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Developement of A Computer Program for Drop Time and Impact Velocity of the Rod Cluster Control Assembly

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제어봉집합체의 낙하시간과 충격속도 계산을 위한 프로그램 개발

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Abstract

In a PWR rod cluster control assembly(RCCA) for shutdown is released upon action of control rod drive mechanism and falls down through the guide thimble by its weight. Drop time and impact velocity of the RCCA are two key parameters with respect to reactivity insertion time and the mechanical integrity of fuel assembly. Therefore, the precise control of drop time and impact velocity is prerequisite to modifying the existing design features of the RCCA and guide thimble or newly designing them.

During its falling down into the core, the RCCA is retarded by various forces acting on it such as fluid resistance caused by the RCCA movement, buoyance and mechanical friction caused by contacting inner surface of the guide thimble, etc. However, complicated coupling of the various forces makes it difficult to derive an analytical dynamic equation for the drop time and impact velocity.

This paper deals with the development of a computer program containing an analytical dynamic equation applicable to the Korean Fuel Assembly(KOFA). The computer program is benchmarked with an available single control rod drop tests. Since the predicted values are in good agreement with the test results, the computer program developed in this paper can be employed to modify the exiting design features of the RCCA and guide thimble and to develope their new design features for advanced nuclear reactors.

요 약

원자로운전정지시 사용되는 제어봉집합체는 제어봉구동장치에서 분리되어 핵연료집합체의 안내관으로 자유낙하한다. 이 제어봉집합체의 주요변수로는 낙하시간과 충격속도가 있는데, 낙하시간은 원자로안전정지와 관계가 있으며, 충격속도는 핵연료집합체의 건전성과 관계가 있다. 따라서, 제어봉 낙하시간과 충격속도의 적절한 결정은 제어봉집합체와 핵연료집합체의 설계에 매우 중요하다.

제어봉집합체는 낙하도중 유체저항이나 마찰력 및 부력과 같은 여러 힘들에 의해 낙하시간이 감소하

게 되는데, 이러한 여러가지 힘의 복잡한 결합으로 인해 낙하시간과 충격속도를 해석적으로 유추하는 것은 매우 어렵다.

본 논문에서는 국산핵연료집합체에 적용되는 해석적인 방정식을 포함하고 있는 프로그램을 개발하였고, 이 프로그램을 단일제어봉 낙하시험과 비교하였다. 비교결과 시험 및 해석결과가 잘일치하고 있음으로써 개발된 프로그램의 검증을 확인할 수 있었고, 따라서 이 프로그램이 제어봉 및 안내관의 설계변경시 매우 유용하게 사용할 수 있게 되었다.

1. Introduction

Rod Cluster Control Assembly, which controls the power of reactor by means of control rod drive mechanism(CRDM), falls down into the guide thimble of a fuel assembly(FA) by its own weight to shutdown the reactor[1]. The final impact velocity of RCCA on the top of FA and droptime must be strictly controlled in view of reactor safe shutdown and mechanical integrity. For the safe shutdown point of view, it is desirable that the RCCA drop as fast as possible, which could results in high impact force on the FA that may deteriorate the mechanical integrity of FA. And for mechanical integrity point of view it is desirable that the RCCA drop as slow as possible, which is the relatively adverse effect with the drop time. Thus the drop time and the impact velocity should be compromised within a certain limit.

Very often the change of parameters which are affecting the drop time and impact velocity, such as the mass of CRDM, the material property of RCCA and geometry data of guide thimble in a FA, etc., might occur. In the past, full size testing was required to determine if the criteria of drop time and impact velocity was met in the case of parameter change[1][2][3]. Testing is necessary to verify the design, however, analysis permits optimization of the design. In most cases, design changes made as a result of anomalies uncovered by a test are costly and result in scheduling conflicts. These problem may have been avoided if an analytical method been available. In all probability, the analysis would have spotted the problem in the preliminary design stages, thus resulting in an integrated redesign and avoiding considerable time and expenses.

For the developement of the analytical method, when a RCCA falls down into a guide thimble of a FA, several forces such as fluid resistance force must be considered. Thus this paper deals with the modelling of drop of the RCCA and the program which predicts the drop time and impact velocity of it on the fuel assembly using non-linear differential equations. And the data herein used are quoted from 17x17 type KOFA because this type of fuel assembly is widely prevalent in Korea. For the verification of the developed computer program, the calculation results are compared with the test results which were performed at other fuel vendors. And the comparison results show that this program can be used for the prediction of rod drop time and impact velocity.

