Lecture 12
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WELDING INSTITUTE REPRINT

FITNESS FOR PURPOSE VALIDATION OF WELDED CONSTRUCTIONS

London 17-19 November 1981

The importance of contractual requirements in determining quality costs in the fabrication industry

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INTRODUCTION

As welded fabrications become more complex, more costly, and more technically advanced the need for a greater and more rigorous assurance of quality has emerged. Consequently, over the last five to ten years the fabrication industry has increasingly been required to conform to formalised quality assurance system requirements, e.g. BS 5750 and MOD DEF STAN 05/21-29. An important part of quality assurance in this industry is the validation of both procedures and the welded structures themselves. The cost of such activities (the appraisal cost) can be large and its magnitude is determined to a considerable degree by the requirements of the controlling standard or specification, e.g. how much NDT is required and what the acceptance standard is. Such matters are not usually determined by the fabricator. The traditional quality assurance philosophy implies that the manufacturer is totally responsible for the quality of his product, but this is unrealistic for a fabricator when important elements which determine his quality costs are imposed from outside. This Paper shows that the precise contractual relationship between client, main contractor, and fabricator could have a very great effect on the quality costs (particularly the appraisal costs) and that the approach to quality assurance responsibilities should take this into account.

QUALITY COSTS AND THEIR EXPECTED MAGNITUDE

Using Groocock's definitions[1] we can say that the quality cost comprises appraisal cost plus failure cost plus prevention cost where:

Appraisal cost is the cost of inspecting and testing products because of the possibility of failure
Failure cost is the cost resulting from the failure of products during manufacture or use
Prevention cost is the cost incurred in trying to reduce failure and appraisal costs

It is often stated, although actual data are rarely quoted, that prevention costs are 5%, appraisal costs 40%, and failure costs 55% of total quality costs and that total quality costs could be 10% of turnover (Groocock[1] stated that in ITT quality costs were reduced from 14% to 4% of sales by cost improvement programmes). These figures do not relate specifically to the fabrication industry but, if we assume that they are of a similar order of magnitude, the appraisal (or validation) cost alone could be 5% of a fabricator's turnover.

For a welded fabrication the appraisal cost will comprise:

1. Auditing and surveillance of the fabricator by the client
2. Auditing and surveillance of supplier by the fabricator
3. Inspection of bought-in items (including welding consumables)
4. Production and approval of welding procedures
5. Training and qualification of welders and welding operators
6. Production and approval of inspection procedures
7. Training and qualification of inspection operators, e.g. NDT personnel
8. Inspection of the fabrication (including proof or pressure testing where applicable)

Direct failure cost (cost incurred during fabrication and excluding costs related to subsequent failure in service) will comprise:

1. Repair or rework of defective areas
2. Reinspection of repairs
3. Income foregone because of reduced throughput resulting from the need for remedial work

The fabricator will incur costs in each of these eleven categories and in most cases he bears all the cost incurred. Very little published information is available in this area, the most recent and detailed being that given by Nicholson and Walton,[2] Table 1. The figures given in Table 1 suggest that an appraisal cost of 5% of turnover is not out of the question and may be an underestimate.

QUALITY COST ESTIMATES FOR A TYPICAL HIGH QUALITY FABRICATION

In an attempt to produce some real figures to evaluate the importance of quality

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Table 1 Estimates of quality costs borne by fabricators[2] (1978 prices)

Auditor training	£250+
Training of one ultrasonic operator to CSWIP standard	£5000
Audit of a major supplier	£250-£1000
Audit by a major client	£5000-£40 000
Welding procedure qualification (per procedure)	£400
Welder qualification (per welder)	£100

standards and appraisal (validation) requirements on fabricators' costs, an analysis has been made of the appraisal and direct failure costs of a steel fabrication where a high degree of validation of the structure was called for.

Description of the fabrication

The fabrication consisted of three equipment modules for part of an oilfield installation and was shop fabricated. The overall external dimensions of each unit were approximately 14 x 4 x 4m and comprised mainly fabricated beams and rolled steel sections in a carbon-manganese structural steel. Some of the detail design was quite intricate leading to access problems during fabrication (see, for example, Fig.1).

The manufacturing specification was extremely detailed and rigorous in respect of validation requirements. All plate was required to be ultrasonically tested in accordance with BS DD21 to prevent the generation of through-thickness defects, and all plate had to be fully identified throughout fabrication. All welders and welding procedures were to be approved according to ASME Boiler and Pressure Vessel Code Section IX together with extra requirements which in practice resulted in an increase in the number of essential variables. Extensive nondestructive examination of each fabrication was specified: magnetic particle (MPI) or dye penetrant inspection of all critical fillet welds and 25% of all other fillet welds, e.g. those attaching stiffeners; radiography of all butt welds in the main frame and 50% of all other butt welds; ultrasonic inspection of all full penetration T butt welds. Ultrasonic operators were required to be qualified at least to CSWIP 4.3.1 or 4.3.2 or to ASNT level 2. The defect acceptance standard was in accordance with ASME Boiler and Pressure Vessel Code Section VIII and the Engineer could specify additional inspection if he believed that a defect existed in a weld. The cost of such additional inspection was to be chargeable to the fabricator if an unacceptable defect was found and to the client if not.

Estimation of quality level

Examination of inspection records showed that surface inspection (MPI) disclosed no defects which required repair. Over 3500 welds were radiographed or ultrasonically tested (a few welds were examined by both methods) and 580 repairs were required. The rejection rate on ultrasonic inspection was 10.5% and on radiography 18.8%. This is the rejection rate on first inspection, i.e. not counting rejection of repair welds. A random sample of sixty-one radiographs which disclosed a repair situation was examined (Fig.2 summarises the results) and showed that the majority of unacceptable defects were minor slag inclusions and the reason for rejection was that the total added length of slag inclusion in the section of weld exceeded the permitted level. This defect rate, although apparently high, is not out of line with what has been found in other, similar, structures.[3,4]

A more significant fact was the amount of re-repairing which was required. This is illustrated in Fig.3 which shows that with radiographic inspection there is at least a 30% probability that a repair weld will not be of acceptable quality. Inspection of radiographs showed that this high re-rejection rate was sometimes a result of a failure to remove the original defect, but more often a result of the repair welding introducing fresh defects. The re-rejection rate with ultrasonic testing was much lower (<10%) which perhaps shows that radiography is a very reliable and sensitive technique for finding small defects. This implies that the validation method itself has some bearing on the failure cost, irrespective of the inherent quality of the fabrication.

Estimation of quality costs

Manufacturing and inspection records permitted an estimate to be made of the man hours required for inspection and rectification work and their proportion of the total number of manufacturing hours required for fabrication. These estimates therefore comprise the direct failure costs borne by the fabricator together with some of the appraisal costs borne by him. They do not include, therefore, the costs of auditing, being audited, training and qualification of welders and NDT operators, or qualification of welding procedures.

The direct man hours spent on NDT was estimated to be 8314 for the three structures. This was calculated from the number of inspection results reported and the allowed unit times for inspection (note, the unit times for MPI and ultrasonic inspection are very similar to those quoted by Norman[5] from other sources):

	Total estimated time, hr
1759 radiographs	6262
1926 ultrasonic reports	963
3300 MPI reports	1089
	8314

Table 2 Estimated mean 'effective defect length' and mean repair time

Mean effective defect length	29mm
Mean grinding time per defect (estimated)	5min*
Mean welding time per defect (estimated)	1min, 10sec*

* these times were multiplied by four in the cost analysis on the assumption that duty cycles were 25%

The number of manufacturing man hours credited to the construction was 26 651, therefore the validation inspection (initial NDT) increased fabrication man hours by almost one-third.

