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UNITED STATES
NUCLEAR REGULATORY COMMISSION
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MEMORANDUM TO: Richard J. Barrett, Chief
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FROM: Farouk Eltawila, Chief
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SUBJECT: EFFECT OF FISSION PRODUCT INVENTORY AND AIR INGRESSION ON SPENT FUEL POOL ACCIDENT CONSEQUENCES

As part of its generic study, undertaken to develop generic, risk-informed requirements for plants that are being decommissioned, the Office of Nuclear Reactor Regulation (NRR) requested the Office of Nuclear Regulatory Research (RES) to perform an evaluation of the offsite radiological consequences of spent fuel pool accidents involving sustained loss of cooling. The results of our evaluation are documented in *Assessment of Offsite Consequences for a Severe Spent Fuel Pool Accident*, SMSAB-99-02, November 1999. Our evaluation was based on a complete release of volatile isotopes (i.e., cesium and any remaining noble gases and iodine) from the number of fuel assemblies equivalent to 3.5 cores. As a follow up to this evaluation, we identified further opportunities to reduce uncertainty and potentially unnecessary conservatism (*Opportunities to Reduce Uncertainty in Consequence Assessment for Spent Fuel Pool Accidents*, memorandum from F. Eltawila to J. Hannon, December 10, 1999). In this memorandum, we stated that basing the consequence assessment on a release of the fission product inventory from 3.5 cores of fuel assemblies may be overly conservative, because, as a result of a year of radioactive decay, assemblies other than the final core may not reach temperatures high enough to release fission products.

We subsequently addressed ACRS issues on spent fuel accident analysis (*Issues Related to Spent Fuel Pool Accident Analysis*, memorandum from F. Eltawila to J. Hannon, January 19, 2000). In this memorandum, we concluded that significant air ingression, influencing fission product release, will occur in spent fuel pool accidents involving quick drain-down, and the consequence assessment we performed should accommodate any reasonable uncertainty in the progression of the accident with the possible exception of an increase in the ruthenium release. Small-scale Canadian experiments show that, in an air environment, significant ruthenium releases begin after the oxidation of 75% to 100% of the cladding.

To assess the effect of fission product inventory and ruthenium releases on spent fuel pool accident consequences, we performed supplemental sensitivity studies on spent fuel pool

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accident consequences using the MACCS code (MELCOR Accident Consequence Code System). Our assessment, which is attached, showed that for cases with early evacuation the overall effect of ruthenium releases on prompt fatalities is insignificant, because the number of prompt fatalities predicted remains less than 1. Early evacuation is modeled as beginning three hours before the fission product release. For cases with late evacuation (beginning after the fission product release), the effect on prompt fatalities is an increase of one to two orders of magnitude as a result of ruthenium's high radiological dose per curie inhaled relative to that of cesium which was previously the dominant fission product released. Specifically, the prompt fatalities increased from 9 to 134 and from 1 to 95 for a uniform population density and for the Surry population density, respectively. However, *Draft Final Technical Study on Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants*, February 2000, states that, after a year of decay, it will take at least 10 hours for the fuel with the highest decay power density to heat up to the point of releasing fission products in the fastest progressing accident scenarios. Therefore, an early evacuation is more likely, and an increase in the ruthenium release will not alter short term consequences.

We also assessed the effect of ruthenium releases on long-term consequences by calculating societal dose and cancer fatalities within 100 miles and within 500 miles. The effect of ruthenium releases on societal dose ranged from no increase to a factor-of-two increase. The effect on cancer fatalities ranged from no increase to a factor-of-four increase. Overall, the effect on long-term consequences is a modest increase.

With respect to limiting the fission product inventory available for release to that in the final reactor core (1 core versus 3.5 cores), we assessed offsite consequences for cases with late evacuation. Our assessment showed that for sequences involving boil-off or slow drain-down (i.e., no ruthenium release) prompt fatalities would be eliminated. Our assessment showed that for sequences involving rapid drain-down and air ingression (i.e., significant ruthenium release) prompt fatalities would only be reduced by up to 50%, because most of the inventory of the dominant fission product, ruthenium, is in the final core offload due to its 1 year half-life. Finally, regardless of whether a significant ruthenium release occurs, limiting the fission product inventory released to that in the final core offload reduced the long-term consequences by only a modest amount (20 to 40%).

