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## Assessment of Slurry Pressure Letdown Valve and Slurry Block Valve Technology for Direct Coal Liquefaction Demonstration and Pioneer Commercial Plants

R. P. Krishnan

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Engineering Technology Division

ASSESSMENT OF SLURRY PRESSURE LETDOWN VALVE AND SLURRY BLOCK  
VALVE TECHNOLOGY FOR DIRECT COAL LIQUEFACTION DEMONSTRATION  
AND PIONEER COMMERCIAL PLANTS

R. P. Krishnan

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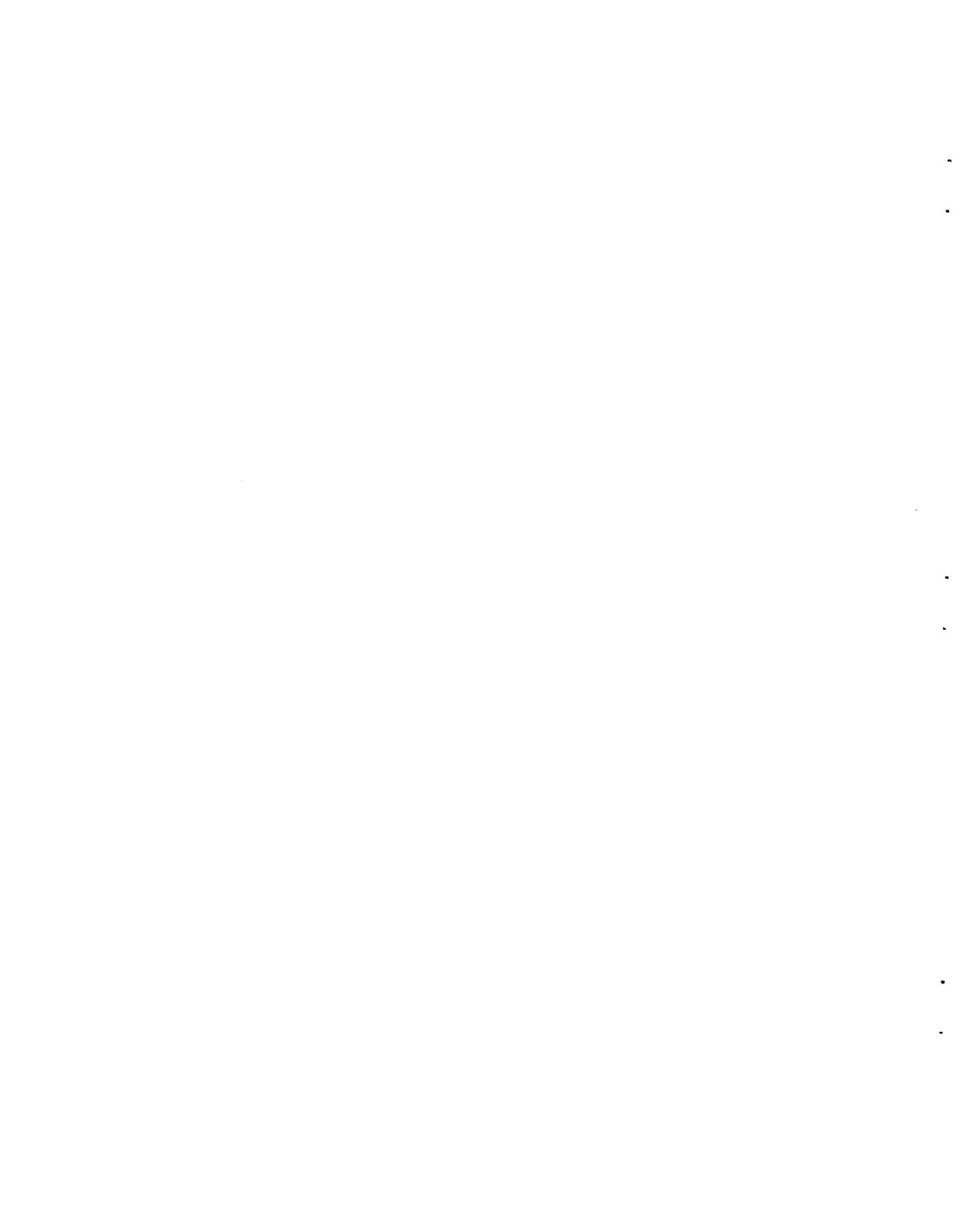
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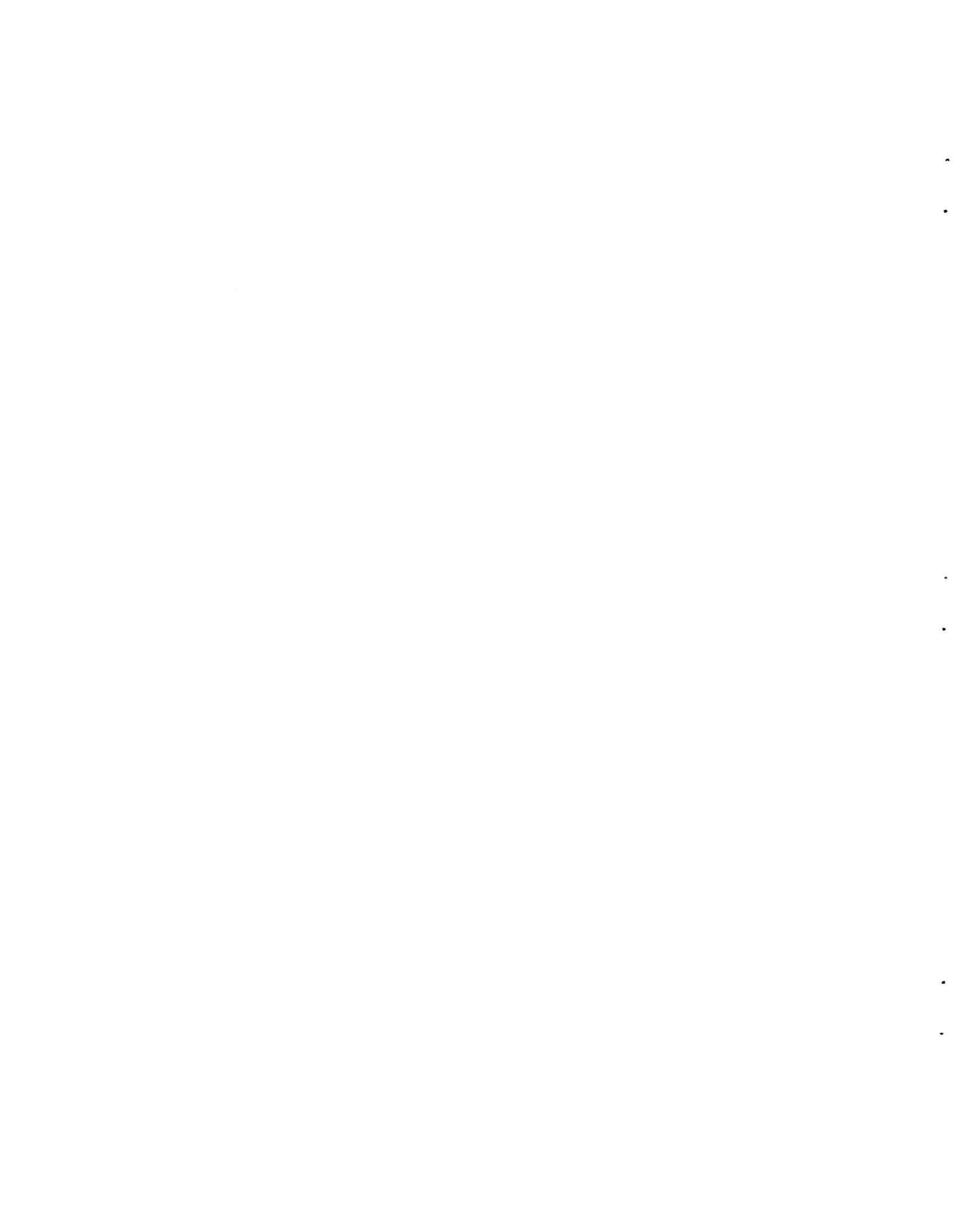
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ASSESSMENT OF SLURRY PRESSURE LETDOWN VALVE AND SLURRY BLOCK  
VALVE TECHNOLOGY FOR DIRECT COAL LIQUEFACTION DEMONSTRATION  
AND PIONEER COMMERCIAL PLANTS

R. P. Krishnan

ABSTRACT

This report examines the status of the technology of high pressure slurry letdown valves and slurry block valves in coal liquefaction service. All of the demonstration and pioneer commercial direct liquefaction plant designs call for the use of high pressure slurry letdown valves for flow control and slurry block valves for flow isolation. Successful performance and reliability of these valves is a serious concern because of the severity of the process streams and the limited experience and performance data on these valves under such conditions.

The objectives of this report are 1) to examine the existing data base on these valves from the four major direct coal liquefaction pilot plants in the U.S., 2) to present the recommendations from the pilot plant experience, 3) to examine the specifications for the letdown and block valves in the demonstration/pioneer commercial designs, 4) to identify the scale-up issues, data gaps, and development and testing needs.

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1. INTRODUCTION

1.1 Background

The U.S. Department of Energy (DOE) has been supporting the development of direct liquefaction technology for converting coal into clean liquids. In processing coal in this mode, the refined product is produced at high pressure and high temperature and later separated into vapor and slurry components by letdown to a low pressure of only a few atmospheres. The approach used in the four major liquefaction pilot plants in the U.S. (SRC-I, SRC-II, H-Coal, and EDS) has been to use slurry pressure letdown valves to effect this pressure letdown. These valves usually control the level in the upstream pressure vessel, which receives direct effluent from the product reactor and allows a high pressure vapor liquid separation. In conjunction with the pressure letdown valves, slurry block valves upstream and downstream of the pressure

letdown valves have been used to isolate the letdown valves for maintenance/repair and by-pass of the process stream. The block valves have also been used for process stream isolation, sampling and instrumentation, and isolation of other equipment, such as pumps, reactors, hydroclones, etc. Experience gathered from the pilot plants has indicated that the extreme conditions under which slurry letdown and block valves operate and the lifetime required make the selection of off-the-shelf equipment extremely difficult, if not impossible.

Reliability and successful operation of these valves in the larger demonstration and pioneer commercial plant is a serious concern. Since valves in the sizes required for these large plants have not been built to date, there is doubt concerning the scale-up and the performance of these valves in the larger plants. The plant availability is heavily dependent on the reliability and successful operation of these critical valves.

## 1.2 Objectives and Scope

The objectives of this study are 1) to identify the technology gaps in the sizing methods and/or scale-up of the slurry pressure letdown and slurry block valves and 2) to identify the development needs for these components to eliminate some of the scale-up and/or performance related data gaps.

This is the second of two reports prepared by Oak Ridge National Laboratory for the U.S. Department of Energy as a result of the liquefaction critical components assessment program. The first report addressed coal slurry pumps. In this report, first the experience gathered in slurry letdown and block valves in the SRC-I, SRC-II, H-Coal, and EDS pilot plants and the recommendation and lessons learned from the pilot plants are briefly described. Next, the valve specifications (size, numbers, design features) for the larger demonstration and/or pioneer commercial plants (SRC-I, H-Coal, and EDS) are presented. The technical risks/data gaps in scaling the valves from the pilot plant size to the commercial size are discussed. To the extent possible, the development and testing needs for these two critical valves are also identified.

## 2. LETDOWN VALVES

### 2.1 Function and Service Conditions of Letdown Valves

The letdown valves in direct coal liquefaction processes are designed to throttle the flow of the high temperature liquid coal slurry from a high pressure source (dissolver) as it passes to a low pressure receiver (vapor/liquid separator). As this high-temperature, high pressure slurry is throttled, the more volatile hydrocarbon constituents flash into vapor, resulting in high velocity flow of a three phase gas/liquid/solid mixture. The valves are, in reality, slurry control valves and they respond to changes in the level in the vapor/liquid separator drums.

Figure 1 is a typical configuration of the pressure letdown system.<sup>1</sup> The effluent from the dissolver undergoes phase separation initially in a high pressure separator, and subsequently as the remaining slurry phase undergoes pressure reduction through a letdown valve. The total required pressure drop is obtained in one or more steps (two in the example shown), the number of which presumably represents a compromise between the plant complexity and the magnitude of the required pressure drop across the valves.

The letdown valves typically operate under pressure differentials greater than 6.9 MPa (1000 psi) and temperatures as high as 426°C (800°F), while throttling slurries of 10 or more percent by weight of very fine, abrasive solids. The high pressure drop and flashing conditions along with particulates limit the selection of valves available for this service. Only a few special valve designs, which employ streamlined internal geometries and the hardest materials within the throttling areas where high velocities, swirling, and slurry impingement occur, have proved successful. A brief discussion on the valves tested in the various pilot plants and the operating experience gathered is given in the following section.

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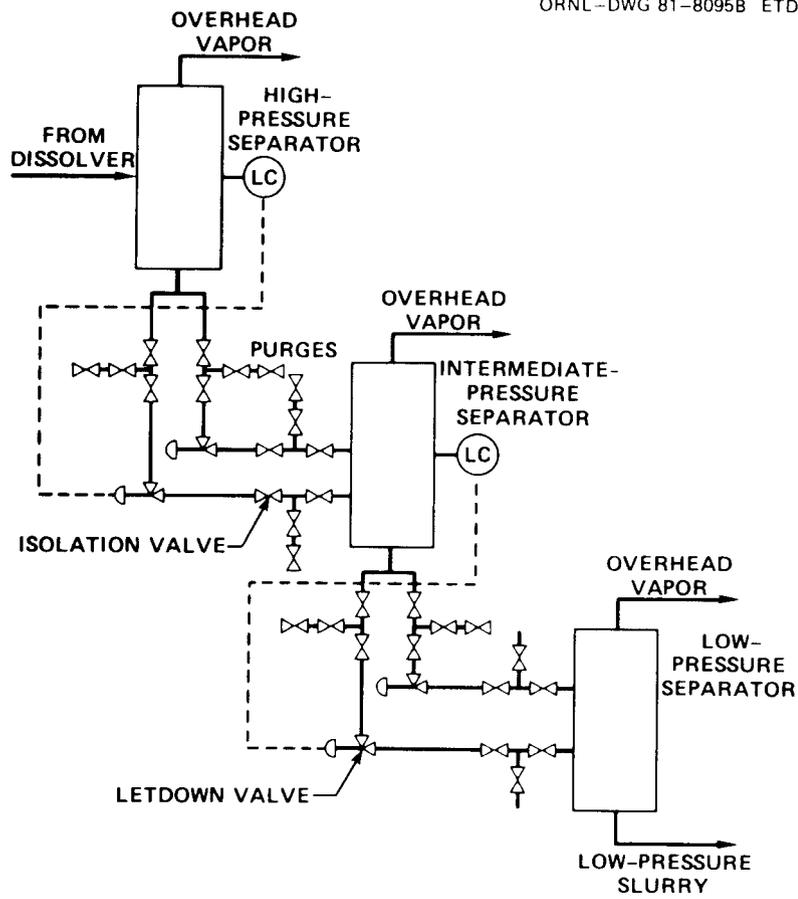


Fig. 1. Typical Coal Slurry Pressure Letdown System Configuration.

## 2.2 Letdown Valve Experience in Pilot Plants

Overcoming the short service life of high-pressure letdown valves has been a major engineering problem in the coal liquefaction pilot plants. While the technology still remains to be perfected, the reliability of these valves have been improved significantly by adopting novel valve designs and selection of proper materials for valves and valve trim materials in the pilot plants. This section describes briefly the process conditions, letdown system configuration, and letdown valves tested and the valve performance of each of the four pilot plants. Detailed treatments of the letdown valve experience in the pilot plants can be found in Dahl,<sup>2</sup> and the recent study by Catalytic<sup>3</sup> on the slurry letdown system for the SRC-I demonstration plant.

### SRC-I

The process conditions and valve parameters for the high-pressure letdown system at the Wilsonville pilot plant are as follows:<sup>2</sup>

1. pressure drop across the valves, 13,800 kPa (2000 psi);
2. temperature of fluid (valve inlet), 315-425°C (600-800°F);
3. fluid velocity (valve inlet), 0.366-0.396 m/s (1.2-1.3 ft/s);
4. mass flowrate, 408-544 kg/h (900-1200 lb/h);
5. percent weight coal (valve inlet), 2.5-3.5;
6. percent weight ash (valve inlet), 3.5-4.5;
7. percent volume vapor (valve inlet), ~10;
8. valve type, Fisher DBAQ;
9. seat type, 316 stainless steel and K-703 tungsten carbide;
10. trim size, 3/8-in. orifice with modified microflute stem;
11. design Cv, 3.36 for liquid service (Fisher);
12. normal operating position, 20% open.

The entire pressure drop is taken across a single Fisher DBAQ angle valve. The high pressure slurry enters the valve horizontally via 1-in. schedule 80 stainless steel piping, then turns 90° downward to enter the valve turn. The slurry is discharged into a 1-ft section of a 2-in., schedule 160, stainless steel piping. The flow then turns another 90° horizontally in a capped-tee connection, runs about 4 ft, and finally discharges downward via an elbow into the flash tank.<sup>2</sup>

A vendor supplied Fisher DBAQ valve with a stellite trim was used initially. Cracking and severe erosion of the trim occurred within only a few hours of operation. The performance was improved subsequently by redesigning the valve trim (plug and seat), modifying the downstream piping and switching from Stellite to Kennametal K703 seats and stems (Fig. 2). Details pertaining to these changes can be found in Reference 2. Tighter clearances between the plug and seat (0.001-0.002 in) helped reduce the vibration of the plug tip and stem breakage.<sup>4</sup> The service life of the valve improved considerably and is of the order of 2000 to 4000 h.

