The 14 July 2015 Iran Agreement:
Joint Comprehensive Plan of Action-- JCPoA

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The Iran Agreement—the JCPoA

On July 14, 2015, Iran and the EU+3 (France, Germany, UK, China, USA, Russia) reached a historic agreement on limiting Iran's activities in the field of nuclear energy to those that are entirely and transparently civil. This is the JCPoA (for Joint Comprehensive Plan of Action) colloquially known as the Iran Deal[2]. It is *not* primarily a USA-Iran Agreement.

Many, including myself, have been concerned that Iran would acquire nuclear weapons, and Iran, on the other hand, has been suffering under sanctions imposed by the United Nations, the United States, and other countries, primarily as a response to its activities in the nuclear area.

Iran has always maintained that its activities have been peaceful and oriented toward nuclear power for its grid, as exemplified by the reactor at Bushehr, built initially by Germany and completed and put into operation by Russia. Indeed, during the 1970s Iran under the Shah was seeking a full-scope nuclear power program, including 20

[2] Announced at a joint press conference by Federica Mogherini and Iranian Foreign Minister Javad Zarif, http://eeas.europa.eu/statements-eeas/2015/150714_01_en.htm (Also posts the JCPoA and six annexes. The total is 159 pages, of which 62 are a list of people, entities, aircraft and ships related to sanctions.

light-water power reactors, enrichment, and reprocessing[3]. The argument was that oil would not last forever and that Iran should use nuclear power-- electrical energy from uranium-- in order to spare its oil reserves for higher-value uses. Such a nuclear program was encouraged under the 1970 NPT, subject to safeguards implemented by the IAEA, but the U.S. administrations of Presidents Gerald Ford and Jimmy Carter attempted to impose further restrictions on Iran beyond the NPT, perhaps because in 1974 "… the Shah told *Le Monde* that one day 'sooner than is believed,' Iran would be 'in possession of a nuclear bomb.' "[4]

Iran's nuclear program was put on hold for at least two reasons. First came the revolution in 1979, after which the United States was not interested in having Iran acquire nuclear capabilities. Furthermore, the economics of nuclear power were such that it could not compete against oil or gas production of electrical energy, especially in a resource-rich country such as Iran. Of course, if the cost of fossil fuel includes preventing industrial CO_2 from entering the atmosphere, nuclear power is advantaged economically.

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[3] http://media.snn.ir/Original/archive/21-2-1393%5CFILE635354886585732024.pdf *TACKLING THE IRAN-U.S. CRISIS: THE NEED EOR A PARADIGM SHIFT*, by Mohammad Javad Zarif, Columbia University *Journal of International Affairs*, Spring/Summer 2007, vol. 60, no. 2.
[4] http://foreignpolicy.com/2010/12/29/the-shahs-atomic-dreams/

Iran joined the NPT in 1970, and was thus required to inform the IAEA of its activities in the nuclear power sector. It did not so fully inform, and although Iran has always maintained that its work with uranium, including enrichment of uranium was acceptable under the NPT for a non-nuclear weapon state, sanctions were imposed, as least in part for this failure to comply with the NPT.

In addition, Iran until 2003 explored the development and fabrication of nuclear weapons—the “possible military dimensions” (PMD) that figured prominently in the negotiations. Much of that is now ancient history, still heatedly disputed by many on either side.

Under the political leadership of Hassan Rouhani, who took office in August 2013, and his Foreign Minister Javad Zarif, diplomats and scientists and engineers from Iran negotiated over the last several years for an agreement that would remove the sanctions that have been burdening Iran's commercial and industrial sector, and that would allow movement toward the indigenous supply of nuclear power within Iran.

Although electrical energy from fission need not convey a capability to build nuclear weapons, it has in many cases been used to provide such a latent capability. A non-proliferant nuclear-power sector would also very likely be the most economical way to obtain nuclear energy-- the use of light-water reactors either designed and built indigenously or bought under contract from abroad, with fuel enriched and fabricated abroad, which fuel would be shipped out of the using country after its typical four-year life in the reactor, plus a few years for "cooling" to reduce the fierce radioactivity and "decay heat" of the spent fuel.