Attachment: As stated

cc: G. Holahan

SMSAB-00-02

United States
Nuclear Regulatory Commission

Effect of Fission Product Inventory and Air Ingression on Spent Fuel Pool Accident Consequences

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March 2000

Effect of Fission Product Inventory and Air Ingression on Spent Fuel Pool Accident Consequences

Introduction

As part of its generic study, undertaken to develop generic, risk-informed requirements for plants that are being decommissioned, the Office of Nuclear Reactor Regulation (NRR) requested the Office of Nuclear Regulatory Research (RES) to perform an evaluation of the offsite radiological consequences of spent fuel pool accidents involving sustained loss of cooling. The results of our evaluation are documented in *Assessment of Offsite Consequences for a Severe Spent Fuel Pool Accident*, SMSAB-99-02, November 1999. Our evaluation was based on a complete release of volatile isotopes (i.e., cesium and any remaining noble gases and iodine) from the number of fuel assemblies equivalent to 3.5 cores. As a follow up to this evaluation, we identified further opportunities to reduce uncertainty and potentially unnecessary conservatism (*Opportunities to Reduce Uncertainty in Consequence Assessment for Spent Fuel Pool Accidents*, memorandum from F. Eltawila to J. Hannon, December 10, 1999). In this memorandum, we stated that basing the consequence assessment on a release of the fission product inventory from 3.5 cores of fuel assemblies may be overly conservative, because, as a result of a year of radioactive decay, assemblies other than the final core may not reach temperatures high enough to release fission products.

We subsequently addressed ACRS issues on spent fuel accident analysis (*Issues Related to Spent Fuel Pool Accident Analysis*, memorandum from F. Eltawila to J. Hannon, January 19, 2000). In this memorandum, we concluded that significant air ingression, influencing fission product release, will occur in spent fuel pool accidents involving quick drain-down, and the consequence assessment we performed should accommodate any reasonable uncertainty in the progression of the accident with the possible exception of an increase in the ruthenium release. Small-scale Canadian experiments show that, in an air environment, significant ruthenium releases begin after the oxidation of 75% to 100% of the cladding.

To assess the effect of fission product inventory and ruthenium releases on spent fuel pool accident consequences, we performed supplemental sensitivity studies on spent fuel pool accident consequences using the MACCS code (MELCOR Accident Consequence Code System).[1] The results of our assessment are given below.

Effect of Air Ingression

To assess the sensitivity of the consequences to air ingression, we performed consequence calculations with and without significant ruthenium releases. The starting point for this assessment was the Base Case calculation from *Assessment of Offsite Consequences for a Severe Spent Fuel Pool Accident*, November 1999. The Base Case calculation assumed that evacuation begins 1.4 hours after the fission product release begins. However, *Draft Final Technical Study on Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants*, February 2000, states that, after a year of decay, it will take at least 10 hours for the fuel with the highest decay power density to heat up to the point of releasing fission products in the fastest progressing accident scenarios. Therefore, it is more likely to have evacuation before the release begins. As a result of these considerations, the Base Case calculation then was modified to begin the evacuation 3 hours before the fission product release begins. This modified Base Case is called Case 13. The MACCS input decks for Case 13 are given in Appendix A. A total of eight cases were run varying the evacuation start time and the population density. The results for these eight cases are given in Table 1.

Table 1 Cases varying the evacuation start time and the population distribution

Case	Evacuation	Population Density*	Ruthenium release fraction	Distance	Prompt Fatalities	Societal Dose (Sv)	Cancer Fatalities
13	early	Surry	$2x10^{-5}$	0-100	.0048	41,800	1,990
				0-500	.0048	591,000	26,500
14	early	Surry	1	0-100	.132	67,500	6,300
				0-500	.132	597,000	31,000
15	early	uniform	$2x10^{-5}$	0-100	.045	46,500	2,170
				0-500	.045	473,000	21,300
16	early	uniform	1	0-100	.277	63,800	4,940
				0-500	.277	470,000	24,200
Base Case	late	Surry	$2x10^{-5}$	0-100	1.01	45,400	2,320
				0-500	1.01	595,000	26,800
11	late	Surry	1	0-100	95.3	95,300	9,150
				0-500	95.3	624,000	33,900
21	late	uniform	$2x10^{-5}$	0-100	9.33	50,500	2,490
				0-500	9.33	477,000	21,600
22	late	uniform	1	0-100	134	94,600	6,490
				0-500	134	501,000	25,700

*The uniform population density site has a population density of 100 people/mi^2 with an Exclusion Area Boundary of .75 miles.