The man hours spent on repair work (grinding out defects, inspection, repair welding, and reinspection) was estimated to be 2500 of which 2270 were inspection and a mere 230 were removal of defects and repair welding. The time estimates for repair welding were based on Norman's work,[5] and Welding Institute Standard Data and metal removal times were obtained from laboratory tests in which simulated defects were ground out of plates. In all cases a 25% duty cycle was assumed. The defect size distributions were used to obtain a mean 'effective defect length' and therefore a mean time for grinding and repair welding (these figures are given in Table 2). It can be seen that the repair costs are dominated by the inspection costs (~90% of the man hours involved) and therefore the somewhat arbitrary nature of the estimates for repair welding are unimportant in establishing repair costs. The total repair man hours (defect removal, repair, and inspection) are 9% of the fabrication man hours.

Table 3 summarises the various validation and failure costs estimated for this fabrication.

CONTRACTUAL AGREEMENTS AND THEIR EFFECT ON QUALITY COSTS

In the fabrication of components for large projects such as power stations, oil refineries, and chemical plants there are inevitably a number of possible contractual arrangements between clients, main contractors, and subcontractors. Different contractual patterns are found for different projects and not all are straightforward. The most logical from a quality assurance point of view are those where organisations at each level in the hierarchy are responsible for, and define, the detailed quality requirements of those organisations immediately beneath them. With this type of contractual pattern, organisations at each level have a direct interest in devising appropriate validation requirements as they are held responsible for the quality of their subcontractors. Examples of this type of contractual arrangement are those devised by the CEGB for the SGHWR Programme,[6] and the arrangements planned for future nuclear programmes in the UK. This system will work well when, as in the power generation industry in the UK, there are sufficient technical resources to define the quality standards and validation requirements in an appropriate way.

In many other cases, though, the contractual pattern is more complicated so that the organisations responsible for establishing the quality standards and validation requirements have no direct responsibility for the manufacture and assurance of quality. Such contractual patterns are often necessary, unfortunately, in order that appropriate expertise in design, manufacture, and project management can be deployed, but it does lead to confusion and sometimes excessive validation costs.

The contractual pattern within which the structure analysed in the previous Section was designed and built is a case in point, Fig.4. This arrangement illustrates the fact that the fabricator is responsible to the main contractor for the fabrication of components to an agreed price and delivery and to a defined specification. His dealings on technical and commercial matters are primarily with the main contractor even though the conceptual and detail design and the manufacturing specification have been determined by organisations with whom he has no contact. When we consider that the decisions of the detail designer have produced a design which is difficult to weld and inspect, Fig.1, which has added to the cost of fabrication and, also, to the failure cost, and the decisions of the primary design organisation have led to validation requirements which add more than 30% to the total number of man hours required

Table 3 Summary of validation and direct repair costs for a structural fabrication

	Man hours	% of manufacturing man hours	% of total construction man hours
Direct manufacturing	26 651	100	71
Validation inspection	8 314	31	22
Repair and reinspection of defective welding	2 500	9	7

to produce the fabrication, this is a serious matter. It is to everyone's advantage that appraisal costs (and other quality costs) are kept as low as possible, but with a contractual pattern of this type (which is not untypical of what is found in the fabrication industry) it is only the fabricator who has a direct financial incentive to reduce quality costs and in one important area, validation (appraisal) costs, he has no control. The Inspecting Authority has the responsibility of interpreting the quality requirements and ensuring that the fabricator adheres to them, but has no direct responsibility for the design and manufacturing specifications and has no remit to seek to minimise quality costs. The design organisations have the responsibility of producing a design and associated manufacturing specification which will meet the client's technical requirements as laid down by the main contractor and major subcontractor. The design organisations will probably not be aware of the magnitude of the quality costs which are likely to be incurred and will certainly not bear the financial consequences of excessive validation requirements. A design organisation acting in this way will naturally err on the side of overspecification as the way to assurance that the fabrication meets the client's requirements. Since those responsible for design are not responsible for manufacture there is no financial incentive for them to incur extra costs (prevention costs) to minimise failure and appraisal costs, i.e. by producing a design which is easier to weld or inspect or which is sufficiently 'safe' to tolerate a lower or more variable level of assurance of quality.

This particular pattern of contractual responsibilities (and others like it) make it difficult to implement the doctrines of Groocock,[1] Juran,[7] and Fiegenbaum[8] who quite rightly state that the manufacturer should be responsible for the quality of what he makes and should organise his business to maintain quality and minimise total quality costs. If important variables which affect perceived quality and quality costs are outside the control of the manufacturer, he cannot control his quality costs, in particular the appraisal (validation) cost, and he cannot, in justice, be held completely responsible for the quality of what he makes.

Therefore, to realise the aim of quality assurance policies and minimise quality costs, it is desirable to reallocate responsibilities in a contractual sense so that there is a specific incentive on those who control major quality costs to minimise them. This is probably impracticable in many, if not most, examples in the fabrication industry so alternatives must be found. Firstly, there should be a greater general awareness of the magnitude of validation (and other) quality costs, and that excessive validation requirements may merely result in significantly increased costs of fabrication without substantially improving integrity. Secondly, maximum use should be made of established national and international standards to define quality and validation requirements instead of specially written qualifications. This would at least regularise validation requirements and, in the long run, reduce the present excessive cost of validation in the fabrication industry.

CONCLUSIONS

1 There is little available information on the magnitude of quality costs in general and validation (or appraisal) costs in particular in the fabrication industry.

Analysis of a typical structural fabrication constructed to a rigorous specification has shown that the man hours involved in validation inspection can be an extra 30% of the manufacturing man hours. If all appraisal costs were taken into account this figure would be greater still.

2 The complicated contractual pattern in many cases divorces responsiblity for setting validation requirements from the financial implications of applying them. This makes the control and minimising of validation costs (and other quality costs) very difficult. The tendency is for validation requirements to become more rigorous without necessarily increasing the assurance of quality

3 It is unreasonable to expect that contractual patterns will be significantly altered to minimise validation costs, but it is important that the possible magnitude of such costs should be generally known. In the long run these could be minimised if there were a greater reliance on established national and international standards for quality and validation procedures in place of the special requirements which are often called up in contracts

