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FACTORS IN THE DESIGN AND MANUFACTURE OF LARGE HIGH PRESSURE AND HIGH TEMPERATURE TRIAXIAL CELLS

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Abstract: Factors important to the design of vessels for testing the physical and hydraulic properties of rock samples of the order of one meter diameter by three meters long are discussed. The stored energy of water and nitrogen gas pressurized at 60 MPa and 200° C are shown to be comparable. Some constraints imposed by heating needs, vessel material selection, cell geometry, materials handling, and safety are reviewed.

Introduction

Because of our need to understand the effect of the sample size upon rock and fracture behavior, triaxial tests on rock samples of the order of one meter in diameter have been suggested (Pratt *et al.*, 1972) and a few tests on samples up to 0.9 m have been reported. IIT Research Institute tests (Singh and Huck, 1972) used the horizontal arrangement shown in Figure 1 to study the mechanical response of granite and limestone at confining pressures to 40 MPa and LBL is currently using the system shown in Figure 2 (capable of confining pressure to 5 MPa) to study the hydraulic characteristics of fractured granite. Both systems were designed to operate at ambient temperature. It seems probable that any large new triaxial cell will be required to extend these test parameters. For example, an elevated temperature capability as well as a larger stress range will surely be specified in view of the requirements of the energy and waste storage programs. These requirements will significantly increase the cost and complexity of the unit as well as the time required for a suite of tests.

To establish a sense of what the word "large" might imply when discussing a triaxial cell for rock testing, let us make the following assumptions: the sample will be one meter in diameter, it will have an l/d ratio of three, and, an additional half meter of length will be required for a load cell, etc. A radial space of 0.2 meters will be allowed for the instrumentation and assembly clearance, but no internal heater will be required - or, if required, it will be used with a smaller sample. These assumptions define a pressurized volume of 1.4 m diameter by 3.5 m high, or 5.4 m^3. The cell end closures may add 2.5 diameters to the height and the load frame may add a similar amount. This defines a cell assembly 6 m high and a load frame 9 m high. By the time one adds 3 m for a heavy bridge crane, the room height is 12 m.

From the estimated cell size we can make some similarly crude estimates of costs. If we assume a cell wall thickness of 0.25m and add 40% additional weight for end closures, the cell would weigh about 90 tons. Since this type of special hardware is likely to cost $10 to $20 per pound, we have an order of magnitude cost of $3 million. That is just for the cell. By the time we add the load frame, the heating and pressurizing gear, instrumentation and controls, the cost might be of the order of $10 million. That figure may double from the addition of buildings, foundations, blast walls, cranes, rock manipulators and miscellaneous support facilities. If inflation adds ten per cent per year and the project is funded in five years, the total cost would increase to $32 million. An additional rule of thumb may be borrowed from experience with large nuclear accelerators where the annual operating budget can be estimated at 20% of the capital cost. If the facility requires 5 years to engineer and erect, the average operating budget and average yearly construction budgets will be similar. In the absence of any performance specifications, these numbers have little value other than to provide a frame of reference for the following comments.

The cell volume is one of the most important design parameters not only because of its impact on the size of the system but also because of its impact upon safety as a result of the energy stored in the pressurized volume. The hydrostatic fluid will also have a large impact on this stored energy and upon other aspects of the design. While pressurized water at room temperature has a relatively low value of stored energy per unit volume, its stored energy can be surprisingly large if the water is at high temperature. One cubic meter of water at 60 MPa and ambient temperature would have a stored energy of about 30 MJ, but, at 200°C it would have a stored energy of about 800 MJ. If it were suddenly released to atmospheric pressure, about 20 percent of the water would be converted to steam and about 125 MJ of energy would be available to do work (Hansen, 1980). However an equal volume of hot nitrogen gas would have a stored energy of 143 MJ. If we note that TNT has an explosive energy of about 4.5 MJ/kg we can gain a considerable respect for the potential damage in case of a sudden vessel failure.