For the cases with early evacuation (Cases 13-16), the effect of ruthenium on prompt fatalities is insignificant, because the number of prompt fatalities predicted remains less than 1. Also, the effect on societal dose and cancer fatalities is a modest increase, with the largest effect being a factor-of-three increase in cancer fatalities within 100 miles.

For the cases with late evacuation (Base Case, Cases 11, 21, 22), the effect of ruthenium is to increase the number of prompt fatalities by one to two orders of magnitude. However, as discussed above, late evacuation is less likely than early evacuation. Also, for the cases with late evacuation, the effect of ruthenium on societal dose and cancer fatalities is about the same as for the cases with early evacuation.

The total number of prompt fatalities is calculated in MACCS by multiplying, in each sector, the individual risk of a prompt fatality by the total number of people in that sector. For the cases with late evacuation, Table 2 gives the MACCS results for the individual risk of a prompt fatality in each radial ring which is composed of 16 sectors. The individual risk of a prompt fatality is a function of the dose to an individual and is independent of the population density. For the cases with late evacuation in Table 1, the total number of prompt fatalities increases by a larger factor for Surry than for the uniform population density when a significant ruthenium release is included. This is caused by Surry's non-uniform population density which also is shown in Table 2. Table 3, which is the result of multiplying the individual risk of a prompt fatality in each ring by the population in each ring, demonstrates that Surry's higher increase in prompt fatalities is caused by the jump in the Surry population density at 8.1 km.

Table 2 Individual Risk of a Prompt Fatality for Cases with Late Evacuation

Distance (km)	Individual risk of a prompt fatality		Ratio	Surry population density* (persons/ km^2)
	Base Case and Case 21, Ru release fraction of $2x10^{-5}$	Cases 11 and 22, Ru release fraction of 1		
0 - .2	.146	.169	1.16	0
.2 - .5	.0302	.0657	2.18	0
.5 - 1.2	.0138	.0374	2.71	1.33
1.2 - 1.6	.00828	.0301	3.64	1.13
1.6 - 2.1	.00575	.0266	4.63	1.80
2.1 - 3.2	.00326	.0216	6.63	1.58
3.2 - 4.0	.00151	.0146	9.67	7.15
4.0 - 4.8	.00167	.0132	7.90	7.77
4.8 - 5.6	.00171	.0110	6.43	7.84
5.6 - 8.1	.0000672	.0131	194.94	8.07
8.1 - 11.3	.000000254	.00301	11850.39	117.80
11.3 - 16.1	0	.0000225	NA	118.36
16.1 - 20.9	0	)	NA	83.75

*This data is from the MACCS input file SURSIT.INP.

Table 3 Number of Prompt Fatalities in Each Radial Ring for Cases with Late Evacuation

Distance (km)	Number of early fatalities with Surry population density		Number of early fatalities with uniform population density	
	Base Case, Ru release fraction of $2x10^{-5}$	Case 11, Ru release fraction of 1	Case 21, Ru release fraction of $2x10^{-5}$	Case 22, Ru release fraction of 1
0 - .2	0	0	0	0
.2 - .5	0	0	0	0
.5 - 1.2	.0690	.1870	0	0
1.2 - 1.6	.0331	.1204	1.1329	4.1184
1.6 - 2.1	.0633	.2926	1.3564	6.2750
2.1 - 3.2	.0945	.6264	2.3060	15.2788
3.2 - 4.0	..1963	1.8980	1.0609	10.2574
4.0 - 4.8	.2923	2.3100	1.4521	11.4777
4.8 - 5.6	.3523	2.2660	1.7357	11.1653
5.6 - 8.1	.0564	10.9909	.2699	52.6050
8.1 - 11.3	.0058	69.2661	.0019	22.7135
11.3 - 16.1	0	1.1027	0	.3599
16.1 - 20.9	0	0	0	0
Total	1.16	89.06	9.32	134.25