The Iran Deal verifiably closes the two routes to obtaining weapon-usable fissile material-- that of enriching uranium from the natural 0.71% U-235 concentration to the 80+% that would be useful for a nuclear explosive, and the acquisition of Pu-239 as a result of neutron capture on the abundant U-238 in a nuclear reactor.

Specifically, the plutonium route, which implies nuclear weapons only of the implosion type, and in which high explosive is used to assemble a sub-critical mass of plutonium metal into a more compact configuration so that it can explode, is blocked by Iran's commitment not to reprocess any fuel, to ship out of the country the spent power-reactor fuel from Bushehr that is supplied by Russia, and to completely reconfigure the planned heavy-water reactor at Arak that had been designed by Iran to use natural-uranium fuel, which is a copious producer of Pu-239. As initially designed, the 40-MWth Arak reactor was to be very similar to the Israeli reactor at Dimona that over the years secretly produced fuel for Israel's nuclear weapons. At its nominal 40 MW of fission power, Arak would have produced 40 grams of Pu-239 per day—a “significant quantity” (SQ) of 8kg of Pu in 200 days; enough for more than two Nagasaki-type bombs per year.

Instead, Iran's nuclear specialists worked closely with the technologists of the negotiating partners, agreeing to remove the interior structure of the initial Arak design, fill that structure with concrete, replace it with a core of low-enriched uranium (<3.67% U-235), and limit the reactor power to 20MWth . Iran agreed not to reprocess the fuel or to have a capability to do so, and to send the spent fuel out of the country. The only chemical separation activity to be undertaken at Arak will be that to obtain isotopes of medical and industrial importance from the low-enriched uranium "targets" that will be irradiated eventually in the newly designed Arak reactor. In addition, the JCPoA bars Iran from working on metallic uranium or plutonium-- an important limitation.

On this particular question an interesting sidelight is provided in the SCIENCE Magazine interview[5] with Ali Akbar Salehi, president of the Atomic Energy Organization of Iran (AEOI) and the chief technical negotiator in the last months before agreement on 14 July 2015.

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[5] http://news.sciencemag.org/people-events/2015/08/exclusive-iran-s-atomic-czar-explains-how-he-helped-seal-iran-nuclear?rss=1

Salehi: *"We said that if we need some depleted uranium, we may ask for it from [the P5+1] during this period. This is an implicit understanding. But we will not produce the metal. We did reprocessing, and produced plutonium. And we told the IAEA, that's it. That was in 2003."*

Uranium enrichment for nuclear energy has a long history, beginning with that performed on a massive scale at Oak Ridge, Tennessee, to produce the highly enriched uranium (HEU) for the gun-assembled weapon that destroyed Hiroshima. Although the gaseous diffusion process was used for most of the "separative work" required, the "electromagnetic process" (Calutrons) was used for the final step of enrichment to HEU of >80% U-235.

As an economic matter, both approaches have been largely replaced by the gas centrifuge, which in its modern, efficient design goes by the name of [Gernot] Zippe in the West and [Evgeni] Kamenev-centrifuge in Russia. Whatever the name, the gas centrifuge since the early 1960s is a marvel of invention and industrial design with its self-pumping vacuum, large open hole in the upper end cap of the rotor, and internal gas circulation that increases the separation factor in a centrifuge operating at a peripheral speed of 400 m/s from 1.02 to 1.12 or more. Note that the pressure of the UF6 gas in the rapidly rotating rotor is maximum at the wall and drops off rapidly within millimeters of the wall (the "law of atmospheres" but with Earth's gravity *g* replaced by v^2/R which is typically 200,000 *g)*. The UF6 pressure at the wall is typically estimated as 100 torr and in the interconnections between centrifuges about 4 torr[6], allowing centrifuges to be connected to one another without pumping the UF6 gas.

Centrifuges are connected in a *cascade*, and Iran, following designs promulgated by A.Q. Khan of Pakistan who stole them from the European enrichment center, Urenco[7], has used a cascade of modules of 164 identical machines—the IR-1. In the early 2000s, concern was raised about Iran's pursuit of enrichment, and difficult discussions begun. Part of the difficulty was that the United States had no diplomatic relations with Iran.

