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DESIGN FEATURES OF A UNIQUE SWING BRIDGE

HYDRAULIC AND CONTROL SYSTEM

by

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INTRODUCTION

In general, the design of movable span bridges to date has been more a result of evolution and discovery than of new technological innovation. With today's technology has come advances in computer science, electronics, materials, and mechanical systems. As engineers and designers we have the opportunity to combine new technology with innovation and imagination to build bridges that are stronger, safer, larger, more reliable, more maintenance free, have longer life and at less cost.

This paper presents design features of a unique hydraulic system for a new and innovative bridge. Although only the hydraulics are discussed in this paper, you will see from Mr. Tom Mahoney's companion paper that the bridge as a whole represents creative and imaginative engineering.

SUMMARY

The 1930 bascule bridge which links West Seattle to Harbor Island had long served as a principal traffic link between West Seattle and downtown Seattle. A channel dredging project, planned by the Corps of Engineers and the Port of Seattle, requires replacement of the existing bascule bridge to accommodate the wider channel clearance. A double leaf, concrete swing bridge with a main span of 480 feet between pivot piers is under construction as a replacement for the existing bascule structure. The movable portion of the bridge consists of two 7,500-ton asymmetrical leaves with a joint at mid-channel (Figure 1). The 45-degree skew alignment provides for a 250-foot clear navigation channel. The bridge carries two lanes of vehicular traffic on a 34-foot wide roadway and a 12-foot pedestrian and bicycle path. The project is located in a moderately active seismic zone and detail consideration was given to the seismic design criteria. Operating machinery is enclosed within the 42-foot diameter circular pivot piers. Each pivot pier is supported on a group of 600-ton capacity concrete filled steel pipe piles. The control house is located on the west bank and will have unobstructed visibility of the waterway and roadway.

Because the movable mass is considerably greater than previous bridges of this type, the use of a conventional operating system was not practical. For this reason, a new hydraulic operating and control system was proposed.

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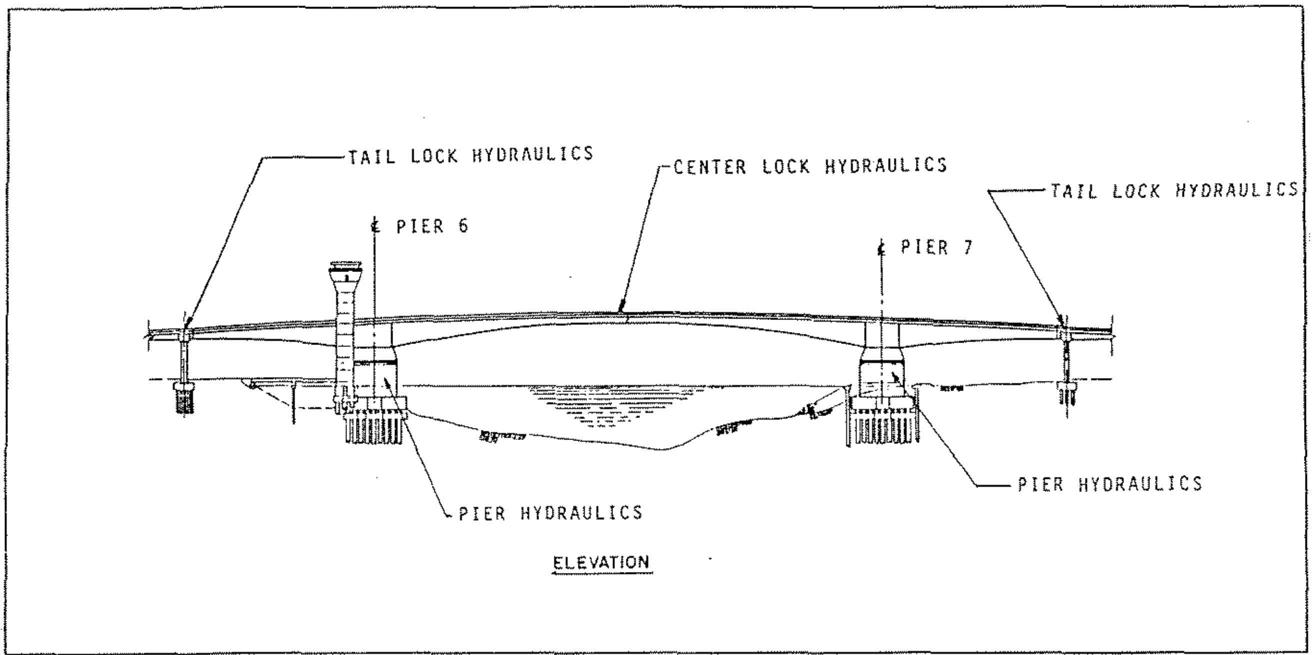

Figure 1 - Elevation

Service bearings are located at roof level of the machinery housing (Figure 2). These bearings carry dead load, live load, wind and seismic load directly to the walls of the machinery housing when the bridge is in the closed position. Each bearing is attached to the superstructure and bears against a steel ring on the machinery housing. The steel ring is machined in a plane perpendicular to the axis of the pivot shaft. Thus, the movable leaf may be lowered to the service bearings at any point on the swing arc.

Vertical stability during bridge swing is maintained by two sets of guide bearings, one at the roof level of the machinery housing and one at the machinery floor level. They bear against turned rings on the pivot shaft. Rotational torque is applied to the pivot shaft by a pair of double acting hydraulic slewing cylinders. Each cylinder has a 22-inch diameter bore, an 84-inch stroke and a 10-inch diameter rod.