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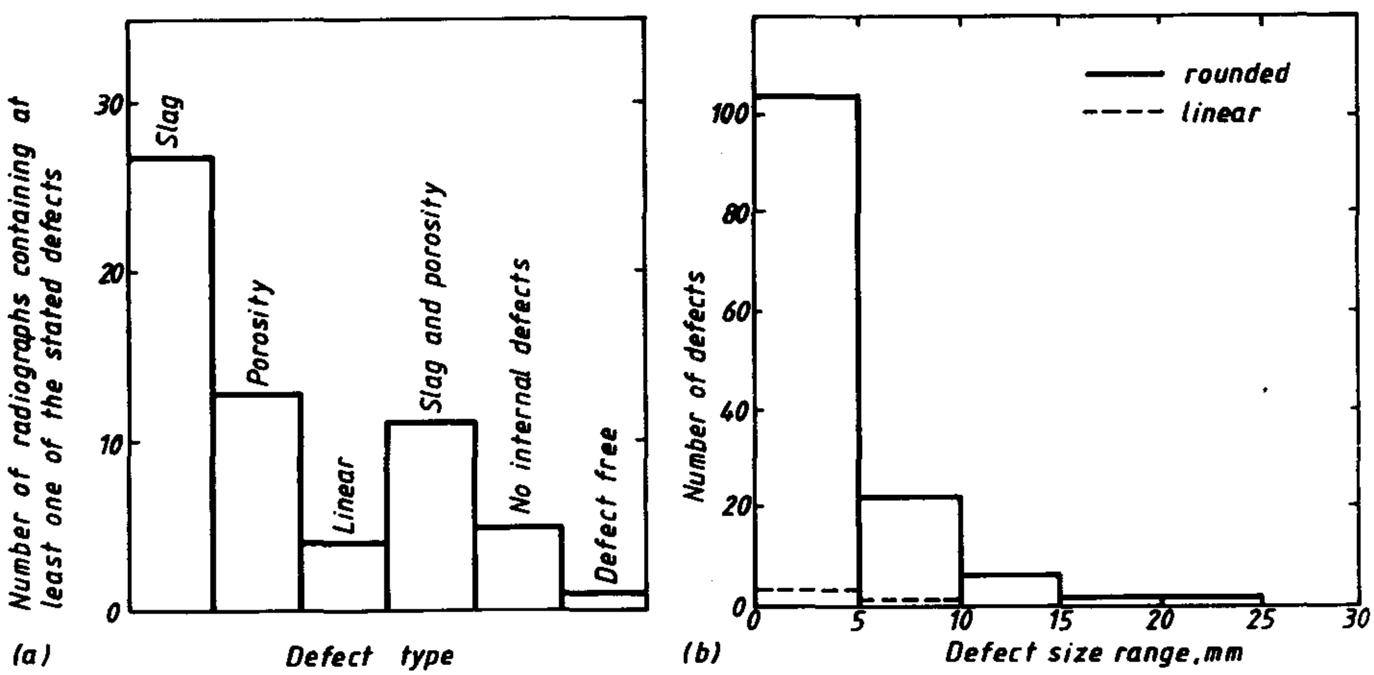
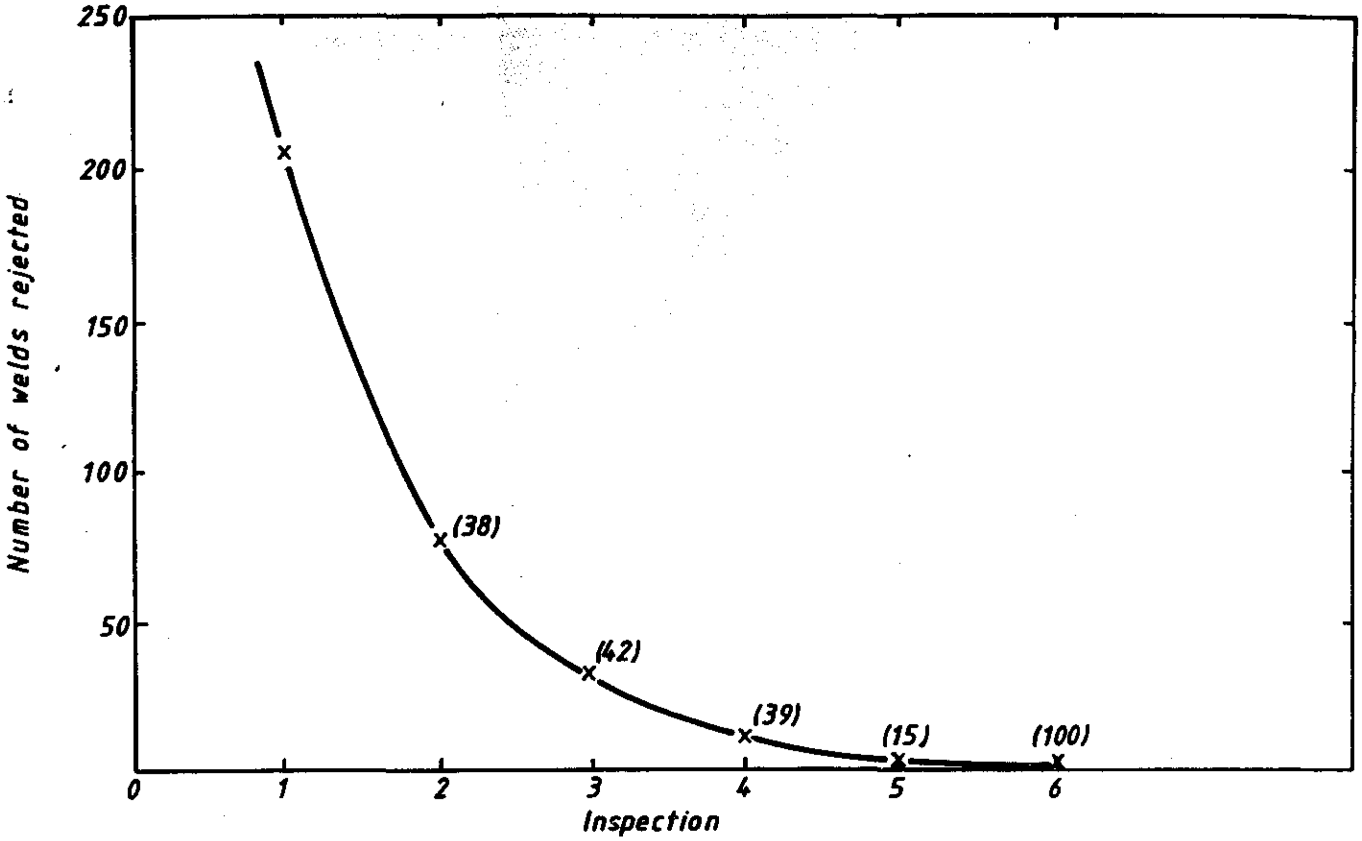
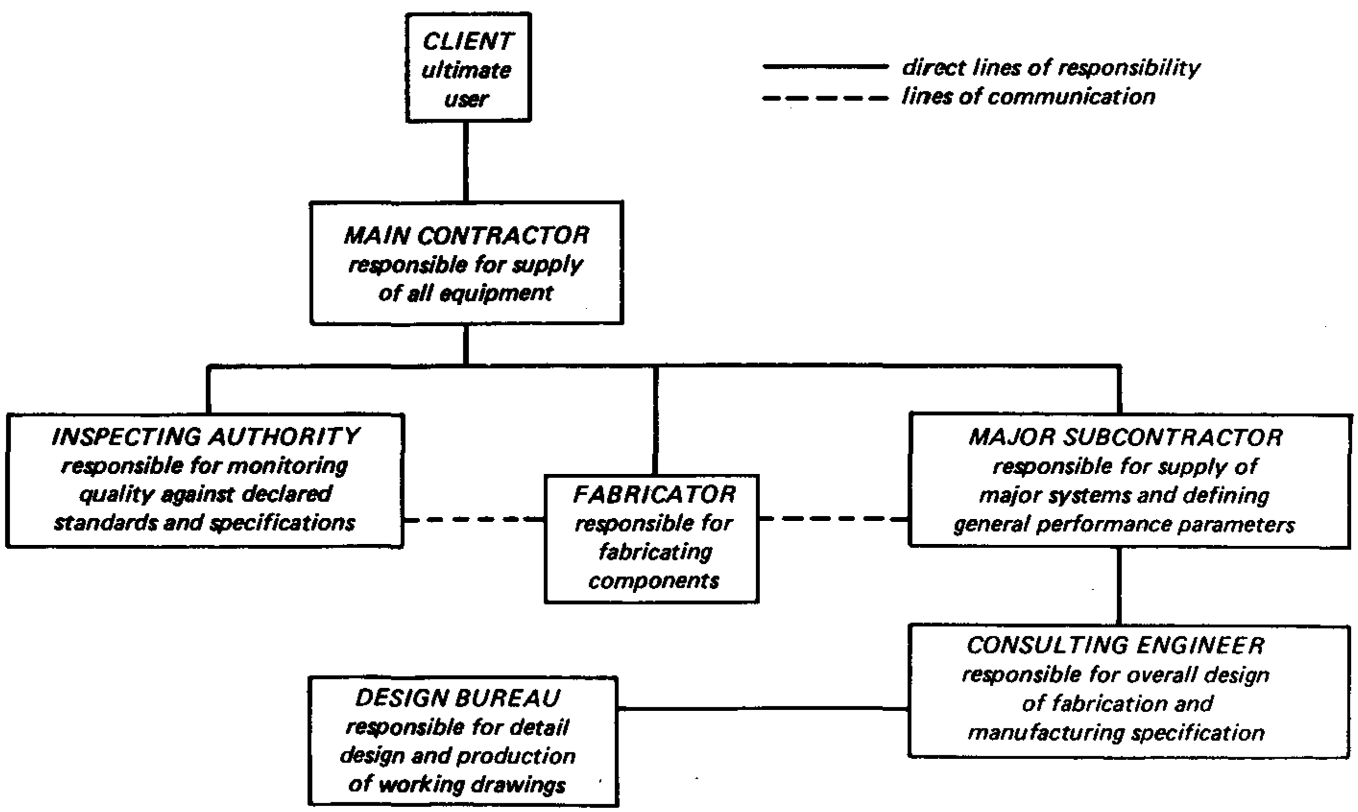
1 Typical joint detail