Sample Heating

There are a number of factors which hinge on the sample heating specifications. If the heater is to be located within the vessel, the volume of the vessel grows and, along with that volume, the stored energy grows. The internal heater is vulnerable to damage during sample installation, its servicing becomes more constrained by the problem of access, and it may represent a hazard to the rock instrumentation. On the other hand, if the heater is outside the vessel, the thermal gradient through the vessel wall causes undesirable thermal stresses in the vessel and the elevated vessel temperature may create problems in maintaining seals. Elastomeric seals are simple and reliable to at least 200° C. Metallic seals are applicable to much higher temperatures but are difficult to maintain - especially in very large sizes. If a sample temperature greater than 200 °C is specified, an internal heater will probably be required.

In heating or cooling a rock sample, the dominant time lag is probably imposed by the need to protect the sample from large thermal stresses and the need to wait for thermal equilibrium to reestablish itself. Hansen, (1980) used a limiting thermal gradient of 80 K/m in a finite difference computer program to predict the heatup rate for a 0.75 m diameter granite sample when using an external heater limited to 200° C and nitrogen gas at 70 MPa - see Figure 3.

Vessel Material

Vessels manufactured for this type of service may become a safety hazard unless the alloy and its processing are very carefully selected, a rigorous quality assurance program is implemented, and the vessel is periodically inspected during its operating life (Pohoto, 1975).

Alloys are available which can be heat treated to very high strength levels; however, their toughness is then sacrificed (Imhof & Barsom, 1972) with a resultant tendency to exhibit a sudden brittle type failure. The need for fracture toughness then limits the strength level to which a material can safely be heat treated for this service. As a result, the manufacturers of very high pressure forged steel vessels may insist upon using a material whose ultimate tensile strength is limited to about 1,000 MPa. Another material limit which may be encountered is the need for very thick vessel walls. The thicker walls are less uniformly heat treated, and, therefore, have less uniform mechanical properties. Although alloys do lose strength at elevated temperatures, this is not a serious problem at temperatures of 300°C or below. The safety of a cell is more likely to be a problem at low temperatures because of a loss of toughness and as a result, it may even be necessary to limit the minimum temperature at which the cell can be operated.

Cell Geometry

The geometry of a triaxial cell is intimately tied in with the design of the load frame with which it will operate, the test configurations it must accommodate, and with the materials handling scheme which is to be used.

The most compact and least expensive cell geometry probably consists of a tube with screwed in end plugs. This design also has the advantage that it provides axial constraint of the end closures against the hydrostatic pressurizing force. That characteristic allows the design of the load frame to be relatively independent of the cell design. Cells of this type have been used extensively for hot isostatic pressing (HIP) of powder metallurgy and ceramic parts. In that application the pressure is hydrostatic only and no axial force is applied. Therefore, a load frame is not required. This geometry has two serious disadvantages: 1) it increases the possibility for a sudden failure by creating a notch and a complex stress pattern at the thread root; and 2) it requires the assembly of very large threaded members. Large threads can be troublesome, particularly if they are cycled to elevated temperatures.

There are several variations of a cell geometry which depend upon the load frame for axial constraint of the cell end closures. This axial constraint removes the need for threads or clamps on the cell to constrain the end closures.

Many of the HIP cell users are now operating cells of this type. The IIT Research Institute triaxial cell used this geometry - with the addition of a piston and a second pressure source to provide a separately controlled axial load (see Figure 1). Note that the shell of this vessel is assembled from several ring forgings, which makes the fabrication and quality control much easier. There are several advantages which can accrue from multiwall construction (Witkin and Mraz, 1976), and multiwall construction is facilitated by providing the axial constraint through the load frame. At least one manufacturer has provided cells of this geometry which utilize a thin pressure tight inner liner wound with high strength wire in place of thick forgings. They assert that this wire-wound design is immune to sudden failure and that progressive failure is easily monitored. A vessel of this type cannot bear the ASME pressure vessel Code stamp, however, since that code does not encompass wire wound construction.