Lifting of the leaf from the service bearings is accomplished by a lift piston operating between the bottom of the pivot shaft and a pedestal on the footing. These pistons are 104-inches in diameter. The normal stroke is 1-inch with the ability of 5-inches to be used for maintenance.

Hydraulic power for lifting and slewing is provided by three variable flow hydraulic pumps in each machinery housing. Normally two of the three pumps are used on an alternating basis with the third pump as a back-up. The pumps are powered by 100 hp. electric motors. A standby diesel driven generator set can provide each pivot pier with sufficient power for reduced speed operation in the event of a power failure.

The project owner is the City of Seattle with funding assistance provided by the Port of Seattle. Design consultants are the West Seattle Bridge-2 Design Team, a joint venture of Andersen - Bjornstad - Kane - Jacobs, Inc., Parsons Brinckerhoff Quade and Douglas, Inc., and Tudor Engineering Co. Hamilton Engineering, *Inc.* is the design consultant for the hydraulic machinery and control system.

BRIDGE OPERATION

Typical operation consists of an orderly operation of traffic lights, control gates, and barrier gates following a procedure common to most movable span bridges. The operator then initiates the withdrawal of the center lock and tail locks.

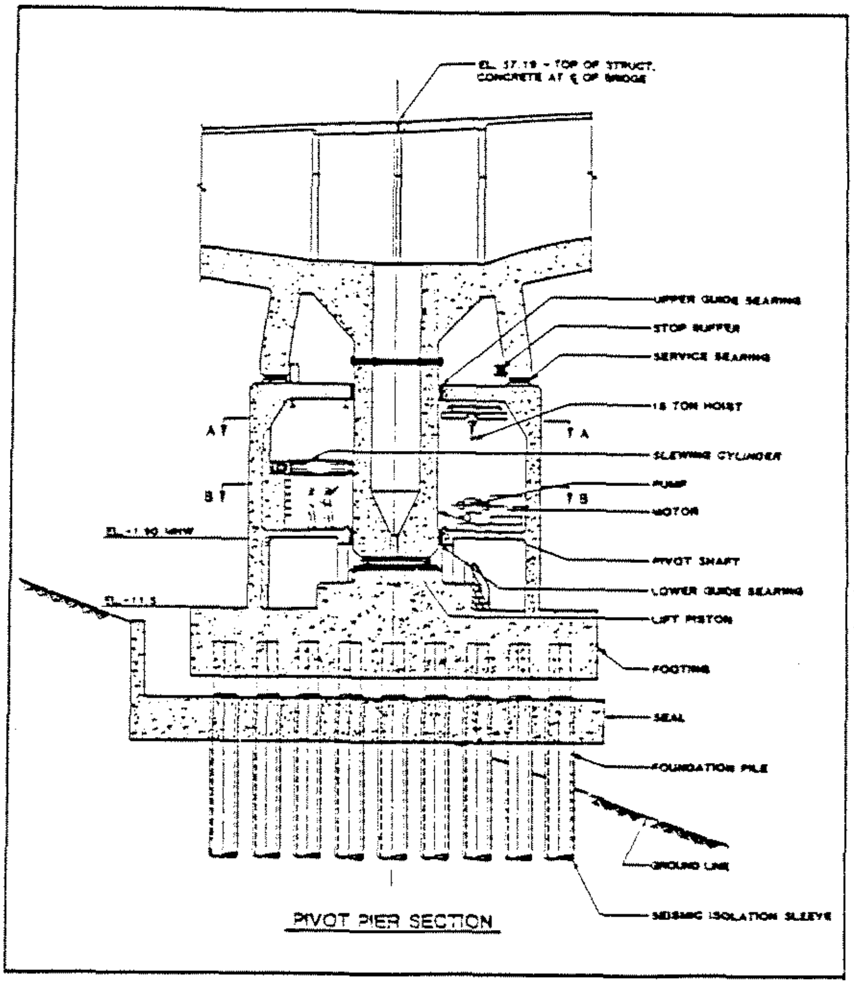

Figure 2 - Pivot Pier Section

After all locks have been withdrawn, the operator initiates SPAN LIFT. The spans can be opened simultaneously or independently at the discretion of the operator. The lift is normally completed in 20 seconds.

The operator now initiates slewing of the bridge. The motion control system monitors the bridge position continuously and the position feedback keeps the deceleration of the span within specified limits. To stop the slew in any position, the operator can let go of the OPEN/CLOSE handles, causing the bridge to decelerate and stop.

After the vessel has passed through the open channel, the operator can initiate span closing. At a pre-determined point, the bridge decelerates. At the 10° open point, a READY TO DOCK indication, displayed on the CRT, tells the operator that the bridge is in the creep mode. The CRT then displays a readout in INCHES TO DOCK. When the bridge is in the fully closed position, the SPAN CLOSED lights come on and the CRT reads AGAINST STOP.

At this point, the operator initiates lowering of the spans, and, when this is completed, proceeds to drive the tail locks and the center lock.

HYDRAULIC SYSTEM DESIGN

Hydraulic Machinery

The swing bridge has two identical hydraulic systems, one in each pivot pier. The two systems can operate either independently or simultaneously. The operator has independent control of each system. Each hydraulic system consists of lift and slew actuators, fluid transmission lines, a reservoir and a power pack which contains pumps and control valves. The hydraulic schematic diagram of the pivot pier system is shown in Figure 3.