2. Equation for the Modelling of RCCA

When the control rod drops by its own weight, it is exerted various kinds of retarding forces which deter its drop velocity, consequently drop time will be increase. The weights of components of RCCA and CRDM act downward, the retarding forces act upward. Those forces are fluid resistance force, buoyance force and mechanicd friction between control rod and guide thinble. The basic model is shown in Fig. 1.

Among these forces, the fluid resistance force comprise pressure force and shear drog force on the control rod in the guide thimble.

Considering those resultant forces the equation of motion of control rod can be formulated as:

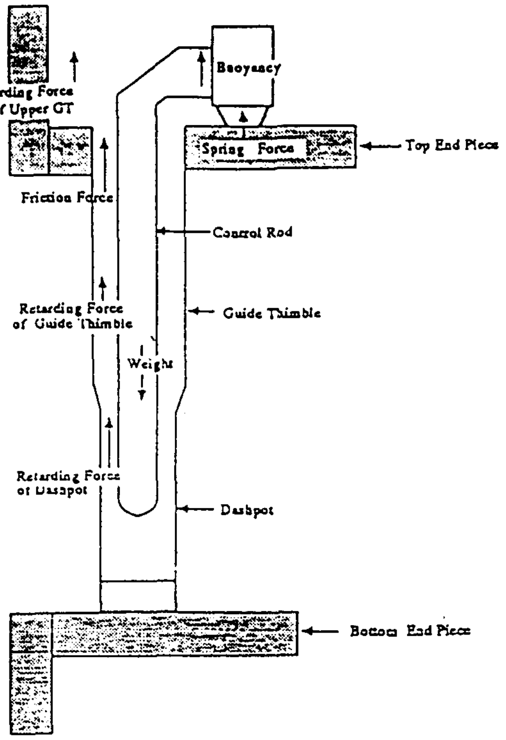

Fig. 1. Retarding Forces in Guide Thimble when Control Rod Drops

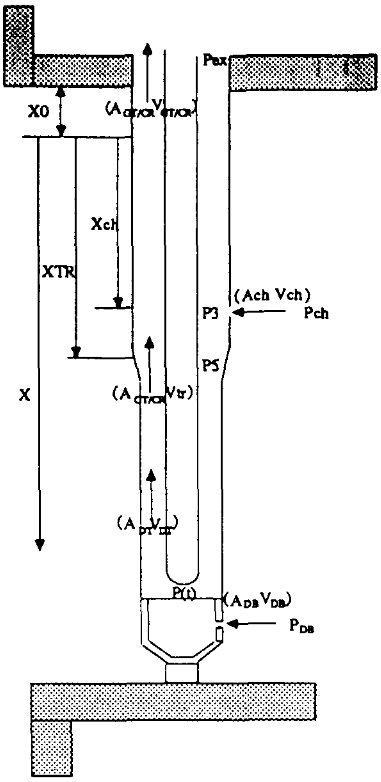

Fig. 2. Schemetic Diagram of Pressure and Flow Paths in Guide Thimble When Control Rod Drops

$$\sum F = M\ddot{X} = W - F_{BUOY} - F_{FRIC} - F_P - F_{SPRING} \qquad (1)$$

, where W : Weight of RCCA
F_{BUOY} : Buoyance of RCCA
F_{FRIC} : Mechanical friction force between control rod and guide thimble
F_P : Fluid resistance force
F_{SPRIG} : Force exerted by retainer spring after contact

2.1. Fluid Resistance Force in a Guide Thimble

When RCCA falls down into a guide thimble, the drop velocity of control rod is decreased due to the resistance of internal hydraulic pressure of guide thimble as shown in Fig. 2, and at that moment the coolant which is outside of guide thimble is applied the pressure on it simultaneously.