2 Defect type (a) and size (b) distribution from analysis of sixty-one randomly selected radiographs



3 *Rejection rate of repair welds; figures in parentheses are percentages re-rejected at each stage*



4 *Example of contractual pattern for fabrication*

Lecture 13

Girth Weld Defects in Mechanized GMA Field-Welded Pipelines

Analysis of nearly 60,000 welded joints in pipelines shows defect incidence connected to season, pass, quadrant and project size

BY M. J. WAGNER AND B. M. PATCHETT

Since the early 1970s, Canadian pipeline construction contractors have gained considerable experience in the use of a mechanized girth welding system for cross-country natural gas pipeline construction. To date, there have been few such applications of mechanized welding on a production basis for cross-country pipelines in the United States, although considerable use has been made of the system there in offshore applications (Refs. 1-13). The use of high-strength, low-carbon-content large-diameter heavy-wall line pipe by Canadian natural gas transmission companies in recent years has prompted the use of mechanized welding. Such line pipe has typically been specified as having a minimum yield strength of 65,000 psi (448 MPa) or greater and a carbon content of less than 0.10%. Pipe diameters in the range of 36 to 48 in. (914 to 1218 mm) and wall thicknesses in the range of 0.347 to 0.761 in. (8.81 to 19.34 mm) have been common. The trend in material selection is clearly toward higher yield strengths and heavier wall thicknesses and, in general, more difficulties for the pipeline contractor in terms of pipe weldability.

Contractors have found that conventional shielded metal arc or manual welding of these higher grades of steel under field conditions often result in an unacceptable combination of low production and high repair rates (Refs. 14-20). To alleviate this situation, owning companies encouraged contractors to introduce mechanized welding to their operations. Early results suggested that a better compromise between weld production and repair rates could be achieved. It is noted, however, that site-specific conditions may vary considerably from project to project and that such variation may have a significant impact on repair rates and the occurrence of defects in general.

There is a distinction between a "repair" and a "defect" in this report. A defect is a discontinuity which exceeds by some measure, usually linear, a limiting value as expressed in the workmanship standards embodied in the regulatory codes to which pipelines are designed and constructed. The most common defects found in pipeline welds are melt-through, cracks, incomplete fusion and porosity. For more details, see Appendix 1. A defect may also be deemed to be threatening to the structural integrity of the pipeline on the basis of an engineering critical assessment (ECA).

A repair, on the other hand, refers to a weld containing one or more defects not complying with the fabrication code and which must be repaired. From the perspective of the contractor's cost to repair a defective weld, low incremental cost is incurred when repairing a weld with multiple defects as opposed to a weld containing a single defect. By far the greatest cost component of the repair is related to the remobilization and initial set-up activities associated with the repair operation. Thus, the motivation is to reduce the repair rate and not necessarily the frequency of occurrence of single or multiple defects or that of specific types of defects. This primary focus does not readily lend itself to correction of the procedural or environmental conditions that are responsible for the defects.

This study examined a number of project characteristics or conditions which affect overall weld quality. It is important to recognize that many of these characteristics are not directly related to the welding process or procedure being employed *per se*, rather they are indicative of environmental conditions, which may affect any welding process. One objective was to develop one or more models incorporating a variety of job characteristics to predict repair rates and frequencies of occurrences of specific defect types. Armed with such information, a contractor may be able to reduce overall construction costs.

The analysis involved more than 59,000 welds.

The mechanized welding system used on all jobs (Refs. 21-23) was first introduced in 1968, and to date over 12,000 miles (19,000 kilometers) of pipelines ranging in size from 16 to 60 in. (406 to 1524 mm) in diameter have been installed in all types of environments. Figure 1 shows a typical "spread" in use in the field. The system is not an "automatic" system in the strictest sense. The only fully automatic component is the internal line-up clamp/welding machine and, even then, this device requires skilled tradesmen to control its travel and initial alignment at each weld, as well as to maintain it. The system is more accurately characterized as a mechanical system. Details regarding system operation are provided in Appendix 2.

Data Analysis

The development of models involving procedural and environmental variables was made on the basis of an analysis of repair rate and defect occurrence histories of nine construction projects involving more than 59,000 welds. Each project involved varying climatic conditions and terrain types. The work was performed for two unrelated pipeline-owning companies by four different contractors, all of whom staffed their jobs with qualified union tradesmen. All four contractors