The bridge will also have hydraulic systems to drive each of two tail locks and the center locks. The hydraulic schematic diagram of these systems is shown in Figure 7.

Lift and Slew System Design

The following is a description of the lift and slew hydraulic system.

Start-Up. The operator starts the lift and slew system by turning on two of the three pump motors from the control panel. Upon start-up the main drive pump pressure compensator is at its low pressure setting to reduce the start-up load on the motors and heat generation in the system. Flow from the boost pumps and from the docking pumps is ported over relief valves.

Lift. When the LIFT SPAN buttons are pushed, the lift control valve is opened, the main pump's compensator circuits blocked, and the stroke limiters set to provide full flow of 65 gpm from each pump. High pressure oil from the pumps, now working in a fixed displacement mode, flows to the Lift/Turn Cylinder. The bridge lifts one inch in 20 seconds to clear the main service bearings on top of the pier housing.

The bridge continues to lift automatically until the UP limit switches are engaged. Two seconds after tripping these switches, the lift valve closes and the main pump compensator is activated to a setting of 1,500 psi. At the same time, the main pump's stroke limiters are re-set to their maximum flow of 95 gpm. The bridge is now locked in the lift position by the closed lift valve. In order to minimize leakage and resulting bridge sag, the system uses poppet-type cartridge valves for the lift valve application. The lift circuit is protected by the 2,300 psi setting of a relief valve during normal operations.

Slew Open. With the bridge in the lifted position, the main directional control valve can be shifted from its spring centered position, allowing oil to flow from the pumps to the slewing cylinders. Both the deceleration servo-valve and the by-pass relief valve are actuated to their open position, allowing oil to flow freely from the slewing cylinders back to the tank. The counter-balance valves in the return lines are set to open by supply pressure in excess of 65 psi.

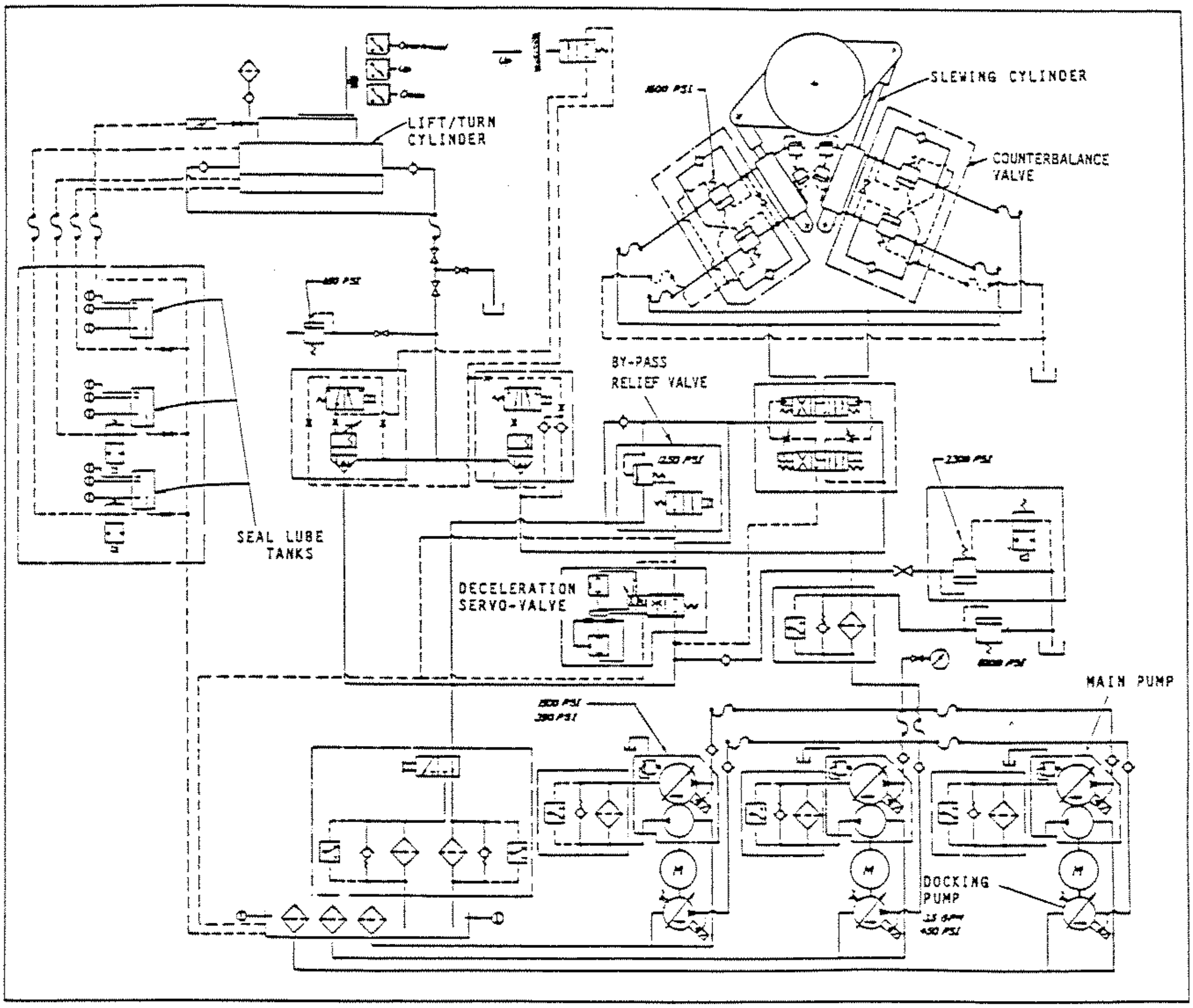

Figure 3 - Pier Hydraulic Schematic

The bridge is accelerated by the slewing cylinders as the oil flow from the pumps increases to the maximum at full stroke. During the acceleration period, the pump compensators limit the maximum slewing cylinder pressure during acceleration. As the bridge reaches a uniform angular velocity, the system pressure drops to match the resistive forces generated by line pressure drop, friction and wind. During the slew, the bridge position, velocity and acceleration are continuously monitored by linear position sensors mounted in the pier housing.

