ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

SUMMARY REPORT
ML-1 PRESSURE VESSEL TECHNOLOGY EVALUATION

By

W. K. Eggert
W. F. English

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Approved by:

R. H. Chesworth / GBE
R. H. Chesworth
Supervising Representative
Contract AT(10-1)-880

AEROJET-GENERAL NUCLEONICS

San Ramon, California

A Division of Aerojet-General Corporation

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ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

SUMMARY REPORT

ML-1 PRESSURE VESSEL TECHNOLOGY EVALUATION

I. INTRODUCTION

In early FY 1965, a program was initiated under the AGCRSP which has as basic goals the determination of the limits of the ML-1 technology and, where appropriate, the extension or extrapolation of this technology for use in higher-performance compact nuclear power plants.* One of the areas selected for investigation was the calandria/pressure vessel. The objectives of the work were to refine the analytical techniques employed in the design of ML-1 type pressure vessels (to permit the definition of the probable performance limits of the existing unit as well as to provide a firm basis for the design of higher performance reactors) and to evaluate high-performance materials for potential use in an advanced pressure vessel.

Work on this task began in November 1964. In December of that year, the USAEC directed that the activity be brought to an orderly conclusion and that the conceptual design of an advanced pressure vessel be prepared which incorporated the limited results developed under the investigation. The conceptual design has been presented in a separate document (Ref. 1); this report has been prepared to summarize the activity completed under the pressure vessel technology task of the ML-1 Technology Program.

*For a fuller discussion of the ML-1 Technology Program, see AN-AGCR-769A, Section XII, October 1964.

II. SUMMARY

A limited program of evaluation of the ML-1 technology as related to the design of the calandria/pressure vessel assembly was completed. This work included:

- A photoelastic experimental program which resulted in the conclusion that values recommended by Langer and O'Donnell for the effective elastic constants employed in the analysis of ligament stresses in the ML-1 type tube sheets in the past results in a good approximation of the bending constants but in a value of the tensile elastic modulus which is about 40% too high.
- Several modifications to the TSA computer code for stress calculations which improved the precision and flexibility of the code.
- A very preliminary evaluation of the properties of candidate materials for use in a high-performance, advanced ML-1 type pressure vessel.

III. OBJECTIVES

The objectives of the pressure vessel technology task were:

a. Refine the analytical techniques employed in the design of ML-1 type calandria/pressure vessel assemblies including:

1. Experimental verification of the effective elastic constants (modulus of elasticity and Poisson's ratio) used in the stress calculations.
2. Refinement of the TSA computer code for calculation of deflections and stresses in ML-1 type pressure vessels to incorporate the latest advances in calculational techniques and increase the versatility of the code.
3. Review and refinement, if indicated, of the 2DRZ computer code for calculating temperature profiles in ML-1 type pressure vessels.

b. Evaluate the characteristics of various high performance materials which might be used in an advanced pressure vessel.

As a result of the directive to bring the work to an orderly conclusion, only a very limited effort was expended in the accomplishment of objectives a.3 and b above.

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IV. DISCUSSION

A. DESCRIPTION OF CALANDRIA/PRESSURE VESSEL

The configuration of the assembly under investigation is best described by a review of the ML-1 pressure vessel assembly. The unit is, basically, a 61-tube calandria with tube sheets at either end. The tube sheets are integral with the inlet and outlet plenums which, together with the plenum caps, form the pressure vessel (Figure 1).

The hot pressurized gas enters the upper plenum, flows downward through the fuel elements which are contained in the calandria tubes and is collected in the lower plenum from which it flows out the outlet duct. The tube sheets are thermally insulated and are cooled by water flowing in internal passages. The tubes are rolled into the tube sheets and seal welded. The upper plenum cap is removable to permit access to the fuel elements.

Nominal ML-1 pressure vessel operating conditions are presented in Table 1.