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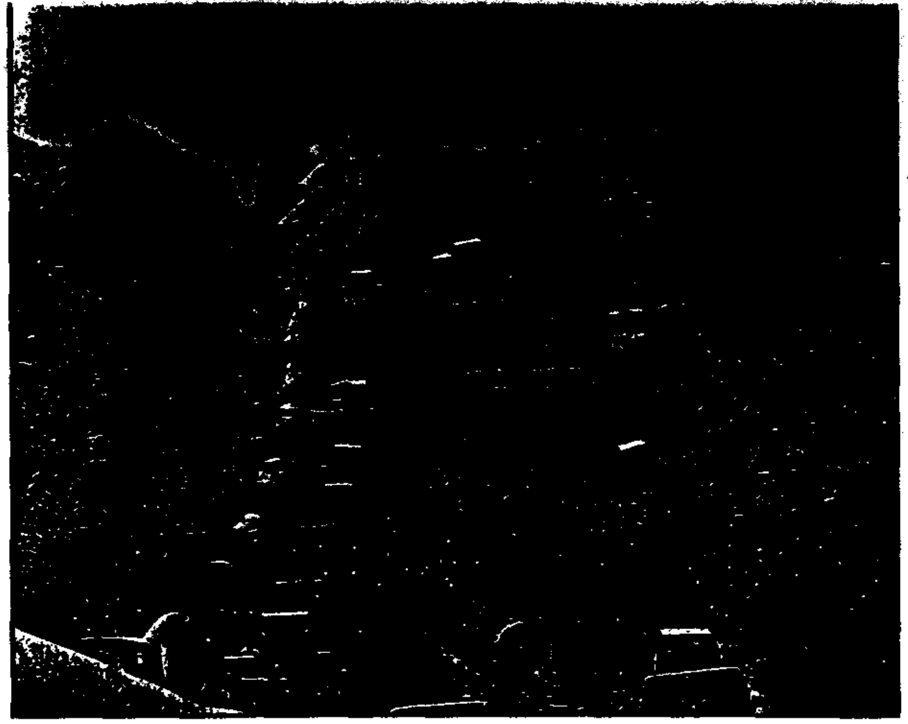

Fig. 1 — Typical field setting for automatic pipeline welding operations.

had previous experience with the mechanized welding equipment and procedures employed for cross-country pipeline welding applications. Table 1 is a summary of the primary characteristics of the projects.

The nondestructive examination and subsequent documentation of defects for each of the welds made on the nine jobs was conducted in accordance with normal pipeline construction practices as prescribed by the appropriate regulatory code and owning company standards. The usual documentation of defects as prepared by the owning companies was the primary data source for this study. In the case of the nine projects studied for this report, the CSA Standard Z184-M1979 (Ref. 24) was the controlling document with respect to workmanship standards.

The total mileage installed was some 930 miles (1475 kilometers) of large-diameter transmission line involving the completion of 59,520 girth welds on 80-ft sections using the mechanized welding system. Of those welds, 12,444 were defective, thus requiring repair. The defective welds contained a total of 16,653 individual defects. Each girth weld was completely radiographed as was each repaired weld. Seventeen characteristics, each suspected of being related to weld quality, were used to describe each defect recorded in the database. They included: owning company, contractor, pipe size and grade, date on which weld was radiographed, type, location (both circumferentially and by pass), and length. For purposes of analysis, a useful segregation of circumferential defect locations by quadrant was employed: top, bottom, workside and ditchside. The top quadrant, looking from the open end of the pipe, is from 315 (−45 deg) to 45 deg and the bottom quadrant is from 135 to 225 deg. The ditchside quadrant is from 45 to 135 deg and the workside quadrant is from 225 to 315 deg.

Several categories of defect type were combined for the statistical analysis. For example, undercut is grouped with incomplete fusion. Similarly, the weld pass categories were modified in those cases where a multiple fill pass condition was specified by the welding procedure. This modification led to all of the fill passes being combined into the single category "fill pass." In all multiple fill procedures, the subsequent fill passes were placed by the same type of welding carriage (bug) using the same welding operator technique. Indeed, in some cases, all fill passes were made by the same piece of equipment and welding operator before the fill station moved on to the next joint. Therefore, all defects were combined for analysis on the basis of a four weld pass configuration consisting of root, hot, fill and cap passes.

Two-way and multi-way frequency tables were prepared as a first step in describing and organizing the data (Refs. 25-27). Preparation of two-way frequency tables was also useful for the calculation of gross statistics for the sample. Chisquare tests of independence for all pairs of variables were conducted. The Chisquare test statistically determines if a particular observed data set differs significantly from an expected pattern. An assessment of loglinear models was also performed (Refs. 28-29). This is a primary tool in the analysis of relationships between variables cross-tabulated into multiway frequency tables. The loglinear model represents the logarithm of an expected cell frequency as a linear combination of effects. This method is similar to an analysis of variance (ANOVA) model except that the logarithm of the expected cell frequency replaces the expected value in the ANOVA model. This step in the analysis fitted and tested various combinations of variables in an effort to identify the interactions between variables.

A simplified correspondence analysis suitable for visual interpretation of two-way tables was conducted to convert frequency table data into graphical displays in which rows and columns are depicted as points. This provides a method for comparing row or column proportions in the table. Mathematically, correspondence analysis decomposes a measure of association for the table into components. This measure of association is referred to as inertia and is proportional to the chisquare statistic. This step in the analysis describes in terms of categories of variables just how the variables were related (Ref. 29).

Results

Repair Rate Analysis

Table 2 lists the repair rate summary by project. Projects were classified as "large" when more than 10,000 welds were involved, and "small" if less than 5000 welds were done. The

Table 1—Summary of Project Descriptions

Project	Owner	Contractor	Pipe	Length	Season
1	1	A	914 mm × Gr 483 (36 in. × 70 ksi)	111 km (69 mi.)	Winter
2	2	A	1218 mm × Gr 448 (48 in. × 65 ksi)	291 km (181 mi.)	Summer
3	2	A	914 mm × Gr 448 (36 in. × 65 ksi)	232 km (144 mi.)	Summer
4	1	A	1067 mm × Gr 483 (42 in. × 70 ksi)	8 km (5 mi.)	Summer
5	1	B	914 mm × Gr 483 (36 in. × 70 ksi)	93 km (58 mi.)	Winter
6	1	C	1067 mm × Gr 483 (42 in. × 70 ksi)	161 km (100 mi.)	Winter
7	2	D	914 mm × Gr 448 (36 in. × 65 ksi)	190 km (118 mi.)	Summer
8	2	D	1218 mm × Gr 448 (48 in. × 65 ksi)	186 km (116 mi.)	Summer
9	2	C	1067 mm × Gr 483 (42 in. × 70 ksi)	203 km (126 mi.)	Winter

Table 2—Repair Rate Summary by Project

Project #	Total Welds	Welds Repaired	Repair Rate, %
1	4,308	1,592	37
2	12,439	2,123	17
3	8,154	906	11
4	298	91	31
5	4,034	1,278	32
6	6,889	1,201	17
7	5,873	1,443	25
8	7,777	1,166	15
9	9,748	2,644	27
Totals	59,520	12,444	21% average

Table 3—Overall Repair Rate Measures

	Weighting, % of Total Welds	Overall Repair Rate, %
Owning Company:		
1	26	27
2	74	19
Contractor:		
A	42	19
B	7	32
C	28	23
D	23	19
Contractor Season:		
Summer	58	17
Winter	42	27
Pipe Diameter:		
36 in. (914 mm)	38	23
42 in. (1067 mm)	28	23
48 in. (1218 mm)	34	16
Pipe Grade:		
X-65 (Grade 448)	58	21
X-70 (Grade 483)	42	37
Project Size, welds/project:		
<5,000	15	34
5,000-10,000	64	19
>10,000	21	17
Fill Pass Condition, # of passes:		
1	21	49
2	(—)	21
3	(79)	10

result of statistical calculations suggests that variations in certain categories of characteristics have more influence on repair rates than do variations in others. It is the authors' experience that repair rates during the early production stages of a project tend to be high relative to the overall repair-rate statistics for a project as determined at its conclusion. This is a reflection of the influence of the classical learning curve as the welding crew and equipment is fine-tuned within the parameters of the approved welding procedure during the first few days of production welding. Useful information with respect to production counts, against which corresponding repair counts could be matched, was not accurately recorded. Such data are necessary to provide a measure against which the impact of project start-up periods on repair-rate values can be quantified.

