REVISIONS, REPAIRS, AND REWORK ON LARGE PROJECTS

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ABSTRACT: The effects of revisions, repairs, and rework on large, complex projects are very substantial and are not frequently dealt with in a comprehensive, consistent, or effective manner, even in industries that deal constantly with very large projects, such as the commercial nuclear power industry. Large-scale commercial nuclear projects require multiple work phases and disciplines that result in substantial and significant interdependencies among these work phases and disciplines. These interdependencies and the complex interactions that result are key factors in understanding, controlling, and managing such projects. Of particular relevance are the consequences of these interdependencies upon effective project work scope caused by revisions, repairs, and rework. This study examines these effects using a simplified mathematical model constructed to correspond with intuitive reasoning and empirical observations. A range of hypothetical examples is also provided to illustrate the consequences of these effects.

INTRODUCTION

In the commercial nuclear power industry, many projects have gone far astray from original estimates and projections, causing extremely difficult and even disasterous effects upon the fiscal parameters of utilities and, in some instances, raising very serious questions concerning management fitness and integrity, bearing directly upon vital issues dealing with the public safety as well as legal and ethical obligations from positions of trust.

This study examines methods to measure and compute progress completion status for large projects and seeks to illustrate the divergencies that can arise between "reported" progress and "actual" progress. Also, this study examines the interrelationships that appear to connect reported progress and actual progress, by constructing a model that depicts these relationships and agrees with intuitive and empirical observations.

The study investigates the effects of conditions encountered in individual disciplines and work phases to examine whether project conditions as a whole are reflected by project status measurements in individual disciplines. Also, the study examines the factors that appear to contribute to the fact that reported progress, cost projections, and remaining projected project durations are consistently and repeatedly more optimistic than actual achieved results in virtually all large commercial nuclear projects in recent years.

For example, first consider the consequences of emergency backup diesel

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                  0 : START
MINOR                  \/  Wso          MAJOR
RETURN                 \/               RETURN
CYCLE, a               \/               CYCLE, b
     --> 1 : ENGINEERING <-----<-------<
    /                  \/  Ws1                 |
   <----               \/                      |
     --> 2 : DESIGN >----->----->----->|
    /                  \/  Ws2                 |
   <----               \/                      |
     --> 3 : CLIENT REVIEWS >----->--->|
    /                  \/  Ws3                 |
   <----               \/                      |
     --> 4 : REGULATORY REVIEWS >----->|
    /                  \/  Ws4                 |
   <----               \/                      |
     --> 5 : PROCUREMENT >----->------>|
    /                  \/  Ws5                 |
   <----               \/                      |
     --> 6   : MANUFACTURING >----->--->|
    /                  \/  Ws6                 |
   <----               \/                      |
     --> 7   : DELIVERY >------>------->|
    /                  \/  Ws7                 |
   <----               \/                      |
     --> 8   : WAREHOUSE STORAGE >----->|
    /                  \/  Ws8                 |
   <----               \/                      |
     --> 9   : ASSEMBLY, FABRICATION -->|
    /                  \/  Ws9                 |
   <----               \/                      |
     --> 10 : INSTALLATION >----->---->|
    /                  \/  Ws10                |
   <----               \/                      |
     --> 11 : INPLACE STORAGE >------->|
    /                  \/  Ws11                |
   <----               \/                      |
     --> 12 : INSPECTION >----->------>|
    /                  \/  Ws12                |
   <----               \/                      |
     --> 13 : REWORK >----->----->---->|
    /                  \/  Ws13                |
   <----               \/                      |
     --> 14 : INITIAL TESTING >------->|
    /                  \/  Ws14                |
   <----               \/                      |
         15 : PREOPERATIONAL TESTING ->|
                       \/  Ws15
                       \/
         16 FINISH, OPERATING PLANT
                       Ws16 = Wsf = Wso
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FIG. 1.—Typical Flow Diagram for Components, Systems, and Structures

generators failing during the preoperational testing phase, requiring complete reevaluation and reengineering of the emergency backup system, removal of the existing diesél generators, and replacement generators procured to the same or more stringent specifications, delivery, installation, and retesting to achieve operational requirements.