TABLE 1 - ML-1 PRESSURE VESSEL OPERATING CONDITIONS

Gas inlet temperature, °F	800
Gas outlet temperature, °F	1200
Gas pressure, psig	300
Gas flow, lb/sec	26.5

B. PRESSURE VESSEL DESIGN ANALYSIS

The design of a calandria/pressure vessel assembly of the ML-1 type requires that several complex analyses be performed to permit the selection of appropriate materials, to establish dimensions and to assure that the assembly will perform satisfactorily. The temperature profiles in the tube sheets must be estimated; this calculation must include consideration of the heat flow from the gas through the insulation, heat flow from the hot gas through the fuel ele-

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FIGURE 1. ML-1 PRESSURE VESSEL POSITIONED IN REACTOR SKID

ment "seat" and heat removal by the internal coolant and by the moderator water (both directly where the water is in contact with the inner surface of the tube sheet and indirectly by conduction along the tubes). The elastic properties of the tube sheet must be estimated; this determination must include consideration of the effect of the tube sheet perforations, the trepanned section for the tube-to-tube sheet seal welds, the tube sheet internal cooling passages and the non-symmetrical perforation pattern. Finally, the results of the temperature profile and the determination of elastic properties must be combined in the calculation of deflections and stresses in the tube sheet and plenum walls; this calculation must include consideration of the "elastic foundation" provided by the calandria tubes, the loading resulting from the gas pressure and possible stress concentrations which exist in the design.

Several acceptable methods are available for analyzing the deflections and stresses in perforated plates. Most of these methods involve the definition of an equivalent solid plate which has the same characteristics as the perforated plate but which is significantly simpler to analyze. The equivalent solid plate is normally defined as having the same dimensions as the perforated plate but the perforations are accounted for by either assuming a lower value for the flexural rigidity or by estimating appropriately adjusted values for the modulus of elasticity and Poisson's ratio. The latter method was used in the analysis of both the ML-1 and ML-1A calandriae.

The optimum method for estimating the "effective" values of the modulus of elasticity and Poisson's ratio (hereafter called the elastic constants) has been the subject of considerable investigation in recent years. The initial activity was concerned with the theoretical derivation of elastic constants; this technique was used in the ML-1 design analysis. More recently, photoelastic experimental techniques have been employed to develop data from which the elastic constants can be derived. The work of Langer and O'Donnell (Ref. 2) was based on this experimental technique and the constants derived by these investigators were used for the analysis of the ML-1A pressure vessel design.

Actually, while the Langer and O'Donnell approximations of the elastic constants represent a significant improvement over the theoretically-derived values, these are not really valid for the analysis of ML-1 type tube

sheets; the plate thickness to hole pitch ratio (H/R) in the ML-1 case is less than the value of 4 used by Langer and O'Donnell and the constants derived by those investigators makes no allowance for trepanning and internal cooling passages. This situation represents the primary justification for undertaking the work reported herein.

C. EXPERIMENTAL DERIVATION OF ELASTIC CONSTANTS

Stress analysis of an ML-1 type pressure vessel is difficult because of the complex configuration of the tube sheet (i.e., internal cooling passages, trepanning for tube-to-tube sheet seal welds and the nonsymmetrical perforation pattern). Acceptable methods have been developed for the analysis of perforated plates with a uniformly spaced, symmetric hole pattern and a large plate thickness-to-hole pitch ratio. The error associated with the use of this method for design of an ML-1 type tube sheet is not known. Consequently, an experimental program was undertaken to derive values for the effective elastic constants and to evaluate the stress concentration factors in an ML-1 type tube sheet. After careful evaluation of several applicable experimental techniques, it was concluded that the photoelastic technique would provide the greatest amount of data pertinent to the problem. The photoelastic experiments were performed at the Sacramento Facilities of AGC under the direct supervision of R. C. Sampson, who earlier performed the experimental photoelastic work used by Langer and O'Donnell (Ref. 2).

The photoelastic experimental program had two principal objectives:

1. To derive the elastic constants for a perforated tube sheet of the ML-1 type and compare the results with the data given by Langer and O'Donnell to determine the suitability of those data (or develop revised data) for general design optimization calculations.
2. To determine the effectiveness of the design calculational procedures to predict accurately the stresses and deflections in an ML-1 type tube sheet when subjected to a differential pressure loading.

It has previously been demonstrated (Ref. 2) that the effective elastic properties of a perforated plate (i.e., the effective elastic constants E^*/E and ν^*) can be determined from photoelastic tests of perforated coupons subjected to pure bending or simple tension. Extensive data obtained from such

tests, conducted by Sampson, were included in the design procedures presented by Langer and O'Donnell. However, these data pertain to the bending of plates with a thickness-to-hole pitch ratio (H/R) of 4 or more, which is greater than that of the ML-1 tube sheet. In addition, these data do not include the effects of the coolant passages or the trepanning in the ML-1 design.