To determine the isotope responsible for the increase in prompt fatalities when a significant ruthenium release is included in the consequence calculations, sensitivity cases were run varying the amount of each isotope in the ruthenium group. The isotopes in the ruthenium group remaining after a year of radioactive decay are Co-58, Co-60, Ru-103, and Ru-106. These cases were run starting with a case for which a significant number of early fatalities was predicted (Base Case). The results of these calculations are shown in Table 4. These results indicate that the isotope responsible for the increase in prompt fatalities is Ru-106.

Table 4 Cases varying the inventories of the isotopes in the ruthenium group

Case	Description of Case	Distance	Prompt Fatalities	Societal Dose (Sv)	Cancer Fatalities
Base Case	Ru release fraction of $2x10^{-5}$	0-100	1.01	45,400	2,320
		0-500	1.01	595,000	26,800
11	Ru release fraction of 1	0-100	95.3	95,300	9,150
		0-500	95.3	624,000	33,900
11a	Ru release fraction of 1 No Co isotopes	0-100	94.4	95,100	9,120
		0-500	94.4	627,000	34,000
11b	Ru release fraction of 1 No Co isotopes Only Ru-106	0-100	94.3	95,100	9,120
		0-500	94.3	627,000	34,000
11c	Ru release fraction of 1 No Co isotopes Only Ru-103	0-100	1.02	45,400	2,320
		0-500	1.02	595,000	26,800

Table 2 shows that the individual risk of a prompt fatality generally increases by more than a factor of 2 when ruthenium is included in the consequence calculation. However, the amounts (Bq) of the dominant cesium isotope (Cs-137) and the dominant ruthenium isotope (Ru-106) are about the same in a spent fuel pool at one year after final shutdown. A comparison of the dose conversion factors for Cs-137 and Ru-106 is given in Table 5. These dose conversion factors were taken from the MACCS input file DOSDATA.INP. An examination of these dose conversion factors indicates that the large Ru-106 inhalation dose conversion factor in MACCS used to calculate acute doses is partly responsible for the increase in individual risk of a prompt fatality beyond what would be expected as a result of the additional amount of Ru-106.

Table 5 Dose conversion factors for Ru-106 and Cs-137

	organ	cloud-shine (Sv sec/ Bq m^3)	ground-shine (Sv sec/ Bq m^2)	inhalation/ acute (Sv/Bq)	inhalation/ chronic (Sv/Bq)	ingestion (Sv/Bq)
Ru-106	lungs	7.99E-15	1.58E-16	2.09E-08	1.04E-06	1.48E-09
	red marrow	8.05E-15	1.61E-16	8.74E-11	1.77E-09	1.48E-09
Cs-137	lungs	2.88E-14	4.35E-16	8.29E-10	8.80E-09	1.27E-08
	red marrow	2.22E-14	4.41E-16	5.63E-10	8.30E-09	1.32E-08
Ratio of Ru-106 to Cs-137	lungs	.4	.4	25	118	.1
	red marrow	.4	.4	.2	.2	.1

Effect of Fission Product Inventory

To assess the sensitivity of the consequences to the fission product inventory released, we performed consequence calculations with 3.5 cores releasing fission products and 1 core releasing fission products. These calculations were run starting with cases for which a significant number of early fatalities was predicted (Base Case, Case 21). The inventories for the cases with 1 core releasing fission products were based on Table A.5 of NUREG/CR-4982. Table A.5 gives inventories in the reactor core at the beginning of refueling outage 11. The inventories used in the MACCS calculations for 1 core are the Table A.5 inventories reduced by one year of radioactive decay. The results of the MACCS calculations are given in Table 6. The inventories used in these calculations are shown in Appendix B.