Also, consider the consequences of engineering, designing, fabricating, and installing thousands of piping supports in spatially congested permanent plant facilities surrounded by multidiscipline components, systems, and structures and the statistical probability of incurring inter-

TABLE 1.—Revisions, Repairs, and Rework Coefficients by Individual Work Phase/ Discipline

Reference number (1)	Work phase/discipline (2)	Work Phase Coefficients		Work phase work scope (5)
		Minor path (3)	Major path (4)	
i		*ai*	*bi*	*Wsi*
0	Start	NA	NA	10,000
1	Engineering	NA	NA	26,331
2	Design	8.0%	6.5%	24,181
3	Client reviews	6.0%	4.5%	22,601
4	Regulatory reviews	3.5%	2.5%	22,649
5	Procurement	6.5%	5.0%	21,654
6	Manufacturing	7.5%	6.0%	19,930
7	Delivery	5.0%	4.0%	19,343
8	Warehouse storage	6.0%	4.5%	19,225
9	Assembly, fabrication	10.5%	7.5%	18,105
10	Installation	13.0%	8.5%	16,449
11	Inplace storage	12.5%	9.1%	15,041
12	Inspection	14.4%	10.0%	12,816
13	Rework	7.0%	3.5%	12,852
14	Initial testing	12.0%	7.5%	11,550
15	Preoperational testing	9.5%	6.0%	10,000
16	Finish, operating plant	0.0%	0.0%	10,000
	Average values	8.7%	6.1%	

Note: Revisions, repairs, and rework coefficient, r = 45.0%. Range, estimated upper limit for r = 52.5%. Range, estimated lower limit for r = 37.5%.

ferences that require substantial, if not total, reengineering and redesign.

These two examples are both well recognized in the commercial nuclear industry. The first, an isolated major event, and the second, a frequently encountered event, statistically predictable, serve to illustrate the kinds of circumstances encountered that collectively require a systematic adjustment to scheduling and cost projections to consistently permit re-

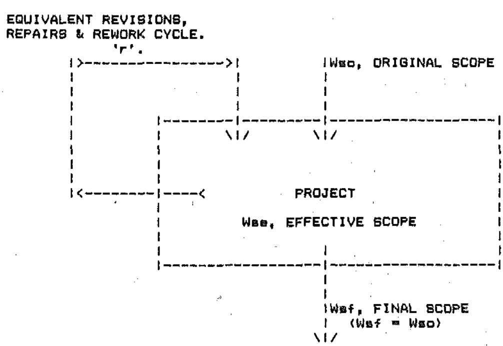

FIG. 2.—Equivalent Flow Diagram for Components, Systems, and Structures

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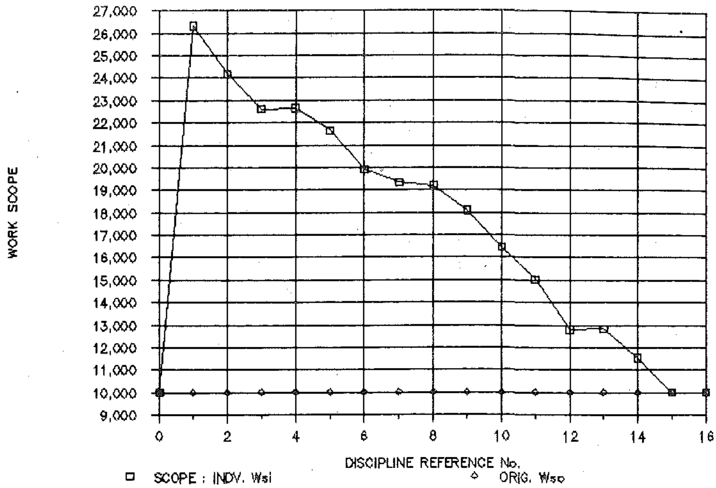

FIG. 3.—Work Scopes versus Discipline for Each Individual Discipline

alistic projections while maintaining quality and regulatory requirements intact.