Wilsonville used a Kielely-Muller streamlined angle flow valve in the pressure letdown service but switched to the Fisher DBAQ angle valve because of the ease of maintenance.

#### SRC-II

The pressure letdown system in the SRC-II Ft. Lewis pilot plant consisted of two stages of pressure letdown. The first stage occurred between the high-pressure flash drum and the intermediate-pressure flash drum. The second stage letdown occurred between the intermediate-pressure flash and either the slurry recycle stripper or the filter-feed flash vessel. Two valves were installed in parallel in each stage, with one valve in each stage kept as standby, making a total of four letdown valves.<sup>2,5-6</sup>

Flow entered the letdown valves horizontally, via a 2-in. schedule xx, 347 stainless steel pipe, then turned 90° inside the 1-in valve body to enter the 1/4 in. seat. The discharge section was a 2-in. schedule xx, 347 stainless steel pipe about 6 ft. long. A 3/16-in orifice (commonly called a bean) was installed 7-3/4 in. from the discharge of one of the first stage high pressure valves. A similar flow arrangement without the downstream orifice (bean) was used in the intermediate pressure valves.

The typical operating conditions for these valves were:<sup>2</sup>

1. first-stage letdown, LCV 166,  $\Delta P$ ; 9650 to 4130 kPa (1400 to 600 psi);

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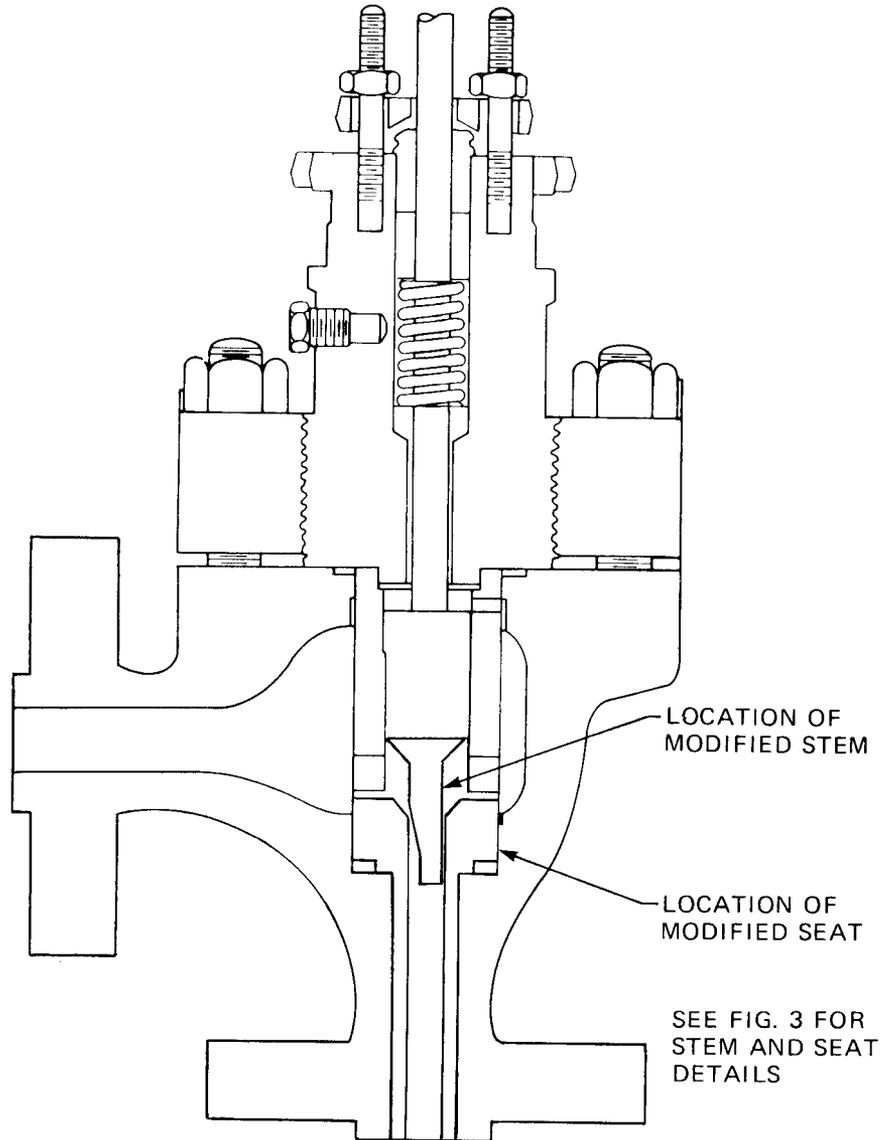


Fig. 2. Fisher DBAQ Valve Body with Outline of Stem and Seat Modifications made by Catalytic for the SRC-I Pilot Plant at Wilsonville, Alabama (Ref. 2).

2. second-stage letdown, LCV 175,  $\Delta P$ ; 6200 to 2750 kPa (900 to 400 psi);
3. first-stage inlet temperature, 340 to 400°C (650 to 750°F);
4. inlet fluid velocity, ~1.5 m/s (~5 ft/s);
5. mass flowrate, 37.8-56.7 L/min (10-15 gpm);
6. percent coal, 6-8% SRC-I mode; 24-28% SRC-II mode;
7. percent ash, 4-6% SRC-I; 18-20% SRC-II;
8. percent vapor, ~2% SRC-I and SRC-II;
9. typical lifetimes, 2500 h;
10. seat type, K602;
11. trim size, 1/4-in. microform;
12. operating position, 25% open, without orifice installed; 40% open with orifice installed;
13. orifice size, 3/16 in. (one loop only).

Three different valves were tested in the letdown service. Two of the valves were angle valves (1-in. Fisher DBAQ and a 1-in Willis MIHT) and the third was a globe valve (1-in. Fisher DBQ). The globe valve was taken out of service due to unsatisfactory performance. The valve body and valve trim eroded badly after only 4 days of operation.

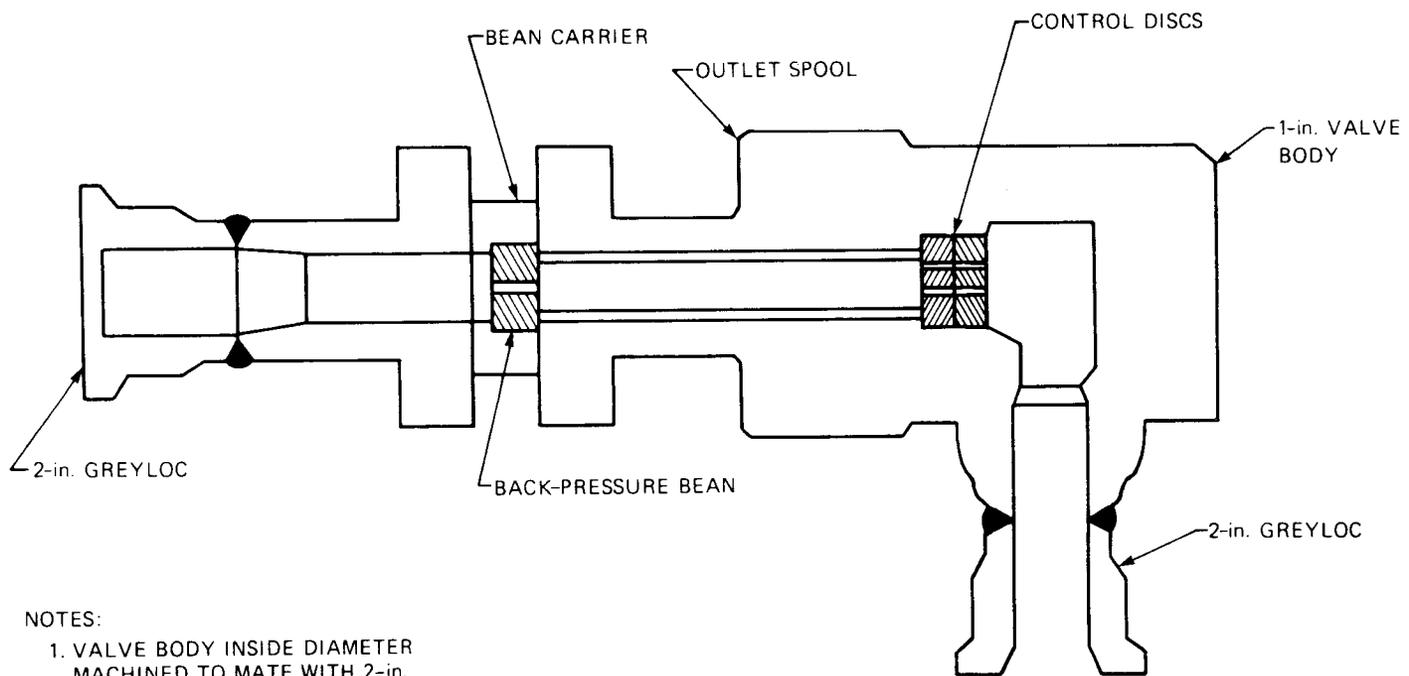
The two valves in the first stage of letdown were 1-in Fisher and 1-in. Willis valves. Both valves in the second stage of letdown were 1-in. Fisher DBAQ valves. The Willis valve (Fig. 3) in the first stage was later replaced by a 1-in. Fisher DBAQ valve (Fig. 4) with a downstream back pressure bean.

The main variables that affected valve life were:<sup>5</sup>

- valve design
- trim materials
- valve sizing
- pressure drop

Of these, the most significant variable in the life of the valve was the trim material. The materials tested included stellite, standard grade of tungsten carbide with 6% cobalt binder, Kennametal K-602 (<1.5% cobalt binder), K-701, K-703, and Valenite 134. The performance of tungsten carbide was judged at least 100 times better than that of Stellite. The material most favored by Fort Lewis in this application

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NOTES:

1. VALVE BODY INSIDE DIAMETER  
MACHINED TO MATE WITH 2-in.  
GREYLOC

2. NOT TO SCALE

Fig. 3. Fort Lewis SRC Pilot Plant Willis M1HT Letdown Valve Configuration with Low Pressure Beam Downstream Orifice (Ref. 2).

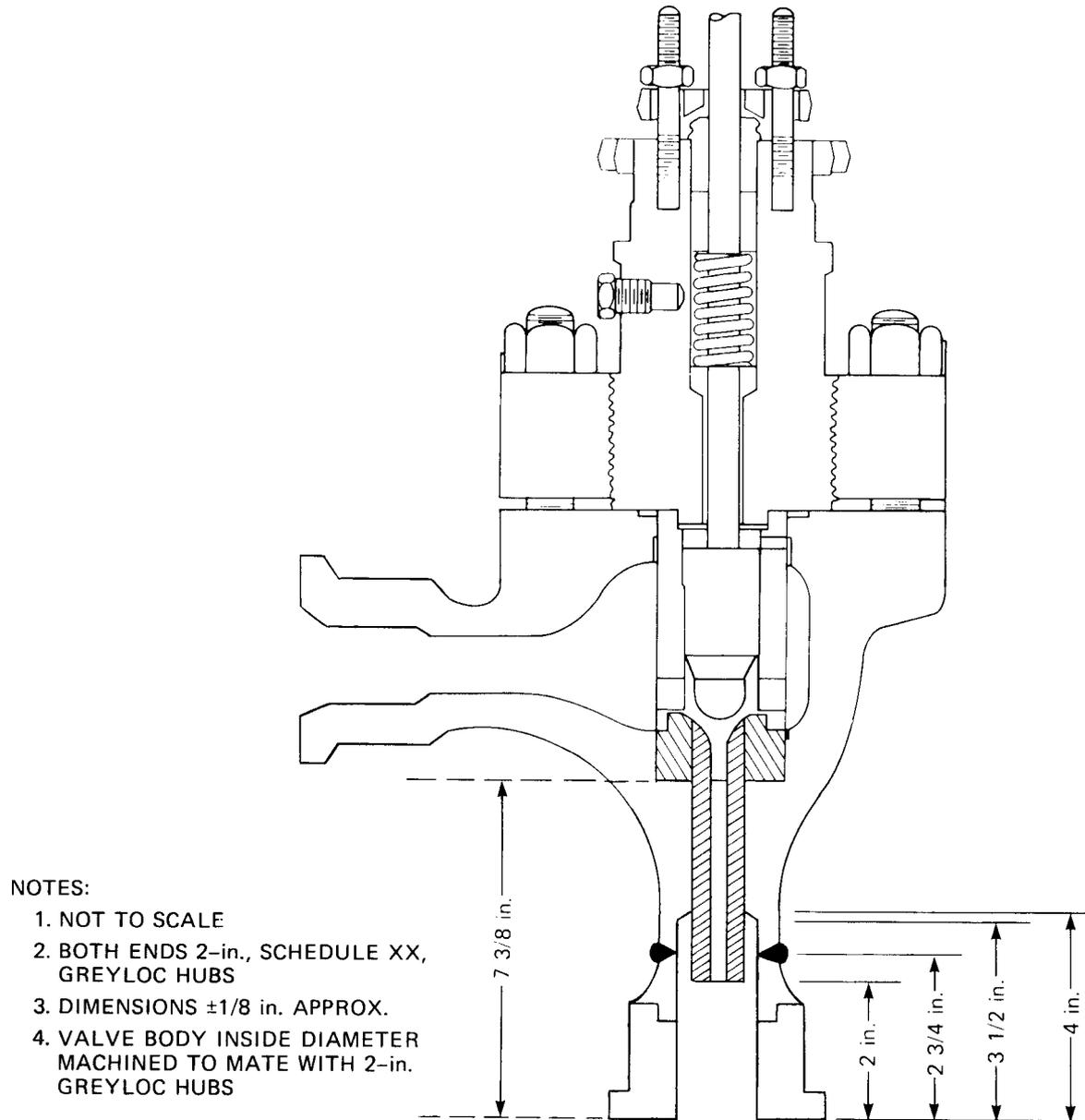


Fig. 4. Fort Lewis SRC Pilot Plant Modified Fisher DBAQ Valve (Ref. 2).

is tungsten carbide Kennametal K-602. The Fisher DBAQ valve out-performed the Willis valve by at least a factor of three and closer to a factor of eight. Compared to the 16 days valve life with the Willis valve, the Fisher valve operated 100 days before trim failure. The difference was attributed to the differences in the impingement angle between the two valves. In the DBAQ valve, the impingement angle was low compared to approximately  $90^\circ$  in the Willis valve.

One advantage of the MIHT Willis valve over the Fisher DBAQ valve was that with the former valve, the trim could be fabricated with erosion-resistant material in compression. The Fisher valve trim, on the other hand, could not be fabricated with 100% of the tungsten carbide (WC) in compression because of the brittle property of WC. The tip of the WC trim was vulnerable to tensile stresses resulting in trim breakage. Increasing the trim size from 1/4-in. to 1/2-in. (four times the cross sectional area) in the Fisher valve resulted in less breakage. However, the integrated life of the 1/2-in. trim was shorter compared to a 1/4-in. broken trim because the 1/2-in. trim was oversized for the process conditions.

Trim life was extended in both valves by addition of a fixed orifice downstream of the valves. The advantages of the fixed orifice were

- Lower pressure differential across the trim;
- Less downstream erosion (Willis valve only);
- Larger trim size (Fisher valve only).

On the other hand, the disadvantage of the fixed orifice was the control characteristics of both valves were adversely affected. However, the inherent flow characteristics of the Willis valve required that the valve be operated with a fixed orifice. Without the orifice the discharge from the Willis valve had a tendency to swirl and cause downstream erosion. Addition of the fixed orifice reduced the swirling effect and therefore the downstream erosion. Furthermore, increasing the pressure drop across the fixed orifice from 40% to 80% also improved the overall valve performance (mainly trim life).

Four plug configurations were tested in the 1-in Fisher valve: (1) tapered microform, (2) snub-nose microform, (3) snub-nose microform with a sharpened tip, and (4)  $30^\circ$  cone. The snub-nose plug (case 2) was

considered to be the most desirable configuration with lifetimes of about 2500 h.

Toward the end of the operation Fort Lewis experienced very few operating failures with their trim. The valve trim could be changed conveniently during scheduled shut down when it had eroded. Very little stem breakage was also observed using 1/4-in. plug, especially after modifications in the startup procedures.

### ECLP

The high-pressure slurry letdown valve in the ECLP pilot plant in Baytown, Texas controlled the level of slurry in the reactor separator drum. The entire pressure drop was taken across a single valve. Process conditions in the letdown system were:<sup>2,7</sup>

1. flow rate (normal), 55,198 kg/h (25,090 lb/h);
2. design temperature, 450°C (840°F);
3. normal differential pressure, 12,720 kPa (1845 psig);
4. upstream conditions: liquid, ~88% wt; vapor, nil; solid, 9-16 wt.; liquid/solid density at conditions, 3.88 kg/L (50 lb/ft<sup>3</sup>);
5. downstream conditions: liquid, ~65% wt; vapor, ~32% wt; solid, 9-16% wt;
6. valve body size, 2-in, 2500 Class ANSI; and
7. normal valve operating position, 30-35% open.

Flow entered the valve through the side nozzle and traveled vertically downwards and exited horizontally into the horizontal receiver vessel lined with a fiber-reinforced refractory. Two separate valve assemblies connected in parallel were installed for the letdown service. No block or bypass valves were used.

To eliminate operational and maintenance problems caused by coke buildup and formation, a special purging system was developed by Exxon. A constant flush of the small annular space (i.e. 0.10 in.) between the valve plug and its guide bushing was used.