Materials Handling and Throughput

A 100 mm diameter rock sample can easily be lifted, inverted, and slid about by hand. However, a piece of rock one meter in diameter by three meters long might weigh 6,000 kg and it would require power operated equipment for all of these motions. The relative inflexibility of power operated equipment, the vulnerability of the rock to damage during handling, plus the time and space required to manipulate it, all suggest that the materials handling requirements should be carefully studied before selecting the geometry for a large triaxial cell installation.

It seems likely that the throughput requirements will mandate that a sample with its instrumentation and feedthroughs should be mounted on a triaxial cell bottom closure so that its instruumentation and feedthroughs can be installed and pre-tested at some time and location which does not interfere with the test currently in progress. The cell assembly scheme will then need to be selected to minimize the turn around time as well as to minimize any hazards to the preassembled sample.

Safety

Safety considerations may be dominant in determining the overall arrangement of the test facility and its mode of operation. The guiding philosophy might range from one which assumes that a sudden cell failure will occur, so that the facility must be operated remotely and sited far from other activities, to a philosophy which assumes that the vessel construction will preclude catastrophic failure and manned operation in an industrial area is acceptable.

Regardless of which confining fluid is selected and regardless of the exact cell size, for elevated temperature tests the amount of energy stored in the triaxial cell will probably be large enough to destroy conventional structures over an area larger than that occupied by the building housing the cell.

Conclusion

The design of a triaxial cell requires careful consideration of a wide variety of interrelated constraints. The considerable cost and time required to build such a large system, the inverse effect of triaxial cell and sample size upon throughput, and the complications created by elevated temperature testing encourage one to limit the system parameters to the minimum values which are consistent with the scientific objectives.

Acknowledgements. This study was supported by the Assistant Secretary for Nuclear Energy, Office of Waste Isolation of the U.S. Department of Energy under Contract DE-AC03-76SF00098. Funding of this project is administered by the Office of Nuclear Waste Isolation at Battelle Memorial Institute.

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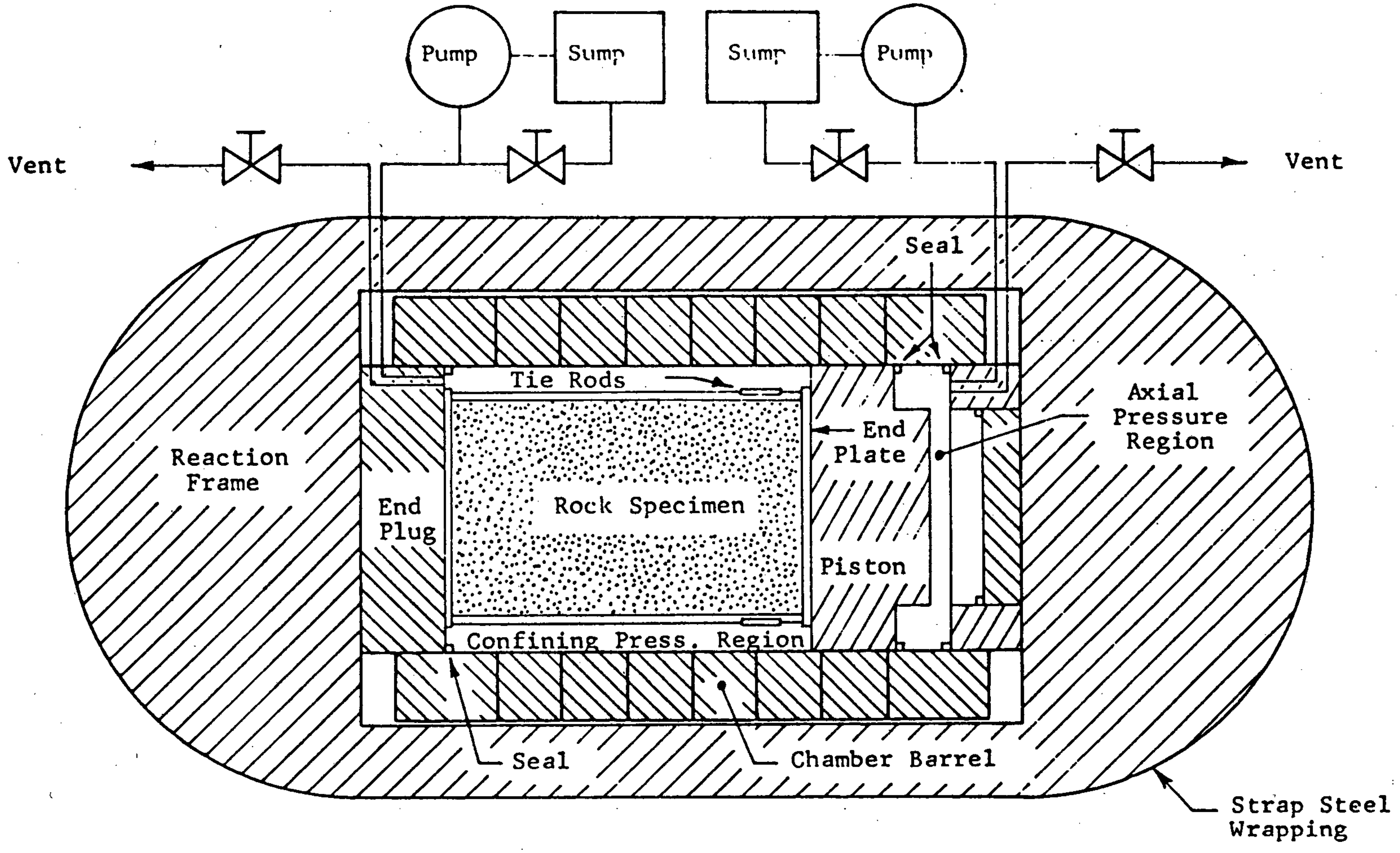