The writers of this study have participated in and studied several cases relating to prudence hearings in connection with several commercial nuclear facilities. It is with the matters of prudently incurred costs in mind that the writers have researched these matters and constructed the model contained in this study. Prudence questions affecting the allocation of billions of dollars in funding for commercial nuclear facilities are being raised in many states at this time and it is likely that the matter will be an increasing issue for years to come.

Model and Method

The approach developed recognizes that for large projects employing many work phases, especially on a "fast-tracked" basis, the effects of revisions, repairs, and rework must be examined broadly across many disciplines and project phases. The methodology used here employs a "revisions, repair, and rework coefficient" and this overall averaged coefficient is applied to all work phases (including repairs and rework) to illustrate the consequences of these effects in a simplified approach.

The revisions, repairs, and rework coefficient is computed from information and data compiled from, and/or projected for, each major work phase and each principal discipline. Fig. 1 shows the work phases and disciplines selected for inclusion in the model used in this study.

Table 1 contains examples of revisions, repairs, and rework coefficients for individual work phases and disciplines, and these values are used in this study to compute the overall average revisions, repairs, and rework coefficient for the simulated project as a whole. For any component, system, or structure, this overall coefficient can be considered

J. Constr. Eng. Manage., 1987, 113(3): 488-500

TABLE 2.—Revisions, Repairs, and Rework Coefficient, 'r': Upper Estimate

Reference percent complete $p(ref)$ (1)	Reported Conditions: Work complete Wcr (2)	Work scope Wsr (3)	Work remaining $Wsr - Wcr$ (4)	Percent complete pr (5)	Project duration Dr (6)	Remaining duration Drr (7)	Actual Conditions: Work complete Wca (8)	Work scope Wsa (9)	Work remaining $Wsa - Wca$ (10)	Percent complete pa (11)	Project duration Da (12)	Remaining duration Dra (13)
0%	0	10,000	10,000	0.0%	5.00	5.00	0	21,053	21,053	0.0%	10.53	10.53
10%	2,105	11,105	9,000	19.0%	5.55	4.50	1,111	21,053	19,942	5.3%	10.53	9.97
20%	4,211	12,211	8,000	34.5%	6.11	4.00	2,442	21,053	18,611	11.6%	10.53	9.31
30%	6,316	13,316	7,000	47.4%	6.66	3.50	3,995	21,053	17,058	19.0%	10.53	8.53
40%	8,421	14,421	6,000	58.4%	7.21	3.00	5,768	21,053	15,284	27.4%	10.53	7.64
50%	10,526	15,526	5,000	67.8%	7.76	2.50	7,763	21,053	13,289	36.9%	10.53	6.64
60%	12,632	16,632	4,000	75.9%	8.32	2.00	9,979	21,053	11,074	47.4%	10.53	5.54
70%	14,737	17,737	3,000	83.1%	8.87	1.50	12,416	21,053	8,637	59.0%	10.53	4.32
80%	16,842	18,842	2,000	89.4%	9.42	1.00	15,074	21,053	5,979	71.6%	10.53	2.99
90%	18,947	19,947	1,000	95.0%	9.97	0.50	17,953	21,053	3,100	85.3%	10.53	1.55
100%	21,053	21,053	0	100.0%	10.53	0.00	21,053	21,053	0	100.0%	10.53	0.00

Note: Input values used (selected for illustration): Original work scope, $Wso = 10{,}000$; Equivalent resources, $Re = 2{,}000$. Calculated values: Revisions, repairs, and rework coefficient, $r = 52.5\%$; Effective work scope, $Wse = 21{,}053$.

an average value representing possible effects from initial conception, through engineering, design, possible client review, procurement, manufacturing, delivery, warehouse storage, installation, in-place storage, inspection, possible rework, initial testing, and final preoperational testing prior to commercial operation.

All of these work phases and disciplines create the potential for revisions, repairs, and rework, including reengineering or redesign. The effects of these individual phases, many interactive, can have a highly substantial cumulative effect upon the overall repair and rework coefficient as developed here.

The model selected for this study, referring to Fig. 1, supposes two possible paths for returning or referring revisions, repairs, and rework to another prior discipline for corrective action. The two paths are designated: (1) Minor revisions, repair, or rework; and (2) major revisions, repair, or rework.