Table 6 Cases varying the amount of fuel assemblies releasing fission products

Case	Evacuation	Population Density	Ruthenium Release Fraction	# of cores	Distance	Prompt Fatalities	Societal Dose (Sv)	Cancer Fatalities
Base Case	late	Surry	2×10^{-5}	3.5	0-100	1.01	45,400	2,320
					0-500	1.01	595,000	26,800
31	late	Surry	2×10^{-5}	1	0-100	.014	32,300	1,530
					0-500	.014	354,000	15,900
11	late	Surry	1	3.5	0-100	95.3	95,300	9,150
					0-500	95.3	624,000	33,900
32	late	Surry	1	1	0-100	50.5	72,500	7,360
					0-500	50.5	376,000	21,900
21	late	uniform	2×10^{-5}	3.5	0-100	9.33	50,500	2,490
					0-500	9.33	477,000	21,600
33	late	uniform	2×10^{-5}	1	0-100	.177	31,000	1,480
					0-500	.177	276,000	12,500
22	late	uniform	1	3.5	0-100	134	94,600	6,490
					0-500	134	501,000	25,700
34	late	uniform	1	1	0-100	103	65,900	4,960
					0-500	103	303,000	16,500

For the cases without a significant ruthenium release, the reduction in prompt fatalities is caused by the reduction in the Cs-137 inventory which decreases from 8.38E17 Bq to 2.11E17 Bq in going from 3.5 cores to 1 core. This was confirmed by repeating Case 33 with a Cs-137 inventory of 8.38E17 Bq. The reductions in prompt fatalities for uniform and Surry population densities are factors of 52 and 72, respectively. These reductions are more than proportional to the factor of 4 reduction in Cs-137 inventory, because of the combined effects of individual risk of early fatality and non-uniform population density as discussed in the above analysis of the effect of air ingression on offsite consequences.

For the cases with a significant ruthenium release, the reduction in prompt fatalities is caused by the reduction in the Ru-106 inventory which decreases from 5.77E17 Bq to 4.59E17 Bq in going from 3.5 cores to 1 core. This was confirmed by repeating Case 34 with a Ru-106 inventory of 5.77E17 Bq. The reductions in prompt fatalities for uniform and Surry population densities are factors of 1.30 and 1.89, respectively. These reductions are nearly proportional to the factor of 1.26 reduction in the Ru-106 inventory. Again, deviations from being proportional are due to the combined effects of individual risk of early fatality and non-uniform population density. Overall, the effect of reducing the number of assemblies on prompt fatalities is less pronounced for the cases with a significant ruthenium release, in part, because the additional 2.5 cores has a small amount of Ru-106 (1 year half-life) in comparison with Cs-137 (30 year half-life). Finally, in all of the cases, the effect of reducing the amount of fuel releasing fission products from 3.5 cores to 1 core is a modest decrease (20 to 40%) in societal dose and latent cancer fatalities.

Conclusion

The objective of this assessment was to determine the effect of fission product inventory and ruthenium release on spent fuel pool accident consequences at a decommissioned reactor. This assessment was performed in support of the NRC's generic evaluation of spent fuel pool risk that is being performed to support related risk-informed requirements for decommissioned reactors. This assessment supplements the earlier assessement of consequences in *Assessment of Offsite Consequences for a Severe Spent Fuel Pool Accident*, SMSAB-99-02, November 1999.

To assess the effect of fission product inventory and ruthenium releases on spent fuel pool accident consequences, we performed supplemental sensitivity studies on spent fuel pool accident consequences using the MACCS code. Our assessment showed that for cases with early evacuation the overall effect of ruthenium releases on prompt fatalities is insignificant, because the number of prompt fatalities predicted remains less than 1. Early evacuation is modeled as beginning three hours before the fission product release. For cases with late evacuation (beginning after the fission product release), the effect on prompt fatalities is an increase of one to two orders of magnitude as a result of ruthenium's high radiological dose per curie inhaled relative to that of cesium which was previously the dominant fission product released. Specifically, the prompt fatalities increased from 9 to 134 and from 1 to 95 for a uniform population density and for the Surry population density, respectively. However, *Draft Final Technical Study on Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants*, February 2000, states that, after a year of decay, it will take at least 10 hours for the fuel with the highest decay power density to heat up to the point of releasing fission products in the fastest progressing accident scenarios. Therefore, an early evacuation is more likely, and an increase in the ruthenium release will not alter short term consequences.