The concern that Iran might develop and stockpile nuclear weapons led to several informal discussions at the time. Iran wished to develop the capability to enrich uranium, nominally to supply fuel for the incomplete power reactor that had been built at Bushehr by Germany, and also for the Tehran Research Reactor that used 19.75%

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[6] **inmm**vienna.org/Presentations/**INMM12_Smith**_GCEP_concepts.pptx (slide 5 shows "*P*~ 4 torr" for the gas centrifuge headers)

[7] http://www.nytimes.com/2006/04/16/world/asia/16chron-khan.html?_r=3& for a timeline of A.Q. Khan's activities.

U-235-- still, technically, low-enriched uranium (LEU);. Highly enriched uranium (HEU) is defined as U-235 content of 20% or above.

Then-President Ahmadinejad inspecting Iran’s IR-1 centrifuges

It is often thought that producing enriched uranium for nuclear weapons is, somehow, a bigger task than producing fuel for a power reactor. In fact, quite the opposite is true. An enrichment facility to supply fuel for the single power reactor at Bushehr, reconfigured, could produce HEU for a nuclear weapon every two weeks.

Ignoring the enrichment required for the initial fuel load of a reactor producing almost 1000 megawatt electric (MWe), just supplying the annual reload of about 25 tons per year of ~4% U-235 fuel is a large job. Such a reactor fissions about a tonne of U-235 per year, and this requires about 1000 kg of U-235 in the annual supply of fuel to the reactor. You will see in a moment (Row 15 in the spreadsheet) it takes about 151,000 SWU/yr to enrich that fuel from the NU feed of 0.711% to a product of 4.4%, with 0.25% “tails.” On the other hand, to enrich to 90% U-235 one can see from Row 8 that only 231 SWU/kg of U-235 is required, so for an SQ of 25 kg of U-235 only about 5775 SWU would be needed.

The 150,000 SWU/yr plant needed to resupply fuel for the single power reactor at Bushehr could produce one bomb’s worth of HEU every 5775/150,000th of a year or every two weeks. This was the problem in the very beginning, and it is the conceptual problem now for an entity that insists that it needs at some time in the future to be able to provide enriched uranium for its nuclear power plants. For Iran, that need is a long time in the future, and within the confines of the Agreement, enrichment can take place only at Natanz for more than 8 years, with only 5060 IR-1 centrifuges, and with none other. And Iran agrees for 15 years not to explore means of enrichment other than the gas centrifuge.

In connection with other work, I had long distributed a SWU calculator spreadsheet, for instance at http://fas.org/rlg/20.htm

SWU per kg for various enrichment parameters. SWU_Calculations_version_3k.xls R.L. Garwin, 12/19/2007

Row												
3	Xp	Xw	Xf	P	W/P	F/P	Vp	Vw	Vf	ΔSWU/	ΔSWU/	ΔSWU/
4	(product)	(waste)	(feed)	kg	kg W/kg P	kg F/kg P	--------------value function------------------			kg product	kg U-235	P kg of
5	% U-235	% U-235	% U-235	kg of product			----------- (2x-1) ln [x/(1-x)] ---------------- ---				in product	product.
6												
7	95.000	0.250	0.711	1.00	204.53	205.53	2.65	5.96	4.87	220.75	232.37	220.75
8	90.000	0.250	0.711	1.00	193.69	194.69	1.76	5.96	4.87	208.03	231.15	208.03
9	80.000	0.250	0.711	1.00	171.99	172.99	0.83	5.96	4.87	183.46	229.32	183.46
10	19.900	0.250	0.711	1.00	41.62	42.62	0.84	5.96	4.87	41.35	207.77	41.35
11	90.000	0.400	0.711	1.00	287.10	288.10	1.76	5.47	4.87	170.42	189.36	170.42
12	3.500	0.400	0.711	1.00	8.97	9.97	3.08	5.47	4.87	3.64	103.89	3.64
13	90.000	0.400	3.500	1.00	27.90	28.90	1.76	5.47	3.08	65.33	72.58	65.33
14	3.500	0.360	0.710	1.00	7.97	8.97	3.08	5.58	4.87	3.89	111.22	3.89
15	4.400	0.250	0.711	1.00	8.00	9.00	2.81	5.96	4.87	6.66	151.41	6.66
16	3.500	0.400	0.710	1.00	9.00	10.00	3.08	5.47	4.87	3.64	104.02	3.64
17	95.000	0.500	0.711	1.00	446.87	447.87	2.65	5.24	4.87	163.79	172.41	163.79
18	95.000	0.500	19.900	1.00	3.87	4.87	2.65	5.24	0.84	18.85	19.84	18.85
19	19.900	0.711	4.400	1.00	4.20	5.20	0.84	4.87	2.81	6.69	33.62	6.69
20	90.000	0.400	3.500	1.00	27.90	28.90	1.76	5.47	3.08	65.33	72.58	65.33