The letdown valves in the Bayton plant were modified streamlined Kieley-Muller angle valves with Kennametal K701 trim (Fig. 5). Exxon's initial approach was to use the best hydrodynamic valve body design coupled with special, upgraded trim materials for valve internals.

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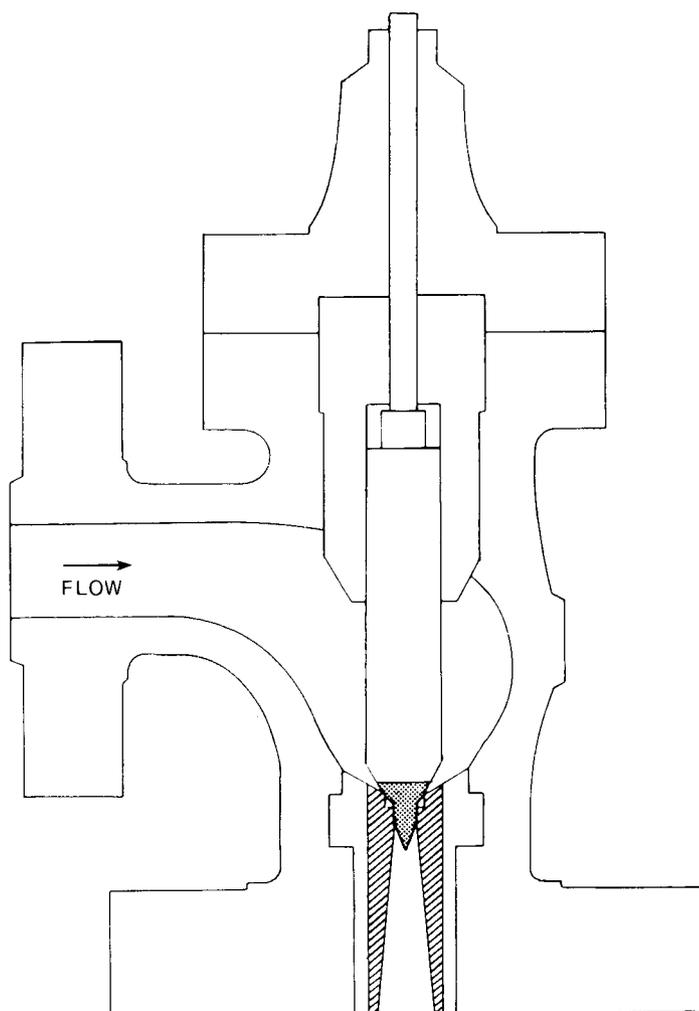


Fig. 5. Sketch of Exxon Kieley-Muller Valve Configuration Valve Used in EDS Pilot Plant in Bayton, Texas (Ref. 2).

Exxon chose the Kielely-Muller 3-x4-in. streamlined angle valve because of their extensive and successful application of the valve in high-pressure letdown, hydrocarbon applications, and because they felt it was relatively easy to scale up to meet the needs of future commercial plants. The internals of the valve were modified to fit a cage in its housing. The cage, which provides extended support to the cantilevered plug, is also used to retain the seat in the valve body. The top entry feature of the cage design also allows ease of the changeout of internal trim parts. The exact changes implemented are not known, but two different designs, one with and one without the cage were planned.

The first set of valve trim controlled successfully with Illinois No. 6 coal in the once through mode of operation. The valve had operated successfully for about 136 d. The erosion of the valve body and the downstream piping was minimal. A second set of trim was installed for operation with Wyoming Wyodak coal. After about 800 h, the trim was removed for inspection. Erosive wear had occurred on one side of the plug and seat even though the valve was controlling successfully. The reasons offered by Exxon for the accelerated wear in the second trim was the higher ash content of the Wyodak coal and operation of the plant in the vacuum tower bottoms recycle mode. Only limited data was gathered in the recycle mode of operation and the data is not sufficient to draw definite conclusions.

Towards the end of the pilot plant operation, the major conclusions were: 1) a valve service life in excess of six months can be projected for the once through mode of operation, 2) in the vacuum bottoms recycle mode of operation, the service life will be less compared to the once through mode, 3) in terms of severity, the Illinois No. 6 is the least severe, followed by Wyodak and Texas lignite, and 4) there is not enough test data on the Texas lignite to predict valve service life.

To date, the best results on letdown valves have been obtained at the ECLP pilot plant. Exxon claims that they can successfully design a letdown valve for a commercial plant. Discussions with Exxon revealed that maintaining an optimum dimensional clearance between the plug and seat while allowing the desired flow is important in the successful operation of the valve. Valve sizing and geometry should take into

account the phase changes occurring inside the valve during the depressurization, the composition, and the thermodynamic properties of the vapor-liquid streams and the residence of the slurry within the confines of the valve seat.<sup>8</sup>

#### H-Coal

The H-Coal pilot plant in Catlettsburg, Kentucky used a two-stage pressure letdown system with two parallel trains, designated A and B (one of which is a standby), in each stage. In the first or high-pressure stage the slurry pressure dropped from 3000 to 1200 psi. The letdown valves in this stage were designated LV202A and LV202B. The second stage dropped the system pressure from 1200 to 50 psi. The letdown valves in this stage were designated LV204A and LV206B. The two stages were separated by a flash drum. Block valves, two upstream and one downstream, in each set of letdowns, were installed to isolate the letdown valves for repairs or replacement.<sup>2</sup>

The process conditions for the two pressure letdown stages are summarized in Table 1.

Although the pressure drops in the first and second stages were 1800 and 1150 psi respectively, these drops were not taken in its entirety through their respective letdown valves. A fixed orifice was installed downstream of the letdown valves in the B train to take part of the pressure drop. The size of the orifice was determined by a trial and error procedure. Where the Willis letdown valve was used, the valve itself, had a second, fixed choke orifice downstream from the adjustable orifice. The adjustable orifice, apart from taking a portion of the pressure drop also provided the operators sufficient time to close the upstream block valves in case of letdown valve failure in the fully open position.

Initially, the Willis rotating disk valve was used in the letdown service in runs 1 through 5. The valve design consisted of two disks with lapped faces, each with one (or two) holes, positioned face to face. One disc was stationary and the other could be rotated. Complete alignment of the holes in the two discs represented full flow conditions and partial alignment caused reduced flow occur. The performance of the

Table 1. Letdown system conditions  
in H-Coal pilot plant<sup>a</sup>

	Valve position	
	LV-202	LV-204
Inlet pressure, kPa (psi)	20,700 (3,000)	8,275 (1,200)
Outlet pressure, kPa (psi)	8,275 (1,200)	345 (50)
Inlet temperature, °C (°F)	450 (850)	400 (750)
Outlet temperature, °C (°F)	400 (750)	395 (740)
Influent, kg/h (lb/h)		
Liquid	18,145 (39,921)	21,652 (47,634)
Solids	2,520 (5,545)	2,543 (5,595)
Effluent, kg/h (lb/h)		
Liquid	17,575 (38,665)	21,401 (47,082)
Solids	2,520 (5,545)	2,543 (5,595)
Vapors	570 (1,256)	251 (522)

<sup>a</sup>Reference 2.

Willis valves was totally unsatisfactory. Erosion was a serious problem and the service life was about 3 to 13 hours. The valve life was extended to 100 hours by in-house redesign of the valve and alternate material selection for the valve parts. Even so, the Willis valve is considered to be a poor choice by H-Coal. An inherent drawback in this type of valve is that the high-pressure slurry impinges on the disc face at a large angle of 90° and cause the hard brittle material to wear faster.<sup>2,9</sup>

Alternate valves were procured for testing in the letdown service in runs 6 through 11. The following valves were obtained in the testing program.

- Cameron (pneumatic and hydraulic actuator),
- Kieley and Muller,
- Hammer-Dahl,
- Masoneilan Sasol,
- Masoneilan Prototype, and
- Paul valve.

A schematic of these valves are shown in Figures 6 to 12. With the exception of the Paul valve, all the others were tested in the letdown service. Table 2 contains a brief description of the design features of these valves and their performance. The cumulative experience on the high pressure letdown valves is that any of the above mentioned valves with some design changes is commercially acceptable. A six month service life for commercial applications is possible. Encouraging results obtained with the erodable plug and reverse flow valve design (Masoneilan Sasol and Masoneilan Prototype) suggest that these may be desirable features in high pressure letdown valves and should be confirmed in larger size plants.

### 2.3 Letdown Valve Specifications for the Demonstration/Pioneer Commercial Plants

Detailed mechanical design and valve sizes for the larger demonstration and pioneer direct coal liquefaction plants are not indicated in the design baseline documents. Only functional specifications without reference to any specific valve are available. What is known are

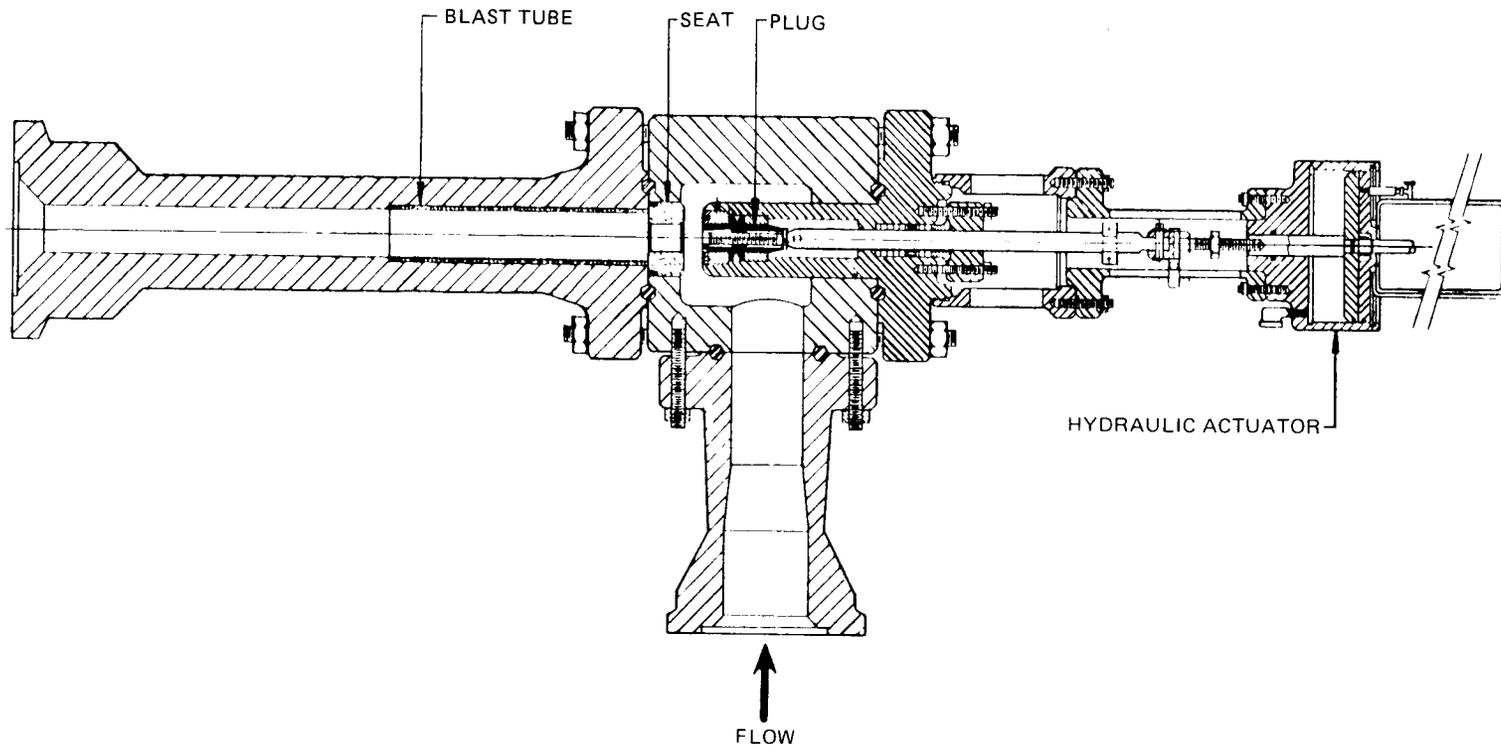


Fig. 6. Cameron Hydraulic Actuator Pressure Letdown Valve  
(Ref. 9).

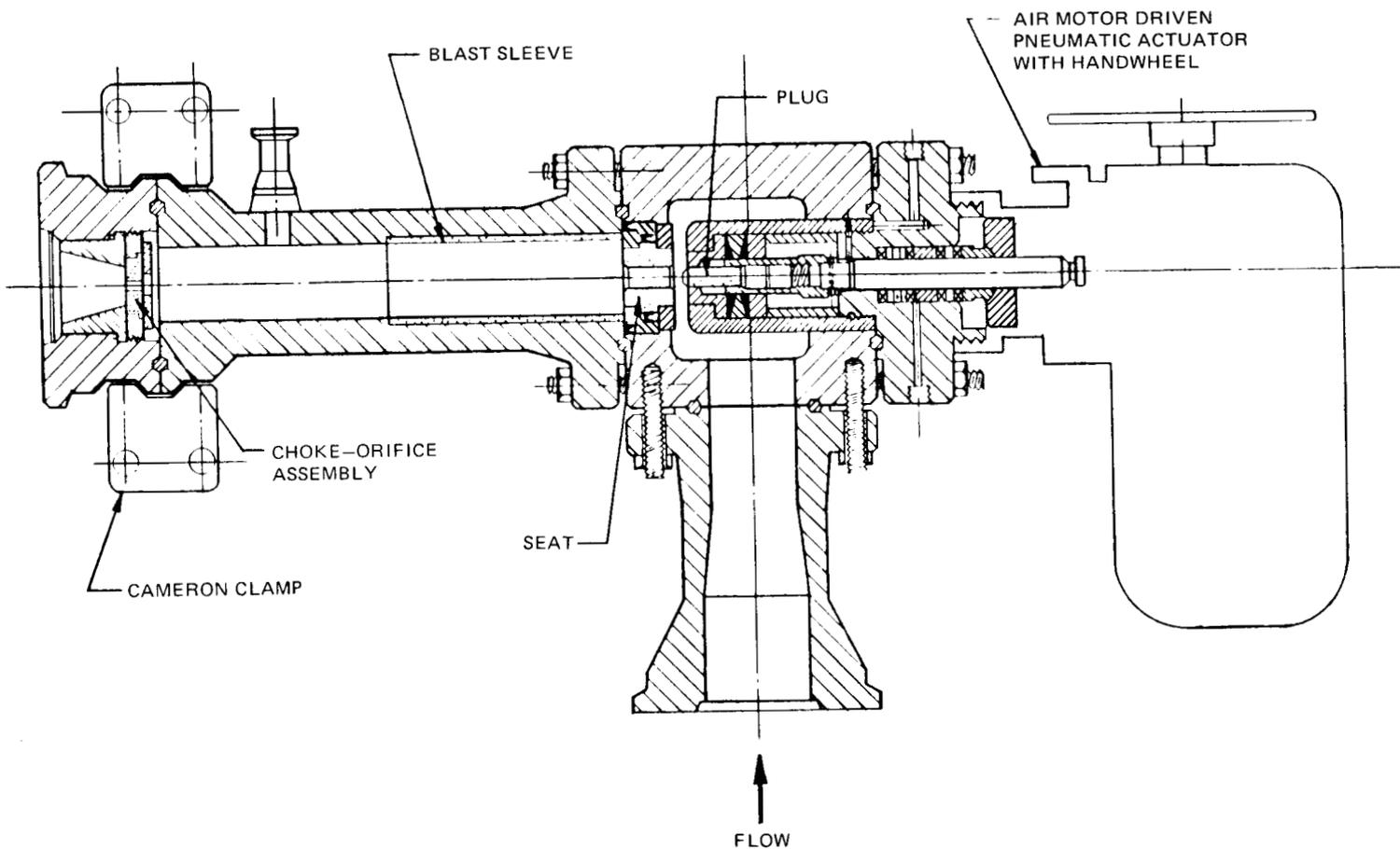


Fig. 7. Cameron Pneumatic Actuator Pressure Letdown Valve  
(Ref. 13).