We also assessed the effect of ruthenium releases on long-term consequences by calculating societal dose and cancer fatalities within 100 miles and within 500 miles. The effect of ruthenium releases on societal dose ranged from no increase to a factor-of-two increase. The effect on cancer fatalities ranged from no increase to a factor-of-four increase. Overall, the effect on long-term consequences is a modest increase.

With respect to limiting the fission product inventory available for release to that in the final reactor core (1 core versus 3.5 cores), we assessed offsite consequences for cases with late evacuation. Our assessment showed that for sequences involving boil-off or slow drain-down (i.e., no ruthenium release) prompt fatalities would be eliminated. Our assessment showed that for sequences involving rapid drain-down and air ingression (i.e., significant ruthenium release) prompt fatalities would only be reduced by up to 50%, because most of the inventory of the dominant fission product, ruthenium, is in the final core offload due to its 1 year half-life. Finally, regardless of whether a significant ruthenium release occurs, limiting the fission product inventory released to that in the final core offload reduced the long-term consequences by only a modest amount (20 to 40%).

Reference

1. *Code Manual for MACCS2*, NUREG/CR-6613, May 1998

Appendix A

MACCS Input Files

This appendix contains the MACCS2 input files for Case 13. MACCS2 uses a total of five input files for each run. The first file (ATMOS.INP) contains the source term and atmospheric dispersion input. The second file (EARLY.INP) contains the input for emergency response and variables that are affected during the first week of the accident. The third file (CHRONC.INP) contains the input for variables that are affected after the first week of the accident. The fourth file (METSUR.INP) gives the meteorological data. For brevity, only the beginning and end of the METSUR.INP file are shown in this appendix. Finally, the fifth file (SURSIT.INP) gives the siting information, such as offsite population in each sector. (Note: SURSIT.INP is not used for Case 13.)

Appendix B

Radionuclide Inventories in 3.5 Cores and 1 Core (Final Reactor Core)

Radionuclide	Half-Life	Inventory at 1 Year after Final Shutdown(Bq)	
		3.5 cores	1 core
Co-58	70.9d	9.17E13	9.20E13
Co-60	5.3y	1.34E16	5.32E15
Kr-85	10.8y	5.94E16	1.86E16
Rb-86	18.7d	2.98E09	3.07E09
Sr-89	50.5d	1.16E16	1.16E16
Sr-90	28.8y	5.98E17	1.54E17
Y-90	28.8y	6.02E17	1.58E17
Y-91	58.5d	2.96E16	2.97E16
Zr-95	64.0d	6.16E16	6.18E16
Nb-95	64.0d	7.95E16	6.33E16
Ru-103	37.3d	3.42E15	3.04E15
Ru-106	1.0y	5.77E17	4.59E17
Te-127	109d	2.39E15	2.40E15
Te-127m	109d	2.43E15	2.40E15
Te-129	33.6d	4.45E13	4.46E13
Te-129m	33.6d	4.43E13	4.46E13
I-131	8.0d	2.13E04	3.25E04
Cs-134	2.1y	2.80E17	1.62E17
Cs-136	13.2d	3.40E08	3.70E08
Cs-137	30.0y	8.38E17	2.[illegible]1E17
Ba-140	12.8d	7.92E09	8.09E09
La-140	12.8d	8.06E09	8.27E09
Ce-141	32.5d	1.22E15	1.22E15

Radionuclide	Half-Life	Inventory at 1 Year after Final Shutdown(Ci)	
		3.5 cores	1 core
Ce-144	284.6d	1.04E18	9.20E17
Pr-143	13.6d	2.21E10	2.28E10
Nd-147	11.0d	1.22E08	1.21E08
Np-239	2.4d	1.07E14	0.00E00
Pu-238	87.7y	1.78E16	3.42E15
Pu-239	24100y	3.87E15	9.21E14
Pu-240	6560y	5.40E15	1.16E15
Pu-241	14.4y	9.32E17	2.54E17
Am-241	432.7y	1.20E16	3.27E14
Cm-242	162.8d	1.77E16	1.64E16
Cm-244	18.1y	8.40E15	2.39E15