Enter your desired set of enrichment parameters in Columns B-D for Xp, Xw, and Xf-- the U-235 concentrations in %, and in Col. E the kg of product.
Rows 23-30 are formatted for this purpose, as are Rows 7-20. If you corrupt the worksheet, download it afresh.

24	90.000	2.000	3.670	25.00	51.69	52.69	1.76	3.74	3.03	35.35	39.28	883.76
25	90.000	10.000	19.750	25.00	7.21	8.21	1.76	1.76	0.85	7.46	8.29	186.58
26	90.000	3.670	19.750	25.00	4.37	5.37	1.76	3.03	0.85	10.43	11.59	260.79
27	4.400	0.250	0.711	1.00	8.00	9.00	2.81	5.96	4.87	6.66	151.41	6.66
28	4.400	0.250	0.711	1.00	8.00	9.00	2.81	5.96	4.87	6.66	151.41	6.66
29	4.400	0.250	0.711	1.00	8.00	9.00	2.81	5.96	4.87	6.66	151.41	6.66
30	4.400	0.250	0.711	1.00	8.00	9.00	2.81	5.96	4.87	6.66	151.41	6.66

SWU_Calculations_version_3k.xls. This live spreadsheet, when downloaded to any computer with Excel or a compatible program, allows the user to specify the U-235 concentration (in per cent) for the "product", "waste" or "tails", and the "feed" to an ideal enrichment cascade.
Optionally, the mass of product (kg) in column E can be specified as well. User inputs in Columns B-E result in calculated outputs in Columns F-M

as indicated in Rows 3-4.
Thus, Column F is the kg of waste per kg of product; Col. G is the kg of feed material per kg of product. Cols. H-J provide the value function (2x-1) ln [x/(1-x)] for the product, waste, and feed concentrations, respectively.
The output Columns K-L show the Separative Work Units that must be provided by the ideal cascade to produce 1 kg of product, or alternatively, per kg of U-235 contained in the product. The rate of SWU production (SWU/yr) of an ideal cascade of identical machines is the product of the unit SWU rating of a centrifuge and the number of centrifuges. Thus if a single centrifuge can be operated at 2 SWU/yr, an assembly of 3000 centrifuges could produce 2x3000 = 6000 SWU/yr, and if assembled into a suitable set of series and parallel configurations would produce enriched uranium at a rate illustrated in one of the rows of the spreadsheet. Row 12 shows that 3.64 SWU must be invested per kg of 3.5% U-235, for a cascade fed natural uranium with Xf = 0.711% U-235, and with a waste stream containing Xw = 0.40% U-235.
Thus a cascade rated at 6000 SWU/yr could produce 6000/3.64 = 1648 kg of 3.5% product per year, containing 6000/103.89 = 57.75 kg of U-235.

that enables anyone to provide the concentration of feed, "tails," and product to determine how much separative work would be required in an ideal separation cascade. For proliferation-related questions I find it useful to discuss this in terms of SWU required per kg of U-235 in the product, which I think is much more revelatory than SWU per kg of product.

Iran had some centrifuges running at the time, and it was the declared purpose of the U.S. administration to achieve an agreement with Iran under which “not a centrifuge would turn.” For Iran, its rights or privileges under the NPT were sacred, and among those rights is to benefit from the non-military uses of nuclear energy, including civil nuclear power.

Under the IAEA, a Significant Quantity (SQ) of HEU is 25 kg of contained U-235, and from Row 11 of the SWU calculator, HEU having 90% U-235 contains 189

SWU/kg of U-235, if produced from 0.71% (natural uranium—NU) feed, with a tails concentration of 0.4% U-235. Thus, to produce an SQ in that way would require 25*189 = 4725 SWU, and at an expected rate of about 1 SWU/yr with the IR-1 centrifuge, that would correspond to 4725/500 = 9.5 years of operation of a bank of 500 centrifuges, which limit of 500 seemed acceptable to Iran. Of course, to conduct such enrichment as a member of the NPT, a state would need to justify it as producing fuel for a specialized reactor.