Therefore the fluid resistance force described in the equation (1) is obtained from the following simplified equation.

$$F_P = [P_A - P_B\} \times A_{EFF} \qquad (2)$$

, where F_P : Fluid resistance force
P_A : Internal pressure of the upper point between two arbitrary points in a guide thimble during control rod drop
P_B : Internal pressure of the lower point between two arbitrary points in a guide thimble during control rod drop
A_{EFF} : Cross-sectional area of the gap between the guide thimble and control rod considering shear drag force $= \pi(D_{CR} + D)^2/4$

D_{CR} , D : Control rod diameter, the gap between the guide thimble and control rod, respectively

For the calculation of internal pressure of guide thimble, guide thimble is considered as the divided three regions according to the geometry change: i. e the flow hole to the outlet of guide thimble, the dashpot transition region to the flow hole position and the control rod tip to the dashpot transition region.

The pressure difference between two points in a guide thimble is calculated by using of the pressure and continuity equations which are established by the Darcy-Weisbach equation[4] and Blausius formula [5]. Based on this approach the pressure differences in guide thimble are obtained as follows:

The pressure relation between the top of guide thimble to the flow hole is

$$P_3-P_{EX}=K_A\frac{\rho}{2}(V_{GT/CR}+\frac{dX}{dt})|V_{GT/CR}+\frac{dX}{dt}| \qquad (3)$$

, where K_A : Pressure loss coefficient

– In case of $X_o < X < X_{ch}$

$$K_A = \frac{0.316(X_o+X)}{D[\frac{\rho D}{\mu}\times|V_{GT/CR}+dX/dt|]^{1/4}} + K_{tep}$$

– In case of $X \geq X_{ch}$

$$K_A = \frac{0.316(X_o+X_{ch})}{D[\frac{\rho D}{\mu}|V_{GT/CR}+dx/dt|]^{1/4}} + K_{tep}$$

X_o : Top end piece lower surface (reference point: see Fig. 2)

X : Control rod tip position from X_o

X_{ch} : Flow hole position from X_o

X_{tr} : Dashpot transition region from X_o

D : Diametral gap between guide thimble and control rod

ρ : Coolant density

K_{tep} : Pressure loss coefficient due to cross-section change at the top of guide thimble

and for the dashpot transition region to the flow hole position

$$P_5-P_3=K_B\frac{\rho}{2}(V_{tr}+\frac{dX}{dt})|V_{tr}+\frac{dX}{dt}| \qquad (4)$$

, where K_B : Pressure loss coefficient

– In case of $X < X_{ch}$

$K_B = 0$

– In case of $X_{ch} < X < X_{tr}$

$$K_B = \frac{0.316(X-X_{ch})}{D[\frac{\rho D}{\mu}|V_{tr}+dX/dt|]^{1/4}}$$

– In case of $X > X_{tr}$

$$K_B = \frac{0.316(X_{tr}-X_{ch})}{D[\frac{\rho D}{\mu}|V_{tr}+dX/dt|]^{1/4}}$$

P_3 : Internal pressure at flow hole position in guide thimble

V_{tr} : Coolant flow velocity between the control rod and the dashpot transition region

for dashpot transition region to control rod tip;

$$P(t)-P_5=K_C\frac{\rho}{2}(V_{DT}+\frac{dX}{dt})|V_{DT}+\frac{dX}{dt}| \qquad (5)$$

, where K_c : Pressure loss coefficient

– In case of $X < X_{tr}$

$K_c = 0$

– In case of $X > X_{tr}$

$$K_c = \frac{0.316(X-X_{tr})}{D_2[\frac{\rho D_2}{X}|V_{DT}+dX/dt|]^{1/4}} + K_{exp}$$

K_{exp} : Pressure loss coefficient due to cross-section change in the dashpot transition region

V_{DT} : Coolant flow velocity between the control rod and the dashpot tube

D_2 : Diametral gap between dashpot tube and control rod

And the other equation is the continuity equation as:

$$\begin{aligned} A_{CR}\times dX/dt &= A_{DT}\times V_{DT}-A_{DB}\times V_{DB} \\ A_{DT}\times V_{DT} &= A_{GT/CR}\times V_{tr} \\ A_{GT/CR}\times V_{GT/CR} &= A_{ch}\times V_{ch}-A_{GT/CR}\times V_{tr} \end{aligned} \qquad (6)$$

, where A_{CR} : Cross-sectional area of control rod

A_{DT} : Cross-sectional area between dashpot tube and control rod

$A_{GT/CR}$: Cross-sectional area between guide thimble and control rod

A_{ch} : Cross-sectional area of flow hole

A_{DB} : Cross-sectional area of drain bore

V_{DB} : Flow velocity at drain bore

Additionally, because the pressure in a guide thimble is affected by the pressure distribution of FA through the drain hole, flow hole and top of guide thimble, the pressure distribution of FA, of which equation is established by aids of the modified Bernoulli's equation[6], should be considered.