The minor path assumes that on average the conditions requiring possible revisions, repairs, or rework can be handled by the prior discipline on the flow path. For modeling purposes, this is frequently realistic, although referring to Fig. 1, it is noted that the convention and order of disciplines selected produces one or two unusual referral paths, e.g.,

5. PROCUREMENT → 4. REGULATORY REVIEWS

These anomalies, however, have a relatively minor effect upon the overall results and do not significantly impair the individual discipline results for the illustrative purposes of this study.

The major path assumes that the conditions requiring possible revisions, repairs, or rework must involve the components, systems, or structures being reexamined or reevaluated by the discipline responsible for engineering. In the commercial nuclear industry, this major referral path for revisions, repair, and rework is consistent with the nuclear in-

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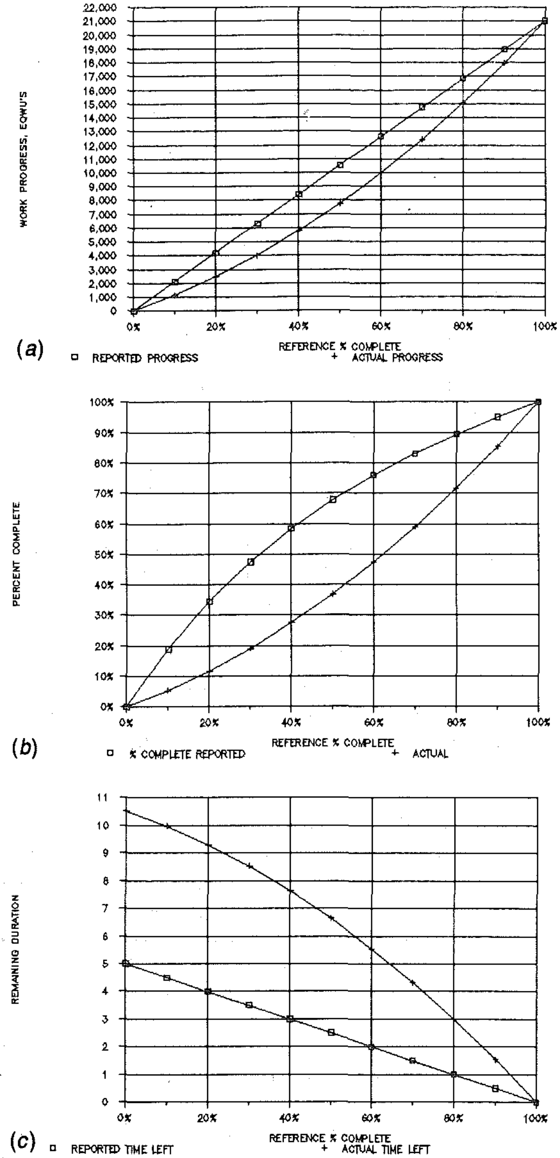

FIG. 4.—Estimated Upper Limit Conditions for r: (*a*) Work Progress, Reported and Actual, versus Reference Percent Complete; (*b*) Percent Complete, Reported and Actual, versus Reference Percent Complete; and (*c*) Remaining Duration, Reported and Actual, versus Reference Percent Complete