Repair rates for the various project sizes, Table 2, agree with the hypothesis that larger projects tend to have lower repair rates as a result of the diluting impact of quantity on relatively poor quality performance during the start-up period. Note, however, that five projects fell into the midsize category and only one in the largest category. In addition, the largest project (by contractor A) represented 21% of all welds completed and was done during the summer season, when repair rates are lower. Overall repair rates by owning company, contractor, season and other variables are given in Table 3. Contractor A had an overall repair rate of 19%, but this contractor completed about 42% of all welds and constructed 45% of all projects investigated; it had to contend with four start-up periods. It also completed the smallest project studied, one involving only 298 welds, where the repair rate was 31%.

Owning Company 1 welds were subject to a 27% repair rate while those of Company 2 had a repair rate of 19%. However, most of Owning Company 1's projects were done in the winter, while most of the other's projects were done during the summer season. Of the total, five projects were completed during the summer season while four were done during the winter. The average project size was about the same for each season's work but the repair rates were 17% for the summer and 27% for the winter work. On the basis of this comparison alone, one is inclined to conclude that winter work takes its toll on weld quality much more so than that done in the summer. But how do these characteristics, whether they are season or pipe diameter or owning company or contractor, affect these statistics?

The chisquare test for independence was applied to pairwise components of the repair-rate data. This test provides an index used to assess departure from pairwise independence. The chisquare values range from 17.5 for owner vs. season to 42.6 for the season vs. defect concentration combinations of repair-rate occurrences. It is easy to conclude that in the case of the combinations of project characteristics considered, the probability of obtaining such large chisquare values is very small. That is, the paired variables exhibit some degree of dependence upon one another or, put another way, an association between each of the pairs of variables is very definitely indicated. Further, the degree of association between season and defect concentration (chisquare = 42.6) is more pronounced than that between season and owner (chisquare = 17.5). This conclusion, however, can be misleading, considering that even though the sample size was large, the sample variability with respect to project characteristic variables was limited. The sample then does not represent the full sample space of the variables considered. Only nine projects were investigated, each identified by a discrete repair rate and a unique set of characteristics.

Defect Frequency Analysis

Defect description (type, length and concentration) and defect location (pass notation and circumferential location) characteristics were analyzed to see if preventive action could be prescribed. Tables 4 and 5 summarize some of the defect frequency measures investigated.

Loglinear analysis of the total sample indicates clearly that

Table 4—Overall Defect Concentration Summary

Defects/Weld	Proportion of All Welds Made, %
0	79.1
1	15.7
2	3.8
3	1.0
4	0.3
5	0.1
6	nil
7	nil
8	nil

Table 5—Overall Defect Frequency Measures

Defect Classifications:	Proportion of All Defects Recorded, %
Incomplete penetration	4.1
Burn through	2.6
Incomplete fusion	66.9
Porosity	22.0
Other	1.3
Cut outs	3.3
Wall Thickness:	
0.347 in. (8.80 mm)	17.8
0.385 in. (9.79 mm)	23.7
0.389 in. (9.88 mm)	8.5
0.400 in. (10.16 mm)	14.3
0.457 in. (11.61 mm)	23.4
0.462 in. (11.73 mm)	0.3
0.504 in. (12.80 mm)	1.4
0.551 in. (14.00 mm)	8.0
0.554 in. (14.07 mm)	0.6
0.559 in. (14.10 mm)	0.8
0.609 in. (15.47 mm)	1.2
Fill Pass Condition—# of fill passes:	
1	50.0
2	41.0
3	9.0
Pass Location:	
not recorded	1.5
root	23.9
hot	10.7
1st fill	35.9
2nd fill	13.3
3rd fill	10.5
cap	4.2

relationships between the variables defect type, concentration, start-of-defect quadrant and pass were all significant, *i.e.*, there was a probability greater than 99% that the variables were not independent. The size of the total sample was 16,653 defects. Analysis indicates that all second-order models (all two-way combinations of variables) and some third- and fourth-order models involving certain combinations of the four variables were significant. A correspondence analysis of the second-order models helps to identify how the categories of each variable are interrelated in a synergistic fashion. Key relationships detected as a result of this analysis of the total sample are included in Table 6.

Discussion and Conclusions

Repair Rate Expectations

Only tentative conclusions can be drawn with respect to repair rates since the sample space was too restricted for an accurate assessment of independence among the variables recorded. At the time of this study (1975–1985), repair rates in the range of 15 to 35% could be expected due to a variety of factors, including the "novelty" of mechanized pipe welding. Presently, expected repair rates are 5 to 10%. One can estimate that the rate will tend toward the higher end of this range if the project can be defined in terms of one or more of the following characteristics:

1) Construction to be completed during the winter season.
2) Pipe diameter less than 48 in. (1218 mm).
3) Pipe material grade greater than X-65 (Grade 448 MPa).
4) Welding procedure specifies a single fill pass condition.
5) Project size, in terms of number of welds, is less than 5000.

Defect Frequency Expectations

Defect type, as well as location (in terms of pass and position around the circumference of the pipe), are important in developing plans to minimize defect occurrence. The total sample of 16,653 defects was well defined in terms of the variable type, pass and start-of-defect quadrant. All were also well defined in terms of the second-order pairing of these variables, with many also being well defined in terms of the three- and four-way combinations of these variables.

When the repair rate for mechanized welding of pipelines is in the range of 15 to 35%, the following conclusions can be drawn as a result of the loglinear analysis for relationships among variables and the correspondence analysis for associations among categories of variables:

1) Most defective welds contained a single defect, but the average was about 1.3 defects.
2) Most defective welds having a high concentration of defects resulted in a cut out.
3) Defects in general were most frequently found in the fill (60%) and root (24%) passes.
4) A higher frequency of defects occurred if the welding procedure specified a single rather than a two-fill condition; likewise, a three-fill condition resulted in substantially fewer defects relative to either a one- or two-fill condition.
5) The most frequently occurring defect types were the categories of incomplete fusion (sidewall) (31%); incomplete fusion (interpass) and undercut (24%); and porosity (21%). The fusion defects identified by radiographic inspection techniques were almost exclusively oriented in the vertical plane.
6) The majority of these defects were found in the fill passes, the incomplete sidewall fusion being the predominant fusion defect type. The fusion defects re-

corded in the root and cap passes were primarily undercut. Planar defects oriented in the transverse or longitudinal planes were difficult if not impossible to detect by radiography. Porosity defects were found to occur in a more or less random fashion in all passes.

7) The concentration of defects in a defective weld was not particularly associated with specific pass locations for various categories of defects, but a positive association was noted between single or low numbers of multiple defects and the workside quadrant.
8) Start-of-defect quadrant locations for several of the key defect types are: melt through – workside (45%) and ditchside (30%); underfill – workside (62%) and ditchside (18%); crack – ditchside (67%) and workside (15%); and the grouping of incomplete fusion and undercut – workside (49%) and ditchside (31%).
9) Melt through, underfill, crack (cut out), and incomplete fusion defects typically started in the workside quadrant.

As was indicated in the case of the repair rate estimates, some modest refinements to the proportions identified above may be made by focusing on specific subsets of the data which correspond more closely to the upcoming project's characteristics.

