1 Heat transfer coefficient circumferential variation around the outside of a finned tube at the entrance region of a helical tube bundle.

1.3.2 Average heat transfer coefficients on the outside of the finned tubes for the entrance region of a helical tube bundle.

1.3.3 Tube bundle friction factors for finned tube bundles with a variation from a square pitch to a staggered pitch.

Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The service conditions of interest are:

Fluid	Helium
Pressure	2.1 to 4.8 MPa (300-700 psia)
Temperature	93 to 177°C (200-350°F)
Reynolds Number	Up to 8,000 (Based on tube hydraulic diameter)
Tube OD (at the base of fins)	28.6 mm (1.125 inch)
Transverse Tube Pitch	43.18 - 44.07 mm (1.7 - 1.735 inch)
Longitudinal Tube Pitch	39.75 mm (1.565 inch)
Fin Height/Thickness	3.18/0.3 mm (0.125/0.012 inch)
Fins/inch	30

2. DESIGNER'S ALTERNATIVES

The alternative is to rely solely on analytical methods utilizing the available experimental data.

[DDN.C.41.03.07]

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected design approach is to perform the heat transfer and flow resistance test utilizing full-scale and sector models to yield the required data.

It is judged that performing the test will minimize conservatism to support the plant design.

4. SCHEDULE REQUIREMENTS

Test results are needed by the end of preliminary design.

5. PRIORITY

Urgency: 1
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

Excessive margin may be required in order to meet performance requirements.

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GT-MHR PROGRAM
PC/IC FINNED TUBE RETENTION/WEAR PROTECTION DEVICE TESTS

DDN.C.41.03.08

PLANT: GT-MHR/System 41

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

Finned tubes in the precooler and intercooler are proposed to be supported by drilled plates or scalloped bars which are in direct contact with the tubes. Currently, a baseline design of the tube retention and wear protection (TRD) device for the bare tube exists; however, this design may have to be modified in order to be installed on externally finned tube helical bundles. This, coupled with the potential complexities of installation and the added cost of the TRD device, indicates a need for a better and simpler design and efficient installation tooling.

1.1 Summary of Functions/Assumptions

"Protect the Capability to Support Heat Transfer Surfaces". Assumption: Vibration wear and sliding wear protection methods will be verified.

1.2 Current Data Base Summary

The functions of the wear protection device in the current precooler and intercooler design are: to suffice as a manufacturing shim; to afford a sacrificial wear material; to provide vibration damping by providing a controlled clearance between the tube and plate; and to possibly transmit seismic loads from the tube to the radial support plates.

A sleeve and wedge type wear protection assembly was used in FSV and THTR designs. The FSV design consists of one piece sleeve and one piece wedge, with both having interlocking machined grooves to prevent their separation. The sleeve has one through length cut which offers extra flexibility without sacrificing the close fit. Both pieces have no hard facing coating for added wear protection. The THTR design consists of one piece sleeve and three piece wedge, and the mating surfaces are tapered machined. The ferritic parts are nitrided and 800H parts are chromium carbide coated.

The test program performed for the NP-MHTGR steam generator at ABB Combustion Engineering (CEGA-002925, Rev. N/C, "TRD Test Evaluation Report," November, 1993), resulted in a one-piece split, curved sleeve with tapered one-piece retention rings. The design and the installation tools were tested in several mockups. The results demonstrated practical, repeatable installation and acceptable design.

All of the above designs are marginally applicable for precooler and intercooler tube protection since they represent designs for bare tubes.

1.3 Data Needed

Data are needed to confirm the adequacy of the selected finned tube retention/wear protection device to perform the design functions throughout the design life of the plant and the ease of installation. Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

Sufficient test data are needed to demonstrate the following:

- The selected TRD is easy to fabricate and does not require overly complex machining.
- The TRD is easy to install with consistent repeatability.
- The TRD will perform its design function at operating temperatures.
- Development of tooling necessary for the TRD installation will also be an integral part of this DDN.
- The TRD will provide the desired wear protection against the flow induced vibration. The flow-induced vibration aspect will be addressed by DDN.C.41.03.05.