A series of four coupon tests was devised to evaluate the perforated plate properties of an ML-1 type tube sheet. The coupon models had a relative thickness (H/R) of 2.48 and a ligament efficiency (h/R) of 0.247 which is typical of the central portion of an ML-1 type tube sheet. The models were cast and machined from a special photoelastic resin. The sequence of coupon fabrication and testing was as follows:

- The coupon was perforated in a uniform pattern and stress-frozen under a pure bending load. The deformations were measured and the effective modulus (E^*/E) and Poisson's ratio (ν^*) were determined. The coupon was annealed to a stress-free condition.
- The perforations were modified to include the trepanned areas and the annular cooling passages and the coupon was stress-frozen under a pure bending load. Deflections were measured and values of E^*/E and ν^* were determined. The coupon was annealed to a stress-free condition.
- Lateral coolant passages were machined through the ligaments of each row of holes. The bending test, measurements and annealing procedures were repeated.
- The coupon was subjected to a simple tension load and stress-frozen. The deformations were measured and values of E^*/E and ν^* were determined for the simple tension case. A sufficient number of slices were removed from the coupon to determine the complete surface stress distribution around a typical hole.

The deflection of a coupon in pure bending is shown in Figure 2.

An analysis of the data from the coupon tests revealed the following:

- The bending elastic moduli quoted in Reference (2) are in good agreement with those determined from the test of the simple perforated coupon.

FIGURE 2. ML-1 TUBE SHEET COUPON DEFLECTED IN
PURE BENDING AND STRESS-FROZEN

- The trepanned region and the annular enlargement of the tube holes in combination reduce the effective bending elastic modulus by approximately 20 percent.
- The elastic properties recommended in Reference (2) provide a satisfactory approximation for purposes of the bending stress analysis of ML-1 type tube sheets.
- The tension elastic modulus observed in the coupon with the ML-1 configuration is approximately 27 percent lower than that of a simply perforated specimen.
- The effective elastic modulus from Reference (2) is not satisfactory for analysis of membrane forces in ML-1 type tube sheets. The value is 40 percent larger than that indicated by the experimental program.
- Uniaxial tension stress concentrations in the ML-1 hole configuration are on the order of 60 percent larger than in simple perforations of the same nominal ligament width/hole pitch ratio.
- Values of the elastic constants applicable to ML-1 type tube sheets are:

E^*/E (bending)	0.196
E^*/E (tension)	0.134
ν^*	0.46

A half-scale photoelastic model of the ML-1 tube sheet was fabricated and tested to compare the measured and calculated values of stress in the tube sheet. A casting mold with 61 cores (Figure 3) was prepared and the scale model tube sheet including tube holes, coolant channels and trepanned regions was cast (Figure 4). The model was positioned in a loading fixture and subjected to uniform differential gas pressure acting across a rubber membrane. Pressure over the tube sheet perforations was counterbalanced by the dead weight of loose-fitting metal cylinders resting on the membrane. The model was simply supported on a ring near the outer diameter. The model was deflected under pressure, at temperature, and frozen in the deformed shape. The deflected shape of the model was determined by detailed measurements. Slices were removed from the model to determine stresses at all critical locations. A photo-

FIGURE 3. ML-1 TUBE SHEET PHOTOELASTIC MODEL CASTING MOLD

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FIGURE 4. HALF-SCALE ML-1 TUBE SHEET MODEL

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elastic representation of stresses in the model is shown in Figure 5.

The relative ligament stresses in the tube sheet model were determined (Figure 6). As this figure indicates, the maximum ligament stresses (53 psi stress per unit differential pressure) occur near the center of the tube sheet at the outer surface of the tube sheet. The compression surface ligaments experience a higher stress than the tension surface at the same radial location (r/a). An appreciable stress concentration occurred at the coolant holes drilled in the rim, normal to the tension surface, although this was not the location of the maximum absolute stress. The details of the photoelastic experiment and analysis are summarized in Reference 3.

D. CODE DEVELOPMENT

1. Temperature Distribution

The 2DRZ program for the IBM 7094 computer was developed to determine the temperature profiles in ML-1 type pressure vessels required for an evaluation of the stresses and deflections. The code calculates the temperature at selected points in a two-dimensional analytical model resulting from heat transfer by conductance and from nuclear heating. A utility code (AS71) is used in conjunction with the 2DRZ program for the solution of simultaneous algebraic equations which, in this case, are of the form:

$$\begin{aligned} Q_{\text{gen}} = & (C_{m-1, n} + C_{m+1, n} + C_{m, n-1} + C_{m, n+1}) T_{m, n} \\ & - (C_{m-1, n} T_{m-1, n}) - (C_{m+1, n} T_{m+1, n}) \\ & - (C_{m, n-1} T_{m, n-1}) - (C_{m, n+1} T_{m, n+1}) \end{aligned}$$

where: Q_{gen} = the volumetric heat generation rate

C = heat conductance

T = temperature, and

m and n are coordinates of the point under investigation in the R-z coordinate system.