During normal operation, the bridge will continue its constant velocity slew until, at a predetermined opening angle, both the deceleration valve and the relief valve close, applying differential braking pressure to the slewing cylinder pistons. At the same time, the main pump compensator setting is reduced, thereby allowing the main pumps to provide makeup oil to the slewing cylinders during deceleration.

During deceleration, bridge motion is controlled by modulating the deceleration servo-valve. The continuous position input to the valve comes from the pier linear position sensors, through the motion control computer. The valve opens or closes to provide a predetermined and controlled deceleration. As the bridge angular velocity slows, flow from the small variable displacement docking pumps moves the bridge slowly to the final open position as determined by the pier linear position sensors. When this position is reached, the bridge is locked in the open position by the counterbalance valves. There is no position control docking pad in the open position. During the normal opening cycle, the bridge is not lowered onto the service bearings while in the open position.

Slew Close. As in the opening operation, the bridge accelerates in the closing direction as pump flow increases to full stroke. As the bridge reaches a uniform angular velocity, the system pressure drops to match the resistive forces, and the bridge continues its constant velocity slew until it reaches a pre-determined closing angle, at which point, deceleration is initiated. The deceleration phase is controlled by the deceleration valve. The deceleration point is detected by the pier linear sensors in addition to a redundant set of backup limit switches located on the approach structures. Because of the magnitude of the pier housing pile twist, the accuracy in detecting the deceleration point, using the pier linear position sensors, might not be adequate. If this is found to be the case during the bridge drive system test, the limit switches on the approach structures will be used for the primary deceleration point detection and the linear position sensors as backup detection.

Docking. As the bridge angular velocity slows to $.02^{\circ}$ per second, the two docking pumps move the bridge slowly to the final closed position against the approach structure bridge stops. The force of the stop is controlled by the 450 psi docking pump compensator setting. The final alignment of the bridge tail spans with the approach structures is within ±.25-inches, as measured by a linear position sensor mounted on the docking deceleration buffer.

The maximum lateral loads generated on the approach structure during normal docking are designed to be less than 40,000 lbs. at the bridge approach stops.

Lowering. With the bridge in final alignment, and pressed against the bridge stops by the 450 psi slewing pressure, the operator can activate the lift/dump valve. Oil from the Lift/Turn Cylinder, forced by the bridge weight, flows through the lift/dump valve and back to the tank. Lowering of the bridge is possible at any slew angle.

Abnormal Operating Conditions

Failure to Decelerate. If the bridge slews past the normal open or closed deceleration initiation points and the system fails to reduce the bridge angular velocity within a prescribed amount, the situation is detected by the linear position sensors, and fed to the PC through the motion control. In the closing cycle, a second set of switches located on the approach structure also are triggered.

If the time taken to slew from the normal deceleration point to the back-up emergency point is less than two seconds, as measured by the PC, the main pump power is shut off and the main directional valve spool moved to its center position. This causes the supply line pressure to drop below 65 psi, activating the counterbalance valves. These valves, set to relieve at 1,600 psi, decelerate the bridge, limiting the maximum lateral force on the approach structure to 100,000 lbs.

If the counterbalance valves fail and the bridge continues to slew past the emergency stop point without decelerating, hydraulic bridge buffers reduce the bridge velocity prior to impact with the fixed bridge stops. The lateral loads generated on the approach structure during this condition are limited to 200,000 lbs.

Emergency Stop. When the operator releases the slew handle to neutral, the bridge decelerates and stops in 10 seconds or less. This is normally accomplished by the regular deceleration valves. If the bridge fails to slow down as specified, (five seconds after release of the handle), or if the operator pushed the emergency stop button directly, the pump power shuts down, the main differential spool valve centers and the counterbalance valves decelerate and stop the bridge.

Emergency Slewing. In the event of a failed lift system, the bridge is capable of slewing with its total weight resting on the service bearings. To do this, the slewing cylinders are actuated by means of the docking pumps. This is accomplished by closing the manual shut off valve leading to the 2,300 psi relief valve, thus activating the 6,000 psi relief valve. The docking pump compensator is then blocked, providing 6,000 psi pressure for the emergency slewing.

Lift/Turn Cylinder Design

A unique feature of the bridge design is the Lift/Turn Cylinder. This cylinder serves two purposes: a) to lift the bridge clear of the "service" bearings and, b) to provide a rotating fluid support bearing upon which the bridge slews.