2. DESIGNER'S ALTERNATIVES

The alternatives are as follows:

2.1 Rely on the designs of Fort St. Vrain, THTR and NP-MHTGR for tube wear protection devices.

2.2 Develop alternate tube bundle support designs that do not require wear protection devices.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to design and test the finned tube retention/wear protection device or devices that have been chosen as a result of engineering trade studies. These tests will provide confidence that the TRD will perform the desired functions throughout the life of the plant, and that it can be installed on finned tube helical coils.

Alternate 2.1 was not chosen because it was not felt that analysis alone could adequately address all of the concerns. In addition, testing of the devices used in Fort St. Vrain, THTR and NP-MHTGR steam generators are for bare tubes.

Alternate 2.2 involves very detailed and costly trade studies, and the alternate tube bundle support method could potentially introduce new concerns in the design of the precooler and intercooler tube bundles.

4. SCHEDULE REQUIREMENTS

The results to be obtained prior to completion of preliminary design.

5. PRIORITY

Urgency: 2
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is Alternative 2.1. This could potentially result in a complex, expensive and unproven TRD design, and reduced heat exchanger reliability.

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Originator Date

7-26-94
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GT-MHR PROGRAM
VIBRATIONAL FRETTING WEAR AND SLIDING WEAR OF TRDs AND FINNED TUBES

DDN.C.41.03.09

PLANT: GT-MHR/System 41

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The wear protection method for the finned tubes, which are in direct contact with the drilled support plates or other support structures, is of concern in the present design of the precooler and intercooler tube bundles.

In the present design it is proposed that a tube retention and wear protection device (TRD) be mechanically attached to the tube at each location where a tube passes through a support. In order to alleviate thermal interaction stresses, the tubes are loosely held in the supports by providing a small clearance between the TRD and the supports. This may result in impact and fretting wear of the TRD due to the flow-induced vibration. Vortex shedding and/or turbulence are the major flow mechanisms which can contribute to the fretting wear of the TRD.

1.1 Summary of Functions/Assumptions

"Protect the Capability to Support Heat Transfer Surfaces". Assumption: Vibrational wear and sliding wear protection methods will be verified.

1.2 Current Data Base Summary

In December 1989 a review of the fretting and wear technology was performed under Subtask 6 of WBS 1713.2 Steam Generator Design Support. The review encompassed the majority of the experimental and analytical work performed at General Atomics and some of the important work done by Sulzer Bros., Central Electricity Research Laboratories (England), and Atomic Energy of Canada.

Based on the review it appears that the necessary fretting and impact wear rate data exists. Also, many analytical models which use the wear rate data to predict the long-term wear also are available. However, the fretting wear prediction analysis is not an exact science and the difference between predicted and actual wear may be significant. The analytical models are typically used to qualitatively examine the relative influence of the various parameters expressed in the equations such as frequency, clearance, impact forces, sliding distance, wear rate, vibration amplitude, and coefficient of friction.

1.3 Data Needed

A significant amount of fretting and impact wear rate data exists and different wear prediction models are available. However, the applicability of the usable data and verified, workable models to analyze the TRD for the precooler and intercooler for wear are marginal.

A testing program is needed to validate the use of existing wear rate data and wear prediction models for the TRD design. The purpose of the proposed test program is not to generate additional wear rate data, but to demonstrate that the existing TRD design is conservative and that it will protect the tube for the design life of the plant.

Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The following presents the applicable range of parameters and service conditions which influence the predicted wear of the TRD.

Temperature: 21°C to 177°C (70°F to 350°F)

Material Substrate: ½ Cr - ½ Mo

Coating: Nitriding

Clearance between tube O.D. and support I.D.: 0.508 mm (0.02 in.) max.

Environment: Helium with impurities - [TBD]

Helium Gap Velocity: 18 m/sec (60 ft/sec)

Natural Frequency of Tube: 24 Hz - 300 Hz

Vibration Amplitude: 0.127 mm - 0.254 mm (0.005 in. - 0.010 in.)