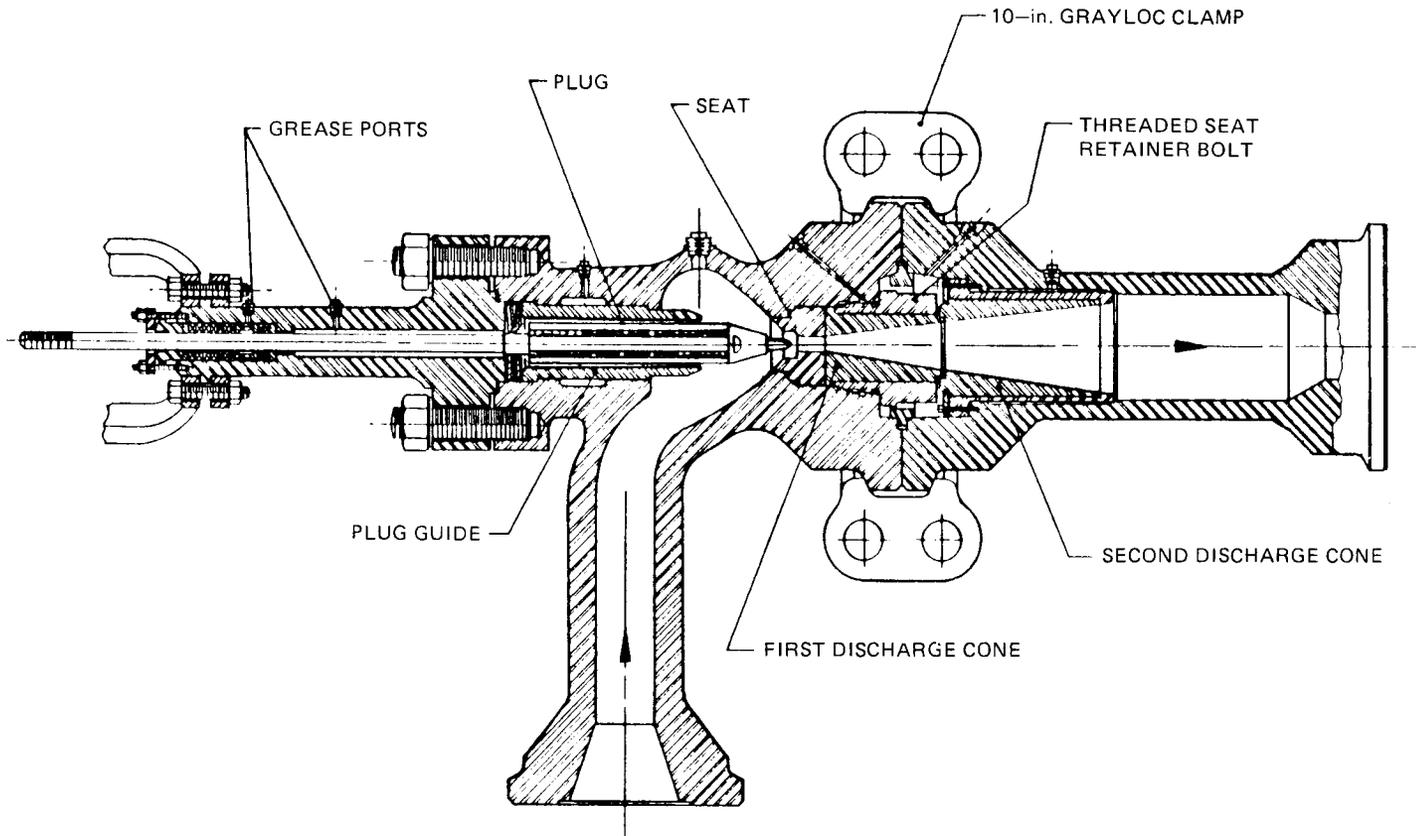


Fig. 8. Kieley-Muller Pressure Letdown Valve (Ref. 9).

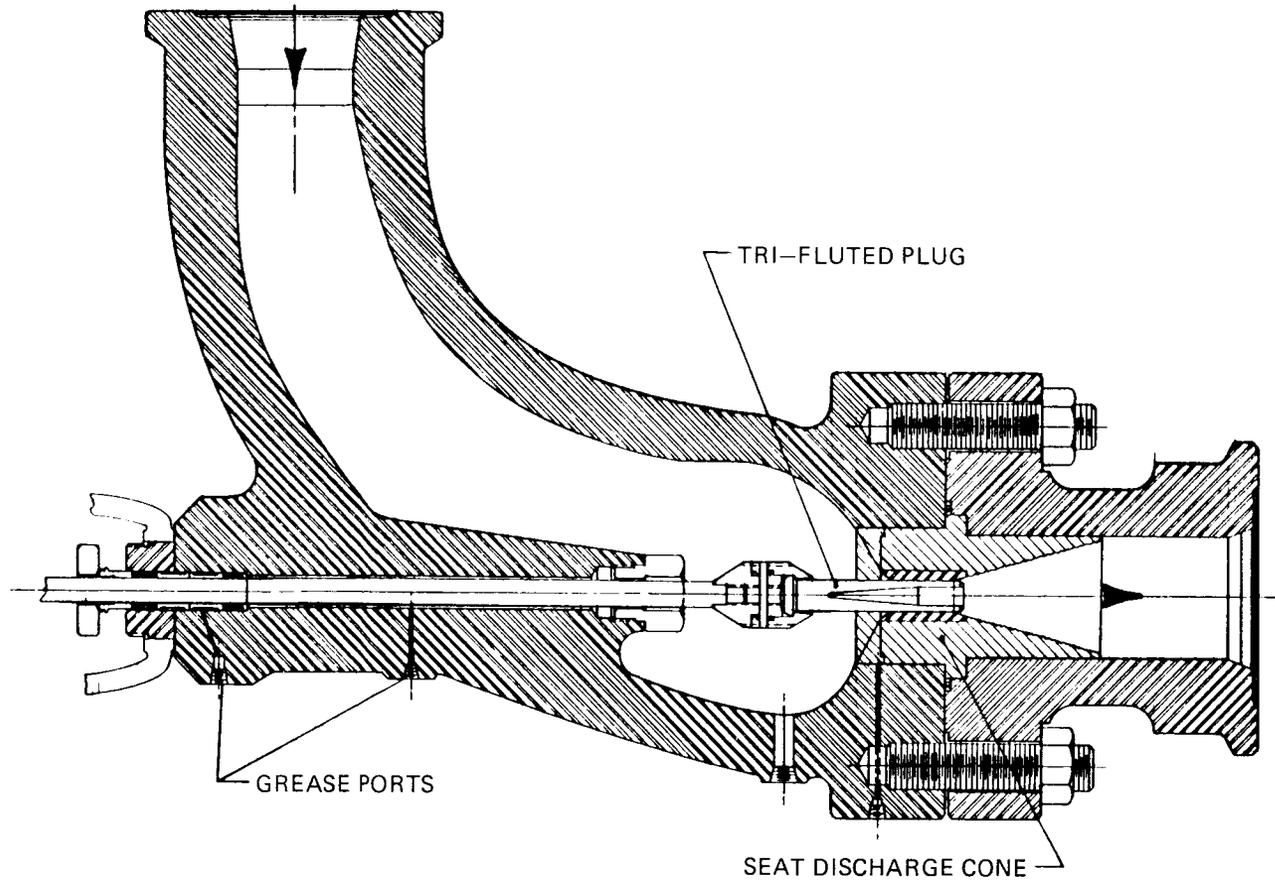


Fig. 9. Hammel Dahl Pressure Letdown Valve (Ref. 9).

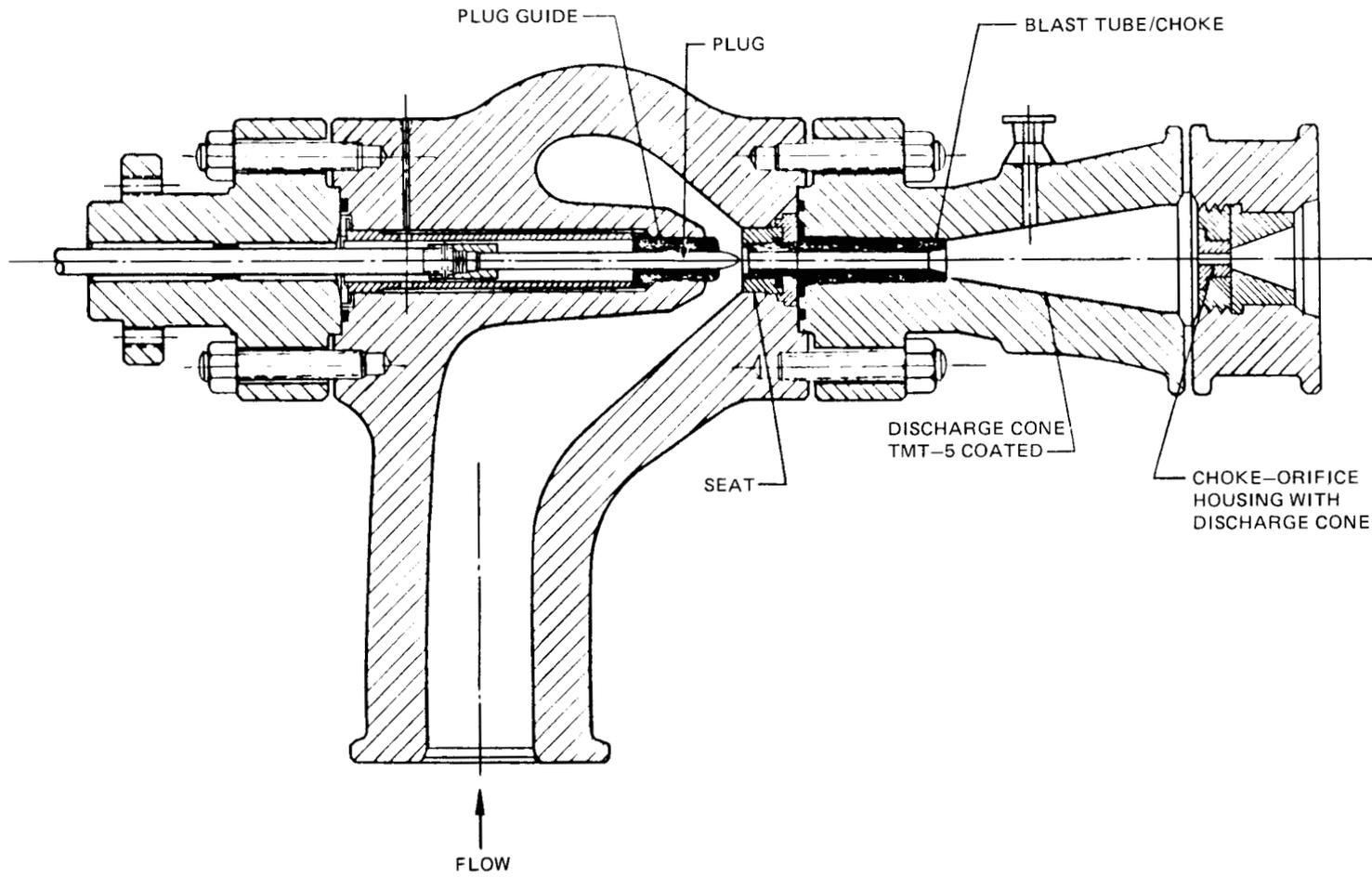


Fig. 10. Masoneilan Sasol Pressure Letdown Valve (Ref. 9).

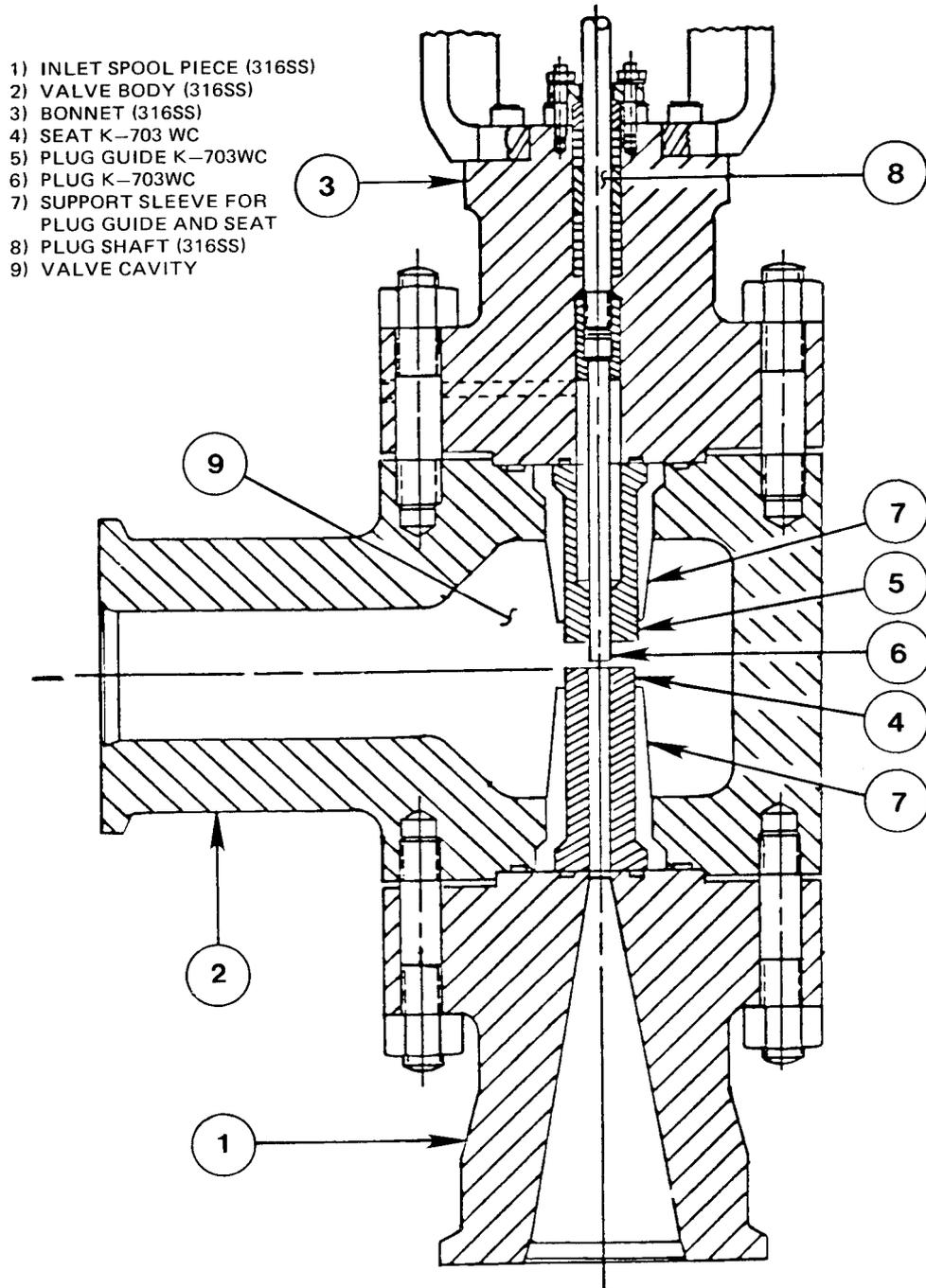


Fig. 11. Masoneilan Prototype Letdown Valve (Ref. 13).

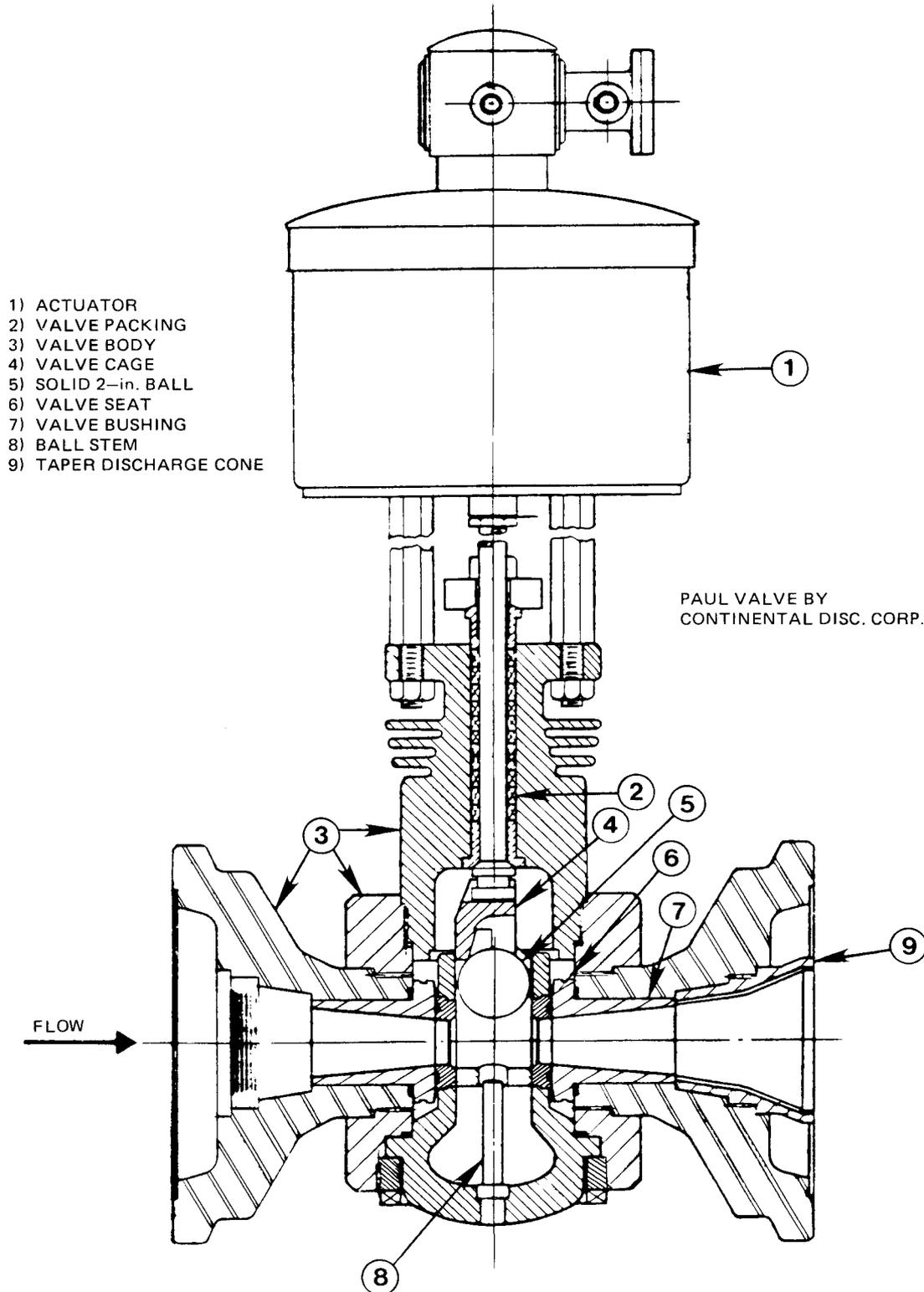


Fig. 12. Paul Pressure Letdown Valve (Ref. 13).