Several important considerations were addressed in the Lift/Turn Cylinder design:

1. Operating pressures - (AASHTO and AREA Specifications);
2. Seal Design - Rotation as well as translation;

3. Manufacture - Physical size, plating requirements, ground-bearing surfaces and materials;

4. Concentricity - Requirements for Lift/Turn Cylinder to be concentric with the bridge pivot shaft during rotation;

5. Reliability and Longevity; and,

6. Maintenance.

Access and Maintenance. Figure 4 shows the location of the Lift/Turn Cylinder under the bridge pivot shaft. Access to the cylinder is by ladder for normal inspection and maintenance. In the event of a major failure, the Lift/Turn Cylinder can be fully retracted allowing the bridge to be supported by the service bearings. This provides clearance for the Lift/Turn Cylinder to be moved out from under the pivot shaft and a replacement moved into the operating position. A 15-ton hoist and removable section in the deck accommodate complete removal of the Lift/Turn Cylinder for repair.

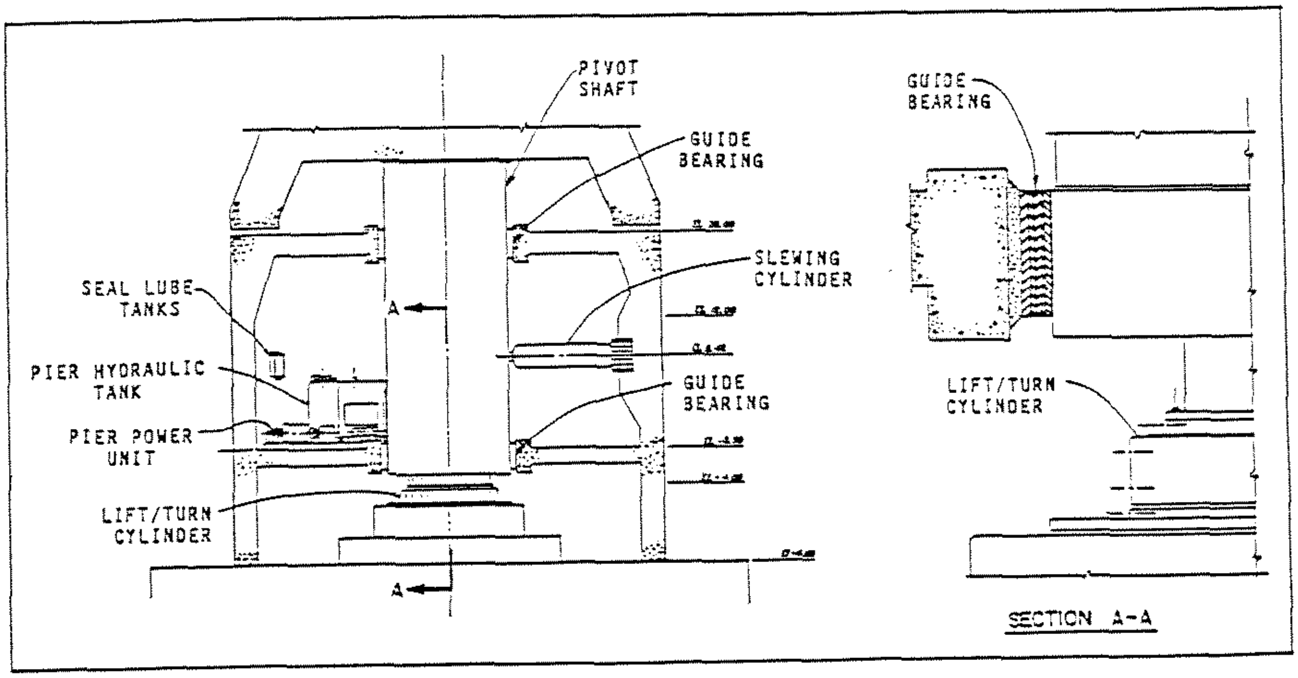

Figure 4 - Lift/Turn Cylinder and Bearing Locations

Floating Cylinder Barrel. Figure 5 shows a half section through the Lift/Turn Cylinder. Due to tolerance build-up in manufacture and installation of the bridge pivot shaft, it is possible that the centerline of the cylinder will not always coincide with the centerline of the Lift/Turn Cylinder. To accommodate this possible eccentric motion during bridge slew, the cylinder barrel is designed to float with respect to its base plate. The bearing surface between the barrel and base plate allows the required motion between the two. Differential area between the top set and bottom set of seals on the barrel provides a hydrostatic force preventing separation between barrel and plate. A ring retainer also serves as a back-up to ensure that the seal integrity between barrel and plate is always maintained.

Barrel Anti-Rotation Pin and Bearing. A bronze bearing block and pin arrangement as shown in Figure 6 allows the required eccentric motion between barrel and plate. The block and pin allows the center of the barrel to move radially relative to the base plate. The pin, however, prevents the barrel from rotating with the piston.