Figure 1. Schematic of 48-inch inside diameter triaxial cell (From Huck, 1972, Effect of specimen size on confined compression testing of rock cores. Permission granted IIT Research Institute.) [XBL 811-7669]

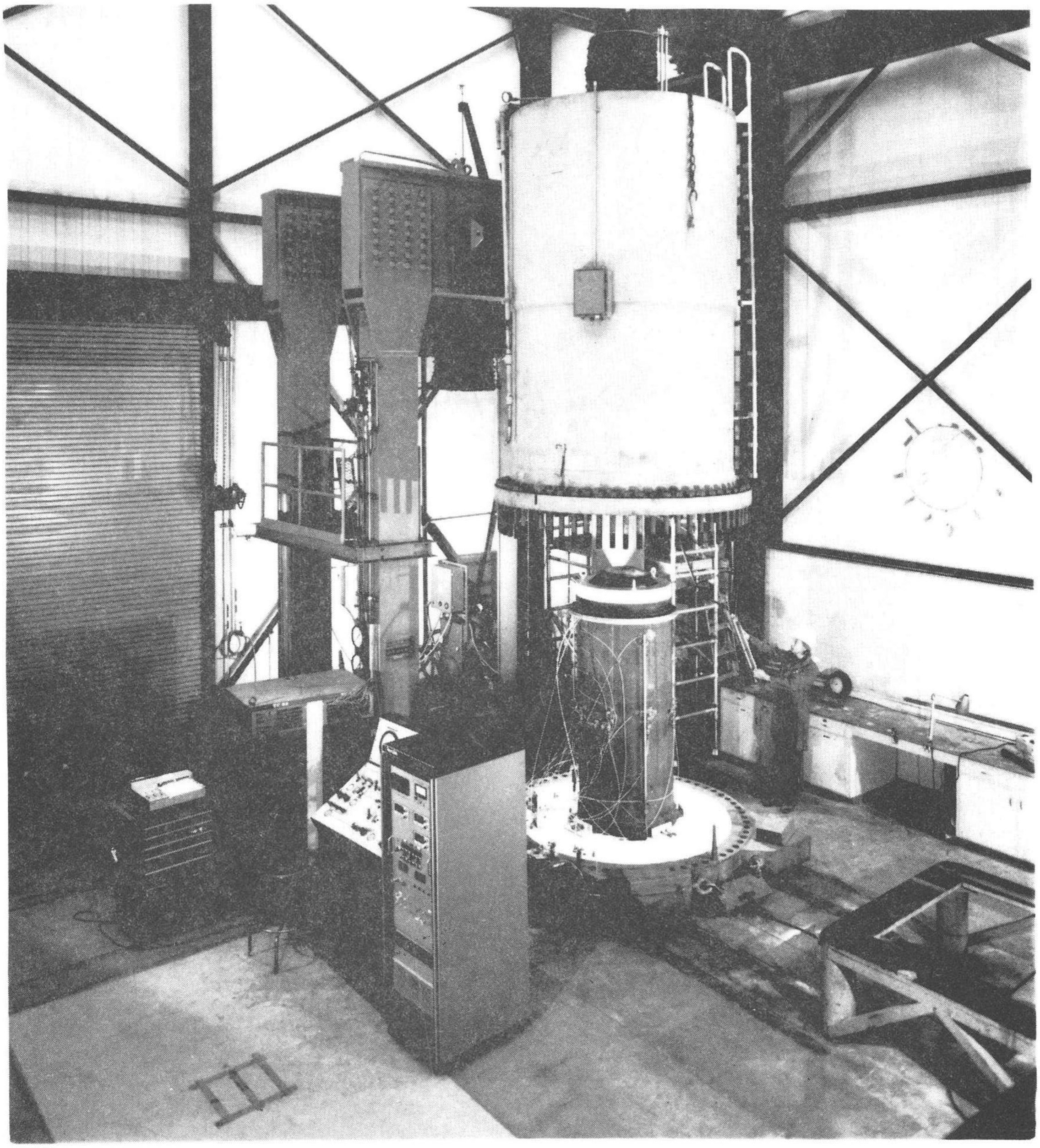