Table 2. Summary of letdown valves tested in runs 6-10 in the H-Coal Pilot Plant

Valve type	Valve design features	Valve trim, material	Service life, hours	Failure mode	Remarks
Cameron	Inlet line size, 6" Valve body size, 6" Valve trim size, 1/2" to 1.0" Actuators: hydraulic and pneumatic Class ANSI 2500 plug and seat angle valve	6% Cr-Co tungsten carbide (Wc) and TMT coating	130-530	<ul style="list-style-type: none"> <li>● Entrapped solids in valve body</li> <li>● Breakage of plug</li> <li>● Plug holder failure</li> </ul>	<ul style="list-style-type: none"> <li>● Flow to close</li> <li>● The 0.5 in. dia. trim averaged 530 hours with 65% open</li> <li>● Hydraulic actuator performed satisfactorily but considered too large</li> <li>● A valve life of 500h can be expected with minor design changes</li> </ul>
Keiley and Muller	Inlet line size, 6" Class 2500 ANSI sweep flow, plug and seat angle valve Valve body size, 3"x4" Valve trim size, 1/2" to 3/4"	3% Cr-Co (binder) WC trim and TMT 5 coating 6% Cr-Co (binder) WC trim and TMT 5 coating	300-1260	<ul style="list-style-type: none"> <li>● Entrapped solids in valve body</li> <li>● Actuator failure</li> <li>● Erosion</li> </ul>	<ul style="list-style-type: none"> <li>● Flow to close</li> <li>● Shorter actuator to minimize vibrations on the brittle plug</li> <li>● The longest duration (1260h) was obtained in Run 8 with 5/8" dia. trim and 3% Cr-Co WC/TMT coated</li> <li>● With new erodible plug trim, the service life can be extended up to 6000 h</li> </ul>

Table 2. (continued)

Valve type	Valve design features	Valve trim, material	Service life, hours	Failure mode	Remarks
Hammel-Dahl	Inlet line size, 6" Sweep flow plug and seat angle valve Valve body size, 6" Valve trim size, 3/4" Actuator pneumatic	6% Cr-Co (binder) WC trim coat with TMT 5	250-1000	<ul style="list-style-type: none"> <li>● Excessive vibration resulting in trim breakage</li> <li>● Erosion</li> <li>● Plug holder failure</li> </ul>	<ul style="list-style-type: none"> <li>● Flow to close</li> <li>● Valve uses a trifluted plug design with an equivalent Cv size for a 3/4" diameter plug</li> <li>● Valve used in low pressure service only (<math>\Delta P \sim 850</math> psi)</li> <li>● Smooth free flow sweep trifluted plug design is close to be wear resistant</li> </ul>
Masoneilon Prototype	Inlet line size, 6" Reverse flow plug and seat (erodible plug) angle valve Valve body, 6" Valve trim size, 3/4" Plug length, 4"	Kennametal-703	1300	<ul style="list-style-type: none"> <li>● Wear of the expendable plug (erosion)</li> <li>● Solids build up in plug region preventing proper actuation</li> </ul>	<ul style="list-style-type: none"> <li>● Flow to open</li> <li>● Flashing occurs in the valve body</li> <li>● Expendable plug (lipstick design)</li> <li>● Only plug faces the flow and is subjected to wear</li> <li>● Good thermal resistance</li> <li>● Wear occurs due to whirling action of slurry rather than direct impingement</li> </ul>

Table 2. (continued)

Valve type	Valve design features	Valve trim, material	Service life, hours	Failure mode	Remarks
Masoneilon Sasol	Inlet size, 6" Sweep flow, plug and seat (erodible plug) angle valve Valve body, 6" Valve trim size, 3/4" Plug length, 6"	6% Cr-Co WC with TMT coating	800	<ul style="list-style-type: none"> <li>Wear of the expendable plug (erosion)</li> </ul>	<ul style="list-style-type: none"> <li>Flow to close</li> <li>Expendable plug (lipstick design)</li> <li>Square plug trim modified to parabolic shape plug for less wear</li> </ul>

the service conditions anticipated for the valves, the potential valves that can meet the service requirements and the desirable features in the valves for successful operation.

### SRC-I

The process conditions for the high-pressure letdown system of the SRC-I demonstration plant are listed in Table 3. Slurry from the coal dissolver effluent separator at 2015 psia is cooled from 840°F to 750°F in the high pressure slurry/hot oil exchanger, combined with the dissolver blow down solids and reduced in pressure to 115 psia, flashed and phase separated in the medium pressure flash drum. The pressure of the flashed slurry is further reduced to 40 psia, flashed and phase separated in the low pressure flash drum. The twice flashed slurry is then transferred to the vacuum section.

Of the many possible configurations of the high pressure letdown system (2015 psia to 115 psia) the single stage pressure letdown with two parallel trains is considered to be the optimum from the standpoint of reliability (system unavailability), and total system cost (capital/operating and maintenance). This scheme consists of single stage letdown pressure from 2000 psig to 100 psig, having two (2) parallel vessels and two (2) high pressure letdown valves. The normal operation is one (1) vessel and one (1) letdown valve operating while the second vessel and valve act as spare. Each vessel/valve trim will be heat-traced (650°F) to minimize temperature shocks. Slurry block valves, two upstream and two downstream of each letdown valve are provided to deactivate a failed letdown valve and to bring the spare letdown valve on stream. Provisions for flushing/purging of the letdown valves and block valves with high pressure flush solvent is indicated in the process and instrumentation diagrams. However, the flush requirements are not currently specified and is to be determined after the final selection and testing of the valves in the full size plant.

It is estimated that the trim diameter for the high pressure letdown valve will be roughly 1.75 to 2.0 inches at 65 to 70% valve lift. Any deviation between the calculated and actual size requirements will be met by providing adequate margins (up to 1.5 times the design) in the valve body size to accommodate trim changes.

Table 3. SRC-I demonstration plant  
high-pressure slurry letdown valve  
service conditions<sup>a</sup>

	Upstream	Downstream
Pressure (psia)	2,010	115
Pressure differential	1,895	
Temperature (°F)	780	730
Flow (lb/hr)	1,200,000	1,200,000
Flow (gpm)	2,823	
Wt % solids	6	6
Wt % liquids	94	54
Wt % gas	0	40
Line size (in.)	16	TBD <sup>b</sup>

<sup>a</sup>Reference 3.

<sup>b</sup>To be determined.

The valve body size is estimated to be around 6 to 8 inches in diameter. Control valve sizing equations contained in ANSI/ISA Standard S75.01 have been used in the calculations. A flow-to-close angle valve is shown in the process and instrumentation diagrams but a flow-to-open valve is maintained as a viable option.

### EDS

There is very little published information on the pressure letdown system for the EDS commercial design. Discussions with personnel at Exxon revealed that a scale-up of 27 times the slurry capacity handled in the ECLP pilot plant is projected.<sup>8</sup> It appears from the process flow diagrams in the EDS commercial plant study update, that single letdown valves will process the reactor effluent slurry from two of the four liquefaction lines (one reactor per line). The slurry flow rate of the valve inlet is estimated to be roughly 650,000 lbs/hr at 540°F and 1935 psi pressure. A back-up system will be provided but the details have not been worked out. The slurry pressure will be reduced in one stage from 1935 psi to 80 psi. The slurry will be fed to the atmospheric tower at 788°F.

Exxon indicated that it has the necessary data to design a letdown valve for these service conditions. A two year service life for the letdown valve in the commercial plant will be the ultimate target. According to Exxon, this can be achieved with continued development and testing. A one year life with the Illinois No. 6 coal in the once through mode of operation is possible with current technology. In the case of the Wyodak coal and Texas lignite, this may not be possible. Also, in the vacuum bottoms recycle mode, the service life can be much lower than the once through mode. At present, there is insufficient test data to project valve service life in commercial plants for the more severe coals and vacuum tower bottoms recycle mode. In any event, Exxon claims to have a good understanding of the critical parameters to design a letdown valve which can last, eventually up to two years. Expansion of the existing limited data base on letdown valves performance with the reactive coals and the recycle mode of operation will be the first step that Exxon would take to develop successful valves for these service conditions.

### H-Coal

The H-Coal pioneer commercial plant is designed to convert 16,500 tons per day of clean washed coal to 50,000 barrels per day of clean hydrocarbon liquids. The total coal feed capacity is provided by eight identical trains (seven operating and one spare), each rated at 2400 TPD coal. The following sequential steps are carried out in each train — coal slurry preparation and pumping, slurry preheating and reaction, phase separation and cooling, and catalyst addition and withdrawal.

The pressure letdown system is an integrated part of the H-Coal phase separation and cooling plant (Plant 4). Here, the two reactor effluent streams from each train are separated into liquid and vapor streams by pressure letdown and/or cooling, followed by flashing and phase separation.<sup>10</sup>

Figure 13 is a schematic of the primary separation and pressure letdown system. The vapor stream from the reactor is cooled and flashed in the high pressure flash drums (4C-102 and 4C-103) to recover the hydrogen. The condensate from the high pressure warm flash drum (4C-102) is cooled, letdown in pressure from 2,975 psi to 735 psi and combined with the liquid stream from the reactor after it has also been letdown in pressure from 2975 to 735 psi. The combined stream is phase separated in the intermediate slurry flash drum (4C-105). The vapor stream from 4C-105 is cooled, flashed in the intermediate pressure warm flash drum (4C-101). The bottoms from 4C-101 is further letdown in pressure to 75 psi and fed to the low pressure slurry flash drum (4C-107). The vapor stream from 4C-101 is cooled and flashed in the intermediate pressure cold flash drum (4C-104). The condensate from the high pressure cold flash drum (4C-103) is letdown in pressure to 715 psi and also flashed in 4C-104). The resulting vapors from 4C-104 are sent to the gas plant. The liquid stream from 4C-104 is reduced in pressure from 715 psi to 50 psi and flashed in the low pressure cold flash drum 4C-108 along with the vapor stream from the low pressure warm flash drum after it has been cooled. The resulting vapor streams from 4C-108 are sent to the gas plant.

The bottom streams from 4C-107 and 4C-108 are combined and sent to the distillation plant. The bottoms from 4C-106 is sent to the recycle

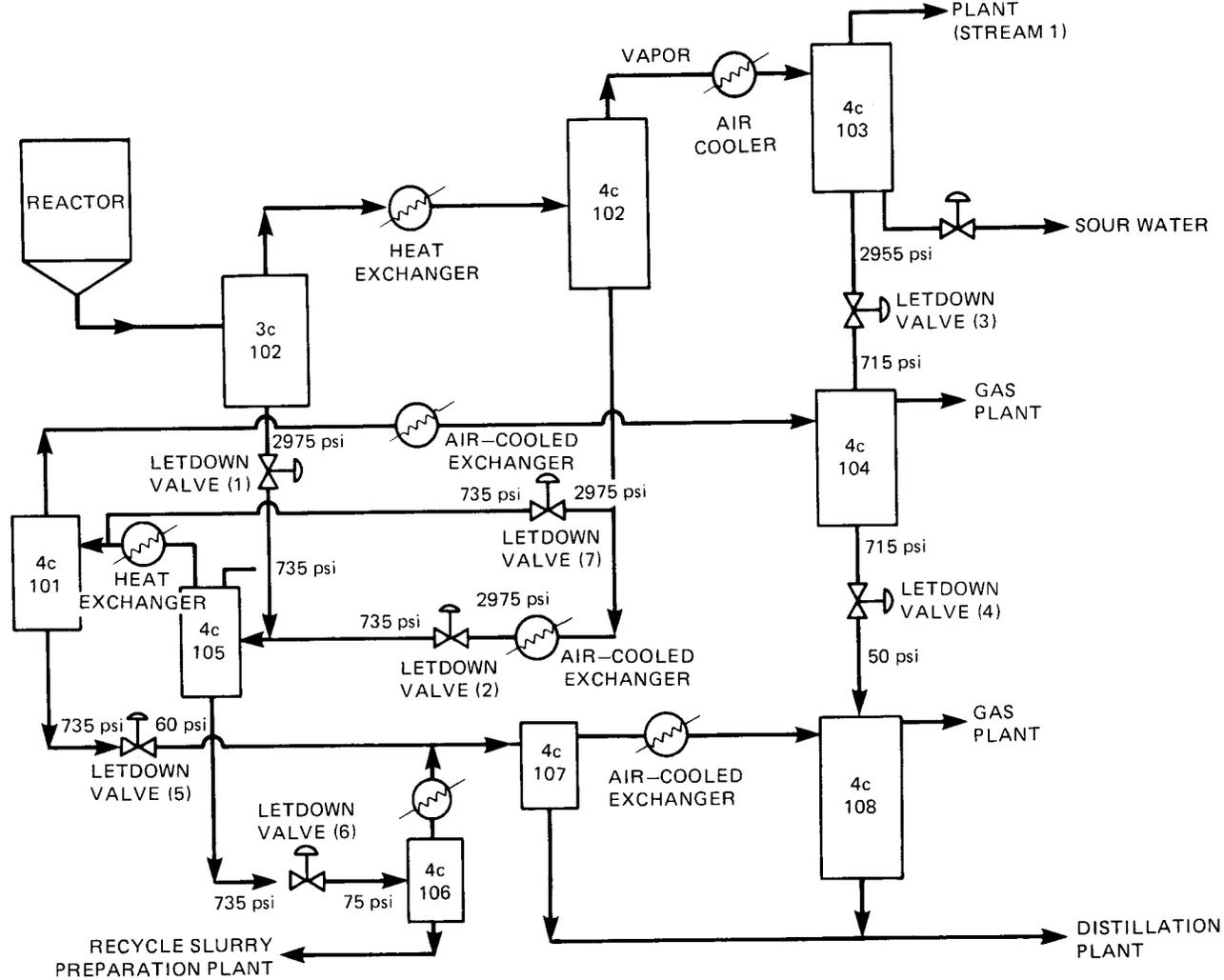


Fig. 13. H-Coal Pioneer Commercial Plant Primary Separation and Pressure Letdown System.

slurry plant. The stream conditions at the five pressure letdown locations shown in Figure 13 are summarized in Table 4. Valve selection and specifications are not reported in the design. It is estimated that the valve trim size will be of the order of 2 inches. Parallel letdown valves will be used in each letdown step which will enable one valve to be repaired while the other valve is in service. H-Coal has opted for the two-stage pressure letdown system.

Based on the H-Coal pilot plant experience on letdown valves, the following guidelines will be used in the selection of valves for the H-Coal commercial plant:<sup>11-13</sup> 1) any of the high pressure letdown valves tested at the H-Coal pilot plant could, with some design changes, be used in the commercial plant; 2) a six month service life out of the valves is desirable; 3) for optimum control, the valve should be designed to operate at 30 to 60 percent open; 4) sweep flow erodable plug in the Masonelian flow-to-open prototype valve is a desirable feature from an erosion standpoint but controllability may be difficult if the valve fails; 5) no particular shape is favored for the plug and seat; 6) plug and shaft should be nearly of the same size to minimize vibration. H-Coal is in the process of issuing the final report on the pilot plant letdown valve experience. Further details on the valves tested in the pilot plant and the recommendations on the commercial readiness of these valves are to be published in the final report.

#### 2.4 Valve Sizing, Scale-Up Data Gaps

Sizing of pressure letdown valves for throttling coal/hydrocarbon mixtures is done by extrapolation of the sizing equations developed for single phase fluids. The method that is widely used by the valve industry is the ANSI/ISA control valve sizing method for single phase flashing fluids.<sup>14</sup> A brief discussion of the method follows.

For a fixed, upstream pressure and a liquid which does not change state, the flow through a restriction is linearly proportional to the square root of the pressure drop measured across the restriction (valve). The slope of the line represents the valve capacity factor,  $C_v$ . When the pressure decreases below the liquid vapor pressure, flashing will occur. As the liquid continues to flow past the point of

Table 4. Process conditions for the letdown valves in the H-Coal commercial design

	LV-1	LV-2	LV-3	LV-4	LV-5	LV-6	LV-7
Flow, lb/hr	460,000	70,000	45,000	48,000	84,000	521,000	84,000
Inlet pressure, psi	2,975	2,975	2,975	715	735	735	2,975
Outlet pressure, psi	750	735	715	50	60	75	735
Temperature, °F	750	550	130	130	550	580	550
Inlet composition, wt%							
Solids	18.1					15.9	
Liquids	81.9	100	100	100	100	84.1	100
Vapor	0.0						
Nominal pipe size, in.							
Inlet	12	4	4	4	4	4	4
Outlet	14	4	4	4	4	4	4
Valve size <sup>a</sup>		2	1.5	1.5	2.0		1.5

<sup>a</sup>Presumably valve trim size.

lowest pressure (vena contracta) which corresponds to the highest velocity, pressure recovery will occur as the velocity head is converted back to pressure head. When this recovery pressure exceeds the liquid vapor pressure, the vapor in the bubbles will recondense; in the extreme case, this will result in cavitation. If the pressure recovery does not rise to the liquid vapor pressure, then a two phase (liquid-vapor) stream will continue along the flow path. When two phase flow is present, the aforementioned linear relationship between the flow and pressure drop is no longer valid and the straight line plot starts to bend — such that the  $C_v$  value begins to decrease. When a significant fraction of the liquid is converted to vapor, the flow may become "choked" and further reduction in pressure (downstream pressure) will not result in an increase in flow. Since with choked flow, it is not possible to use the actual pressure drop measured across the valve, a "pseudo" terminal pressure drop has been used in the sizing of the valve. For sizing purposes, this  $\Delta P_a$  is calculated from the following equation:<sup>3,14,15</sup>

$$\Delta P_a = F_L^2 (P_1 - F_f P_v) \quad (1)$$

or

$$\Delta P_a = F_L^2 (P_1 + P_{vc})$$

where

$\Delta P_a$  = "pseudo" terminal pressure drop across the valve (maximum allowable pressure differential across the valve at a given upstream pressure), psi

$F_L$  = liquid pressure recovery factor which represents the ability of the valve to convert velocity head back to pressure drop;  $F_L$  is a function of the valve internal geometry and must be experimentally determined by the valve manufacturer using a test fluid.