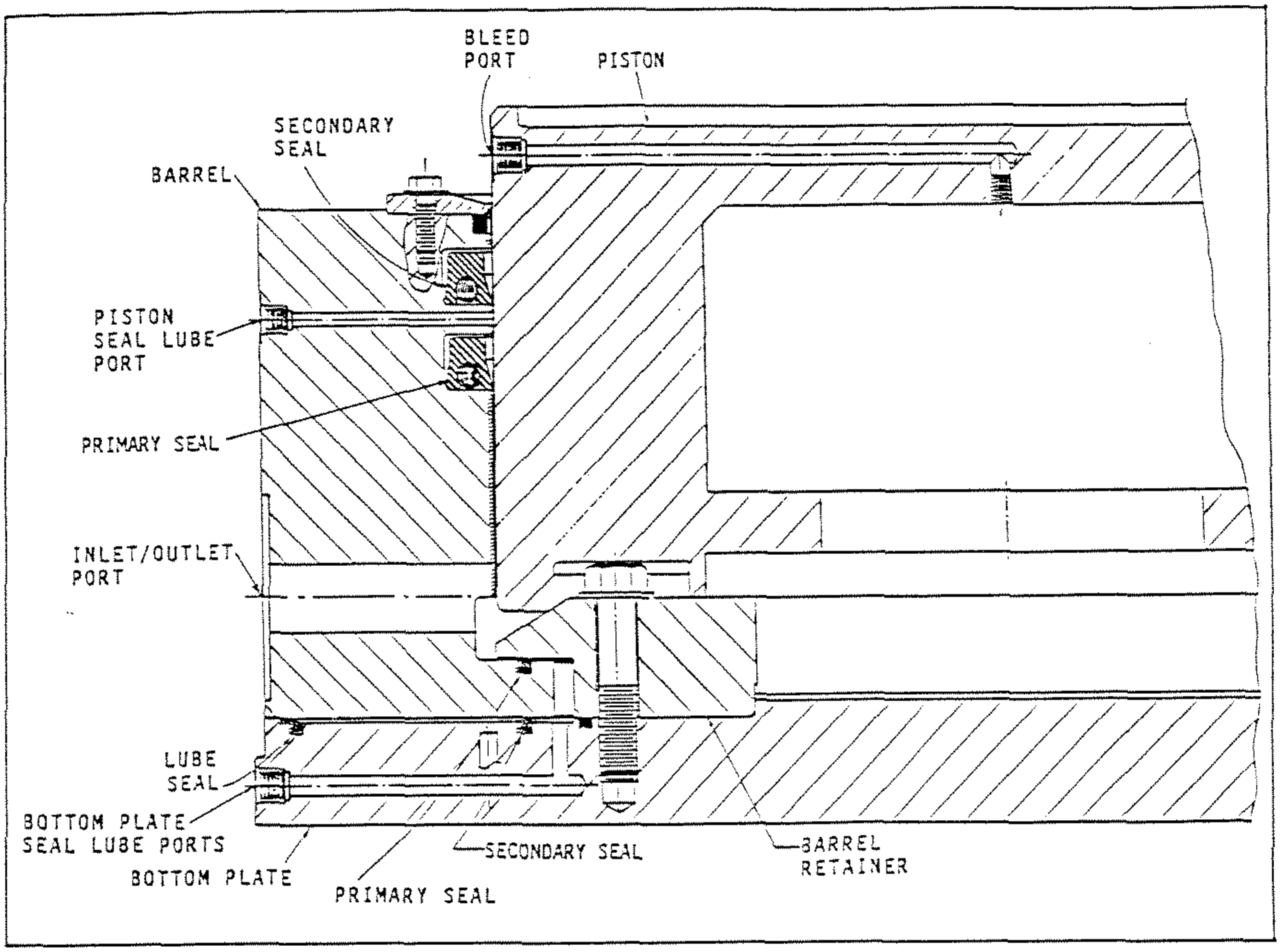

Figure 5 - Lift/Turn Cylinder Half Section

Dual Seal Arrangement. As is seen in Figure 6, the design provides dual seals for all three dynamic sealing surfaces. Ports located between each primary and secondary seal set connect to three separate hydraulic oil lube tanks located approximately 10 feet above the Lift/Turn Cylinder. This system provides low pressure lubrication to the secondary seal, and also provides a detection system in the event of primary seal leakage.

Large, spring activated, polyurethane lip seals were selected for the main seals between barrel and piston. These seals, which have been proven in North Sea oil rig applications, are designed to accommodate not only the piston rotation but also the relatively large gap between barrel and piston. This large gap is necessary to accommodate the differential expansion and contraction of the piston caused by pressurizing the cylinder during the lift cycle.

The outer diameter of the piston has a heavy ground and polished chrome plated surface to provide an excellent sealing surface and reduce wear from the seals during the slew cycle.

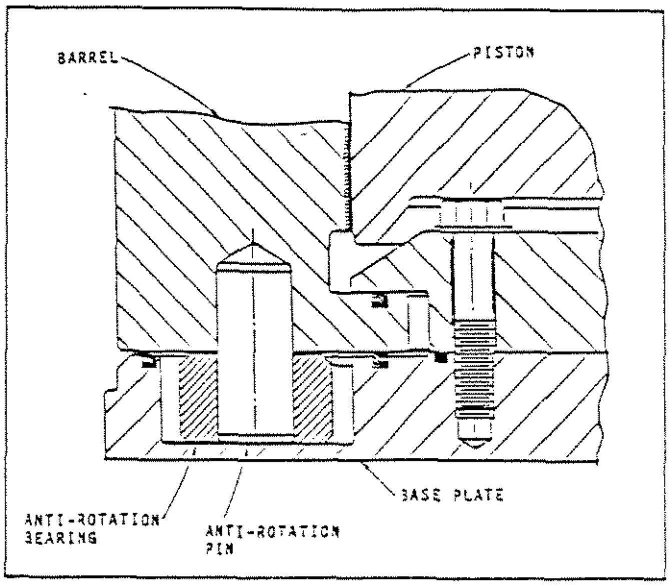

Figure 6 - Barrel Anti-Rotation Pin & Bearing

Safety Features. If the pair of Lift/Turn Cylinder UP limit switches fail to stop the lift, a third pair, located approximately 3/4-inch above the UP limit switches, are engaged. If this happens, the lift is stopped by shutting down the main pump power and closing the lift control valves.

In addition to the two sets of position switches, the Programmable Controller is programmed to shut down the main pumps if the lift continues for more than 40 seconds.