Coefficient of Friction: 0.4 to 0.6 (will be measured experimentally)

Wear Coefficient: [TBD]

Normal Impact Force: 1.4 kg - 3.6 kg (3 lb - 8 lb)

Damping Characteristic of Tube: 1% to 5% (will be measured experimentally)

Material Characteristics: Density and Modulus of Elasticity - ½ Cr - ½ Mo

Tube Geometry: O.D. and I.D., Externally Finned

2. DESIGNER'S ALTERNATIVES

2.1 Utilize the existing vibrational fretting wear and sliding wear data.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to conduct accelerated impact/fretting wear testing under prototypical geometrical and environmental conditions using prototypical tube dynamics.

Prior to initiating testing, a simple but conservative mechanistic model for tube fretting and wear prediction will be developed. This model will be validated by comparing the analytical results with the test results. The development of a complex model which simulates the time dependent motion of the helical tube and accounts for all nonlinearities (such as friction, impact forces, uneven clearances and sliding distance) would not be within the scope of this DDN.

Alternative 2.1 data were not generated using prototypical TRD geometry or tube dynamics (frequency, clearance, vibration amplitude, and normal impact force) and it is therefore difficult to assess the degree of conservatism or nonconservatism in the design of the TRD.

4. SCHEDULE REQUIREMENTS

The results to be available prior to the completion of preliminary design.

5. PRIORITY

Urgency: 2
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is to use the existing fretting and wear data.

The consequences of nonexecution of this test program could potentially result in an overly conservative design of the TRD which may significantly increase the cost of the heat exchangers. Should a nonconservative design emerge, it has the potential consequence of affecting precooler and intercooler performance and possibly life.

M. Basol 7-25-94

Originator Date

Alan M 7-26-94

Engineering Manager Date

Alan M for SAC 7-26-94

Project Manager Date

DATE: 7/25/94

GT-MHR PROGRAM
PC-IC LEAD-IN/LEAD-OUT/EXPANSION LOOP TUBE DESIGN AND FABRICATION

DDN.C.41.03.10

PLANT: GT-MHR/System 41

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

For those portions of each tube circuit not included in the helical bundle, data are needed to develop: spatial envelope; support configurations; thermal movement characteristics including as-installed and operating clearances; and assembly sequence.

1.1 Summary of Functions/Assumptions

"Channel Secondary Coolant Through Heat Exchanger", Assumptions:
Space allocated for the lead-in, lead-out and expansion tubes is sufficient.

Methods will be available to accurately predict support locations in the expansion loop in order to provide adequate thermal expansion accommodation.

Methods will be available to adequately predict the support locations in the lead-out tubes and expansion loop so that adequate tube-to-tube clearances could be provided, and multiple tube interaction and wear could be avoided.

Methods will be available to accurately predict support locations in the lead-out tubes and expansion loop in order to prevent tube binding.

1.2 Current Data Base Summary

Previous experience with similar designs (FSV, THTR) gives some information on spatial requirements for assembly, welding, means of support and wear protection. The information is very configuration dependent and generally not generic.

1.3 Data Needed

For the specific configuration of the GT-MHR precooler and intercooler, development of specific routing and support configurations is needed to confirm the adequacy of the spatial envelope and structural design. Testing via a mock-up of the non-helical portions of the tube bundle is needed to determine: Spatial envelope, characteristic thermal movements and interactions of tubes and supports, and the adequacy of clearances to avoid multiple tube interactions. Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

Test data required are:

- o Overall spatial requirements for assembly.
- o Tube-to-tube dimensional relationship when subjected to deflections representative of thermal movements.
- o Photographic documentation of assembly sequence(s) for the non-helical tubes.

2. DESIGNER'S ALTERNATIVES

The alternatives are as follows:

2.1 Do not perform mock-up test. Rely on design layout work and analysis including CAD and ANSYS (finite element) modeling as well as available FSV, THTR background.

2.2 Use less than prototypical (e.g., small scale plastic models) to partially satisfy data needs, i.e., spatial envelope and assembly sequence.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to perform a near full scale metallic mock-up of the non-helical portions of the tube bundles based on design layouts and analysis to be performed in preliminary design. Test results will be an integral part of the completion of preliminary design and will confirm adequacy of spatial envelope and structural design as inputs to PSSAR.