2.2. Spring and Friction Forces

The spring force of RCCA spring retainer when RCCA falls down is obtained from the following equation.

$$F_{SPRING} = K_S \times X_L + F_{PRE} \qquad (7)$$

, where K_S : Stiffness of RCCA spring retainer

X_L : Deflection of the RCCA spring retainer

F_{PRE} : Spring preload of RCCA spring retainer

And it is assumed that the mechanical friction between guide thimble and control rod is negligible because of the water between control rod and guide thimble through whole length.

The equation of motion is to be solved in iterative manner due to its coupling of motion dependent parameters such as pressure and flow velocity in guide thimble. Thus it was solved separately in the region of guide thimble which is divided in accordance with the flow hole and dashpot position.

3. Solution of the Equation

The mathematical drop model is programmed in FORTRAN. In the cakuational procedure of the equation of motion it must be solved by numerically due to its non-linear coupling of the pressure force and flow velocity.

First of all, the flow velocity of flow hole is estimated using the predicted linear interpolation method[7], and then with this value the pressures and flow velocity in guide thimble is evaluated. Finally these values are used in the next solution of the equation of motion to calculate the drop distance and velocity of the control rod. The solution procedure is presented in Fig. 3.

4. Results and Discussions

As mentioned before, for the verification the analysis is performed on the 17x17 type KOFA. And for the comparison of the calculation results with the test results, the parametric single control rod test results,

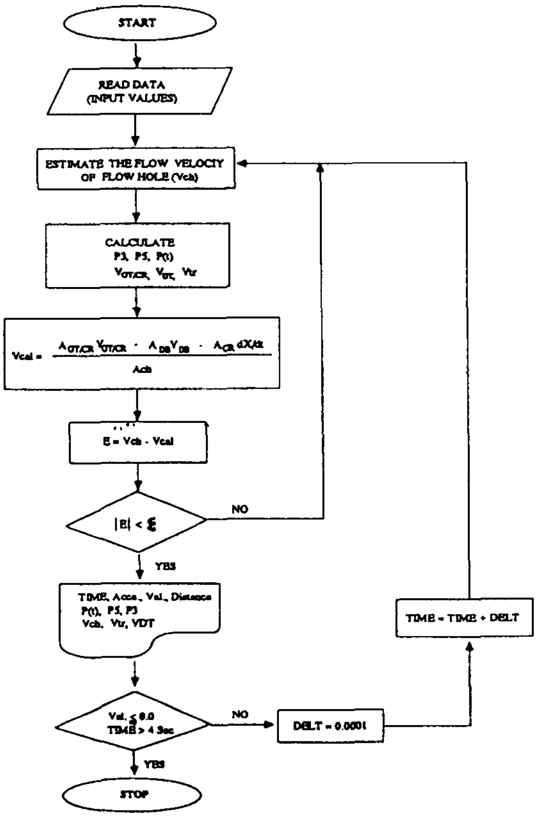

Fig. 3. The Flow Chart for Code Developement

which was performed at Siemens/KWU and of which test setup is shown in Fig. 4, are used.

Table 1 shows the comparison of the total drop time from this calculation with that of inspection report[8]. Fig. 5 shows the comparison of impact velocity with the test results, which was performed to determine the dashpot effects as a function of dashpot entry velocity of control rod.

This figure represents that the final impact velocity of control rod is sensitive to the gap between control rod and dashpot rather than entry velocity. It also shows that the predicted impact velocity agrees well with the test results. Fig. 6 shows the impact velocity as a function of dashpot length with various drain hole diameter, i. e., 1.0, 0.8, 0.0 mm. From this figure the calculation predicts well in coincidence with the test results as the dashpot length increases.

Fig. 7 shows the drop velocity of the control rod as a function of drop distance with the dimension of 17x17 type KOFA and Westinghouse 17x17 type Optimized Fuel Assembly(OFA). Fig. 8 shows internal pressure in the guide thimble as a function of drop distance.