$P_1$  = pressure at valve inlet, psia

$P_v$  = vapor pressure of liquid at inlet temperature, psia

$F_f$  = liquid critical pressure ratio factor; it is the ratio of the apparent vena contracta pressure at choked flow conditions ( $P_{vc}$ ) to the vapor pressure of the liquid ( $P_v$ ) at inlet

temperature (i.e.,  $P_{vc}/P_c$ );  $F_f$  must be determined experimentally and is plotted as a function of  $P_v/P_c$ , where  $P_c$  is the critical pressure of the liquid; in the absence of experimental data,  $F_f$  is estimated from the correlation,

$$F_f = 0.96 - 0.28 \sqrt{P_v/P_c} . \quad (2)$$

The sizing procedure is outlined in the following sequential steps:

1. For the given fluid, determine  $P_v$ , at inlet temperature and  $F_f$  from experimental data or estimate  $F_f$  from (2),
2. For the given valve type, select the appropriate value of  $F_L$  from the valve manufacturers data,
3. Calculate  $\Delta P_a$  from equation (1),
4. Calculate the valve coefficient  $C_v$  from the ISA equation for choked flow.

$$\begin{aligned} \gamma_{\max} &= C_v (\Delta P_a / G)^{1/2} \\ &= F_L C_v [(P_1 - P_{vc}) / G]^{1/2} \end{aligned} \quad (3)$$

where

$\gamma_{\max}$  = terminal volumetric flow rate, gpm

$G$  = specific gravity of the vapor-liquid mixture at flowing temperature and pressure (estimated from: thermodynamic properties of the vapor-liquid mixture)

5. Determine from the valve manufacturer's catalog, the valve size for the  $C_v$  calculated from equation (3).

Proper valve sizing is a calculation that must be made with care using as far as possible experimentally determined values for the various coefficients in the sizing equations. The chief uncertainty is in the numbers provided for  $F_L$  and  $C_v$  by the valve manufacturers.  $C_v$  is usually defined as the quantity of 60°F water in gallons per minute that will pass through a specific valve size at maximum valve lift at 1 psi pressure drop. The ISA standard presents a method for predicting  $C_v$  for pure liquids but this method has extremely narrow limits of applicability, especially if the fluid is other than water. Consequently, extrapolating the  $C_v$  values for other conditions is risky. The prediction

of valve sizes based on incorrect  $C_v$  values gets progressively worse as the fluid changes from water to pure liquids, to liquid mixtures and finally to two or three phase fluids. Furthermore, the  $C_v$  values are obtained in relatively small size valves and extrapolating them to larger size valves introduces additional error in sizing. The extent of error is unknown.

The tendency in the valve industry has been to oversize the valves to compensate for errors in  $C_v$ . However, oversizing the valve can be just as detrimental as the false economy of undersizing the valve. An oversized valve, in order to produce low flow rates, must be throttled down to a nearly closed position. Under conditions of high line pressure, rapid wear to the seating surfaces will occur as the liquid is forced through the narrow space between the seat and valve plug. A properly sized valve, on the other hand, will be able to throttle down to the desired flow with ample space remaining between the plug and seat. An undersized valve will produce poor control by failing to respond quickly to changes in line demands. Bhide<sup>15</sup> states that flow control valves should ideally be sized to operate in the 60 to 80% open range to provide satisfactory flow control and minimize "wear-out of trim" due to erosion.

The liquid pressure recovery factor at choked flow in the equation (1), is the other coefficient for which there is difficulty getting valid numbers.  $F_L$  values, like  $C_v$ , can be determined by testing and is published by valve manufacturers. This factor converts the sizing factor,  $C_v$ , for use with pressure drop  $P_1 - P_{vc}$  where  $P_{vc}$  is the pressure of the vena contracta. Although the relationship is considered reliable, there is a problem in predicting  $P_{vc}$ . If the liquid is non-aqueous, one is forced with the problem of predicting the minimum effective vena-contracta pressure without the benefit of experimental data.

The pressure ratio  $(\Delta P/F_L^2)$  necessary to obtain choke flow is not well defined. The criteria for choked flow for flashing liquids is:

$$\frac{\Delta P}{F_L^2} > (P_1 - F_f P_v) \quad (4)$$

$F_f$  in equation (4) is the liquid critical pressure ratio factor ( $P_{vc}/P_v$ ). It should be estimated from the experimental data on vapor pressure ( $P_v$ ) and the critical pressure  $P_c$  of the liquid since it is not possible to actually measure  $P_{vc}$  at choked flow. However, there is no data on  $P_c$  for coal liquids and the vapor pressure data, if any, is very limited.  $P_c$  is generally estimated from one of the available thermodynamic equations of state for multicomponent vapor/liquid streams assuming a set of key components in the coal liquid. The knowledge of the key species in coal liquids that contribute to flashing is extremely poor. Furthermore, these key species also change with the coal type. Coal liquids from liquefaction processes are complex mixtures of individual chemical compounds. The formation of these components are dependent on the process, the operating conditions, and the coal type used; however, to date, the physical and thermodynamic properties of these liquids are still being researched. There are some published correlations to estimate the physical and thermodynamic properties of coal liquids. A summary of these correlations can be found in Ott and Khan.<sup>16</sup>

It has been reported that  $F_f$  is affected by valve geometry. This probably is related to the non-equilibrium nature of the flashing occurring in the valve. Any value that is used for  $F_f$  in the sizing calculation should have allowed for errors in extrapolating to other valve geometries and should be verified by test data when possible. With greater understanding of the factors which influence  $F_f$ , the level of confidence in sizing letdown valves for choked flow conditions can improve significantly.

Thermodynamic properties such as vapor and liquid compositions, vapor pressure, liquid critical pressure, molecular weight, specific volume, etc. at flow conditions are necessary to accurately estimate valve size. As stated earlier, there is a dearth of such data at present. Once these properties are known, it is possible to calculate the energy change occurring within the valve by analytic models, which can then be verified in valve models. With this information, the preferred valve geometries to dissipate the energy without undue damage to the valve can be developed.

The technique described above to size letdown valves has several limitations and should be regarded, at best, as an approximation. Since no valve in the required size and configuration for this application has been built, any specification for a commercial letdown valve should be regarded only as a functional specification and not a detailed design specification. Valve manufacturers claim that they could size the commercial plant valve to within 1/4 to 3/8 in. of the theoretically required size, but the basis for their claims are not known. The pilot plant experience has improved our understanding of these valves. Manufacturers seem to know what the problems are and have also identified solutions in many cases. Only some of these solutions have been attempted in the pilot plants. The transfer of information from the pilot plant personnel to the valve industry has helped speed up the learning process. Although an optimum valve has not been identified to date, it can be stated that there is general agreement among process designers and valve manufacturers that there are some definite features that are desirable in letdown valves in this application. Some of the characteristics of the successful letdown valves are<sup>17,18</sup> (1) streamlined valve surfaces to reduce slurry impingement angles, (2) an unobstructed seat geometry that delays flashing until the flow is directed into an expanded pipe section or vessel where the pool of downstream liquid may help absorb the energy, (3) proper sizing that allows the choked flow condition to pass the required amount of fluid while keeping the valve in an opened position, (4) a long straight or slightly tapered choking section to delay vaporization, and (5) upgraded trim materials that are fabricated under strict quality control measures and to precise dimensional tolerances. In addition, careful operating and maintenance procedures which allow for the brittle nature and thermal shock effects on the valve trim and special purging connections to valve internals to mitigate coke and solid buildup are important considerations for optimum valve performance.

## 2.5 Development and Testing Needs

While substantial progress was made in the pilot plants in demonstrating the suitability of several different pressure letdown control

valves, there are still serious concerns regarding the scaleability and reliability of these valves for the larger demonstration and/or pioneer commercial plants. Presently, no scientific procedure exists for accurately sizing the letdown valves for flashing three phase fluid streams. Valve manufacturers have relied on their experience in related applications and used a considerable amount of judgement to size valves for the coal liquefaction pilot plants. This has inevitably led to a trial-and-error procedure in the sizing of the valves. While this approach is not unusual in the industry, especially for first of-a-kind component such as the slurry pressure letdown valve, a predictive method should be developed which will not require as many iterations to arrive at the optimum valve size and configuration for the larger plants. This would not only ensure satisfactory valve performance, but would also eliminate the need to stock valve trim in several sizes and frequent replacement of valve trim in a commercial plant.

Scaleability of letdown valves to demonstration/pioneer commercial plant size is currently uncertain. The large plants would require a diametrical scale-up of the existing pilot plant tested valves by a factor of at least 10 or more. It is the consensus of the valve manufacturers that the maximum scale-up of existing valves is no more than three by existing technology. Lack of proven valve life and valve performance in these erosive applications in the sizes required for the large plants is perhaps the number one limitation. Until a full size prototype valve is built and tested, a fair amount of modifications in the design and operation should be anticipated.

Experience in the pilot plants has shown that trim components in the letdown valves are subject to extreme conditions of erosion/corrosion and cavitation and therefore require speciality materials. Premium grades of cemented carbides (tungsten carbide in cobalt-chrome matrix) appear to be the most durable materials. However, even these have a maximum service life measured in weeks, or at best, a few months. The design of and fabrication of cemented carbide valve trim is a highly specialized skill and has to be carried out in special shops experienced in this technology. Advanced candidate trim materials and surface treatment of materials which are in the initial stages of characterization and erosion testing could be the solution in the long run.

The question of single-stage versus multiple stage pressure letdown (i.e. pressure letdown through a single valve versus pressure letdown through multiple valves in series) is still open. SRC-I and EDS have opted for the single stage letdown. The H-Coal design specifies multi-stage pressure letdown, presumably for process reasons. The selection has been mainly based on pilot plant experience, economics, and some preliminary reliability calculations. What is known from these studies is that the single stage letdown is probably adequate and economically attractive compared to the multistage. However, from the standpoint of valve life and performance, maintenance requirements, and reliability the answers are not obvious. Actual testing of the concept in the demonstration and/or pioneer commercial plant will be required to recommend the optimum scheme.

The flush requirements and the design of the flush system for pressure letdown valves are not currently known. Limited data have been collected in the pilot plants and may be available in future reports. However, this is an area that has not been addressed sufficiently. Successful operation of valves in slurry service will require a dedicated flush system. A data base is needed for specifying flush requirements, design of the flush system, etc. for the large plants.

While the technology is available to provide letdown valves for the larger plants, it is not adequate from the standpoint of reliability, service life, and overall economics. The following areas are considered to be critical in the successful design and operation of slurry pressure letdown valves. Further work is needed in these areas to bridge the existing data gaps.

#### 2.5.1 Valve Sizing and Scale-Up

Efforts in this area should focus on first developing analytical models to describe and simulate the fluid flow, phase change with chemical reaction and energy dissipation. Proper understanding of these phenomena will reveal the validity, the limitations, the range of applicability, and modifications needed (in quantitative terms) to the existing correlations. Secondly, the models should be verified with test data from laboratory and/or the pilot plant scale valves. Data on

pressures (upstream/downstream), flow rates, fluid temperatures, solids content in the stream, solids particle size, valve position, rate of change of valve position with time and fluid parameters (density, viscosity, vapor pressure, critical pressure, etc.) should be recorded in the experiments over a variation of upstream pressure, pressure drop, and flow quantity. A 4 to 1 variation has been suggested by a valve manufacturer. These data can be used in the model to predict the onset of flashing, the compositions of the stream, the residence time, and the pressure drop, etc. inside the valve which are otherwise difficult to measure.

#### 2.5.2 Valve Geometry and Configuration

Testing of various valve geometries and configuration should continue with different types of coal and process conditions. To some extent, these tests were carried out at the pilot plants but the tests have not been conclusive.

#### 2.5.3 Thermodynamic and Physical Property Data Base

A sound data base should be developed for use by valve designers and process engineers. The critical properties of coal liquids should be determined on various coals, coal/hydrocarbon mixtures at temperatures and pressures commensurate with the needs of the coal liquefaction process.

#### 2.5.4 Materials

Advanced materials, surface coatings, composites, etc. should be identified and tested for the erosion, corrosion, and mechanical strength. Ongoing efforts in the materials area should continue and should be considered a long-term commitment.

#### 2.5.5 Maintenance and Quality Assurance Procedures

These are critical items in the successful operation of the larger plants. Valuable information on valve assembly procedures, start-up and operation, maintenance needs, valve malfunction and failures, has been

gathered in the pilot plant. In addition, solutions to problems resulting from thermal shock, vibration and chipping of the plug and seat, actuator failures, etc. have also been documented in the pilot plant. A thorough analysis of the pilot plant records should be made and a documented data base on the maintenance, quality assurance and start-up and operating procedures for future plants should be established.

### 3. BLOCK VALVES

#### 3.1 Function and Service Conditions of Block Valves

Block valves are used throughout the plant to isolate process equipment such as pumps, pressure letdown valves, sampling lines, instrumentation, by-pass lines, etc. from the flow medium when these equipment need repair or replacement. The basic requirement in the design of block valves is that they offer minimum flow restriction and pressure loss when open. Because of the combination of temperatures to 850°F, pressures to 3000 psig, and the abrasiveness of the coal particles in the slurry, these valves require special considerations in the design, selection of materials, and fabrication. In addition, there are operational requirements such as size, cycling frequency of the valve, actuation time, pressure drop across the valve seat, and flushing or purging to minimize solids buildup in the valve body cavity and solids entrapment between the seating surfaces. Tight shutoff is also required in these valves to provide isolation for removal and maintenance of equipment in areas where the pressures are in excess of a few hundred pounds. As a precautionary measure, double block valves are usually provided on either side of the equipment for safe removal and replacement.

#### 3.2 Block Valve Experience in Pilot Plants<sup>4,19</sup>

Several different valve types have been tested for their acceptability as block valves in slurry service. While a detailed discussion of the experience on these valves is beyond the scope of this report, a synopsis by facility is presented in the following paragraphs.

##### 3.2.1 Wilsonville (SRC-I) Pilot Plant

The 6-ton per day SRC-I pilot plant at Wilsonville, Alabama is using the Rockwell Edwards Y-Pattern Globe Valves as blocking valves on all slurry service. Other manufacturer's block valves (EPG, Kamyr, WKM with trim 18, Hills McCanna) have been tested in the plant with varying degrees of success. The inlet line size was 1 or 2 inches, the line

pressure 2000 psig, and the process stream temperature 600°F. The valve trim material in the Rockwell globe valve is Stellite 6. The valve body is 347 stainless steel. The valves are operated as double block and bleed with minimal flushing. These valves have operated with moderate success with some seat leakage. The normal service life has been roughly 1-2 years.<sup>19</sup>

### 3.2.2 Fort Lewis (SRC-II) Pilot Plant

In the SRC-II Fort Lewis pilot plant, the Rockwell-Edward Y-pattern globe valve (Model 6624) was used exclusively for all block services. The pressure rating on the valve was 2000 psi.<sup>5-6</sup> The stream temperature range was 500-800°F, and the solids content of the slurry was 5-48 percent. Valves were procured with 347 stainless steel bodies and stellite trim. The line size was 1 to 3 inches. Most recurrent problems with these were stem leakage in hydrogen and slurry service and through leaks in slurry service. In locations with several hundred pounds pressure drop, one or a few openings and reclosings on slurry service led to block valve failure. All valves in the high pressure service were double-block and bleed valves with flushing. Fort Lewis has tested other valves in the high pressure slurry service. These included Gulf and Western EBV ball valves, the Willis rotating disc block valves, and the Walworth pressure-seal gate valve. The EBV ball valves did not function well because of recurrent packing failure. They were replaced with the Rockwell globe valve which was continued to be used till plant shutdown. Slurry leakage was also a problem with the Willis valve. The cause was attributed to a manufacturing defect which was later corrected and the valve operated satisfactorily for about six months. Experience on the Walworth block valve was satisfactory except for slight leakage.

A block valve testing program was being initiated at the time the plant operations ceased. No definite conclusions were reached in the Fort Lewis SRC-II pilot plant on block valves because of the insufficient operating experience.