Alternative 2.1 represents risk of later changes to spatial envelope and consequent impacts on overall Nuclear Island design. The design configuration differs significantly enough in layout and size (number of tubes, tube size, finned tubes) from FSV and THTR that direct application of experience is questionable.

Alternative 2.2 will partially address the uncertainties of spatial envelope and assembly sequence, but will have limited value for determining structural adequacy.

4. SCHEDULE REQUIREMENTS

The results are needed prior to the completion of preliminary design.

5. PRIORITY

Urgency: 2
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback positions are Alternatives 2.1 and 2.2. Either alternative may lead to design schedule delays and design changes, and higher cost design/analysis iterations to arrive at a defensible final design.

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Originator Date

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Engineering Manager Date

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Project Manager Date

DATE: 7/25/94

GT-MHR PROGRAM
PC/IC INSTRUMENTATION ATTACHMENT TESTS

DDN.C.41.03.11

PLANT: GT-MHR/System 41

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

The lessons learned from earlier gas cooled reactors indicate that temperature measurements will be required at various locations within the tube bundles. The Instrumentation Requirements Study performed for the NP-MHTGR steam generator, for example, has recommended that measurements be made for gas temperature, steam/tube temperature, and structural considerations of stress, strain, and acceleration for first-of-a-kind (FOAK) instrumentation. Instrumentation will be required to obtain input for the Reactor Protection System, Investment Protection System, and Plant Control, Data, and Instrumentation System.

A testing program is needed to obtain data to be used in designing and installing the necessary instrumentation for operation of the GT-MHR precooler and intercooler. This includes heat exchanger performance instrumentation and those required by the control system, both of which are required for the lifetime of the unit. It also includes FOAK instrumentation which need only last for the early stages of the heat exchanger lifetime. Mockups are needed to confirm both the design and installation techniques for critical instrumentation as well as to confirm the ability for removal and replacement for lifetime instrumentation.

1.1 Summary of Functions/Assumptions

"Transfer Heat from Primary Coolant to Heat Exchanger (Performance Evaluation Methodology will be Verified)". Assumption: Instrumentation, particularly for the FOAK unit, is needed to confirm heat exchanger performance predictions implicit in the evaluation models. Instrumentation can be installed in critical locations within the heat exchanger and such instrumentation will be reliable with long-term integrity. Some instrumentation must be removable in order to be replaced in the event that it is rendered inoperable.

1.2 Current Data Base Summary

Prior HTGR steam generators have required instrumentation (ABB Report DPS-91-269, "Instrumentation Requirements Study for NP-MHTGR Steam Generator," September, 1991).

AGR - One of four steam generators in the first reactor at each site was extensively instrumented for measurements of vibrations and strains. Thermocouples were installed in all steam generators.

THTR - The internal instrumentation consisted of 71 thermocouples; 21 were for gas temperatures around the tubes and 50 were for steam/water temperatures inside the tubes. Accelerometers and strain gages were considered not to be reliable enough and they were not included.

FSV - The instrumentation was extensive and is difficult to summarize. There were 13 units (steam generators) built, one of which was fully instrumented with 116 thermocouples while the standard units had 24 thermocouples. One unit had 70 strain gages for vibration data. Five units had additional thermocouples to provide gas temperatures and superheater temperature distribution.

1.3 Data Needed

Test data are needed for use in designing and installing into the precooler and intercooler, the appropriate instrumentation for reliable operation of the units. Mockups will confirm the designs and assembly techniques for critical instrumentation. The ease of removal and replacement can be demonstrated to a degree. Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

The data are required at the following service conditions:

Coolant	-	Helium on the shell side and water on the tube side
Operating Conditions	-	[15%] to 100% core power
Helium inlet temp.	-	Up to 177°C (350°F) at bundle inlet
Helium outlet temp.	-	25°C (78°F) at bundle outlet
Helium pressure	-	Up to 4.8 MPa (700 psia) at bundle inlet
Helium flow	-	Up to 341 kg/s (850 lb/s)
Water inlet temp.	-	Up to 38°C (100°F)
Water pressure	-	Up to 0.7 MPa (100 psia) inlet
Water flow	-	3.3 m/s (10 ft/s)
Water outlet temp.	-	Up to 93°C (200°F)

2. DESIGNER'S ALTERNATIVE

2.1 Utilize previous designs which may not be suitable for the GT-MHR precooler/intercooler designs.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected approach is to use mockups to replicate the internal surfaces where instrumentation will be required. The design and assembly techniques will be used on representative surfaces.