Defect Causes and Cures

The analysis of the data has indicated a distinct tendency for defects to occur most frequently in the root and fill passes and for their starting location to be in a workside quadrant. These results should prompt the contractor and inspection staff to be particularly attentive to the welding procedure in these areas. Likewise, the equipment manufacturer should review the design of the equipment with a view to improving its operation or its ability to be manipulated by the welder in these positions.

Seventeen [illegible] were used to describe [illegible] recorded.

In the case of root pass defects, contractor attention should be given to the careful control of the end facing operation, proper maintenance of the internal line-up clamp/welding machine and proper skills levels and training for the clamp operator. Manufacturers should focus on the design of the drive mechanism for the internal machine as it relates to the ease with which the operator can ensure proper line-up, giving due consideration to the impact of terrain and climatic conditions which must be faced by the contractors.

The prominence of fill pass defects and their locations on the workside suggests that attention should be given to welding operator skill level and training needs with respect to the fill pass bugs as well as manufacturer attention to the basic design of the external welding units as they are used on the workside of the pipe. Operation of the fill-pass bugs requires that the welding operator simultaneously control arc length and the oscillation band within the joint as the pass is being made. These controlling actions are accomplished through the manipulation of two control knobs on the bug. Control of these two actions is particularly critical in the case of high/low or other joint geometry conditions in which the actual geometry deviates from that specified. The location of these knobs, as well as that of the welding head itself, is such that the welding operator is required to exert a great deal of physical effort to maintain proper eye contact with the weld pool, while at the same time keeping each hand on one of the two control knobs. This positioning becomes particularly challenging for the welder as the bug passes into the lower portion of the workside quadrant, and the welder has to follow it into the bottom quadrant, all the while visually monitoring the weld pool and managing its behavior through manipulation of the two control knobs. A loss of dexterity, resulting from constraints in the use of right and left hands to control the equipment, can be noted when watching the operation. Likewise, it appears that use of the left hand predominates on the workside operations, which may further aggravate the situation. Restricted vision, particularly of the leading pipe sidewall, may be a major contributing factor to fill pass defects. This restriction of vision is due to a combination of the position of the welding head relative to the carriage including the control box, drive motor and electrode spool assembly, and the positions adopted by the welders during the fill pass operation.

Table 6—Loglinear Analysis Reveals Relationships between Variables

Variable Pairings	Relationships
Type/concentration	1. The occurrence of cracks (cut outs) demonstrates a strong positive association with high multiple-defect concentrations. 2. Other combinations of categories demonstrate little association.
Pass/concentration	1. Little association is apparent between the categories of pass in which a defect is found and the concentration categories of defect in a defective weld.
Start-of-defect/quadrant	1. Single and other low multiple-defect concentrations show a positive association with the workside quadrant (225–315 deg). 2. Little association is evident between other quadrants and defect concentrations.
Type/pass	1. The relationships between categories of these two variables are largely set by definition. For example, insufficient cross penetration is by definition a defect occurring only in the hot pass and underfill can only occur in the cap pass. As a result, the categories of type and pass are not well summarized by the dimensions of the other variable for any clear reason other than definition.
Type-of-defect/quadrant	1. The occurrence of melt through, underfill, crack (cut out), incomplete fusion (interpass, sidewall) and undercut demonstrate a large positive association with the workside quadrant. 2. A strong negative association is evident between the defect insufficient cross-penetration and the workside quadrant. 3. Little association exists between the remainder of the defect types and segments of the pipe's circumference.
Pass/defect quadrant	1. The variables are well defined with respect to one another but little association is distinguishable at the category level.

As is so often the case, improved weld quality can be traced to the need to exercise care and control at the design stage. The most appropriate materials should be selected, including welding consumables. All materials should be properly stored and protected. Welding procedures should be carefully tested, documented and approved. Such procedures should adequately address not only basic welding parameters, including reasonable ranges for the critical ones, but also such issues as joint geometry, as well as preheat and postheat requirements. Welding equipment should be properly designed and maintained, and all welders and their helpers should be properly skilled, trained, supervised and have their work promptly and adequately inspected. ♦

Acknowledgments

The authors wish to thank TransCanada Pipelines Ltd and NOVA Corp. for supplying large amounts of inspection data on pipeline fabrication using automated systems. Thanks are also due to Prof. W. Griffin for guidance on the use of statistical theory for data analysis.

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Appendix 1—Pipeline Weld Defects, Causes and Cures

Melt Through

Heat input of the hot pass bug is too high. Joint geometry dimensions may be out of tolerance. The heat input can be reduced by 1) reducing the electrode feed speed to obtain a lower amperage, 2) by increasing the travel speed, and 3) by increasing the electrode extension. Joint design, as influenced by the quality of the end preparation operation, is critical. Close tolerances on the root face dimension must be met. Check the condition of the facing machine tools; out-of-specification tolerances, especially on the low end, may be the problem.

Crack

A variety of welder errors and equipment malfunctions are likely the cause if the crack has occurred in conjunction with a high number of multiple defects; in many cases, cracks occur as a result of an overstressing of the pipe in the weld during or immediately after placement of the root and hot passes. These stresses are caused by the pipe handling operations. Other likely contributing factors include cold temperatures, moisture in the weld region and misalignment of the joint faces.

Care must be exercized in handling large-diameter pipe with little weld reinforcement in place. The internal line-up clamp/welding machine may have to be held until the hot pass reinforcement is fully placed and, in some circumstances, until additional reinforcing weldment is placed, normally at the top and bottom of the pipe. Proper preheating techniques may be enhanced by the use of electric heat-induction devices rather than the flame-heating methods normally used and the specified preheat temperature should be held between passes. Control of the weld cooling rate by promptly wrapping the weld with a fireproof insulating blanket, after the weld is completed, is an important consideration for cold weather operations. Proper maintenance, alignment and operation of the pipe-facing machine is critical in insuring that the close tolerances required by the joint design are maintained. Consideration should be given to ordering pipe from the mill with the compound bevel specified, requiring that the construction contractor only "touch up" the bevel in the field just ahead of the welding operation. It is best for final joint preparation to be completed just ahead of the welding operation, but it is not cost-effective to cut the complete bevel from a square end of the field.

Incomplete Fusion and Undercut

Misalignment of the welding head is the leading cause of this grouping of defects. High current settings causing excessive heat input may contribute to the defect in the case of undercut and the opposite condition may contribute to occurrences of incomplete fusion. The arc may be too long; that is, the contact-to-work distance may be too great or the electrode extension dimension may be too short. The bead may be excessively wide, especially if this grouping of defects is noted as occurring in the cap pass. The base metal surface may be contaminated, as may the welding consumables, or the weld pool may be too large due to improper manipulation of the welding head.

The welding arc must be directed at the base metal with the arc at the leading edge of the weld pool. Proper manipulation of the pool is the result of an adequate level of welder skill, training and discipline. Potential causes related to various welding parameters focus on the establishment of a proper welding procedure that incorporates a reasonable range of values for each parameter and the careful adherence to the procedure during the production welding operation. Care and consideration with respect to procedures adopted for the storage and handling of consumables and for cleaning the joint just prior to welding is essential.

Incomplete Sidewall Fusion

Incorrect travel speed or electrode feed rates, incorrect oscillation of the welding head and molten metal flowing into areas of unwelded base metal (as the result of too large a weld pool) cause these defects. Cures include: directing the arc at the base metal (with the arc at the leading edge of the weld pool), and reducing the size of the weld pool (by either increasing the travel speed and/or reducing the electrode feed rate).