TABLE 3.—Revisions, Repairs, and Rework Coefficient, 'r': Average Estimate

Reference percent complete $p(ref)$ (1)	Reported Conditions						Actual Conditions					
	Work complete Wcr (2)	Work scope Wsr (3)	Work remaining $Wsr - Wcr$ (4)	Percent complete pr (5)	Project duration Dr (6)	Remaining duration Drr (7)	Work complete Wca (8)	Work scope Wsa (9)	Work remaining $Wsa - Wca$ (10)	Percent complete pa (11)	Project duration Da (12)	Remaining duration Dra (13)
0%	0	10,000	10,000	0.0%	5.00	5.00	0	18,182	18,182	0.0%	9.09	9.09
10%	1,818	10,818	9,000	16.8%	5.41	4.50	1,082	18,182	17,100	5.9%	9.09	8.55
20%	3,636	11,636	8,000	31.3%	5.82	4.00	2,327	18,182	15,855	12.8%	9.09	7.93
30%	5,455	12,455	7,000	43.8%	6.23	3.50	3,736	18,182	14,445	20.5%	9.09	7.22
40%	7,273	13,273	6,000	54.8%	6.64	3.00	5,309	18,182	12,873	29.2%	9.09	6.04
50%	9,091	14,091	5,000	64.5%	7.05	2.50	7,045	18,182	11,136	38.7%	9.09	5.57
60%	10,909	14,909	4,000	73.2%	7.45	2.00	8,945	18,182	9,236	49.2%	9.09	4.62
70%	12,727	15,727	3,000	80.9%	7.86	1.50	11,009	18,182	7,173	60.5%	9.09	3.59
80%	14,545	16,545	2,000	87.9%	8.27	1.00	13,236	18,182	4,945	72.8%	9.09	2.47
90%	16,364	17,364	1,000	94.2%	8.68	0.50	15,627	18,182	2,555	85.9%	9.09	1.28
100%	18,182	18,182	0	100.0%	9.09	0.00	18,182	18,182	0	100.0%	9.09	0.00

Note: Input values used (selected for illustration): Original work scope, Wso = 10,000; Equivalent resources, Re = 2,000. Calculated values: Revisions, repairs, and rework coefficient, r = 45.0%; Effective work scope, Wse = 18,182.

dustry regulatory guidelines that specify reevaluation and reapproval of all revisions, repairs, and rework by the originating discipline (usually engineering).

It is this major revisions, repairs, and rework path that has contributed most significantly in the case of delays and cost escalations in the commercial nuclear power industry. The consequences of this requirement, implemented in its most rigorous form under the regulatory environment that exists in that industry, have caused project schedules and cost estimates to be so consistently and substantially more optimistic than the actual results achieved.

The mathematical model of these effects is constructed using the array of algebraic equalities implicit in the work flow relationships depicted in Fig. 1 and as reduced to an equivalent simplified model in Fig. 2.

The model comprises an array of linear equations for each work phase or discipline identified (in this case 15) and is effectively reduced to an equivalent single algebraic relationship as depicted by Fig. 2. For the purposes of illustrating within this paper the relationships between average effective work scopes and project durations, the project duration remaining is obtained by dividing the effective corresponding project work scope by an equivalent project resource level (resource rate per unit time).

Reported progress in this model is identified as that progress achieved without consideration to an automatic adjustment for potential errors that would give rise to revisions, repairs, and rework. Reported project work scope is that which initially corresponds to the original project work scope, then is progressively amended to take account of adjustments and allowances for revisions, repairs, and rework as they arise. For the purposes of this model, these adjustments are made progressively in a linear manner, whereas under actual project conditions such adjustments are at best made intermittently as schedules and estimates are