4. SCHEDULE REQUIREMENTS

Test results are needed early in final design in order to finalize the precooler and intercooler designs and to be used in interfaces with Instrumentation organizations. The expected designs for instrumentation are expected to be incorporated into component test plans to determine their effects on gas flow distribution where critical.

5. PRIORITY

Urgency: 2
Cost Benefit: M
Uncertainty in Existing Data: M
Importance of New Data: M

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The fallback position is to use data from earlier designs which are not the same as the GT-MHR precooler and intercooler designs.

The consequences of nonexecution of this program would place at risk the ability to provide adequate instrumentation for the heat exchangers for either the FOAK or NOAK units. Performance of the units would have to be evaluated on the basis of the resulting instrumentation.

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Originator Date

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Project Manager Date

DATE: 7/25/94

GT-MHR PROGRAM
TUBESIDE EROSION/CORROSION TESTS

DDN.C.41.03.14

PLANT: GT-MHR/SYSTEM 41

1. REQUIREMENT OR DESIGN FEATURE REQUIRING EXPERIMENTAL DATA OR VALIDATION TESTING

½ Cr - ½ Mo material is used for the precooler and intercooler tubing. During the sizing of the tubing for these heat exchangers, certain erosion/corrosion allowance is included in order to account for tube wall thinning, during the life of these units, due to this phenomena. These phenomena are dependent on the water chemistry, tube material, operating conditions (flow rate, temperatures), and tube bundle geometry.

1.1 Summary of Functions/Assumptions

"Protect the Capability to Transfer Heat from Primary Coolant to Heat Exchanger," Assumption :

The erosion/corrosion allowance used in the design of the heat exchanger tubing is conservative.

1.2 Current Data Base Summary

The phenomena of erosion/corrosion is defined as the interaction of mechanical wear and corrosion, where the corrosive action is initiated by erosion of the protective metal oxide layer from the metal surface. Without this protective layer, i.e., magnetite, the steel alloys are vulnerable to general corrosion/dissolution.

Some limited experimental work has been performed in U.S. and Europe (i.e., "Mechanistic Aspects of Erosion-Corrosion Under Boiler Feedwater Conditions," G. J. Bignold, et al, Water Chemistry of Nuclear Reactor Systems 3, Volume 1, British Nuclear Energy Society, London, 1983) investigating the effect on wall thinning of various water chemistry parameters (pH and oxygen), geometry factors, and operating conditions (flow rates and temperatures). This work was performed on carbon steel materials up to high chrome materials. Even though neither the materials nor the parameters exactly duplicated that of the GT-MHR precooler and intercooler materials and parameters, some approximate indication of the erosion/corrosion rates can be calculated from the existing data.

1.3 Data Needed

Data are needed to quantify the tubeside erosion/corrosion rates for the precooler and intercooler tubing as a function of the operating parameters, water chemistry ranges, and tube geometry. The workscope for the organization executing this data would consist of, as a minimum:

a. Extensive review of the available literature and data on this subject,

b. Perform testing under anticipated operating conditions, including off-nominal water chemistry,

c. Quantify the erosion/corrosion rates,

d. Provide basis and justification for the above recommendations,

Quality assurance must be in accordance with the requirements for experimental data or validation testing for non-safety related components.

1.4 Data Parameters/Service Conditions

Sufficient data are required to quantify the tube side erosion/corrosion characteristics of the ½ Cr - ½ Mo tubing material under representative GT-MHR operating conditions and water chemistry.

The test should be conducted to simulate the following conditions:

a. Normal Operating Conditions:

- 68°F (20°C) to 200°F (93°C) water temperature
- Up to 0.7 MPa (100 psia) water pressure
- Water chemistry [TBD]
- 1000 kg/s (2200 lb/s) water flow rate
- Duration (TBD)

b. Off-Normal Operating Conditions:

- TBD

2. DESIGNER'S ALTERNATIVES

The alternatives are as follows:

2.1 Using the limited data available make conservative estimates of erosion/corrosion rates under GT-MHR conditions for the precooler and intercooler tubing.