### 3.2.3 Exxon Donor Solvent Pilot Plant

In the 250 ton-per-day pilot plant in Baytown, Texas, five commercially available block valve designs were evaluated.<sup>20,21</sup> The valve types evaluated were the through conduit gate valve, a metal seated trunnion mounted ball valve, a lubricated plug valve, a wedge type gate valve, and a ramseal valve. There were about 50 valves in the size range 1-6 inches. The design features of these valves are given in Table 5. In order to establish long-term reliability and valve flushing requirement, a block valve project was carried out at the pilot plant. These efforts are described in the EDS quarterly reports, in particular the report for the period October 1 — December 31, 1979. The final EDS project report, which is in publication, should contain the final conclusions and recommendations from the block valve project. A summary of the pilot plant block valve experience is presented in Table 6. For isolating high temperature (800°F), high pressure (2000 psi), high solids content (up to 45%) process streams, Exxon indicated that the preferred choice is the WKM through conduit gate valve (Fig. 14). The only stringent requirement with this valve is a good flush system since in these valves the gates and seats are not in contact during cycling and there is the potential of solid build up in the body. The 6-in. valve used about 10 gpm of high pressure flush system. The metal seated ball valves were tested in less severe service (bottoms recycle). A schematic of the valve is shown in Fig. 15. The valve performance was judged satisfactory. The main concern with this valve was solids build up in the spring cavity which was minimized by flushing. Operational problem areas experienced with the lubricated plug and seat valve (Fig. 16). Recurrent jamming of the valves occurred. The valves were inadequate for severe service. The maintenance needs for the plug valves were also excessive. The valves were also limited by temperature (650°F max) due to lack of proven high temperature sealants. Other concerns with these valves are that they are not a full-port design and there is the potential for the pressure balancing ports to plug or coke up with solids. The plug and seat valves were also very expensive in comparison to the other valves. The wedge type gate valve were used on the suction side of the atmospheric bottoms pump. They did not require flushing

Table 5. Design features of EDS pilot plant block valves

Valve type	Design feature
WKM through-conduit gate valves	Full-port design; a smooth streamlined, flow path; seats positioned out of the flow stream; split gate design to isolate the body cavity from the flow stream in open and closed positions; hard-face seating surfaces, body cavity flushing connections; valve internals totally isolated from flow stream
Metal seated trunnion mounted ball valves	Full-port design; streamlined flow patch; seats positioned out of flow stream; spring pre-loaded metal seats to prevent solids buildup in body cavity and solids entrapment between the seating surface; hard-face seating and trunnion bearing surfaces; body and spring cavity flushing connections
Tapered lubricated plug and seat valve	Streamlined flow path; seating surface out of flow stream and in constant contact; balancing ports to equalize pressure between the plug and bore and the sealant cavities; hard-face seating surface, body cavity not exposed to solids
Wedge-type gas valve	Full-port design, hard-face seating surface
Ram-type valve	Full-port design

Table 6. EDS pilot plant block valve experience<sup>a</sup>

Valve type(s)	Sizes	Number of test valves	Cycles range	Operability and leak tightness
Through conduit gate	2"-6"	15	0-93	100% capable of isolation 80% passed leakage testing
Metal seated ball	1"-6"	12	1-27	100% capable of isolation 60% passed leakage testing
Lubricated plug valve	2"-4"	11	1-77	Operability problems prevented isolation of equipment 10% passed leakage
Wedge gate	3"-4"	7	2-93	50% passed leakage testing after 93 cycles
Ramseal	1"-6"	3	3-24	Valves inoperable and damaged

<sup>a</sup>Personal communication with A. D. Radha Krishnan, Exxon Engineering, Florham Park.

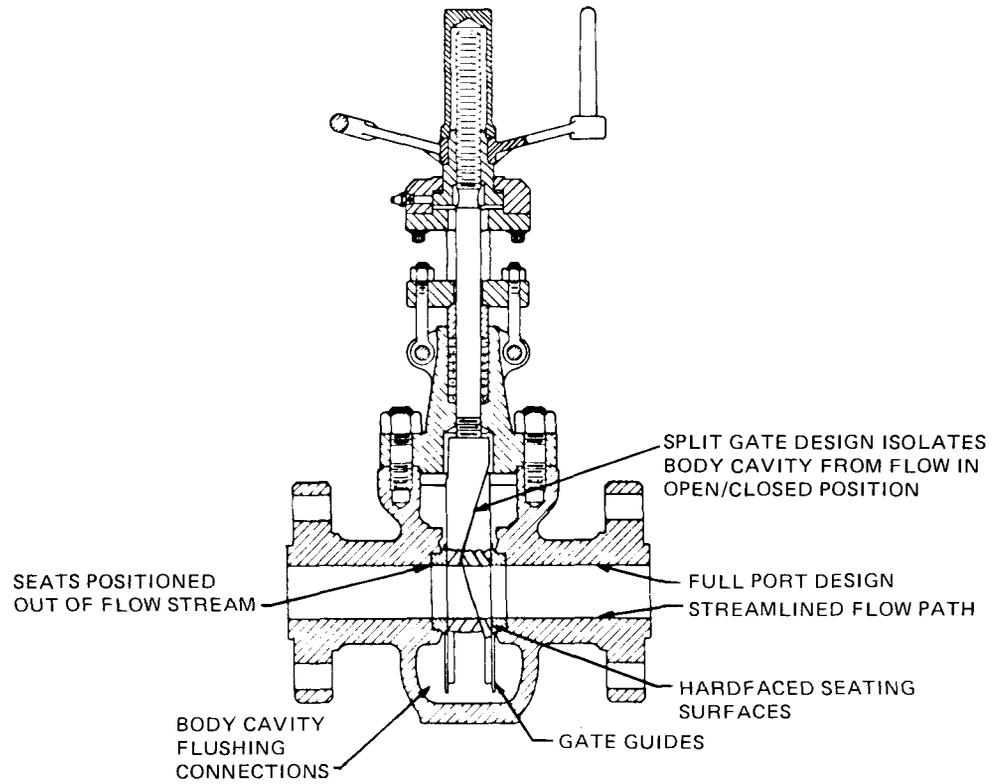


Fig. 14. Through Conduit Gate Valve Used at the Exxon Donor Solvent Pilot Plant (Ref. 20).

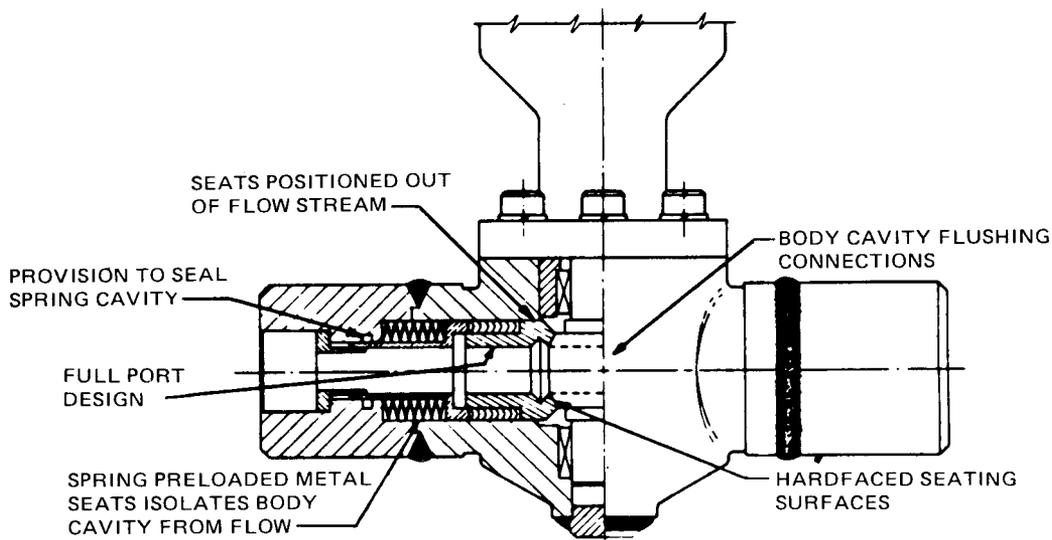


Fig. 15. Trunnion-mounted Ball Valve Used at the Exxon Donor Solvent Pilot Plant (Ref. 20).

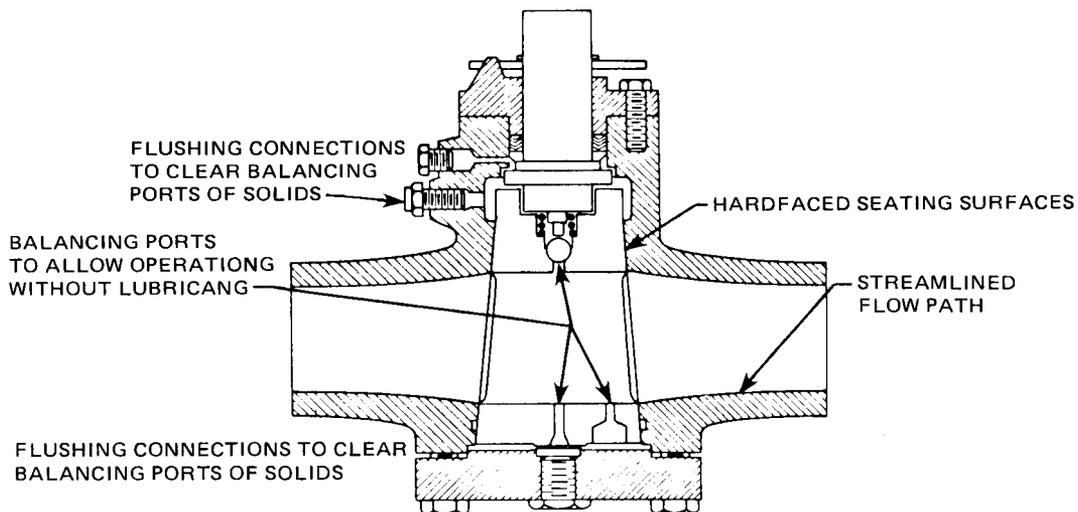


Fig. 16. Lubricated Plug and Seat Valve Used at the Exxon Donor Solvent Pilot Plant (Ref. 20).

because they closed on diluted slurry. The wedge gate valves is considered adequate in locations where a tight shut-off is not absolutely essential and some leakage can be tolerated.

#### 3.2.4 H-Coal Catlettsburg Pilot Plant

In the H-Coal T/day coal liquefaction pilot plant, there are in excess of 15,000 valves; approximately 80% are block valves, primarily gate valves. Block valves are used in the slurry pressure letdown system, reactor catalyst addition and withdrawal system, vacuum tower area, cyclone feed area and the hydroclone area. Of these, the block valves in the plant slurry letdown system are considered to be in the most severe service and require specially designed valves. Valves used in the lower pressure, lower temperature areas of the plant are exposed to less severe conditions, and the requirements have been met by conventional valves. Operating experience on the various block valves tested at the H-Coal plant is briefly summarized here. A more complete review of the subject can be found in the H-Coal topical reports on block valves.<sup>22,23</sup>

Initially, (Runs 1 through 5) the Gulf and Western EPG full ported, quarter-turn ball valves with metal-to-metal seating were used (Fig. 17). Service conditions for the design of these valves were 3600 psig pressure, 875°F, solids content 20%. The line size was 6 and 10-inch. The valves consisted of a solid body design with bolted bonnet and trunnion mounted ball. The seal is obtained by a combination of system pressure and internal loading provided by a ring of coil springs behind the seal. Valve body was 316 SS with stellite 6 overlay and the ball/trunnion 316 SS with Haynes 25 overlay and Metco plasma spray. The springs were made of Hastalloy.

The EPG valves were found to be inadequate for slurry service. Problems experienced with these valves included

1. Spool and stem packing failure causing leakage and erosion,
2. Stress corrosion cracking,
3. Spring material inadequate for high temperature,
4. Spring cavity plugged with solids,
5. Difficulties in disassembly,

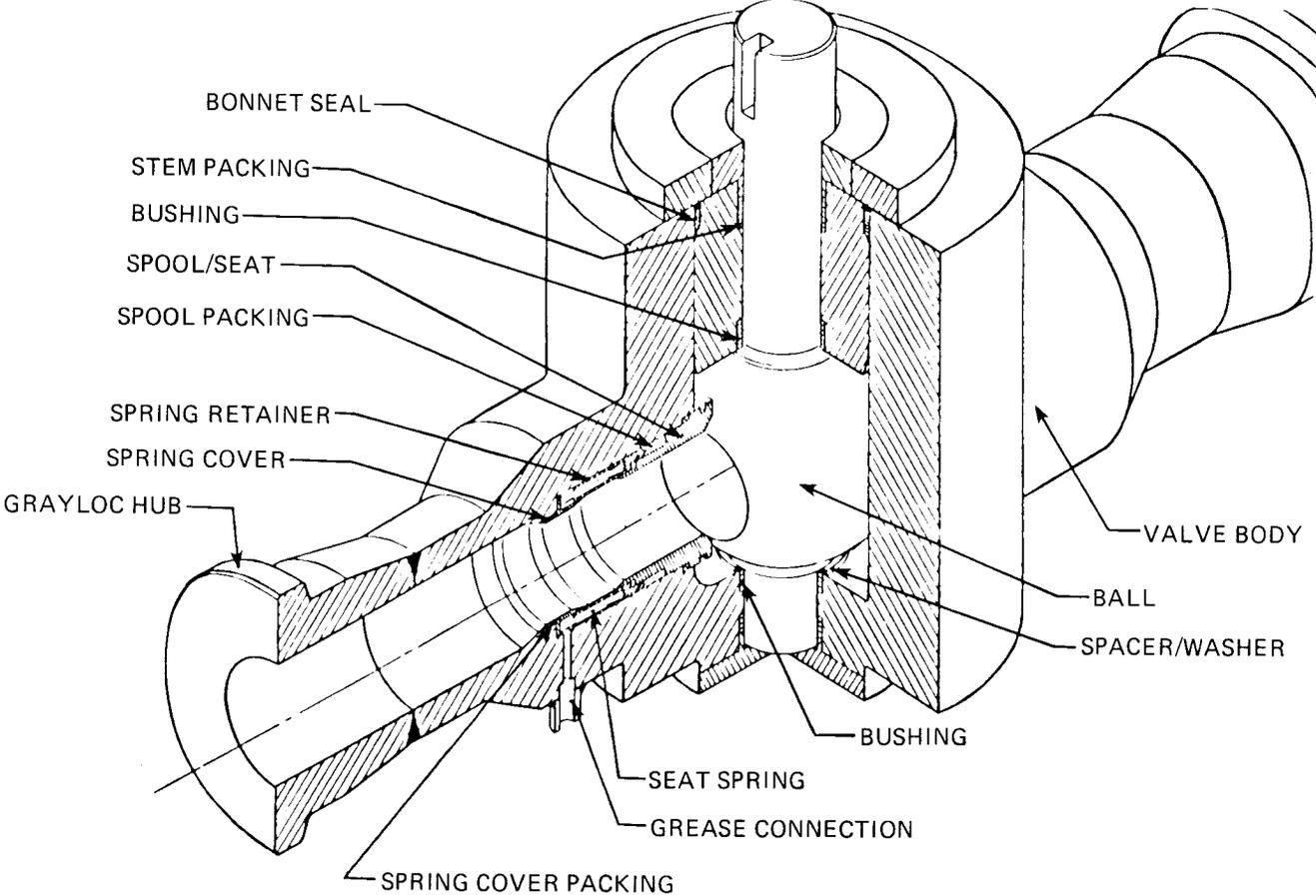


Fig. 17. EPG Ball Valve Used at the H-Coal Pilot Plant (Ref. 22).

6. Balls and seats not interchangeable,
7. Poor quality control.

Because of numerous problems, alternate replacement valves for the slurry had to be considered.

The Mogas C-1 floating ball valve was installed in Run No. 6 and was used extensively in the plant until the last run (Run 11) (Fig. 18). The valve is a split body design with a floating ball. Seats are held against the ball by a single bevel washing type load spring. A unique feature of the valve is the double accurate bow type curvature on the ball which gives a wide point entry for the flow and consequently reduces wear. Several materials were tested for the balls. These included 410 SS with chrome carbide coating, 316 SS with stellite-6 overlay, and 431 SS with TMT-5 coating seats, solid stellite-3. The Mogas valve was the easiest to disassemble. There were no serious problems with the valve except for isolated instances of valve seizures during temperature excursions, solids intrusion, and minor steam leakage. Operational changes eliminated most of these problems.

The Kamyr K-7 ball valves were used in Run No. 9 through 11 (Fig. 19). The valve is a solid one-piece body design, having bolted bonnet and bolted seat inserts which allow seat removal. Balls are trunnion mounted with almost no ball cavity. The balls are 316 SS with nickel boron coating. These valves are compact, have a good resistance to thermal shock, and resilience from incorporation of graphite. Problems experienced with these valves were valve seizures, pitted coating, and chipped ball. These were not considered serious and the overall performance was judged to be good.

Metal coated ball valves manufactured by Cameron Iron Works were also tested in Runs 9-11 (Fig. 20). The ball and seats were made of a substrate base (347 H SS, 422 SS, H-13 tool steel) and coated with TMT-5. The valves were 2500 ANSI pressure class. At the end of the pilot plant operation, these valves had received 30 to 50 cycles and both the body and the coat were in excellent condition. The Cameron valve was judged to be one of the best valves by the H-Coal staff and is also the most expensive valve.