The fourth safety feature on lift overtravel is a mechanical vent valve. Actuation of this valve vents the lift dump valve, directing oil flow from the pump back to tank.

In case all of the overlift protection fails and the piston uncovers the primary seals, oil will escape to the piston seal lube tank, which makes up one compartment of the seal tank. When oil in the seal tank reaches the high level sensor, a warning light is turned on at the operator's station. The operator can now elect to shut the lift down by pushing the EMERGENCY STOP button.

If a primary Lift/Turn Cylinder piston or bottom seal suddenly fails during bridge operation, the level in the respective lube tank will also increase. The intermediate and high limit sensors in the lube tanks will trip and warn the operator of this situation. The seal lube line valves will close if the limit sensor trips. If the lift has not continued beyond 40 seconds, the pump power will not shut down. This enables the bridge to complete the swing cycle, working on the secondary cylinder seals.

Lock System Design

The lock hydraulic system consists of two identical tail lock hydraulic power units; one in each of the two fixed approaches, and one center lock hydraulic power unit located in the west swing span near the center of the bridge.

Each power unit consists of a constant horsepower hydraulic pump, hydraulic cylinder, reservoir, and associated control components, as is illustrated by the schematic diagram (Figure 7).

The variable volume hydraulic pump, with constant horsepower control, imparts fast motion to the lock bar except during that part of the locking cycle in which high friction forces are encountered.

Counterbalance valves prevent movement of the lock cylinders unless the applicable main control valve is energized. Lock Bar limit switches provide positive feedback to the Programmable Controller, and indicator lights on the operator's console indicate that locks are either DRIVEN or WITHDRAWN.

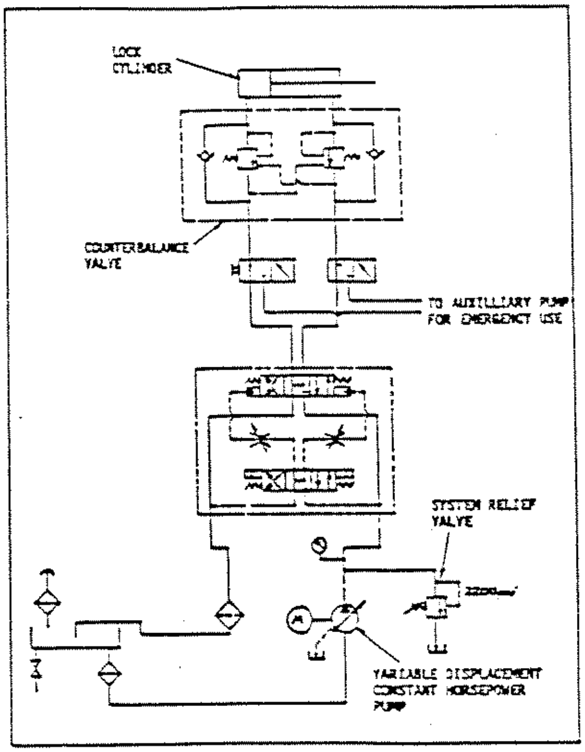

Figure 7 - Locks Hydraulic Schematic

A low level fluid sensor is provided in each reservoir to activate a hard alarm if fluid is below the critical level.

Manual control valves are provided so an auxiliary hydraulic power unit can be used to activate the appropriate lock cylinders in an emergency, excluding hydraulic cylinder failure.

SYSTEM PERFORMANCE CRITERIA

CONDITION	SPECIFICATION
- Opening or closing sequence	- Less than 120 seconds
- Controls disengaged or drive system failure occurs	- Bridge motion will stop in less than 10 seconds
- Rate of Open/Close Cycles	- A minimum of 50 openings and closings in 24 hour period

Design life of system components	Twenty year normal operation without major overhaul
Design operating frequency	Seven openings per 24 hours, 360 days per year
Docking accuracy	Position and hold bridge during docking within ±.25 inches at the tail span/approach structure interface.
When stopped at any position	Bridge will hold against wind loads per AASHTO specifications
Docking impact force at end of tail span	Less than 40,000 lb. for normal operation and 350,000 lb. for emergency situation
Impact force on pivot pier stopping buffer	Less than 40,000 lb. for normal operation and 500,000 lb. for emergency situation
Slewing Cylinder Failure	Capable of rotating bridge in event of one slewing cylinder failure
Lift/Turn Cylinder failure	Operating pressure of 6,000 psi maximum, move bridge on Teflon service bearings with a design friction coefficient of .12
Angular velocity profile	Control system shall continuously monitor selected parameters during bridge operation and warn operator and/or stop operation if specified limits are exceeded

SYSTEM DESIGN CRITERIA

CONDITION	SPECIFICATION
Design working pressure	2,000 psig
Maximum design pressure relief setting	2,300 psig
Maximum rated working pressure	4,000 psi for hydraulic components except Lift/Turn Cylinder which shall be 2,500 psi
Safety factor for high pressure lines, hose, fittings, and ports	Four (4) times rated working pressure

- Safety factor for slewing cylinders - Five (5) times rated working pressure
- Minimum safety factor of all other hydraulic components - Three (3) times rated working pressure
- Maximum angular bridge speed - 0.75 deg/sec.

RECOMMENDATIONS

Considering the capabilities of modern industrial hydraulic components, the old AASHTO and the updated (1984) AREA Specifications currently used in the design of movable bridge hydraulic systems are both very "conservative." Both specifications focus on system pressure as the only important variable affecting overall reliability.