2.2 Use high chrome tube material to reduce uncertainty.

3. SELECTED DESIGN APPROACH AND EXPLANATION

The selected design approach is to use ½ Cr - ½ Mo material for the precooler and intercooler tubing, and perform limited tubeside erosion/corrosion tests under simulated GT-MHR conditions to verify the assumed erosion/corrosion rates. Alternative 2.1 may lead to an overly conservative or nonconservative design depending on the interpretation of the existing data. Alternative 2.2 would result in more expensive tube bundles.

4. SCHEDULE REQUIREMENTS

Initial test data and the accompanying recommendations are needed by the end of the preliminary design phase. If necessary, the test program could be continued through final design to obtain long-term confirmatory data.

5. PRIORITY

Urgency: 2
Cost Benefit: H
Uncertainty in Existing Data: H
Importance of New Data: H

6. FALLBACK POSITION AND CONSEQUENCES OF NONEXECUTION

The consequences to the program of nonexecution would be to limit or compromise precooler and intercooler operation, or higher than necessary capital costs.

M. Basol 7-25-94
Originator Date

7-26-94
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DATE: 6/30/94

GT-MHR PROGRAM
PCS COMPONENT REMOTE REPLACEMENT DESIGN VERIFICATION
DDN C.41.05.01

PLANT: GT-MHR/System 41

[LATER]

APPENDIX A
GT-MHR SERVICE CONDITIONS FOR FUEL/FISSION PRODUCT DDNs

This Appendix summarizes preliminary GT-MHR service conditions which are referenced in Fuel/Fission Product DDNs.

Table A-1 contains the reactor core parameters for normal operation based on preliminary calculations and engineering judgment. The allowances represent additional variation of the nominal values from both calculation uncertainties and design evolution based on engineering judgment. The allowances are additive to the nominal values. The coolant impurity level estimates come from consideration of Dragon reactor and THTR with low moisture ingress, plus Peach Bottom and Fort St. Vrain experience.

Table A-2 shows reactor conditions under design-basis events of cooldown. Since moisture transport under accident conditions has not been extensively analyzed, the moisture levels indicated are conservative estimates subject to change.

Table A-3 summarizes service conditions of the GT-MHR Power Conversion System and reactor vessel for fission product transport during normal operation and design-basis events.

Table A-1
REACTOR SERVICE CONDITIONS FOR NORMAL OPERATION

Parameters	Value
Environment	Helium
Nominal fuel operating temperature range[(a)], (instantaneous @ full power)	[550° to 1250°C (1022° to 2282°F)]
Additional allowance for design uncertainties	[150°C (270°F)][(b)]
Maximum nominal time-averaged fuel temperature	[1150°C (2102°F)]
Additional allowance for design uncertainties	[70°C (125°F)]
Maximum nominal fissile particle burnup, FIMA	[25%]
Design allowance on fissile burnup, FIMA	[1%]
Maximum nominal fertile particle burnup, FIMA	[6%]
Design allowance on fertile burnup, FIMA	[0.5%]
Maximum fast neutron fluence ($E \geq 29$ fJ)	[4.2×10^{25} n/m^2]
Design allowance on fast neutron fluence	[0.5×10^{25} n/m^2]
Maximum coolant pressure	[7.07 MPa (1025 psi)]
Range of coolant impurity levels during power operation:	
H_2O	[0.07 to 0.7 Pa (0.01 to 0.1 ppmv)]
CO	[1.5 to 6 Pa (0.2 to 0.8 ppmv)]
CO_2	[0.2 to 1.5 Pa Pa (0.03 to 0.2 ppmv)]
Total oxidants	[<7 Pa (<1 ppmv)]
H_2	[3 to 10 Pa (0.5 to 1.5 ppmv)]
CH_4	[0.3 to 1.5 Pa (0.05 to 0.2 ppmv)]
Nominal fuel temperature range, refueling	[100° to 500°C (212° to 932°F)]
Environment, refueling	Helium @ [0.1 MPa (1 atm)]

(a)Fuel operating temperatures are based on "fuel placement" refueling strategy.