Figure 2. Triaxial test cell at University of California, Berkeley, Richmond Field Station.
[CBB 800-11819]

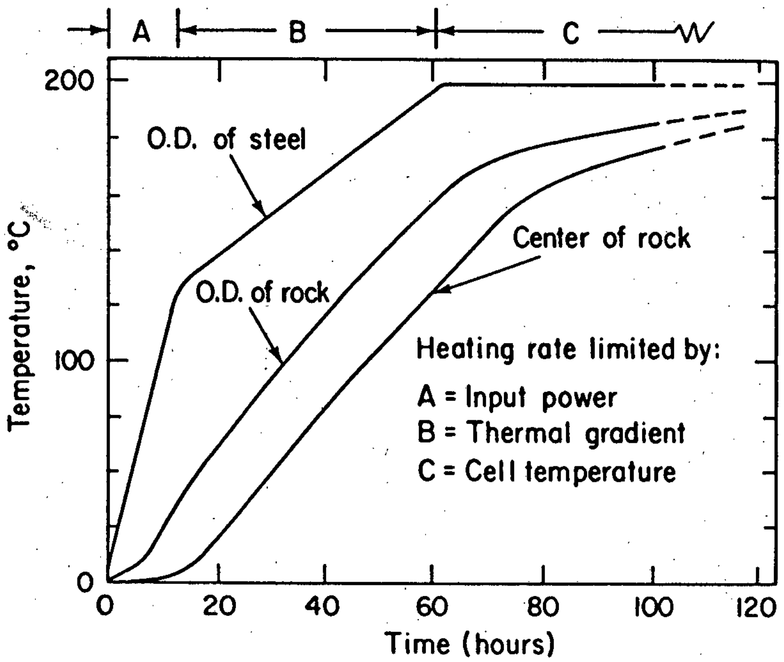

Figure 3. Heating cycle for 1.5 m O.D. triaxial cell and 0.75 m diameter granite sample. [XBL 812-4452]

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