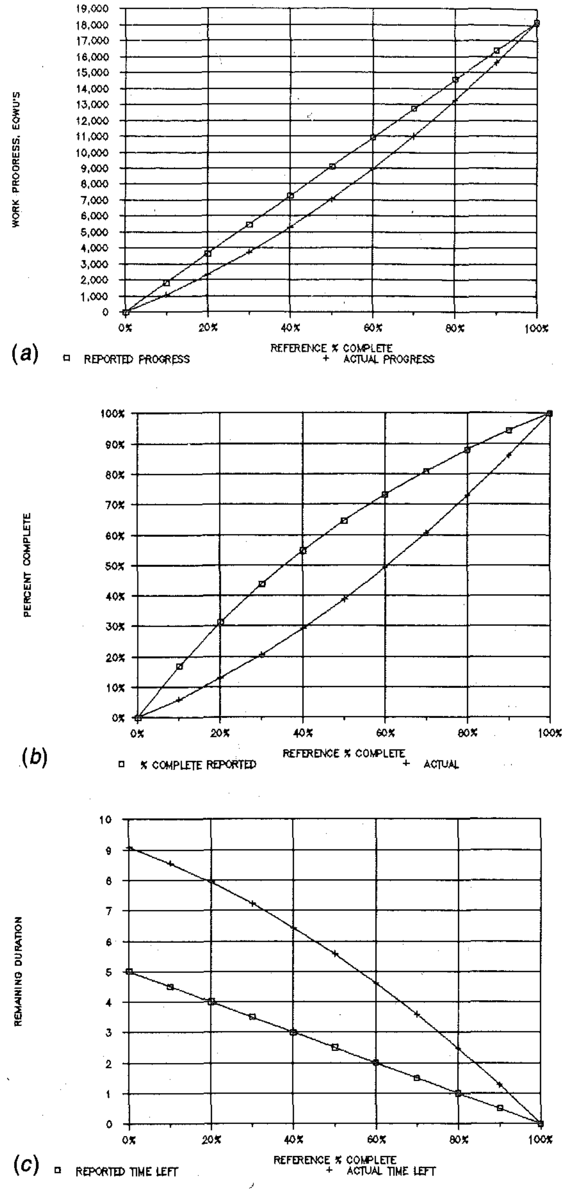

FIG. 5.—Estimated Average Conditions for *r*: (*a*) Work Progress, Reported and Actual, versus Reference Percent Complete; (*b*) Percent Complete, Reported and Actual, versus Reference Percent Complete; and (*c*) Remaining Duration, Reported and Actual, versus Reference Percent Complete

TABLE 4.—Revisions, Repairs, and Rework Coefficient 'r': Lower Estimate

Reference percent complete $p(ref)$ (1)	Reported Conditions: Work complete Wcr (2)	Work scope Wsr (3)	Work remaining $Wsr - Wcr$ (4)	Percent complete pr (5)	Project duration Dr (6)	Remaining duration Drr (7)	Actual Conditions: Work complete Wca (8)	Work scope Wsa (9)	Work remaining $Wsa - Wca$ (10)	Percent complete pa (11)	Project duration Da (12)	Remaining duration Dra (13)
0%	0	10,000	10,000	0.0%	5.00	5.00	0	16,000	16,000	0.0%	8.00	8.00
10%	1,600	10,600	9,000	15.1%	5.30	4.50	1,060	16,000	14,940	6.6%	8.00	7.47
20%	3,200	11,200	8,000	28.6%	5.60	4.00	2,240	16,000	13,760	14.0%	8.00	6.88
30%	4,800	11,800	7,000	40.7%	5.90	3.50	3,540	16,000	12,460	22.1%	8.00	6.23
40%	6,400	12,400	6,000	51.6%	6.20	3.00	4,960	16,000	11,040	31.0%	8.00	5.52
50%	8,000	13,000	5,000	61.5%	6.50	2.50	6,500	16,000	9,500	40.6%	8.00	4.75
60%	9,600	13,600	4,000	70.6%	6.80	2.00	8,160	16,000	7,840	51.0%	8.00	3.92
70%	11,200	14,200	3,000	78.9%	7.10	1.50	9,940	16,000	6,060	62.1%	8.00	3.03
80%	12,800	14,800	2,000	86.5%	7.40	1.00	11,840	16,000	4,160	74.0%	8.00	2.08
90%	14,400	15,400	1,000	93.5%	7.70	0.50	13,860	16,000	2,140	86.6%	8.00	1.07
100%	16,000	16,000	0	100.0%	8.00	0.00	16,000	16,000	0	100.0%	8.00	0.00

Note: Input values used (selected for illustration): Original work scope, Wso = 10,000; Equivalent resources, Re = 2,000. Calculated values: Revisions, repairs, and rework coefficient, r = 37.5%; Effective work scope, Wse = 16,000.

adjusted to reflect project conditions known to be at variance with actual conditions.

Actual progress conditions as depicted in this model immediately and fully take account of allowances for revisions, repairs, and rework, initially anticipating nominal values in lieu of actual historical data, then permitting marginal corrections for actual project conditions as a "track record" of trends arises.

The model is effective for a wide range of project conditions and can compute divergencies between reported and actual conditions in a consistent manner, from "perfect" conditions (zero divergence) to "failed project" conditions (approaching infinite divergence).