(b)Conversion for allowance is for a differential temperature and the 32°F adjustment does not apply.

Table A-2
REACTOR CONDITIONS FOR CORE CONDUCTION COOLDOWN EVENTS

Parameters	Value
Environment for transient events (depressurized conduction cooldown):	He $He/H_2O/CO/H_2$ $He/CO/N_2$
H_2O	[Negligible to TBD]
CO	[0 to 35 kPa (0 to 0.35 atm)]
N_2	[0 to 65 kPa (0 to 0.65 atm)]
Range of H_2O impurity levels (pressurized conduction cooldown)	[1 to TBD kPa (0.01 to TBD atm)]
Fuel temperature range during pressurized cooldown event	[550° to 1300°C (1022° to 2372°F)]
Additional allowance in peak for design uncertainty	[100°C (180°F)]
Fuel temperature range during depressurized cooldown event	[550° to 1600°C (1022° to 2912°F)]
Additional allowance in peak for design uncertainty	[125°C (225°F)][a]
Duration of event:	
Pressurized conduction cooldown	[100 hr]
Depressurized conduction cooldown	[150 hr]

[a]Conversion for allowance is for a differential temperature and the 32°F adjustment does not apply.

Table A-3
POWER CONVERSION SYSTEM AND VESSEL SURFACE CONDITIONS DURING NORMAL OPERATION AND ACCIDENTS

Parameters	Value
Normal Operation	
Reynolds Number	>5000
PCS Materials (Candidate Materials)	[IN 100, SS316L, 1/2%Cr-1/2%Mo, 9%Cr-1Mo-V]
Metal temperature range:	
IN 100 (turbine)	[450 to 900°C (842 to 1652°F)]
SS316L (recuperator)	[100 to 550°C (212 to 1022°F)]
1/2%Cr, 1/2%Mo (precooler)	[100 to 150°C (212 to 302°F)]
9%Cr-1Mo-V (vessel)	[100 to 550°C (212 to 1022°F)]
Particulate matter:	
Composition	[Amorphous carbon, ferritic metaloxide, graphite]
Particle size distribution	[0.01 to 10] μm
Gasborne concentration	[3 x 10-3 g/m^3]
Surface loading	[5] g/m^2
Rapid Depressurization	
Environment	He
Coolant outlet temperature range	TBD to 850°C (TBD to 1562°F)
Range of coolant impurity levels:	
H_2O	[14 to TBD Pa (140 to TBD μatm)]
CO	[35 Pa (350 μatm)]
CO_2	[14 Pa (140 μatm)]
Total oxidants	[<70 to TBD Pa (700 to TBD μatm)]
H_2	[70 Pa (700 μatm)]
Coolant pressure range	70 to 1 atm
Shear ratio	[0.5 -3]
Blowdown duration	1 to 2 min
Reynolds Number	TBD
Metal temperature range:	
IN 100 (turbine)	[450 to TBD°C (842 to TBD°F)]
SS316L (recuperator)	[100 to TBD°C (842 to TBD°F)]
1/2%Cr-1/2%Mo (precooler/intercooler))	[100 to TBD°C (212 to TBD°F)]
9%Cr-1Mo-V (vessel)	[100 to TBD°C (212 to TBD°F)]

Table A-3 (Continued)

Parameters	Value
Water Ingress (PCS)	
Environment	He/H_2O
Coolant temperature range	100 to TBD°C (212 to TBD°F)
Range of coolant impurity levels	[0.01 to TBD] atm H_20
Coolant pressure range	70 to 1 atm
Metal temperature range:	
IN 100 (turbine)	[450 to TBD°C (842 to TBD°F)]
SS316L (recuperator)	[100 to TBD°C (212 to TBD°F)]
1/2%Cr,1/2%Mo (precooler/intercooler)	[100 to TBD°C (212 to TBD°F)]
9%Cr-1Mo-V (vessel)	[100 to TBD°C (212 to TBD°F)]
Reynolds Number	>5000
Shear ratio	<1
Steam quality	[0 to 100]%
Contact time	[0.1 to TBD] hr

GENERAL ATOMICS

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