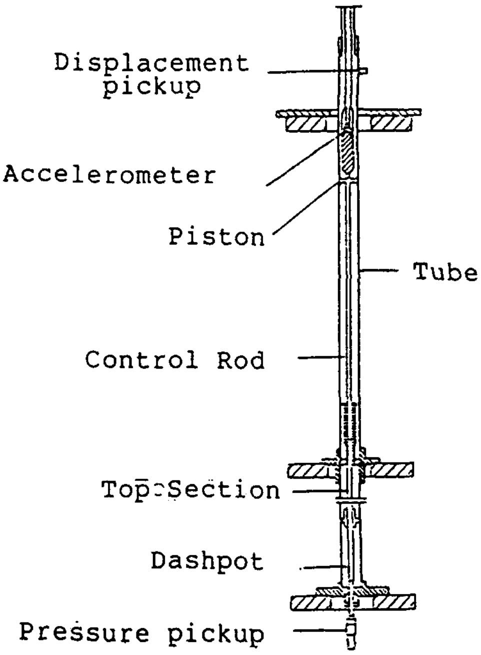

Fig. 4. The Schematic Diagram of Single Control Rod Test Setup

5. Conclusion

To predict the drop time and impact velocity of control rod during the RCCA scram, a program was developed based on the dynamic equation of motion and some fluid equation. The computer program is benchmarked with an available single control rod drop tests. Since the predicted values are in good agreement with the test results, the computer program developed in this paper has many varity applications. When the reactor size is changed, the program can be used to check the scram times. It can be also used as a design aid in determining how certain geometry changes will affect the drop time and can therefore optimized design. And further, it can be used to modify the exciting design features of the RCCA and guide thimble and to develope their new design features for advanced nuclear reactors.

Table 1. Comparison of Drop Time at Dashpot with Inspection Report[8]

	Inspection Report (R)		This Program (A)		Relative Deviation
	Hf/B_4C,	Ag/In/Cd	Hf/B_4C	Ag/In/Cd	(D) *
Time(sec)	1.65	1.49	1.74	1.60	0.05 – 0.07