Example and Results

A brief explanation of examples and results follows, with reference to the appropriate tables and figures:

Table 1 and Fig. 3.—Values for revisions, repairs, and rework coefficients for individual work phases and disciplines as depicted in flow diagram model (Fig. 1) are provided as examples. These are input values selected here for illustration purposes only. Applications to actual project conditions could be based upon actual historical data and/or estimates or projections of anticipated conditions.

Table 2 and Figs. 4(a–c).—These are calculated values of reported and actual conditions progressively throughout the hypothetical project for a range of selected conditions nominally identified as the upper range limit of the expected rates for revisions, repairs, and rework. The reported and actual conditions are expressed in terms of the reference progress or percent complete parameter, $p(ref) = Wcr/Wse$, where Wcr is the work progress as reported and Wse is the effective work scope, both in consistent units.

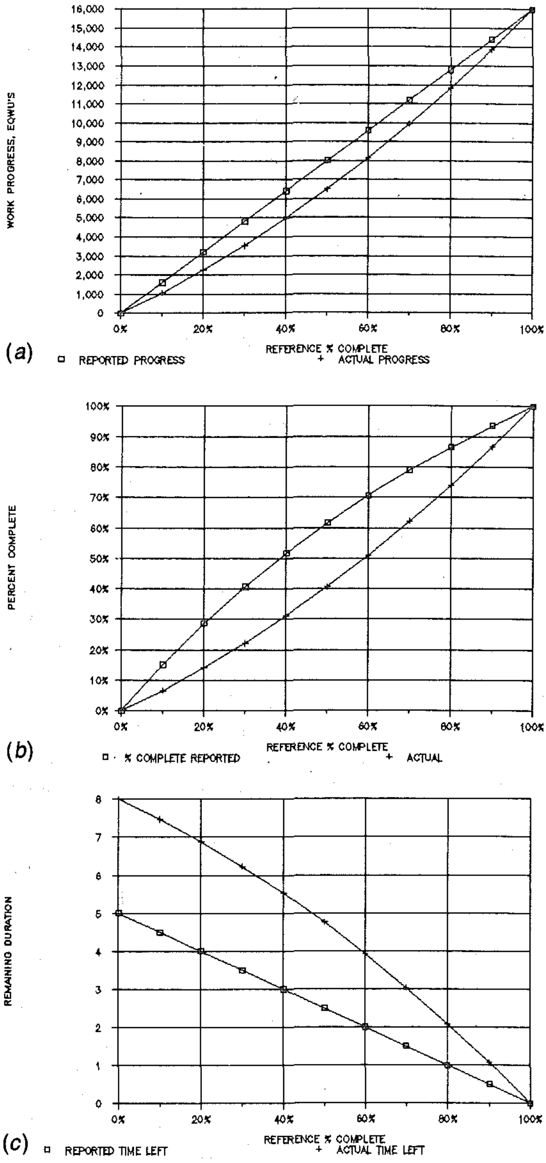

FIG. 6.—Estimate Lower Limit Conditions for r: (*a*) Work Progress, Reported and Actual, versus Reference Percent Complete; (*b*) Percent Complete, Reported and Actual, versus Reference Percent Complete; and (*c*) Remaining Duration, Reported and Actual, versus Reference Percent Complete

J. Constr. Eng. Manage., 1987, 113(3): 488-500

Table 3 and Figs. 5(*a–c*).—These are calculated values of reported and actual conditions progressively throughout the hypothetical project for a range of selected conditions nominally identified as the average range of the expected rates for revisions, repairs, and rework.

Table 4 and Figs. 6(*a–c*).—These are calculated values of reported and actual conditions progressively throughout the hypothetical project for a range of selected conditions nominally identified as the lower range limit of the expected rates for revisions, repairs, and rework.

Review and Conclusions

The conditions and results simulated here have been observed by the writers of this study on several very large projects, particularly commercial nuclear power-generating stations. These effects, when taken and examined on an individual, discipline-by-discipline basis, always appeared to yield results, which, on cursory examination, were inconsistent with the apparent overall project effects.

These results tended to produce the conclusion that the causes of serious project delays must lie in a place other than the function or discipline being examined. After all, how could an individual function or discipline experiencing such a small and seemingly reasonable "error" rate be causing an overall problem of such seemingly substantial proportions?