During the design of the new movable West Seattle-2 bridge it became clear that due to the large power demand and low operating pressure (1,000 psi) specified by AREA, the flow rates had to be very large.

The reliability of a hydraulic system is a function of flow as well as pressure, particularly when a very large flow demand dictates the size of, and thus severely limits, the choice of pumps and other hydraulic components. Figure 8 shows typical reliability curves, illustrating that for a given horsepower, the overall reliability of the system will not necessarily increase with lower pressure.

Most industrial hydraulic components available today are rated to operate continuously at 4,000 psi or above. Since the AREA pressure specification of 1,000 psi is well below the component ratings, a reduction in pressure below the rated component value will not bring a proportional increase in reliability. For a given flow rate, any reduction in pressure below 2,500 psi is estimated to have a negligible effect on the operation and maintenance of the system.

For a given power demand, the increased flow required by reducing the pressure will have a significant effect on system cost, complexity and maintainability. This is particularly noticeable in large high power systems such as the new West Seattle-2 bridge. Therefore, the theoretical benefits gained by following the "conservative" AREA specifications do not match the disadvantage of handling the large flow.

Based on current experience with modern industrial hydraulics, it is felt that bridge designers should not be governed by detailed pressure limitations dictated without regard to flow and power considerations.

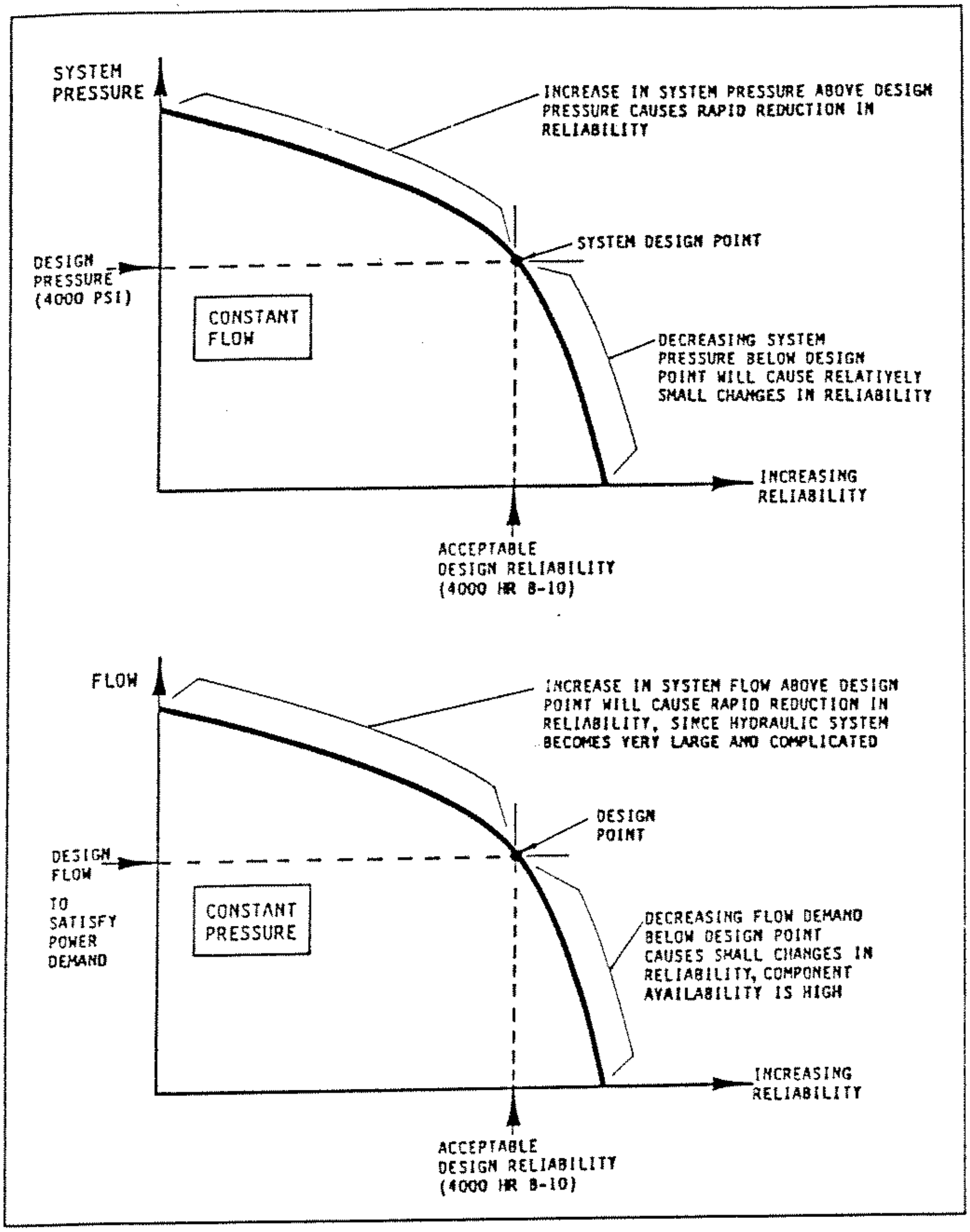

Figure 8 - Hydraulic System Reliability

Since the inclusion of these additional factors would need a prohibitively complicated specification, it is probably in the public interest that the selection of both pressure and flow in bridge hydraulic systems be left to the designers and component manufacturer.

If maximum pressure limitations are to be specified, however, they should be updated to reflect the current state-of-the-art of hydraulic components.

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