*D = (R−A)/R

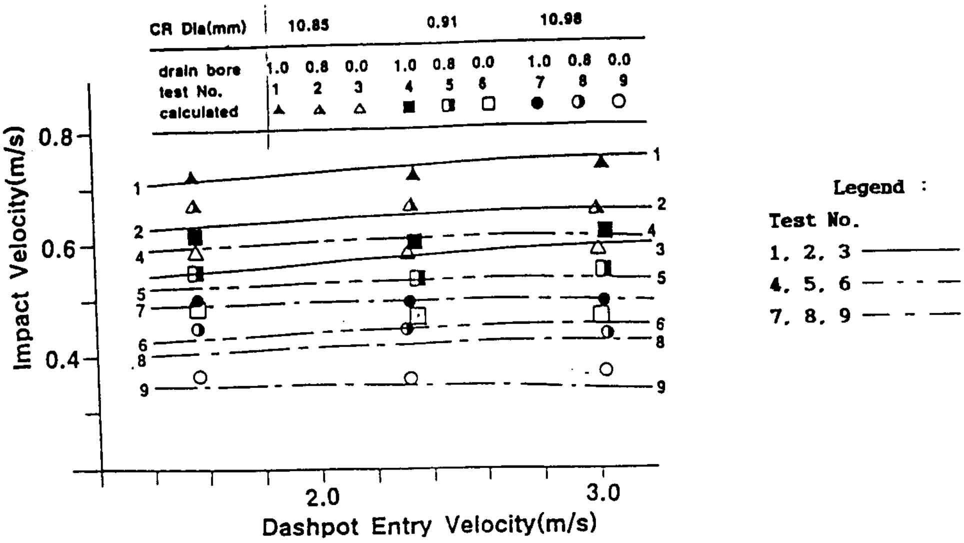

Fig. 5. Impact Velocity as a Function of the Dashpot Entry Velocity

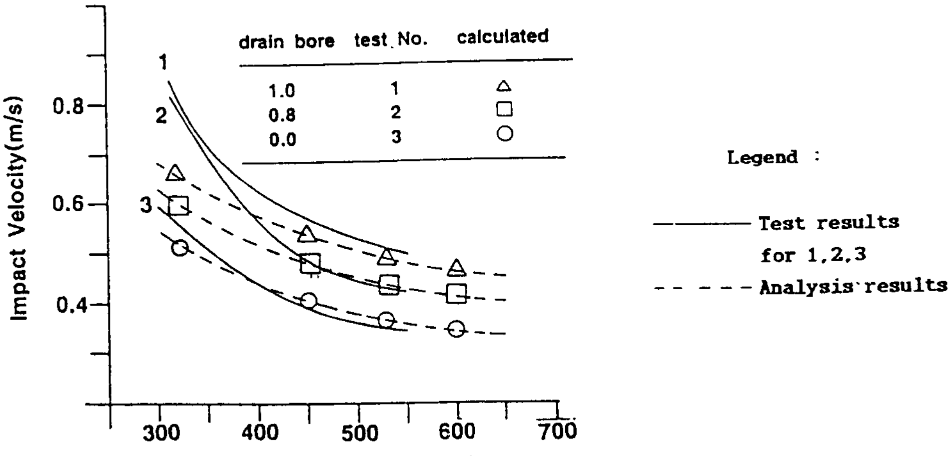

Fig. 6. The Impact Velocity as a function of the Dashpot Tube Length

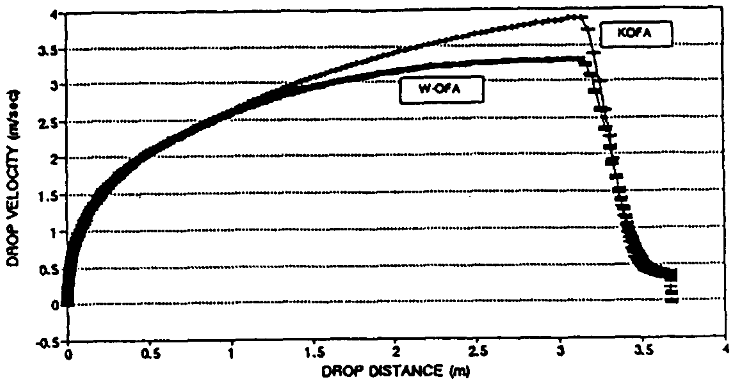

Fig. 7. The Drop Velocity as a Function of Drop Distance

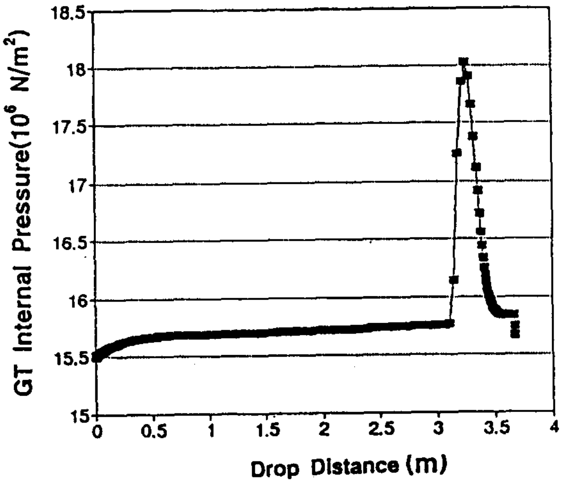

Fig. 8. The Internal Pressure in Guide Thimble as a Function of Drop Distance

References

1. "Westinghouse PWR System Manual", Vol. 1, IAEA
2. "Mechanical Design Report", Fragema, ITB/84/40 93. Rev. C, 1988
3. Kunz, Schiffer et al., "Fuel Assembly Mechanical Design Manual", Siemens/KWU, 1986
4. Robert D. Blevins, "Applied Fluid Dynamics Handbook", Van Nostrand Reinhok Company, 1986
5. L.E. Idel Chick, "Handbook of Hydraulic Resistance Coefficient of Local Resistance and Friction", 1966
6. 손병진, 유체역학 , 선중당, 1984
7. James, Smith, Wolford, "Applied Numerical Method for Digital Computation", Happer & Row Publisher Inc., 1985
8. KORI Nuclear Unit 3 Inspection Report, KINS/AR−011, Jan., 1990