This result seemed to prevail from discipline to discipline, from function to function, and even from project to project, yet the overall condition of the projects was frequently found to be at wide variance with the individual or segmented findings.

Encountering these conditions repeatedly, the writers sought to examine alternative explanations, one being that the "yardsticks" for measuring large projects must be modified and cannot simply by viewed as a simple summation of individual yardsticks taken discipline by discipline, system by system, or component by component.

This study sought to provide such an integrated yardstick suitable for a large multidiscipline project. The results presented here suggest the effort was fruitful and certainly appear to explain the anomalies that arise between individual discipline and cumulative total project effects.

Principal conclusions summarized from the results are as follows.

1. The overall effects of revisions, repairs, and rework on large projects can be very significant, even when the individual effects of specific functions and disciplines appear small and within "normal" acceptable practices.
2. The interactive and cumulative effects of individual functions and disciplines significantly magnify the detrimental effect to the project as a whole.
3. Variations between actual progress and reported progress can be very substantial and highly significant. In the example illustrated in this study, actual work completed is seen to lag behind reported work completed [Fig. 5(*c*)], by almost 2,000 equivalent work units relative to 10,909 equivalent work units reported completed when the project is 60% completed on the reference scale of measurement as defined.

4. Reported progress in terms of percent complete relative to a suitable reference parameter tends to curve or "bend" optimistically higher than actual progress, which tends to bend lower than the same reference parameter. Again, using the example [Fig. 5(*c*)], at the 60% reference complete mark, the project is reported to be 73.2% complete when actual percent complete is assessed to be 49.2%, or a running difference in the region of 24% difference.

5. Actual project durations can be substantially longer than reported project durations, causing reporting problems and detrimental effects with respect to cash flow projections and project funding requirements. Again taking the illustration of Fig. 5(*c*), at the reference complete mark of 60%, the reported remaining duration is 2 time units while the actual projected time remaining is 4.62 time units or more than twice that reported.

6. Without recognition of these effects and without careful monitoring, measurements, or corrective adjustments, project resources can be seriously misapplied, affecting overall project efficiency and productivity very substantially, and thereby further impairing project progress.

7. The cumulative effects of these conditions can seriously impact effective project management and project control. In turn, these conditions can (and have) resulted in serious project disruptions, cancellations, and other effects that, in the case of the commercial nuclear industry, have included virtual cessation of the industry as a whole, at least in the domestic United States.

Practical Applications

The model and methods described in this paper have applications for large complex projects in a variety of areas, including the following:

1. A basis to develop a systematic technique to account for revisions, repairs, and rework in a consistent and effective manner throughout the duration of large projects.
2. A method to evaluate project status in progress that systematically accounts for revisions, repairs, and rework and can eliminate the large divergencies between reported and actual conditions requiring step changes or reductions in the completion percentage.
3. A basis to evaluate existing projects retrospectively in matters dealing with prudently incurred costs such as commercial nuclear projects presently undergoing prudency reviews.
4. A method to include, in future contracts for large projects, a basis for measuring the actual project status in progress and a method to account for the effects of revisions, repairs, and rework in progress.

Appendix.—Notation

The following symbols are used in this paper:

a = revisions, repairs, and rework factor, "minor" cycle;
b = revisions, repairs, and rework factor, "major" cycle;
D = project duration (Dr = Project duration remaining);

i = suffix, identifying the work phase or discipline;
pa = percent complete, actual;
pr = percent complete, reported;
Re = resource effort, applied average per unit time, equivalent resource units (EQRU);
r = revisions, repairs, and rework coefficient, effective;
Wca = work completed, actual, EQWU;
Wcr = work completed, reported, EQWU;
Wsa = work scope, actual, EQWU;
Wse = work scope, effective, EQWU;
Wsf = work scope, final, EQWU;
Wsi = work scope, individual discipline, i ($1 <= i <= 15$), EQWU;
Wso = work scope, original, equivalent work units (EQWU); and
Wsr = work scope, reported, EQWU.

J. Constr. Eng. Manage., 1987, 113(3): 488-500