Underfill

Incorrect oscillation of the welding head is the main problem here. Welding parameters, including a reasonable range of values for each parameter, must be established in the welding procedure and the procedure must be followed by the welder during the production operation.

Porosity

Loss of shielding gas due to wind or draft is a prime cause of porosity. Gas flow set too low is another. Excessive shielding gas flow will cause mixing and turbulence with the air and thus an insufficient shield. Clogged or defective gas systems, *e.g.* spatter clogging the gas nozzle, a broken gas line, defective fittings in the gas system, inoperative gas valves, or frozen regulators, will cause porosity, as will contaminated shielding gases (usually from moisture).

Housing the welding operation in a proper shelter, taking into account site specific environment factors, is important. At a minimum, shielding the immediate area near the welding head from wind currents is mandatory. Proper maintenance and operation of the shielding gas system must be a part of a properly prepared and administered set of welding procedures. Shielding gases should be obtained from reputable suppliers, clearly specifying the purity required. Gases, as is the case with all consumables, must be properly stored and handled at the construction site.

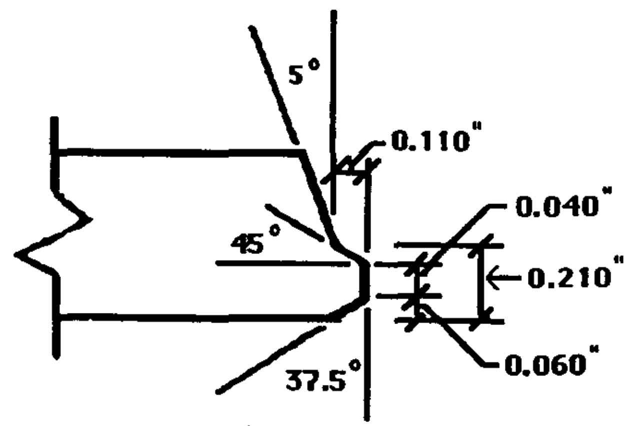

Fig. 2 — Compound bevel joint design.

Appendix 2—The Automated Pipeline Welding System

The welding system is a small-diameter electrode, gas metal arc welding (GMAW) system developed specifically for welding line pipe. The three major mechanical components of the system include a pipe end-facing machine used to prepare a compound bevel; a combination internal line-up clamp/welding machine; and an orbiting, external carriage that travels on spring steel bands temporarily attached to the pipe.

Line pipe manufactured to American Petroleum Institute (API) standards calls for the pipe ends to be beveled at a 30-deg angle and have a root face of about 1/16 in. (1.6 mm). This standard mill-applied bevel presents several shortcomings with respect to mechanized welding. Pipe is often not perfectly round when the mill bevel is cut, thus producing variations in root face thickness. Another problem can be encountered when the internal line-up clamp (used for most pipeline welding) rounds out pipe ends and distorts what may have been an originally flat plane for the bevel. These two difficulties normally create little or no trouble for shielded metal arc welding (SMAW) but can cause serious problems for the mechanized GMAW process. The API bevel also requires that a relatively large volume of weld metal be placed. The joint design used in the system is a compound bevel, as shown in Figure 2.

There is no root opening in the joint fitup, and the root pass is welded from inside the pipe. The absence of a root opening further decreases the weld metal volume, reduces joint fitup time and significantly reduces the number of melt-through defects. It also allows for the hot pass to be placed almost simultaneously with the root pass, thus, speeding up the welding time and providing a more heavily reinforced partial weld when the line-up clamp is removed.

The internal line-up clamp/welding machine aligns the two pipe ends, holds them in place and automatically places the root pass on the inside of the joint. The clamp portion of the apparatus is essentially a typical pneumatically operated line-up clamp. The welding portion of the machine consists of either four heads for pipe sizes less than 40 in. (1016 mm) in diameter or six heads for larger sizes. These heads are symmetrically mounted around a ring gear that is driven by a 24-V electric motor. Each welding head contains a 3.25-lb (1.5-kg) spool of 0.035-in. (0.9-mm) diameter welding electrode. Shielding gas is stored on the machine in rechargeable cylinders.

In operation, a four-headed machine begins welding with two heads at the 12 and 3 o'clock positions, as seen from the open end of the pipe. These heads weld downhill to the 3 and 6 o'clock positions, respectively. Simultaneously, the other heads move into position at 12 and 9 o'clock. When the first two heads are finished, the second two weld from 12 to 6 o'clock, respectively. Operation of the six-head machine is similar, but with three heads welding simultaneously. The shielding gas mixture for the root pass is typically 75% argon—25% CO_2. The heads weld at approximately 30 in. (760 mm) per minute with electrode feed speeds of 340 to 360 in. (8.6 to 9.1 m) per minute. The internal line-up clamp/welding machine is actuated from a control box on the end of a reach rod, extending through the pipe joint being added to the line. Welding power and compressed air are also supplied through the reach rod. Power for electrode feed and travel motors is taken from batteries on the machine. After the root pass is completed, the clamping shoes are retracted and the internal machine propels itself from the pipe joint just welded and stops automatically at the next open end.

The external welding carriages used with the system are commonly referred to as "bugs." Different bug configurations are used for each of the external passes: hot, fill and cap. The differences are in the design of the shielding nozzles, travel speeds and tip oscillation. The bugs travel by means of a 24-V drive motor and gearbox on spring steel bands that are placed near the pipe ends after the modified bevel has been machined. An aligner ring is used to position the bands. The bug control box contains printed circuit boards that control travel speed, electrode feed speed, tip oscillation frequency, and an electrode and gas shut off delay. The delay board allows the electrode and shielding gas to continue feeding for a short time (after travel has stopped) to eliminate the shrinkage crater at the end of a weld pass. There are button controls for each function of the bug. The welding section of the bug consists of the welding tip, electrode feed drive motor, oscillation motor and gearbox, gas shielding nozzle and a 6-lb (2.7-kg) spool of 0.035-in. (0.9-mm) diameter welding electrode. There is also a mechanism for adjusting the width of oscillation on the fill and cap bugs. Shielding gas for all external passes is usually 100% CO_2; however, on occasion, some procedures call for a mixture of 75% argon and 25% CO_2 for the cap pass.

The hot pass is normally welded at about 50 in. (1.27 m) per minute and at an electrode feed rate of about 500 in. (12.7 m) per minute. Fill and cap passes are generally welded at 13 to 15 in. (330 to 380 mm) per minute and at electrode feed rates in the range of 450 to 650 in. (11.5 to 16.5 m) per minute. The external bugs are used in pairs with each bug making half a weld pass from the 12 o'clock positions. Bugs on the ditchside of the pipe move clockwise while those on the workside move in a counterclockwise direction. The hot pass bugs start to weld as soon as the internal welding heads have gone far enough that they cannot be overtaken. The fill pass bugs begin simultaneously but not at the same point. Typically, for the first fill pass, the workside bug begins welding at 12 o'clock and welds continuously down to 6 o'clock. At the same time, the ditchside bug is started at the 3 o'clock position and welds to the 6 o'clock position, as the workside bug passes the 9 o'clock position. The ditchside welding operator then brings the bug up to the 12 o'clock position and finishes welding down to 3 o'clock. The starting positions are reversed on alternate fill passes to prevent overlapping of starts and stops in the vertical position. As a general rule, one fill pass is normally required for every ⅛ in. (3.2 mm) of pipe wall thickness over 0.312 in. (7.9 mm).