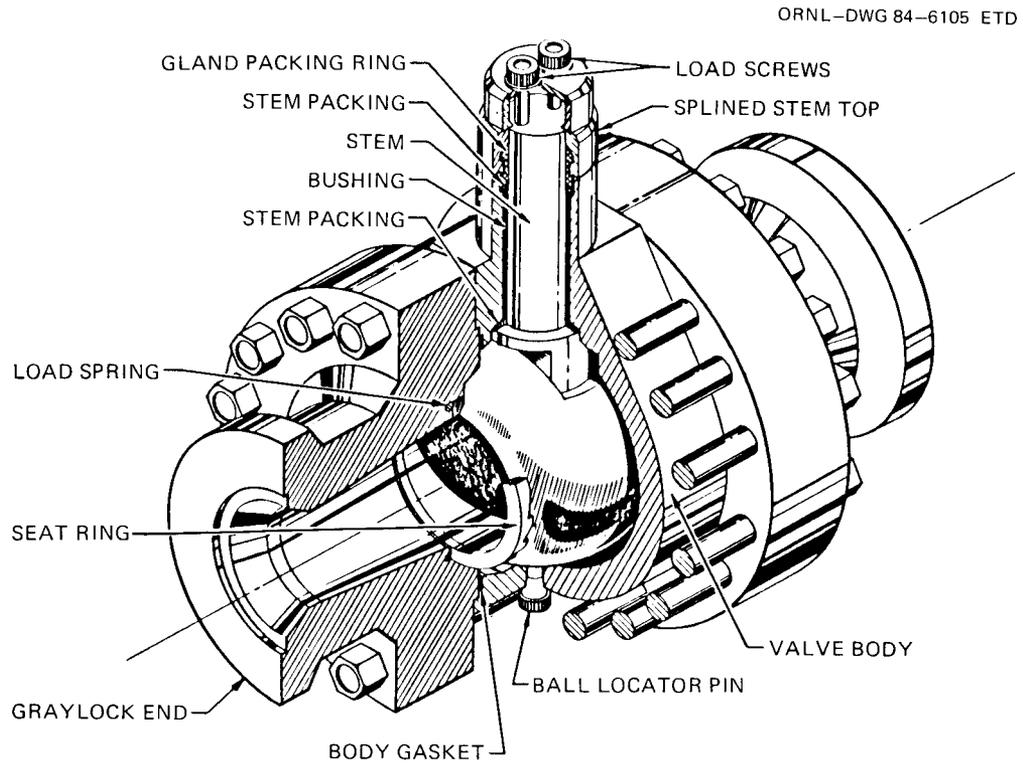


Fig. 18. Mogas Ball Valve Used at the H-Coal Pilot Plant (Ref. 23).

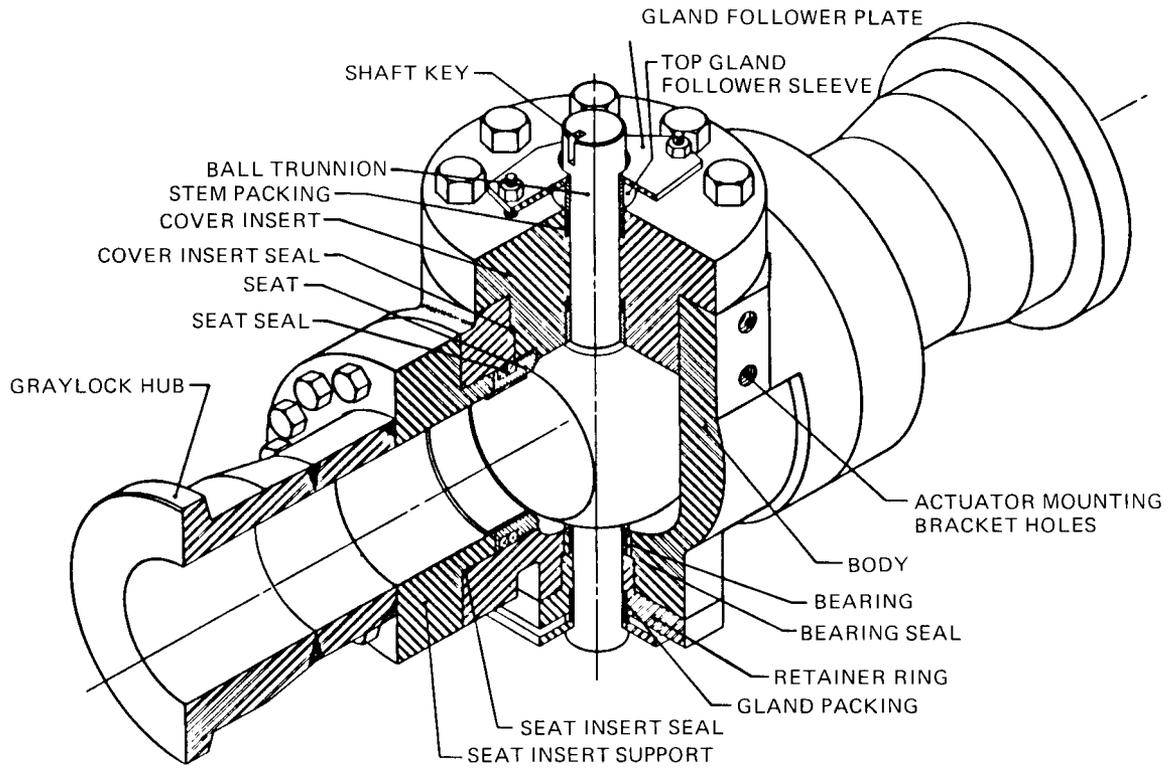


Fig. 19. Kamyr Ball Valve Used at the H-Coal Pilot Plant (Ref. 23).

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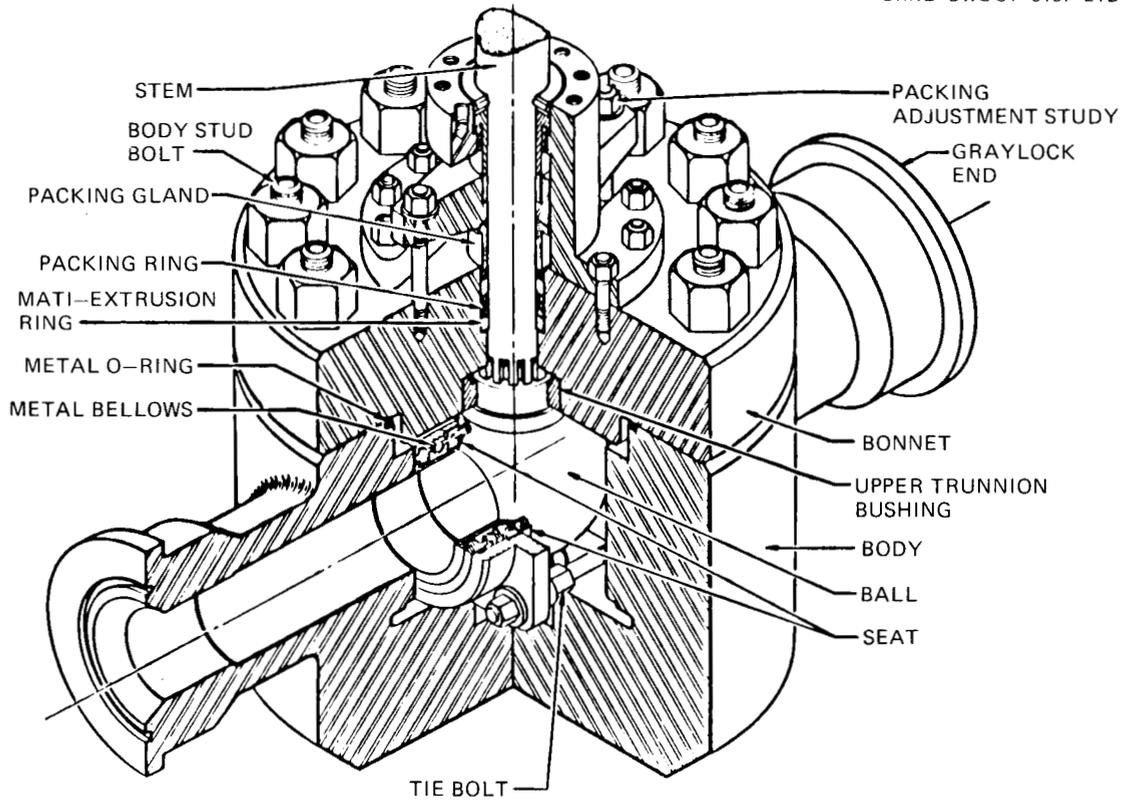


Fig. 20. Cameron Ball Valve Used at the H-Coal Pilot Plant  
(Ref. 23).

Table 7 contains a summary of the block valve performance in the H-Coal plants.<sup>13</sup> The valves are rated in several categories with respect to acceptability for blocking service.

### 3.3 Block Valve Requirements for Demonstration/Pioneer Commercial Plants

The need for slurry block valves as a means of process isolation and control, isolation of process equipment for maintenance purposes and interconnecting of multiple trains will exist for all foreseeable commercial plants. Typically, the large demonstration and/or pioneer commercial plants could use in excess of 3000 block valves.<sup>21</sup> Depending on the location and severity of the process streams, a wide spectrum of valves ranging from conventional wedge gate valves to specially designed gate and/or ball valves will be used in the plants. The criteria for valve selection will be based on the slurry temperature, the slurry concentration, the line pressure, the tolerance limits on leakage and flush requirements. For high temperature, high pressure slurry service the hard metal face alloy steel 2500 pound ANSI class speciality valves will be mandatory. A 10,000 hour service life is considered to be a realistic target for slurry block valves before they are removed for routine maintenance. A cyclic life of 100 cycles for a commercial plant is a reasonable goal. Typically, these valves should not be cycled more than 10 times over a one-year period.<sup>21</sup> The cycling time (time required to close/open the valves) capability of on-line maintenance, flushing requirements, etc. will be a major parameter that needs to be considered in the selection of the valves for the larger plants.

The valve size specified for the demonstration and/or pioneer commercial plants range from 2 to 48-inches. The largest size block valve that was considered in the SRC-I demonstration plant design was a 48-in., 2500 ANSI 347 SS body block valve. The valve was specified for the single stage, high pressure, letdown valve single separator vessel configuration (Case A2 in the Catalytic letdown system configuration study).<sup>3</sup> However, it was recognized that the valve was not cost-effective. The price quoted by one vendor was \$5.0 million. Furthermore, no such valve has ever been manufactured and the risk was

Table 7. H-Coal pilot plant block valve performance

Type valve	EPG	MOGAS	KAMYR	CAMERON
Number of Each	12	14	4	2/6
Cycle/Each				30-50
<u>Parameter</u>				
Stem Leakage	U	?	A	A
Body	A	?	A	A <sup>a</sup>
Thermal Shock	?	?	A	A <sup>b</sup>
Leak-Through	U	A	A	A
Ease of Disassembly <sup>d</sup>	U	A	?/A <sup>e</sup>	A
Ease of Assembly	U	A	A <sup>e</sup>	A
Comments	Good for non-slurry application easiest to disassemble	Does not work well without high differential	All around a good valve probably best for pneumatic transfer	Most expensive probably the best. <sup>f</sup> (Un-acceptable but changing design)
		The only one failing was used as the throttling valve	Compact almost no ball cavity	
		Had more problems to overcome		

LEGEND

U — Unacceptable

A — Acceptable

? — Unsure of divided opinion

<sup>a</sup>Some "O"-ring problems.<sup>b</sup>Some binding on one valve during one cleaning.<sup>c</sup>Appears to have solution.<sup>d</sup>All valves in commercial plant must be removable and repaired.<sup>e</sup>Interchangeability of parts.<sup>f</sup>Cameron valve V-3 after 1st letdown valve faired very well.<sup>g</sup>Reference 13.

considered to be too high. An alternate configuration, viz., a single stage pressure letdown valve with two parallel vessels (Case A1), was chosen for the high pressure letdown system. With this arrangement, the largest size block valve needed would be 16-inches, which is within the limits of the current state-of-the-art.

Discussions with Exxon revealed that the largest size block valve specified for the EDS commercial plant is 18-inches. A 12 to 18 inch range is considered to be both prudent and economically viable range for block valves in slurry service. In clean service, sizes up to 36 inches (ball valves) are not uncommon. Exxon indicated that the cost of the valves increases considerably beyond 18-inches. The speciality valves (high alloy steel, hard face valves) cost roughly ten thousand dollars per inch. The 18-inch valve specified in the EDS design would cost roughly two hundred thousand dollars. Conventional wedge gate valves cost much less (roughly a third or one-fourth the cost of speciality valves) and should be used whenever possible in commercial plants. In the larger sizes (36-48 in.), Exxon indicated that the ball valves and gate valves are definitely not economical. For these sizes, slide valves may be a proper choice. Exxon has used 36 to 48-inch slide valves (a proprietary design) in their petroleum operations.

The EDS commercial plant will use the through conduit gate valves with flushing in the severe applications. The metal seated ball valve will be the next best alternative, although they were only tested under relatively mild conditions (vacuum bottom recycle) in the ECLP pilot plant. However, Exxon indicated that the H-Coal experience on metal seated ball valves is determining and does indicate that these valves will perform satisfactorily in severe service. The lubricated plug valve, which was also tested in the ECLP pilot plant, is the least desirable for severe service. These valves were a disaster according to Exxon in the pilot plant.

Block valves for the H-Coal pioneer commercial plant are expected to be in 2-20 inch size range. Among the valves tested in the pilot plant, three of the valves look promising for the commercial plant. These are the Mogas floating ball valve, the Cameron, and the Kamyrr metal seated ball valves. The WKM through conduit gate valve was used

in the design baseline and may still be considered in the final design. However, the latter requires flushing and H-Coal favors block valves that do not require flushing with coal slurry. The basis for the preference is the pilot plant experience on ball valves. H-Coal indicated that the flush system is not dependable. The critical areas in block valves are considered to be stem packing, seat type, method of disassembly and materials. In addition, the sphericity of the ball is critical and H-Coal indicated that the manufacturers' should be required to give specifications for the ball/seat assembly from a metallurgical standpoint. The 410/422 SS ball with LC-1/H-13/TMT-5 coating, and stellite seats are acceptable within reasonable limits of mechanical loading.<sup>11-13</sup>

The pilot plant experience has demonstrated that any one of the three ball valves could be used in the commercial plant. Improvements are needed in each case to incorporate the best features which have been identified and demonstrated on another type of valve. While the problems are known, the fixes available have not been tested. Scale-up is a problem but not insurmountable. Improvements can be made in block valves with future testing and experience from full scale tests in the larger plants.

#### 3.4 Development and Testing Needs

The design of high pressure, high temperature block valves in the sizes commensurate with the requirements for a large scale liquefaction plant is still in the development stage. A direct scale-up of the pilot plant valves to commercial size is uncertain and poses technical risks. Manufacturers have limited experience on block valves in such severe applications. The approach adopted in the pilot plants have been to use off-the-shelf valves with the understanding that if a valve does not fulfill its missions, then a follow-up engineering effort will be initiated to resolve the problems. However, this is clearly not a desirable approach for a commercial plant because of the negative effect on plant availability. While the problems have been identified, the solutions to the problems have not been tested to the extent desired to recommend the best valve design in this application. What is known is

the desirable features in these valves and the preferred choice of the materials of construction for the valve body and valve internals. Additionally, there is an upper limit of the size for the valves (18-20 inches) beyond which the confidence indicated by the manufacturers is poor. Manufacture of parts for the larger valves in the 2500 pound pressure class are considered to be a serious problem, particularly with regard to material procurement, forging, machining, quality control, and shipping. The delivery time for the large valves may also be quite long (as much as 24 to 36 months). Considering the greater density of valves required for the commercial plant and the limited number of manufacturers available with the capability to fabricate valves in the larger sizes, the availability of the valves and the spare parts in the required size and numbers for the commercial plant is doubtful.

Uncertainties also exist with respect to performance of the larger valves. The major concerns are the extent of valve distortion that will occur in these large sizes due to the thermal gradient, the slurry flow pattern in the larger cavities, solids build-up, ease of disassembly, leakage rates, flushing requirements and maintenance needs. All these issues need to be quantified in a full scale valve test program, presumably in the larger plants itself.

There is also the need to reduce the cost of these valves. It is estimated that the block valves and the associated piping could approach 25 to 30% of the plant cost. The economics of liquefaction plants can be substantially improved if lower cost valves are available.

While it is recognized that most of these issues cannot be addressed in small scale tests and the results extrapolated to the large size valves, there are some areas where further work could prove beneficial in the understanding, selection, and design of slurry block valves for the liquefaction service. These are:

- identification of critical valve areas for erosion and wear under progressively severe conditions,
- leakage measurement over a predetermined number of cycles, (similar to the tests in the pilot plant),
- differential pressurization across the valve seat in conjunction with leakage measurement,

- mechanical cycling of valves in high temperature environment,
- flush system design and flushing,
- requirement of alternative materials/coatings.

Attempts have been focused on some of these issues in the pilot plants but the data base needs to be expanded. Valve manufacturers and other institutions with in-house capability should be encouraged to address these problems.

#### 4. CONCLUSIONS

The conclusions drawn from this assessment are:

1. a limited, but useful, data base exists in slurry pressure let-down and slurry block valves from the pilot plant operation;
2. promising valves for both pressure letdown and blocking services have been identified in the pilot plants which can be used in the larger demonstration and pioneer commercial plants;
3. the service life of six months for the pressure letdown valves and up to a year for slurry block valves prior to routine maintenance is projected;
4. a scale-up factor of at least 10 to 1 from the pilot plant size is to be expected for these valves in the larger plants;
5. only generic specifications for slurry pressure letdown and slurry block valves are available in the demonstration/commercial plant designs;
6. technical uncertainties, mainly with regard to valve sizing techniques, machining, fabrication, quality control, and performance and maintenance exist which need to be resolved for successful operation of these valves in the larger plants;
7. exceptional quality control and careful operating and maintenance procedures which allow for the brittle nature and thermal shock effects on the valve internals and special purging and flushing methods to prevent solids build-up and coking inside the valves are extremely important to ensure successful operation and valve life; and
8. further development and testing, especially with regard to valve sizing, valve design, materials, flushing/purging systems, hydrodynamic considerations in three phase flashing flow and thermodynamics of phase change could substantially improve the present understanding of the design and operation of the valves and possibly also have a significant impact on valve costs.

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