A detailed description of the theory and use of the 2DRZ and AS71 programs is presented in Reference 4.

The programs described above were used to determine the temperature for the evaluation of stresses during the design of both the ML-1 and

FIGURE 5. PHOTOELASTIC REPRESENTATION OF STRESS IN THE DEFLECTED HALF-SCALE ML-1 TUBE SHEET MODEL

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FIGURE 6. PRIMARY STRESS DISTRIBUTION IN SIMPLY SUPPORTED ML-1 TUBE SHEET SUBJECTED TO DIFFERENTIAL PRESSURE LOADING

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ML-1A pressure vessels. During the ML-1 pressure vessel technology investigations reported herein, these codes were reviewed to determine their adequacy for the intended use; this review did not reveal any need for modification of the codes.

2. Stress Calculation

The TSA program for the IBM-7090/7094 computer was developed to calculate the stresses in ML-1 type pressure vessels. Basically, the code solves the classic stress analysis equations for a solid plate "equivalent" to the perforated plate under analysis when supported by an elastic foundation (the calandria tubes). As described earlier, this method of calculation involves the use of "effective" elastic constants and the code includes an option which permits the selection of either theoretically determined or experimentally determined effective constants for use in the calculation. A second option permits the calculation of stresses either with or without consideration of tube sheet internal cooling channels.

The analytical model used in the code is shown in Figure 7. Note that six temperatures (as calculated by the 2DRZ code) are used to establish the temperature profile across the tube sheet TS 1, A, B, C, F and H) and that two zones are provided in the perforated region (to permit the analysis of a calandria with two different pressure tube wall thicknesses). The equation for the temperature profile is determined by the computer program; this equation is a polynomial and the constant coefficients are determined by a curve fitting subroutine.

The TSA code examines only one end of the pressure vessel and the input must represent the end with the most extreme temperature and pressure conditions. The difference in pressure between the two ends of the calandria is small; the equivalent pressure resulting from the fuel element holddown devices (~ 15 psi) and the pressure drop through the pressure tubes (~ 15 psi) results in pressure loadings on the lower tube sheet which are only about 10% less than those on the upper tube sheet. Heat transfer across the fuel element seat (from the hot gas to the tube sheet) results in higher temperatures in the upper tube sheet than are normally found in the lower tube sheet, despite the higher gas temperatures which normally occur in the lower plenum. As a consequence of the conditions described

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FIGURE 7. TSA ANALYTICAL MODEL

above, the upper end of the calandria is normally chosen for TSA analysis. A detailed description of the TSA program, including the FORTRAN input format and a sample problem, is presented in Reference 5.

The analytical methods (Ref. 6 and 7) and the TSA code, as described above, were used to evaluate the GCRE and the ML-1 pressure vessels and were used in the preliminary design of the ML-1A vessel (Ref. 8).

The TSA code was modified under the program reported herein in the following ways:

- Provision was made to convert the stresses in the "equivalent" solid plate to actual perforated plate stresses by the procedures developed by Langer and O'Donnell. This change makes the output of the code more directly useful.
- Provision was made to permit the calculation of pertinent tube sheet parameters at any radius smaller than R_2 (Figure 7).
- Provision was made for the calculation of discontinuity stresses in the pressure tubes at the tube-to-tube sheet joint.
- Provision was made to print out the thermal factors and solutions to the simultaneous boundary equations to permit an examination of these data as a check in the calculation.

E. MATERIALS EVALUATION

As indicated earlier, only a very limited effort was undertaken to evaluate materials which might be suitable for extending the limits of the ML-1 technology. Candidate materials were selected from a review of physical properties as reported in the literature and data reflecting the strength of such materials at various temperatures in the range of interest were developed (Figure 8).

FIGURE 8. PROPERTIES OF CANDIDATE PRESSURE VESSEL MATERIALS

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3. Photoelastic Analysis of the Advanced ML-1 Reactor Plenum Chamber Tube Sheet, AN-AGCR-885 (Technical Memorandum 18SRO, Aerojet-General Corporation, Sacramento Plant), April 1965
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