Note, however, that if a state had access to 3.67% U-235, and was willing to enrich to 90% U-235 with a tails concentration of 2%, then the additional SWU required would be 39.28 SWU/kg of U-235 (Row 24). Enrichment that would require 9.5 years from NU feed would thus require only (39.28*25/500) = 1.96 years with LEU feed at 3.67% to produce 25 kg of U-235 in 90% HEU.

Even more concerning is the minimal SWU requirement to obtain 90% HEU from 19.75% LEU feed. With a tails concentration of 10% U-235 this would be 8.29 SWU/kg of U-235 in 90% product, and with a tails concentration of 3.67% (Row 25), thus using (20-3.67)/20 = 83% of the feed) weapon HEU for a total of 207 SWU for 1 SQ of 90% HEU—just 5 months of operation of a 500-centrifuge establishment. For the 5060 centrifuges Iran would be allowed under the JCPoA, the enrichment would take 15 days—highlighting the necessity to restrict the amount of LEU available to Iran, which could serve as feed for enrichment to weapon-usable HEU.

> *2. Iran will begin phasing out its IR-1 centrifuges in 10 years. During this period, Iran will keep its enrichment capacity at Natanz at up to a total installed uranium enrichment capacity of 5060 IR-1 centrifuges. Excess centrifuges and enrichment-related infrastructure at Natanz will be stored under IAEA continuous monitoring, as specified in Annex I. [JCPoA]*

This exercise illuminates the complexity of the agreement, and its both innovative and stringent character. It involves limiting the amount of LEU on hand, abjuring any amount of HEU, and achieving these goals by shipping excess material out of the country, selling it on the market, and the like.

In return, of course, Iran gains relief from sanctions, which will let it sell its oil freely on the market, and trade more or less normally. It will still abide by many restrictions for 8, 10, or 15 years or more, including continued membership in the NPT, adoption of the Auxiliary Protocol—AP—and restriction to a tiny number of the advanced centrifuges that Iran has been working on—specifically the IR-6 and the IR-8. Only after 8.5 years will Iran be able to have more than 30 (each) of these more advanced centrifuges.

The centrifuges at Fordow will be reduced to 1000 IR-1 machines and will never see uranium—instead, they will be used to provide stable isotopes for medical and industrial purposes.

It is not very polite in diplomatic circles to speak of "breakout" or response to breakout, but surely such questions are taken into account on both sides. An array of 5060 IR-1 centrifuges, even if operating at 1 SWU/yr, never achieved thus far by Iran under strict reporting by IAEA, would take more than a year to produce 1 SQ from natural uranium. But if fresh fuel for Bushehr, delivered on site by Russia, were seized by Iran, converted to UF6 and fed even to the 5060 centrifuges, Row 20 in the Table shows that only 73 SWU need be added per kg of U-235 in the product, so on the order of 1825 SWU (4.3 months) to produce 25 kg of U-235 in weapon uranium starting from Bushehr fuel. And less than one ton of the 25-ton annual refueling would be consumed in this process.

Evidently, the continuous monitoring of the sanctity of Bushehr fresh fuel is important and interference with this reporting link would be taken as violation of the Agreement.

Iran would do well to provide instant reassurance that all was well rather than to delay an urgent inspection.

One should not imagine that the intelligence capabilities of interested parties to this agreement will deteriorate over the years, and means for intervention will also have a high priority, although one hopes they would never be invoked.

Other aspects of the Agreement are also important. Acquiring nuclear weapons would not improve the security of Iran, in my opinion, especially if it resulted in the acquisition of nuclear weapons by nearby states. One can be sure that the EU and the United States will attempt to use their good offices to try to limit proliferation of nuclear weapons to others in the area.

In addition to enrichment of non-uranium stable isotopes at Fordow, Iran will undertake other nuclear-energy research there, and will, one hopes, work with foreign scientists to contribute to the world's advancement in civil fusion energy, medical and industrial imaging, and the like.

It will be a boon to be able to work with our Iranian scientific colleagues on common problems.